Carolinas Integrated Sciences and Assessments
Department of Geography
University of South Carolina

Assessing the Impact of Saltwater Intrusion in the Carolinas under Future Climatic and Sea Level Conditions

PREPARED BY:

Carolinas Integrated Sciences and Assessments

S.C. Sea Grant Consortium

SUPPORTED BY:

National Oceanic and Atmospheric Administration

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Executive Summary

The goal of this research is to support coastal decision-makers in North Carolina and South Carolina by providing information about potential future precipitation and sea level conditions under increased climate variability and by examining how industries, community water and sewer districts, and coastal resource managers might adapt to future changes in the freshwater supply. To this end, scientists from the Carolinas Integrated Sciences and Assessments (CISA), United States Geological Survey (USGS) South Carolina Water Science Center, and Advanced Data Mining International (ADMi) investigated the threat of saltwater intrusion in the Yadkin-Pee Dee River (YPDR) basin under conditions influenced by ongoing and future climatic change, with an emphasis on changes in the frequency and duration of saltwater intrusion events with increasing sea levels. In addition, project leaders enhanced a decision support system (DSS) that is relevant and user-friendly to incorporate planning for future coastal climate change. Of central focus in this study was the ever-present need to address how humans will respond to ongoing and future changes in our environment, particularly under climatic regimes that may not have been felt by present society.

The primary components of the project included empirical and mechanistic modeling of hydrologic conditions in the YPDR system to determine freshwater discharge and resulting salinity intrusion at the coast under future climatic conditions and sea level rise and updating an existing DSS to address saltwater intrusion challenges for resource managers, industry, and water and sewer districts in the study basin. The project team used the Environmental Protectin Agency (EPA) BASINS HSPF model and the "Pee Dee River and Atlantic Intracoastal Waterway Salinity Model" (PRISM) (Conrads and Roehl 2007) to conduct the empirical and modeling analysis. The updated PRISM2 DSS allows users to adjust sea level rise and flow levels in the YPDR basin to generate scenarios of how future climate change (e.g., the potential for more frequent drought conditions) and sea level rise may impact the inland penetration and duration of saltwater intrusion events.

The S.C. Sea Grant Consortium, CISA, and the North Inlet-Winyah Bay National Estuarine Research Reserve (NERR) held a stakeholder workshop on December 14, 2011, in Georgetown, SC, to discuss saltwater intrusion planning challenges and information needs with regional decision makers and to obtain their input regarding the utility of the PRISM2 DSS. Attendees included resource managers, planners, water/sewer utility managers, non-governmental organization (NGO) representatives, private consultants, and education and outreach specialists. Participants were introduced to three alternative flow scenarios that simulated potential impacts from climate change and its resulting effects on the frequency and longevity of saltwater intrusion events in relation to decreased streamflow and rising sea levels.

Workshop participants highlighted several major ecological and water supply infrastructure concerns that would have to be addressed under the provided scenarios. They also contributed salient feedback regarding additional needs for information, planning tools, and procedures. Relevant to the interests of regional stakeholders, the PRISM2 DSS demonstrated the effects of salinity intrusion events on the frequency and duration of higher conductance values in water sources. Such events are 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. Participants suggested that with the addition of further pertinent information (e.g., ecological/species salinity thresholds), the PRISM2 DSS can help decision-makers plan for future severe events (e.g., positioning freshwater intakes and treatment facilities, preparing for increased treatment costs) while increasing the region’s resilience by encouraging preparation for potential changes in the frequency and magnitude of saltwater intrusion events.

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Introduction and Background

To preserve our coastlines and the valuable ecosystem services they provide, managers of coastal systems and other stakeholders need tools and information that help them understand potential climate change impacts. Coastal regions are experiencing dual stresses from increasing human demands for coastal environmental resources and ecosystem services and changing natural conditions, including climate change (Zhang and Leatherman 2011; Scavia et al. 2002). One consequence of these stresses is the shifting balance between freshwater and saltwater quantity and quality. Anthropogenic changes in inland environments alter the delivery of freshwater, nutrients, and other chemical compounds into coastal estuaries. Simultaneously, the impacts of climatic variability and climate change along the East Coast of the United States are likely to include accelerated sea level rise and increased inter-annual climate variability (e.g., more frequent droughts and floods) (Karl et al. 2009; Konrad et al. 2012). As sea levels rise, coastal environments will experience changes in both physical processes, such as greater erosion and inundation rates, and chemical processes, such as increasing likelihood of saltwater intrusion further into freshwater estuaries and rivers.

Broadly speaking, average annual temperatures in the Southeastern United States rose about 1.1°C since 1970, and are projected to increase by 2.5 – 5°C by the 2080s, depending on greenhouse gas emission scenarios (Karl et al. 2009). Precipitation changes are not as predictable as temperature trends, thus several possible hydrological conditions must be considered when evaluating future change. Over the past 30 years, inter-annual summer precipitation variability has been higher over seven Southeastern states (including the Carolinas), with a tendency toward more extremely wet and extremely dry summers (Wang et al. 2010). In general, precipitation levels are projected to increase across the Southeast, but seasonal increases in evaporation may offset these increased amounts of precipitation, making it just as likely that water supplies could decrease (Seager et al. 2009).

