DEVELOPMENT OF A COASTAL DROUGHT INDEX USING SALINITY DATA

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Changes in the salinity concentration of coastal waters during extreme meteorological conditions of droughts and floods can result in substantial short- and long-term environmental responses.

Long-term weather extremes, such as droughts, can have devastating environmental and economic effects on many societal sectors including water management, energy production, and agricultural crops (Wilhite 2000). In the United States the 2012 drought affected 22 states and cost an estimated $30.3 billion in losses and damages (NCEI 2015). In coastal areas, drought has additional effects on environmental and socioeconomic dynamics and public health (such as freshwater availability, waterborne pathogens, and shellfish harvesting) as a result of the interaction of sea level, precipitation, and streamflow affecting the salinity dynamics in coastal rivers and estuaries (Gilbert et al. 2012; Campbell 2014). Scientists have begun to define drought within the context of ecological impacts (Lackstrom et al. 2014; Lake 2003, 2011) and Gilbert et al. (2012) found that salinity was a common ecological drought stressor across estuarine types from tidal freshwater to mesohaline conditions. Extended periods of drought result in increases in salinity concentrations that can have substantial effects on aquatic and vegetative communities. The environmental response to coastal drought can occur over many temporal scales. For example, coastal water purveyors with riverine intakes may be interested in weekly to monthly drought responses whereas coastal land managers are interested in monthly to seasonal responses. Shellfisheries, such as those harvesting blue crabs, may have a response to changing salinity conditions over months whereas the vegetation community composition in tidal marshes may change over a growing season.

This interaction at the freshwater–saltwater interface is an important factor in the ecological and socioeconomic dynamics along the coast. Salinity is a critical coastal environmental variable that integrates hydrological and coastal dynamics such as sea level, tides, tidal cycles, precipitation, streamflow, winds, and tropical storms. There is a large variety of estuarine river systems such as rivers with large contributing watersheds that drain portions of one or more

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physiographic provinces, tidal sloughs with minimal streamflow, and tidal rivers that connect two or more inlets or bays. For each of these coastal systems the position of the freshwater–saltwater interface is a result of different forcing dynamics. The position of the freshwater–saltwater interface for larger coastal rivers results from the interaction of three principal forces: streamflow, mean tidal water levels, and tidal range (Conrads and Roehl 2007). During periods of high streamflow, it is difficult for salinity to intrude upstream, and the saltwater–freshwater interface moves downstream toward the ocean. During periods of low streamflow, the saltwater–freshwater interface is moved upstream by tidal forcing, by an increase in mean coastal water level, a change in tidal range, or a combination of the two. Small tidal sloughs have small drainage areas, minimal upland flow, and are tidally dominated. In these systems, the position of the saltwater–freshwater interface is dominated by tidal forcing. For all of the estuarine systems, the position of the freshwater–saltwater interface determines the composition of aquatic communities and the freshwater availability for municipal and industrial water intakes. During periods of climate extremes, substantial changes in the location of the freshwater–saltwater interface can have substantial consequences on riparian vegetative and aquatic communities.

Salinity changes can affect many coastal resources and economic sectors. Salinity changes can have public health implications owing to compromised water quantity and quality that result in increased incidences of infectious, chronic, and vectorborne diseases (Randa et al. 2004; Baker-Austin et al. 2010). There are also livelihood issues related to the fishing industry. For instance, changes in salinity due to drought can impact the life cycle of blue crabs, hampering blue crab landings during long-term drought (Childress and Parmenter 2012). At present, the South Carolina–North Carolina coast is at capacity use for groundwater, and much of the present (and future) industrial and municipal supplies rely on surface-water sources (Campbell and Coes 2010). Inland surficial aquifers found near estuaries can become more saline where saltwater intrudes up coastal river channels (Barlow and Reichard 2010). In the Sacramento–San Joaquin delta in Northern California, salinity intrusion is controlled by hydroreleases from upstream reservoirs to protect estuarine habitat as well as the aquatic organism and food web relationships by maintaining the approximate location within river reaches of a salinity concentration of 2 practical salinity units (psu; Pitzer 2014). During the California drought of 2014, when flows released into the delta were limited to store more water in reservoirs, the location of the saltwater–freshwater interface moved upstream (Pitzer 2014). The environmental consequences of this change in salinity intrusion are currently (2017) being evaluated.

Salinity data have been used to recreate drought histories and evaluate the interannual-to-decadal variability of estuarine habitat (Stahle et al. 2011). Stahle et al. (2013) used a blue oak (*Quercus douglasii*) tree-ring chronology and 30 years (1922–52) of seasonal salinity data from San Francisco Bay to recreate a 673-yr salinity chronology. From the salinity chronology they concluded that the drought in the 1920–30s was one of the worst over the last 673 years (Stahle et al. 2013). Accurate information on the changing long-term coastal salinity conditions is critical for researchers and decision-makers to evaluate and plan for coastal drought conditions.

Drought is most commonly defined as a decline in precipitation that has negative impacts on water supply and local agriculture (World Meteorological Organization 1986; Mishra and Singh 2010). To characterize drought, indices (hydrological, agricultural, meteorological, and socioeconomic) have been developed, incorporating data such as rainfall, streamflow, soil moisture, groundwater levels, and snowpack (Wilhite and Glantz 1985; Heim 2002; American Meteorological Society 2004). However, these drought indices were developed for upland areas and may not be suitable for characterizing drought in coastal areas. Coastal watersheds vary from small tidal sloughs to large coastal rivers, and upland drought metrics may not capture the magnitude and timing of drought in these various coastal systems, especially with respect to salinity dynamics. These coastal watersheds and wetlands respond differently to tidal conditions, precipitation, and riverine flow, depending on the geologic setting. A coastal index based directly on the critical drought stressor of salinity may be a more effective index than one based on other explanatory variables such as precipitation, streamflow, or soil moisture. For example, in many coastal wetlands, peat is more common than soil and drought indices that include soil moisture and/or groundwater levels in their calculations may not represent the fire potential during coastal drought conditions (Reardon et al. 2009).

Interest in the development of a coastal drought index partially grew out of stakeholder interactions during the initial organization of the National Oceanic and Atmospheric Administration's (NOAA) National Integrated Drought Information System (NIDIS) drought early-warning system pilot program for the

coastal regions of North and South Carolina. It was anticipated that a near-real-time coastal drought index would help in establishing relationships between changing salinity conditions and biological impacts in the coastal zone, complementing other NIDIS drought early warning projects in the Carolinas, and providing a better assessment of drought severity along the coast. A recent needs assessment of coastal land managers in North and South Carolina indicated that drought indices that incorporate information on salinity would be useful for managing coastal natural resources (Nolan et al. 2016).

The availability of many real-time and historical salinity datasets provides an opportunity to leverage these datasets for evaluating coastal drought and developing a methodology for computing a coastal drought index. For example, the daily salinity values at Hagley Landing along the Waccamaw River from 2000 to 2014 are shown in Fig. 1. The Pee Dee River is the largest tributary to the Waccamaw River and streamflow data from the closest gauge to the Hagley Landing site (the Pee Dee River at Pee Dee, South Carolina, gauge—approximately 90 km upstream of the salinity sites) are also shown. The color ramp in the background for Fig. 1 represents the U.S. Drought Monitor (USDM; Svoboda et al. 2002; http://droughtmonitor.unl.edu/) drought categories with D1 being the least intense and D4 being the most intense drought. The D0 category indicates a drought watch area of abnormally dry conditions—either heading to or recovering from drought. The USDM categories for the Yadkin–Pee Dee basin were computed by aggregating the drought level for each county in the basin. Figure 1 highlights some general concepts on coastal drought. First, we see the general inverse relationship between salinity concentrations and drought conditions and salinity concentrations at this particular site with large salinity intrusion events occurring during extended periods of higher drought classifications. The severity of the low-flow events with respect to drought are closely characterized by the USDM classification. Second, Fig. 1 shows timing and drought severity mismatches between the upland inputs and coastal salinity response at this site that may be due to confounding tidal factors and (or) the streamflow data not being proximal to the coastal salinity gauge. For instance, in the last quarter of 2000 there was no salinity response to a brief D3 classification whereas there was a large salinity response to D0 and D1 classifications in the third and fourth quarters, respectively, of 2001. The salinity responses in the summer and fall of 2001 and 2002 are very similar in duration and magnitude but the upland drought declarations for the basin show very different timing and duration of those declarations. The upland D3 declaration for the summer and fall of 2008 is associated with a salinity increase to 2 psu, much smaller than similar upland D3 declarations in 2002 and late 2007. In the fall of 2009 salinity values increased to 6 psu with values over 4 psu for a few months and the upland drought declaration was only in the D0–D1 range. The intent of Fig. 1 is not to illustrate the limitations of upland drought indices or upland input parameters but to illustrate the need for