One of the more salient concerns for coastal regions in the Carolinas regarding on-going and future climatic warming is global sea level rise due to the thermal expansion of water and the melting of major portions of the Greenland and West Antarctica ice sheets (Kemp et al. 2009; Kirwan and Temmerman 2009; Moorhead and Brinson 1995). Many factors govern the relative sea level rise that may be observed in the Carolinas, including local rates of subsidence, offshore currents, and wind patterns. Recent sea level rise rates in Wilmington. NC are on the order of 2.07 mm/yr (1935-2006) based on tidal gage records, whereas a shorter tidal gage record at Springmaid Pier (1957-2006), Myrtle Beach, SC, the closest record to the Pee Dee River, provides an increasing rate of 4.09 mm/yr (NOAA Center for Operational Oceanographic Products and Services 2011).

Saltwater intrusion into freshwater coastal rivers and aquifers has been, and continues to be, one of the most significant global challenges for coastal water resource managers, industries, and agriculture (Ferguson and Gleeson 2012; Niemi et al. 2004). Coastal ecosystems are among the most economically productive areas and densely populated regions in the world (Barbier 2012; Costanza et al. 1997), yet rapid development and increasing water resource consumption is leading to reductions in both the water table and surface water flow. The decline in land-to-ocean water flow is a serious problem in coastal areas because further reductions in surface and groundwater regimes may accelerate the landward movement of the freshwater-saltwater interface. Numerous studies have reported on saltwater intrusion in the United States (Barlow and Reichard 2010) and along Atlantic coastal states, including areas in the Carolina coastal region (e.g., Barlow and Wild 2002). 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 (Barlow and Reichard 2010). The landward movement of saltwater into freshwater environments is also likely to accelerate as a result of sea level rise, climate variability, and drought (Meisler et al. 1984; Ranjan et al. 2006).

Drought conditions greatly exacerbate the saltwater intrusion problem in the Carolinas by reducing freshwater flow into estuaries, thereby allowing the saltwater wedge to move further and further upstream. The saltwater wedge may then come into contact with intakes from industrial centers and water and sewer districts. In the past 15 years alone, there have been two major periods of drought across the Carolinas, which have led to reduced streamflow and reservoir storage and increased vulnerability of community water systems to potential shortages (NCDENR 2004; Weaver 2005). By September 2002, the Pee Dee River was flowing at discharges that were less than half of normal despite the release of water from dams closer to the headwaters in North Carolina (Hicks 2002). During this same period, saltwater intrusion from Winyah Bay reached at least 12 miles inland to the point where drinking water supply intakes became greatly threatened from high salinity levels. In fact, the water supply intake for the city of Georgetown, located 26 miles upstream, was briefly taken offline in August 2002 because of high salinity levels. The problem was repeated during the dry summer of 2011 when heavy rains were too isolated, rapidly increasing inland penetration of the saltwater wedge, which prevented local utilities from withdrawing water from the Waccamaw River at high tide in mid-July (Fuller 2011).

Research Objectives

The goal of this research is to support coastal decision-makers in North Carolina and South Carolina by providing information about potential future precipitation and sea level conditions under increased climate variability and by examining how industries, community water and sewer districts, and coastal resource managers might adapt to future changes in the freshwater supply. To this end, the study investigated the threat of saltwater intrusion in the Yadkin-Pee Dee River (YPDR) basin under conditions influenced by ongoing and future climatic change, with an emphasis on changes in the frequency and duration of saltwater intrusion events with increasing sea levels. Additional goals included 1) enhancing the existing "Pee Dee River and Atlantic Intracoastal Waterway Salinity Model" (PRISM) (Conrads and Roehl 2007) to conduct the empirical and modeling analysis, and 2) engaging with regional stakeholders to obtain their input regarding the utility of the PRISM2 decision support system.

Study Area

The study area, consisting of three different watersheds, spans North and South Carolina. *Figure 1* on page 8 shows each watershed that was modeled, as well as stream channels. Each watershed has a unique Hydrologic Unit Code (HUC). The YPDR is the largest of the three watersheds in the study, and it was split into nine smaller sections by 8-digit hydrologic unit code (HUC-8) watersheds for calibration purposes. These watersheds include the Upper Yadkin, South Yadkin, Lower Yadkin, Upper Pee Dee, Rocky, Lower Pee Dee, Lynches, Lumber, and Little Pee Dee river watersheds. The YPDR begins in North Carolina, where it is called the

Yadkin River, and also includes a small area in southern Virginia. Just north of South Carolina, it becomes the Pee Dee River, flowing through the northeastern section of South Carolina before its confluence with the Waccamaw River just north of Winyah Bay.

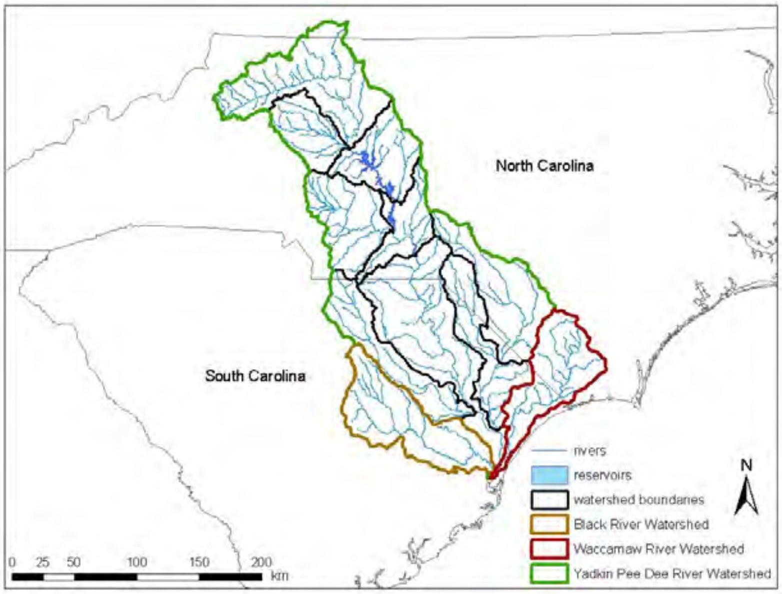

Figure 1. Major hydrographic features of the study area.

The Waccamaw River begins in the southern part of Bladen County in North Carolina. The river flows along the Carolina coast, at times bordering on the Intracoastal Waterway in South Carolina, before reaching the Winyah Bay in Georgetown, South Carolina. The Black River flows through eastern South Carolina, beginning in Kershaw County and flowing along an easterly path before its confluence with the Pee Dee and Waccamaw rivers near Georgetown. The three rivers converge into the Winyah Bay, where the water finally reaches the Atlantic Ocean.

Project Design and Methods

This study was comprised of two primary components. The first component involved empirical and mechanistic modeling of hydrologic conditions in the YPDR system to assess variability in freshwater discharge and resulting salinity intrusion at the coast under future climatic conditions and sea level rise scenarios. Second, project leaders updated existing decision support tools to address challenges associated with saltwater intrusion for industry, water and sewer districts, and individuals in the lower YPDR basin.

The US Environmental Protection Agency (EPA) Hydrologic Simulation Program-Fortran (HSPF) model, a part of the BASINS[1] environment analysis system, has been calibrated and verified for the Waccamaw, Pee Dee, and Black Rivers. HSPF is a continuous simulation, watershed model capable of simulating streamflow at daily and hourly time-scales. The

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[1] http://water.epa.gov/scitech/datait/models/basins/index.cfm

calibrated model was driven under future climate scenarios to generate a streamflow time series that was used as an input into the PRISM model developed by Conrads and Roehl (2007). The PRISM model uses tidal range, mean water level, and streamflow data inputs in artificial neural network (ANN) submodels to estimate specific conductance, and therefore salinity responses, of water discharge under various scenarios. The original PRISM DSS tool was developed in conjunction with YPDR basin stakeholders in Microsoft™ Excel® for the purpose of supporting the FERC (Federal Energy Regulatory Commission) re-licensing process for hydroelectric facilities in North Carolina that regulate some of the flow into the YPDR basin (Conrads and Roehl 2007).

However, in an effort to enhance the usefulness of the PRISM DSS, study leaders set out to provide opportunities for users to manipulate model simulations of 1) streamflow for controlled and uncontrolled rivers in the area, and 2) the degree of sea level rise to allow scenario planning among user groups. To do so, the PRISM model was revised to incorporate inputs from Global Circulation Models (GCMs), sea level rise scenarios, and changing streamflow patterns as a result of precipitation and temperature change. The revised model is called PRISM2 and an enhanced DSS was created to complement the model. For this project, the necessary data to incorporate these elements was acquired through the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) website and the North Carolina State Climate Office. The development of the PRISM2 model involved three central components:

- **Calibrating HSPF**: An automatic calibration program, Parameter Estimation (PEST) was the primary tool used for calibration. Some manual calibration was employed whenever needed. Sensitivity analyses conducted for two of the eleven HUC-8 watersheds to determine if the values generated by PEST were truly the best confirmed PEST's ability to optimize parameter values. Model performance was assessed using several widely recognized statistics (Moriasi et al. 2007) with most reliance on the coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE). A summary of these statistics can be found in *Appendix A*.
    - During the process of calibration, it was determined that precipitation inputs from individual stations were not sufficiently representative of the weather patterns occurring in these watersheds. An area-weighted approach using Thiessen polygons was developed to address this issue (e.g., Grant et al. 2004).
    - Calibration of watersheds located in the Coastal Plain ecoregion required additional steps for two primary reasons. First, the precipitation patterns on the Coastal Plain are more complex than in the Piedmont due to oceanic influence, especially during warm months. Second, streamflow in the Piedmont is closely coupled to surface runoff while in the Coastal Plain there is a much stronger linkage to the surficial aquifer and shallow return flow of infiltrated precipitation. To address the latter problem, changes were made to a number of channel attributes (FTABLES) to influence the volume of flow that an individual reach could hold, such as mean depth and width, side slopes, and maximum channel depth.

- **Downscaling Climate Scenarios**: Continuous simulation watershed-scale models, including HSPF, need meteorological inputs at a finer temporal and spatial scale than a typical GCM output. We used Dr. Katharine Hayhoe's statistically downscaled projections from four Global Circulation Models (GCM), CCSM3 (National Center for Atmospheric Research

(NCAR), USA), GFDL CM2.0 (Geophysical Fluid Dynamics Laboratory, USA), ECHO (Meteorological Institute, University of Bonn, Germany and Meteorological Research Institute of KMA, Korea), and PCM (NCAR, USA) for the A2 emission scenario. The dataset is available under the USGS Geo Data Portal[2] (GDP) project and is based on a modified quantile regression approach. This downscaling method allows the mean, as well as the shape of the distribution of meteorological variables, to change with time (in contrast to other simpler methods) and is expected to work well for impacts that are sensitive to daily and weekly mean and variability (Terando et al. 2010; Vrac et al. 2007). Prior to using the downscaled output, we disaggregated the temperature and precipitation from a daily time-scale to an hourly time-scale, and calculated hourly potential evapotranspiration (from the maximum temperature and minimum temperature) using the built-in algorithms in BASINS-HSPF.