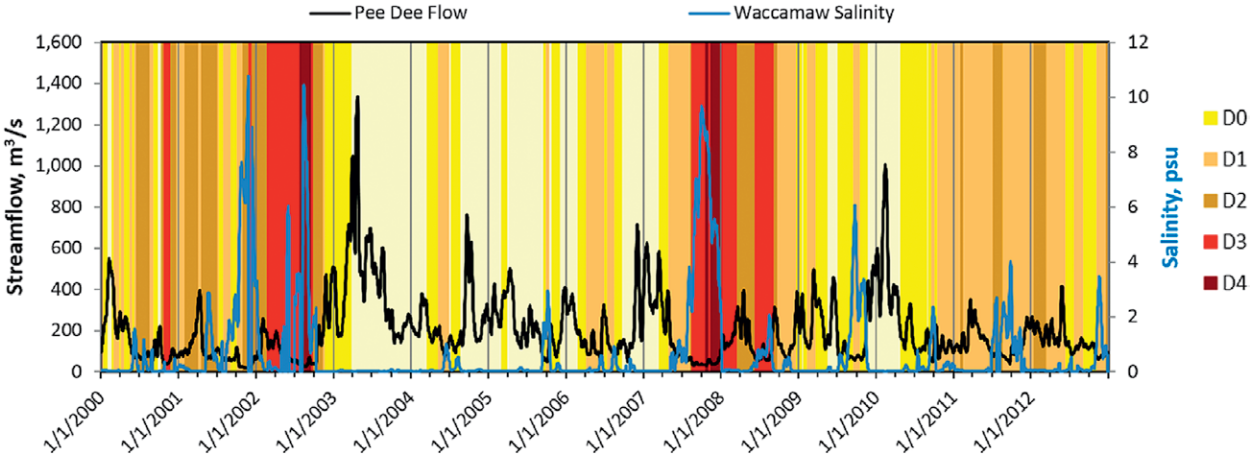


Fig. 1. Plot showing salinity (blue line) at the USGS gauge on the Waccamaw River at Hagley Landing (station 02110815) and streamflow (black line) at the USGS gauge on the Pee Dee River at Pee Dee (station 02131000). The USDM categories (shown to the right) represent the aggregate drought conditions for the basin. Note the spikes in salinity when the river flow is at its lowest levels, and the corresponding periods of D3 (extreme drought) and D4 (exceptional drought). (See the USDM website for a more detailed explanation of the D0–D4 categories: http://droughtmonitor.unl.edu/AboutUs/ClassificationScheme.aspx.)

a unique coastal drought index and the opportunity to compute an index that is computed directly from the principal coastal drought stressor of salinity.