- **Salinity Intrusion Model**: The method for simulating salinity intrusion in the Waccamaw River and Intracoastal Waterway (PRISM DSS) and the Savannah River (M2M DSS) is documented in Conrads et al. (2006) and Conrads and Roehl (2007). The development of the ANN models used USGS streamflow, water level, and specific conductance data from the real-time network along the Grand Strand of South Carolina and the Savannah River in Georgia. 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. In addition, tidal dynamics are a dominant force for estuarine systems, and a tidal range variable was utilized to determine the lunar phase of the tide. The primary chaotic inputs to this system are the flows and the chaotic oceanic disturbances represented in the chaotic component of coastal water level. Water-level time series (or signals) were decomposed into periodic and chaotic components using filtering techniques. Individual ANN models for predicting specific conductance were developed for selected continuous coastal stream gages. To simulate the effect of climate change and sea level rise (SLR), the PRISM DSS was modified to allow user-defined inputs of incremental SLR along with the user-defined inflow hydrographs to the system.

Results

Of significance to regional stakeholders, the PRISM2 DSS demonstrated the effects of salinity intrusion events on the frequency and duration of higher conductance values in water sources. It is problematic for the operations of municipal water treatment plants when the specific conductance values for raw source water are greater than 1,000 to 2,000 µS/cm. Analysis of the frequency distribution of the specific conductance level response at the Pawleys Island stream gage to adding a 1.0 ft (30.5 cm) and a 2.0 ft (61 cm) sea level rise on top of levels for the period July 1995 to August 2009 indicated that a 1-ft sea level rise doubled the frequency of occurrence of specific conductance above 2,000 µS/cm to 8 percent of the day (*Figure 2*). A 2-ft sea level rise quadrupled the frequency to 14 percent of the time. For the 14-year simulation period, the number of days of specific conductance level at or above 2,000 µS/cm was 191 days for the observed sea level conditions. A 1-ft sea level rise increased the number of days to 399 and a 2-ft rise increased it to 697 days.

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[2] http://cida.usgs.gov/climate/gdp/

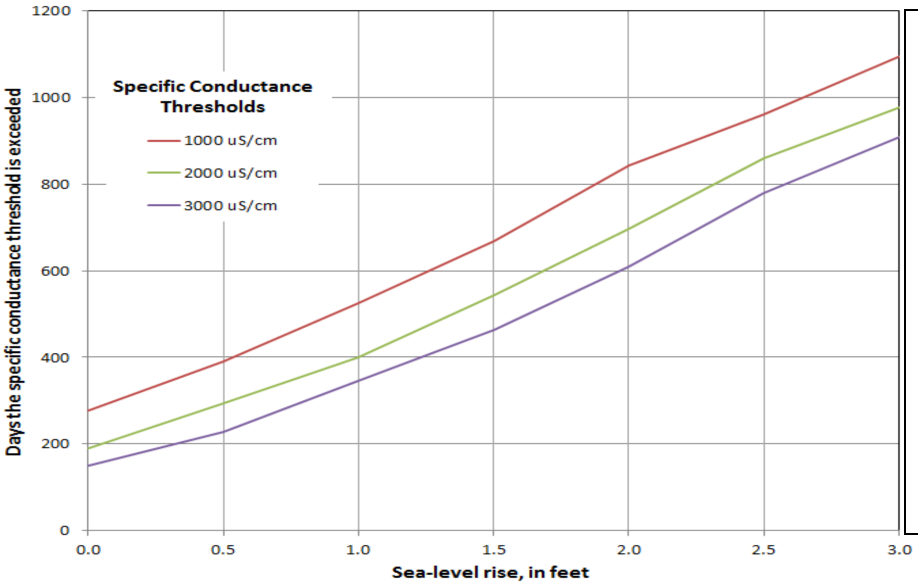

Figure 2: Plot showing the number of days specific conductance thresholds are exceeded for incremental sea level rise on the Waccamaw River near the Pawley's Island water intake for the period July 1995-August 2009.

The combination of sea level rise and reduced streamflow conditions was also evaluated. Nomographs of sea level rise and the number of days specific conductance threshold values were exceeded were developed from multiple model simulations (*Figure 3*). The specific conductance response was evaluated for combinations of sea level rise and reduced streamflows. Historical streamflow values were reduced by 5 percent increments down to 75 percent of historical observed flows.

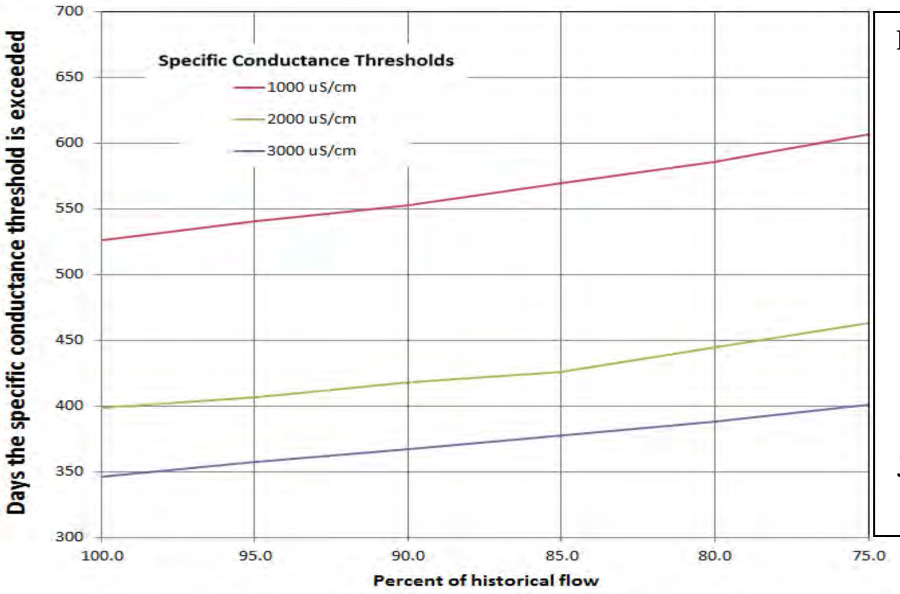

Figure 3: Plot showing the number of days specific conductance thresholds are exceeded for incremental decreases in the historical flow on the Waccamaw River near the Pawley's Island water intake for the period July 1995-August 2009

Stakeholder Workshop

During the development of the PRISM2 DSS, interviews with key informants revealed that PRISM2 would have two distinct audiences: water utilities, who will use the tool itself, and other managers, advocates, and educators, who are very interested in the scenario results and their applications. To disseminate project results and elicit feedback from both of these stakeholder groups, a workshop was held on December 14, 2011, in Georgetown, SC. The 26 attendees included resource managers, planners, water/sewer utility managers, NGO representatives, private consultants, and education and outreach specialists (*Appendix C*).

Participants were introduced to three climate change scenarios (described in the following sections) and the potential impacts on the frequency and longevity of saltwater intrusion events in relation to decreased streamflow, rising sea levels, and a combination of the two.

Breakout sessions allowed attendees to discuss the models and provide feedback on how to improve them. Participants were specifically asked to focus on three questions during break-out discussions:

1. What would the ecological and water supply management impacts be under this scenario?
2. In the next 30 years, what management decisions could be made that would reduce the threat of these impacts?
3. How is the PRISM2 DSS information useful for making these decisions and what additional data is needed?

Following the breakout sessions, a large-group discussion focused on the usefulness of the information provided in each scenario.

The following sections provide descriptions of the three climate scenarios considered by participants in the breakout sessions, brief summaries of the major themes, and recommendations regarding potential management decisions and information needs. The last section reviews the central issues that emerged in the final discussion session.

Scenario One: Reduced Flow

Scenario One was based on reduced flows. It was designed to simulate salinity intrusion levels had the recent time period (i.e., 1995-2009) been drier. To demonstrate this, the measured flows for 1995-2009 were reduced by 5%, 10%, 15%, 20%, and 25%. Participants were provided with four graphs of information: 1) reduced total flow figures under reduced scenarios, 2) percentage of total days in the time period where conductance thresholds of 1000, 2000, and 3000 µS would have been exceeded, 3) the number of events lasting one day or more where specific conductance exceeded 1000, 2000, and 3000 µS due to flow reduction, and 4) the average duration of events lasting one day or more where specific conductance exceeded 1000, 2000, 3000 µS due to reduced flow reduction.

Ecological and Water Supply Impacts

Participants identified the need to relate specific conductance to salinity to link this output with ecological impacts. One group also noted the need to go further than this and identify specific ecological impacts due to salinity intrusion. Participants expressed that changes in habitat will be key drivers in species change. For example, riverine wetlands and seasonally managed wetlands will be lost as salinity increases. Plant stress begins at 2-3 parts per thousand (ppt) and 5 ppt causes a noticeable impact. Other ecological impacts will be felt in the estuaries and reduced flows may alter the sedimentation rate. Participants noted that because of the potential for ecological impacts, the US Fish and Wildlife Service needs to begin thinking about plans that balance traditional fixed management goals with predictions of habitats in motion.

Species-specific ecological impacts mentioned included impacts to fish stocks in Lake Waccamaw. Some reduction in migratory fish stocks is expected with reduced flow. Increasing frequency and duration of hypoxic events resulting from reduced flows also contribute to the impacts to fish stocks. Other related impacts on fish stocks included the potential for a decrease in zooplankton and chlorophyll-nutrient content.

The duration of a reduced flow event was cited by one individual as the biggest factor in determining potential ecological impacts of reduced flow. The longer an event persists the more likely the damage, which is why it was also noted that 1000 µS was not viewed as a critical short-term ecological concern. Others highlighted the time of year as being significant, especially when attempting to determine what type of ecological impacts should be considered.

The discussion on water supply management impacts highlighted several issues. Increasing episodes of reduced flow could affect water supply and quality and lead to a range of impacts, including the overuse of alternate supplies and enacting water restrictions. Salinity events could lead to surface water intake shutdowns that would result in greater pressures on groundwater resources and possible groundwater depletion. There may also be higher treatment costs that would eventually be passed on to consumers. Salinity threats to water supply could be exacerbated by population growth and increasing water demands. Many water systems currently have drought management plans, but these plans may not consider the possibility of increased high conductance or salinity events in the future

Some discussion focused on past events and how these events affected water management. For example, Myrtle Beach had a salinity event in 2002, although the plant did not have to shut down. Instead, the event required the utility managers to monitor the levels and remain cautious. The plant came close to shutting down due to impacts from Hurricane Hugo in 1989; however, this was a short-term event and unlike the event caused by prolonged drought. One individual reflected that salinity intrusion into groundwater wells was one reason that Myrtle Beach and the Grand Strand Water and Sewer Authority ceased to rely on such wells for water supply.

Management Decisions

Participants discussed several types of water management and planning decisions that could be made to reduce the threat of low-flow impacts. Longer-term planning was viewed as particularly important if population and demand on water resources were to continue to increase in the future. Discussion centered on 1) regional management of watershed supplies, allocation, withdrawals, and the need to consider the impacts of upstream withdrawals on downstream water supplies, 2) measures that individual systems could consider to prepare for future salinity events, including developing salinity management plans, building new infrastructure (e.g., freshwater impoundments, storage ponds) to expand storage capacity and secure water supplies, and enhance capacity to treat saltwater through reverse osmosis systems, and 3) strategies and tools to reduce customer demand such as voluntary water restrictions, public awareness or education campaigns to encourage conservation, and incentives to reduce water use for landscape irrigation.