Friedman (1957) identified four criteria that a drought index should meet, and Heim (2002) added a fifth operational criterion:

1) the time scale should be appropriate to the problem at hand;
2) the index should be a quantitative measure of large-scale, long-continuing drought conditions;
3) the index should be applicable to the problem being studied;
4) a long, accurate past record of the index should be available or computable; and
5) the index should be able to be computed on a near-real-time basis.

The objective of this study was to develop a coastal drought index using salinity data that meets the criteria listed above. The duration and magnitude of salinity intrusion events address the first two drought index criteria. The third criterion is addressed by salinity being a common drought stressor for a large range of types of estuaries (Gilbert et al. 2012). Although long-term (greater than 50 years, as with many precipitation records) salinity data records do not exist, there are many coastal salinity records of greater than 5–10 years that could be used for computation. Many of the salinity-monitoring stations operated by the U.S. Geological Survey (USGS), the National Oceanic and Atmospheric Administration's National Estuarine Research Reserves System, and the U.S. Bureau of Reclamation deliver real-time data available for rapid computation of a coastal drought index. There are many more real-time coastal salinity monitoring stations than there are tidal streamflow stations because of the complexity of computing reversing flow conditions. Salinity is a relatively inexpensive parameter to collect as compared to tidal streamflow and turbidity, so the installation of new salinity-monitoring sites in critical coastal areas is quite feasible.

MATERIALS AND METHODS. *Study areas.* The study areas are the coastal riverine reaches of two major watersheds in the Carolinas and Georgia (Fig. 2). The Yadkin–Pee Dee River and Savannah River watersheds are large drainage basins (47,900 and 25,500 km^2, respectively) that drain into the coastal plain of the southeast United States. Both watersheds have major reservoirs that regulate streamflow in large parts of the upland watersheds and supply water to major coastal communities. The Pee Dee River basin, including the Waccamaw River tributary, supplies freshwater to the Grand Strand of South Carolina, an area of rapidly growing coastal communities. The Savannah River forms the state boundary between South Carolina and Georgia to the divergence of the Little Back River near the coast. Three large federal multipurpose dams in the upper Savannah River basin provide hydropower, water supply, recreational facilities, and a limited degree of flood control.

Data networks and data processing. The USGS has been collecting continuous water-level and water quality data on the Waccamaw River since the 1980s to support studies of a variety of coastal water resource issues along the Grand Strand (Carswell et al. 1988; Drewes and Conrads 1995; Conrads et al. 2003; Conrads and Roehl 2007; Conrads et al. 2013). The USGS has maintained a network of water-level and specific conductance (field measurement for salinity) stations on the lower Savannah and Little Back Rivers since the late 1980s. Data are available back to 1986 for USGS station 02110815, Waccamaw River at Hagley Landing (referred to as Hagley Landing in this paper) and back to 1990 for USGS station 021989784, Little Back River at Luchnow Canal (referred to as Luchnow Canal in this paper). The historical range of salinity at Hagley Landing is from 0 to 12.9 psu and the range at Luchnow Canal is from 0 to 1.6 psu. One dataset from each study area was downloaded from the USGS National Water Information System (NWIS; USGS 2015) and used for the development of a coastal drought index.

The specific conductance data were converted to salinity values using the algorithm described in Miller et al. (1988). In each dataset there were periods of missing specific conductance data. These data gaps were filled using a variety of approaches. Salinity simulation models are available for both sites (Conrads et al. 2013). If the data gap fell within the simulation periods of the salinity models for Hagley Landing or Luchnow Canal, the simulated values were used. For dates outside of the model simulation periods, if flows of the upstream river were high (above the 75th percentile), the salinity values were set to the minimum values. For average- and low-flow conditions, artificial neural network models were trained using similar inputs to the published models (Conrads et al. 2006) to generate salinity estimates.