Information Evaluation and Needs

Participants suggested information that could be included to increase the ability to plan under this scenario. For example, participants felt there should be maps of the extent of the salt wedge in addition to the frequency and duration of events exceeding thresholds. The emphasis on location over frequency might help to determine ecological impacts for varying species, like crabs and dolphins, since more is known about their range than their tolerances to salinity levels. There were also suggestions about determining how land conversion and use in the watershed might impact flows, especially forested wetland conversion. Participants also felt that there should be better guidance on how much time is available to develop solutions or mitigation approaches before the event occurs. Knowing the regulatory demarcation and incorporating the locations of certain fisheries was also noted as important. Participants shared a concern that there is not yet sufficient specific local information available to adequately inform planning for this scenario.

Scenario Two: Sea Level Rise

Scenario Two was based on sea level rise. The measured flows for the period 1995-2009 were reduced by 0.5 ft, 1.0 ft, 1.5 ft, 2.0 ft, 2.5 ft, and 3.0 ft to simulate how salinity intrusion events may have occurred if mean sea level had been higher. Participants were provided with graphs that used increased sea level rise increments to predict total flow, the total number of days over the simulation period that salinity exceeded conductance thresholds, the number of salinity intrusion events, and the duration of salinity intrusion events.

Ecological and Water Supply Impacts

Some participants pointed to impacts on the intertidal wetlands and systems that would be affected by an increase in water levels. Specific concerns centered on marshes and their susceptibility to open water. The ability of marshes to migrate inland in response to higher water levels and higher salinities was questioned. Several participants noted ongoing research on this issue which is being conducted in the area. The potential for die-outs of hardwood and forested wetlands from salinity impacts was a concern. Direct changes in shoreline geomorphology, rock revetments, and bulkheads due to increased sea levels were highlighted as well.

Water management concerns focused on the ability of water treatment plants to operate at their current locations. Under increasing sea level rise, it is possible that one of the systems represented at the workshop would not be able to draw freshwater from its existing intake. This system might need to consider alternative sources of water supply, for example groundwater wells or water purchases from other systems.

Management Decisions

Regarding continued water supply, participants suggested that investments should be made in desalinization technology, water reuse systems, and aquifer storage and recovery wells. There were also concerns that the current location of infrastructure may be problematic in the future, and that relocation may become necessary. After reading the graphs, some participants thought that 1.5 feet of sea level rise seemed to be a threshold for longer intrusion events, so this might need to be integrated into management decisions. Other participants highlighted the uncertainty of predicting future events and indicated that it was difficult to suggest specific management decisions without additional visualization.

With these impacts in mind, participants suggested that adaptive management plans and tools should be developed to prepare for future potential events. Some concrete ways to achieve this would be to alter land use patterns and policies in vulnerable areas, develop local and state regulations to guide shoreline development, incorporate regional data into management plans, and develop regional collaboration and policies.

Information Evaluation and Needs

Participants commented that it seemed more difficult to consider scenarios that only change a single variable, such as flow or sea level. They would prefer more holistic scenarios that allowed for changes in multiple variables. Other concerns pertained to the uncertainty of when these events may happen. Many participants wanted to know more specifically how much time could be spent planning for the next event. They noted that rates of sea level and climate change are currently uncertain, but these rates are the subject of continuing investigation. Some participants also had related questions about when the saltwater wedge might move, which were difficult to answer due to the same issue of understanding rates.

Scenario Three: ECHO General Circulation Model Simulation

Scenario Three used the global coupled ocean-atmosphere general circulation model ECHO to simulate precipitation input and sea level rise for the projected time period 2055-2069. The research team selected this model for the scenario exercise because of its ability to predict the flows and specific conductance levels over the measured 1995-2009 period and compare these results with observed data to determine how well ECHO performs. ECHO underestimated the percent of total days in the historical period when specific conductance thresholds were exceeded, the number of events, and the average duration of events. To correct this, the ECHO generated graphs were adjusted to account for this bias.

Six graphs were distributed to participants for the ECHO scenario:

- The first graph depicted total flows as simulated and observed for 1995-2009 and as simulated for 2055-2069.
- The second graph showed cumulative flows in the same manner.
- The third graph showed the percent of total days during the 1995-2009 time period where thresholds of 1000, 2000, and 3000 µS would have been exceeded under both observed and simulated conditions.
- The fourth graph displayed the percent of total days during 2055-2069 where thresholds of 1000, 2000, and 3000 µS would be exceeded under simulated conditions.
- The fifth graph depicted the number of events as projected by ECHO lasting one day or more over the 2055-2069 time period.
- The sixth graph showed the average duration of events lasting one day or more as simulated for 2055-2069.

Due to time constraints, only one of the breakout groups addressed the third scenario. The following sections highlight the key points from this group's discussion.

Ecological and Water Supply Impacts

Ecological concerns focused on habitat change (e.g., estuary creep, increased sedimentation, and shellfish impacts) that could result from combined flow and sea level rise changes. Some participants observed that currently protected areas may be subject to pressure from development if individuals in at-risk areas are forced to move.

Discussion of water supply impacts centered on the impacts sea level rise could have on homes and beachfront property. Potential impacts to septic systems were noted as another concern. They also noted that such impacts could also affect the regional economy which is dependent on the tourism industry and beachfront amenities.