Data analysis: General approach and initial coastal drought index computation. There are daily and weekly salinity changes due to tidal cycles, meteorological

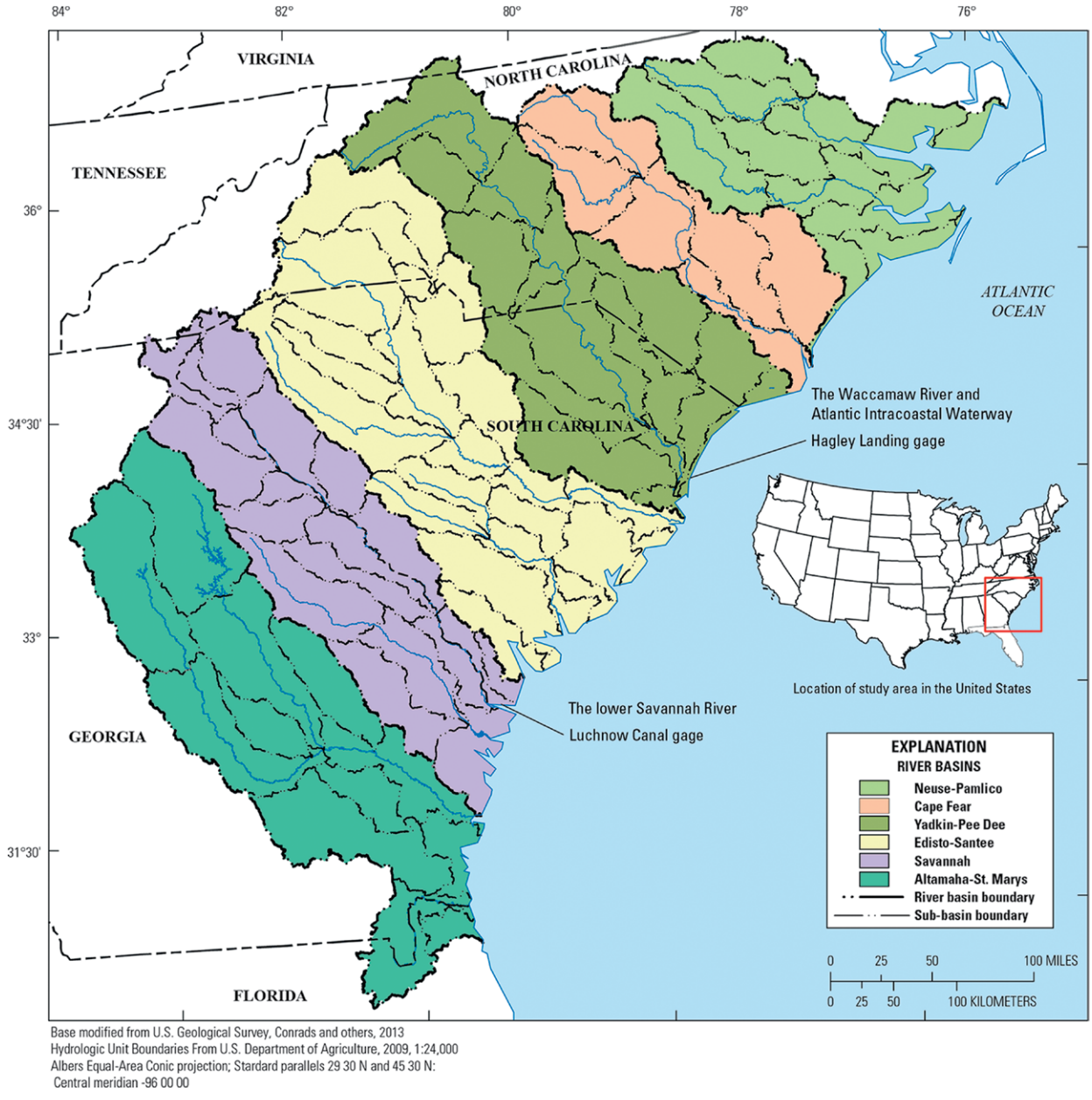


Fig. 2. Locations of the Yadkin–Pee Dee River and Savannah River study areas and selected river basins in NC, SC, and GA.

forcing, and flow conditions. To compute a coastal drought index (CDI) using salinity data, a three-step approach was used. The first step was to extract (or decompose) a drought signal from the daily salinity time series. The second step was to compute a frequency distribution from the decomposed salinity drought signal. The final step was to use the frequency distribution to set thresholds for levels of drought severity. The threshold levels can be set to known salinity responses proximal to where the data were collected or can be set according to the distribution of the data. Various signal transformation techniques were used to extract a drought signal including single mass curves (Searcy and Hardison 1960), cumulative Z scores (Iman and Conover 1983), and a combination of moving window averages and time derivatives (Helsel and Hirsch 1995; Halliday and Resnick 1981).

The initial computation of a CDI used moving window averages and time derivatives (not shown) and showed improvement in the timing of coastal drought, with respect to salinity, as compared to streamflow and the USDM categories for the Yadkin–Pee Dee basin. This initial computation of the CDI was presented to coastal stakeholders and researchers

in the drought community and three critical issues were identified that the CDI methodology would need to address. One issue was that the initial CDI quickly switched between coastal drought severity levels, which could be problematic for drought managers and communication with the public. The second issue to be addressed is that coastal drought response, as noted earlier, occurs on different time scales from weeks/months to seasons/years. Would there be different coastal drought index computations for short- and long-term droughts? The third issue is that a CDI only addresses increases in salinity conditions. Extreme freshwater conditions also are a coastal concern (Aleem 1972; Ardisson and Bourget 1997) and it would be beneficial for the coastal index to also convey degrees of "freshness" in addition to "saltiness."

Standardized precipitation index approach. There is a similarity between the three-step approach used for computing the initial CDI and the computation of the standardized precipitation index (SPI; McKee et al. 1993). The SPI is sometimes described as being analogous to the statistical *Z* score (Wu et al. 2001). The SPI is based on the probability of recording a given amount of precipitation and the probabilities are standardized so that an index of zero indicates the median precipitation amount. The SPI is a dimensionless index, where negative values indicate drought conditions and positive values indicate wet conditions and the SPI is computed for several time scales (typically 1–24 months) to characterize short- and long-term droughts (Heim 2002). For the SPI, weekly or monthly precipitation is fitted to a gamma distribution function and normalized with a probability distribution. The index values are standard deviations from median values. The SPI is an index for dry and wet conditions and is often used for regional comparisons of hydrological conditions.

For this study, the SPI approach was used to compute a coastal salinity index (CSI) by substituting total monthly salinity for total monthly precipitation. The coastal index is named a "coastal salinity index" rather than a coastal drought index because it characterizes both freshwater (wet) and saline (drought) conditions. The World Meteorological Organization (WMO) SPI software package (World Meteorological Organization 2012) was used to compute the CSIs