Management Decisions

Time constraints prohibited full discussion of this question. Most of the discussion focused on the potential impacts to ecology and water supply and how the scenario information could be improved to better determine ecological and structural impacts.

Information Evaluation and Needs

Participants mentioned that a map of the potential impacts would be helpful. Also, increasing the time frame of the scenario from 14 to 20 years would be more relevant for infrastructure planning. To determine potential impacts to a proposed plant and its location, the time periods in the scenarios would need to match the infrastructure planning periods (30-40 years) used by water systems.

Central Themes from the Large-Group Discussion

Following workshop break-out sessions, participants engaged in a large-group discussion regarding the usefulness of the PRISM2 DSS, the information it provides, and opportunities for improvement. Several central themes emerged from this discussion.

Salinity Intrusion Thresholds

Most participants felt that it is easier to identify salinity thresholds and threats for water supply rather than for habitat, since much uncertainty remains regarding ecological thresholds for many species and ecosystems. For example, the characteristics of flushing, flow, and salinity pulses that lead to habitat change are still unknown. Several participants suggested coupling the Sea Level Affecting Marshes Model (SLAMM) with PRISM2 to examine these uncertainties. Participants suggested that Scenario Three could be improved or made more useful by incorporating a layer that demonstrated projected habitat conversion. It was also recommended that any additional water quality monitoring designed to improve understanding of ecological impacts should mesh with existing monitoring practices. Study parameters might include tracking hypoxia via chlorophyll content and zooplankton counts. One participant inquired about the state of knowledge on runoff and recharge by land use type, highlighting the need for this information.

Time Scale of PRISM2 DSS Output

For those stakeholders concerned about ecological impacts, the monthly time scale utilized in PRISM2 DSS works for the assessment of biotic systems. However, water managers prefer hourly data to make management decisions. These managers mentioned that, at the very least, a six hour window of data would be more helpful, since this corresponds with the tidal exchange that would be most relevant to their intake valves. For these stakeholders, more refined data is necessary due to the rapid pace of intrusion events. Participating climate scientists observed that providing downscaled climate model projections with hourly data was not done and not recommended because the models do not have sufficiently refined precision to support an hourly application.

Data Output and Display

One participant recommended that maps that included landscape and elevation layers be used to visually represent model output. Other participants agreed that this type of graphic would be helpful for water managers as well as resource and habitat managers. Several participants commented that to facilitate ease of understanding among elected leaders or the public, outputs should be relatively simple and easy to interpret. Water utility managers found data on water quality at intakes to be the most valuable form of data output. Along these lines, if an output map could depict a specific coverage area, it would be especially helpful in determining where a new intake valve should or could be established. Overall the ECHO projections were considered to be the most useful, provided the projections are relatively accurate. However, it was recognized that many other variables still need to be included to be most useful to potential users. For example, several participants suggested that inclusion of tropical storms and hurricanes was necessary to increase the ECHO model's efficacy.

Summary and Next Steps

The PRISM2 DSS was updated to help YPDR basin decision-makers explore potential changes in freshwater discharge and coastal salinity intrusion events under future climatic conditions and sea level rise. The S.C. Sea Grant Consortium, CISA, and North Inlet-Winyah Bay NERR sponsored a workshop for resource managers, planners, water and sewer utility managers, NGO representatives, private consultants, and education and outreach specialists to learn about drought and salinity intrusion in the YPDR basin. Workshop participants evaluated three flow scenarios created using PRISM2 DSS that considered the impacts of reduced flow and sea level rise both by incremental adjustments and based upon downscaled data from the ECHO model.

All 15 of the 26 participants who completed a workshop evaluation agreed that participating in the workshop was a good use of their time. Nine of the 15 anticipated using some of the workshop information in their work or decision-making; the remaining six indicated they might use the information in their work or decision-making. Many participants noted in their comments that the discussion and scenario exercises were extremely valuable. The participants made several observations about next steps through both a large group discussion and workshop evaluation forms:

- Salinity thresholds are very different for water management and land management stakeholders: The chosen thresholds for workshop scenarios were useful for water management. However, participants were uncertain if lower thresholds would be sufficient to drive changes in habitat. More information is needed about critical salinity thresholds that may alter coastal YPDR basin habitats.
- Maps may be more useful for decision-making: Many stakeholders, especially resource managers, expressed that maps are needed to supplement the graphical PRISM2 DSS output. This type of visual was thought to be critical for applications such aslike determining where water intakes should be moved or for conserving areas where habitats

may be expected to move in response to increased salinity. Further work is needed to tie PRISM2 DSS results to spatial data, including elevation data.
- Having representatives from different sectors and stakeholder groups helped to build a comprehensive perspective on saltwater intrusion concerns for the region: In particular, participants noted that the utility management perspective was very useful during the breakout sessions in helping to interpret the information provided, and including this perspective would be useful in regards to providing a comprehensive perspective on the issue. Future meetings should continue to appeal to a diverse stakeholder audience and include opportunities for networking.