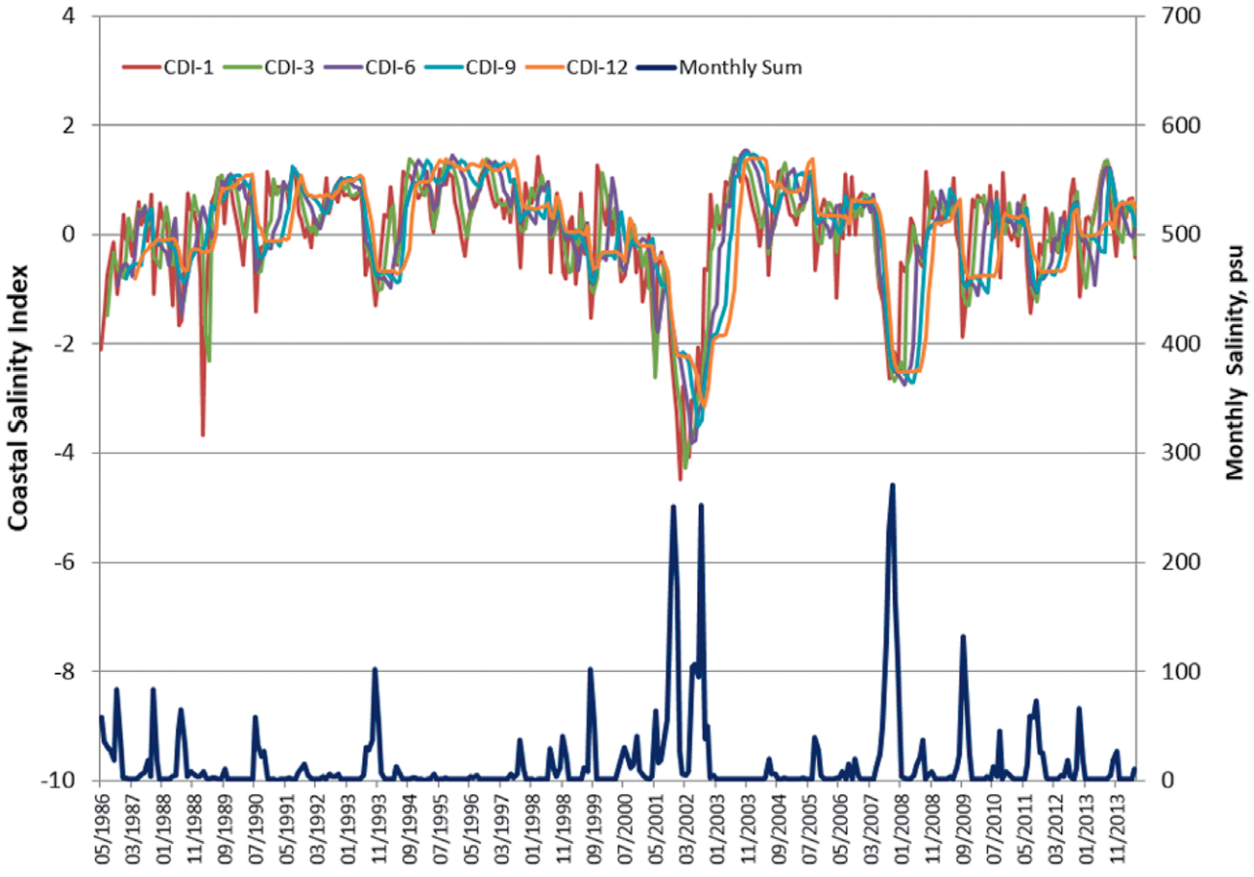


Fig. 3. The 1-, 3-, 6-, 9-, and 12-month values of the CSI for Hagley Landing and the monthly sums of salinity for the period May 1986–Dec 2013.

for the 1-, 3-, 6-, 9-, and 12-month intervals using the Hagley Landing data (Fig. 3). The computation resulted in positive values associated with coastal drought conditions. To align the CSI values with existing standard drought indices, the CSI values were multiplied by –1 so that drought conditions were represented by negative numbers and freshwater (wet) conditions were represented by positive numbers (Fig. 3). For coastal drought declarations, typical SPI threshold values were used (Table 1). The thresholds characterize the historical range of measured salinity data at the site and provide an indication of the severity of the salinity conditions over the interval (e.g., 1, 3, 6, 9, or 12 month) when the CSI was computed. The monthly total salinity values and the 6-month CSIs for Hagley Landing are shown in Fig. 4.

Table 1. Classification labels, descriptions, and threshold values used for the CSI.