About CISA

The Carolinas Integrated Sciences and Assessments (CISA) research collaborative integrates climate science into decision-making by developing information, tools, and processes to support planning and management processes across North Carolina and South Carolina. CISA is one of 11 Regional Integrated Sciences and Assessments (RISA), a NOAA-sponsored program that seeks to advance scientific understanding of climate variability and change and improve society's ability to respond to climatic events and stresses. A hallmark of the RISA program is the focus on partnerships between scientists and decision-makers to produce usable, useful, and accessible climate information. CISA's core activities encompass five general focus areas: drought, climate and watershed modeling, coastal climate, health, and adaptation. Current CISA projects include working with decision-makers on improving their adaptation to drought, linking climate variability to watershed and land use planning, coastal adaptation planning, and characterizing climate vulnerability in the region. For more information, visit www.cisa.sc.edu

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Appendices

Appendix A: Daily Discharge (cubic feet per day-cfd) calibration statistics calculated for each Watershed

Watershed (HUC)	Calibration Point	R^2	Mean (cfd)	Std dev (cfd)	NSE	P BIAS (%)	Coefficient of Efficiency
3040101	1	0.7762	343.645	330.177	0.7751	1.730	0.9305
	2	0.8757	2629.449	2247.261	0.8756	0.785	0.9657
	3	0.8775	1350.651	1082.518	0.8763	1.687	0.9670
	4	0.8082	3518.232	2921.471	0.8067	-1.273	0.9457
3040102	1	0.8266	244.283	311.381	0.8266	-0.654	0.9501
	2	0.8064	408.169	442.663	0.8054	-1.147	0.9450
	3	0.7495	129.003	205.100	0.7495	0.227	0.9227
3040103	1	0.6721	250.783	446.164	0.6642	-14.293	0.8968
3040104	1	0.7448	114.444	298.957	0.7431	10.196	0.9223
3040105	1	0.7912	74.539	194.431	0.7850	-5.949	0.9311
	2	0.8889	1690.573	3548.554	0.8848	-5.006	0.9666
3040201	1	0.6674	202.377	109.595	0.6669	-0.775	0.8926
	2	0.7356	11011.62	10083.146	0.6438	0.379	0.9181
3040202	1	0.6495	30.541	51.130	0.6487	-1.611	0.8848
	2	0.6625	1113.268	880.193	0.6622	1.767	0.8882
3040203	1	0.7536	202.348	144.926	0.7472	1.717	0.9293
	2	0.6838	171.443	159.344	0.6818	-0.995	0.9017
	3	0.7004	1033.700	703.147	0.6979	-0.076	0.9097
3040204	1	0.7045	85.567	54.523	0.7032	-0.808	0.9093
	2	0.6502	2300.205	1616.582	0.6401	-4.334	0.8912
3040205	1	0.6866	501.926	528.364	0.6216	-26.530	0.8983
	2	0.7777	1222.190	945.441	0.7307	-19.386	0.9278
3040206	1	0.5489	782.261	1103.783	0.5206	17.709	0.8430
	2	0.7641	1755.352	2082.392	0.7539	0.518	0.9173

Appendix B: Monthly Total Discharge (cubic feet per month-cfm) calibration statistics calculated for each Watershed.

Watershed (HUC)	Calibration Point	**R^2**	**Mean (cfm)**	**Std dev (cfm)**	**NSE**	**P BIAS (%)**	**Coefficient of Efficiency**
3040101	1	0.9195	10454.73	4994.79	0.9105	-1.761	0.9782
	2	0.9485	79995.91	39697.35	0.9476	-0.792	0.9867
	3	0.9476	41090.97	21611.62	0.9465	-1.716	0.9861
	4	0.9483	107035.44	53025.17	0.9468	1.257	0.9866
3040102	1	0.8898	7431.83	3938.49	0.8573	0.649	0.9676
	2	0.9326	12417.77	7456.86	0.9322	1.134	0.9822
	3	0.8849	3924.66	2726.14	0.8690	-0.228	0.9686
3040103	1	0.9184	7688.47	6476.91	0.9039	10.169	0.9751
3040104	1	0.8480	3121.48	3796.54	0.8244	-20.197	0.9489
3040105	1	0.9077	2267.71	2310.89	0.8931	5.615	0.9742
	2	0.9424	51432.43	48362.83	0.9376	4.768	0.9845
3040201	1	0.7763	6156.92	2620.03	0.7369	0.769	0.9361
	2	0.9636	335007.37	209598.00	0.9636	-0.381	0.9906
3040202	1	0.7471	929.15	742.51	0.7289	1.586	0.9276
	2	0.9116	33869.03	22343.80	0.8917	-1.798	0.9747
3040203	1	0.8848	6156.04	3506.70	0.8820	-1.747	0.9693
	2	0.8138	5215.81	3879.92	0.7722	0.985	0.9467
	3	0.8458	31448.34	18390.00	0.7989	0.076	0.9546
3040204	1	0.8612	2603.20	1177.83	0.8514	0.802	0.9625
	2	0.8187	69979.30	41624.20	0.7838	4.154	0.9483
3040205	1	0.8304	15270.15	12089.92	0.7749	20.967	0.9336
	2	0.8646	37182.77	24551.38	0.8107	16.238	0.9491
3040206	1	0.7336	23815.96	26968.94	0.6011	-21.504	0.9100
	2	0.8906	53436.04	48180.06	0.7022	-0.519	0.9461

Appendix C: Organization and Agencies Represented by Workshop Participants

ACE Basin National Estuarine Research Reserve
American Rivers
Baruch Institute of Coastal Ecology and Forest Science
City of Myrtle Beach
College of Charleston
Evans Hamilton, Inc.
Georgetown County Water and Sewer District
IMSG at NOAA Coastal Services Center
NOAA Coastal Services Center
North Inlet-Winyah Bay National Estuarine Research Reserve
South Carolina Lowcountry Refuges Complex
The Nature Conservancy
US Fish and Wildlife Service
University of South Carolina
USC Baruch Marine Field Lab
Waccamaw Regional Council of Governments
Winyah Rivers Foundation