Coastal salinity classification	Description	Threshold values
CW4	Exceptional freshwater conditions	2
CW3	Extreme freshwater conditions	1.6
CW2	Severe freshwater conditions	1.3
CW1	Moderate freshwater conditions	0.8
CW0	Abnormal freshwater conditions	0.5
N0	Normal salinity conditions	0
CD0	Abnormal salinity conditions	−0.5
CD1	Moderate salinity conditions	−0.8
CD2	Severe salinity conditions	−1.3
CD3	Extreme salinity conditions	−1.6
CD4	Exceptional salinity conditions	−2

RESULTS. A typical approach for evaluating drought, especially where many socioeconomic sectors are affected, is to use multiple indices. In complicated areas, such as the coast, not all drought indicators may work well for all conditions and often a suite of indices are used to characterize drought (Svoboda et al. 2015). To evaluate whether the CSI provides unique information on drought and freshwater coastal conditions, the index was compared with two commonly used drought indices–the SPI, a meteorological index, and the Palmer hydrologic drought index (PHDI), an agricultural drought index. The SPI and PHDI values for South Carolina Climate Division 4 were downloaded from the North American Drought Monitor web page (www.ncdc.noaa.gov/temp-and-precip/drought/nadm). Of the 1-, 3-, 6-, 9-, and 12-month CSI values, the 3-month value of the CSI was most correlated with the PHDI (coefficient of the determination $R^2 = 0.44$), so the 3-month values of the CSI and SPI were used for the comparison. Monthly values for the three indices and monthly salinity for Hagley Landing are plotted in Fig. 5 and the R^2 for the four time series are listed in Table 2. One interpretation of R^2 is as an accounting

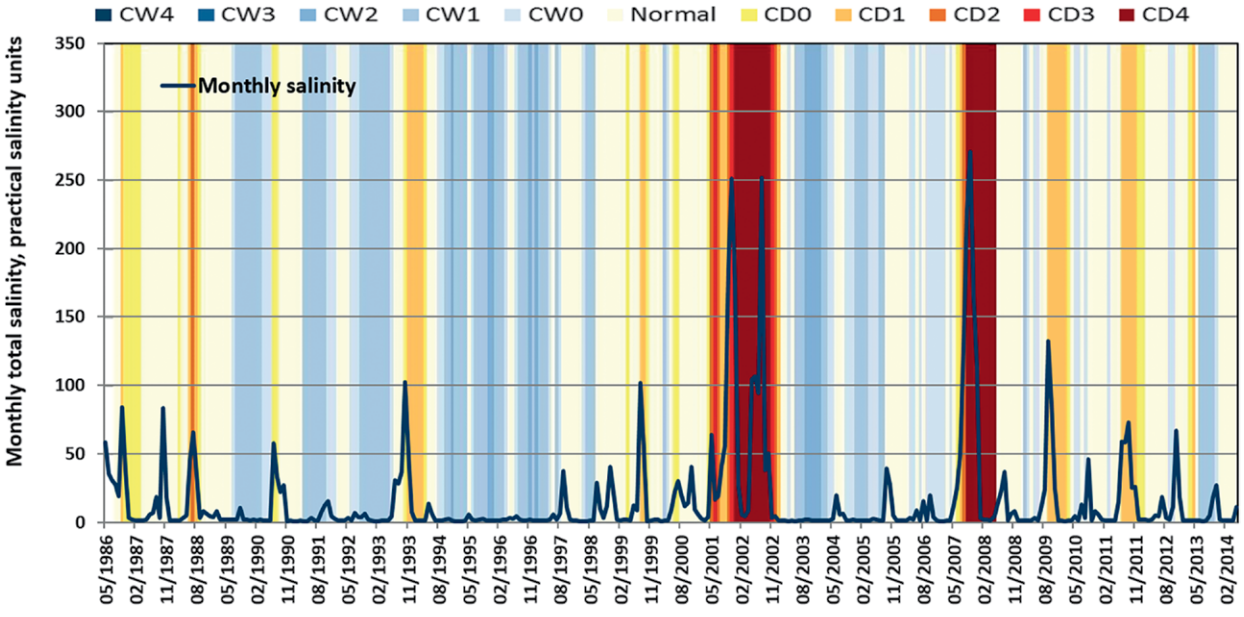


Fig. 4. Computation of the CSI (6-month interval) using the SPI approach for Hagley Landing. The warm color ramp is for increasing coastal drought conditions and the cool color ramp is for increasing wet or "fresh" conditions.

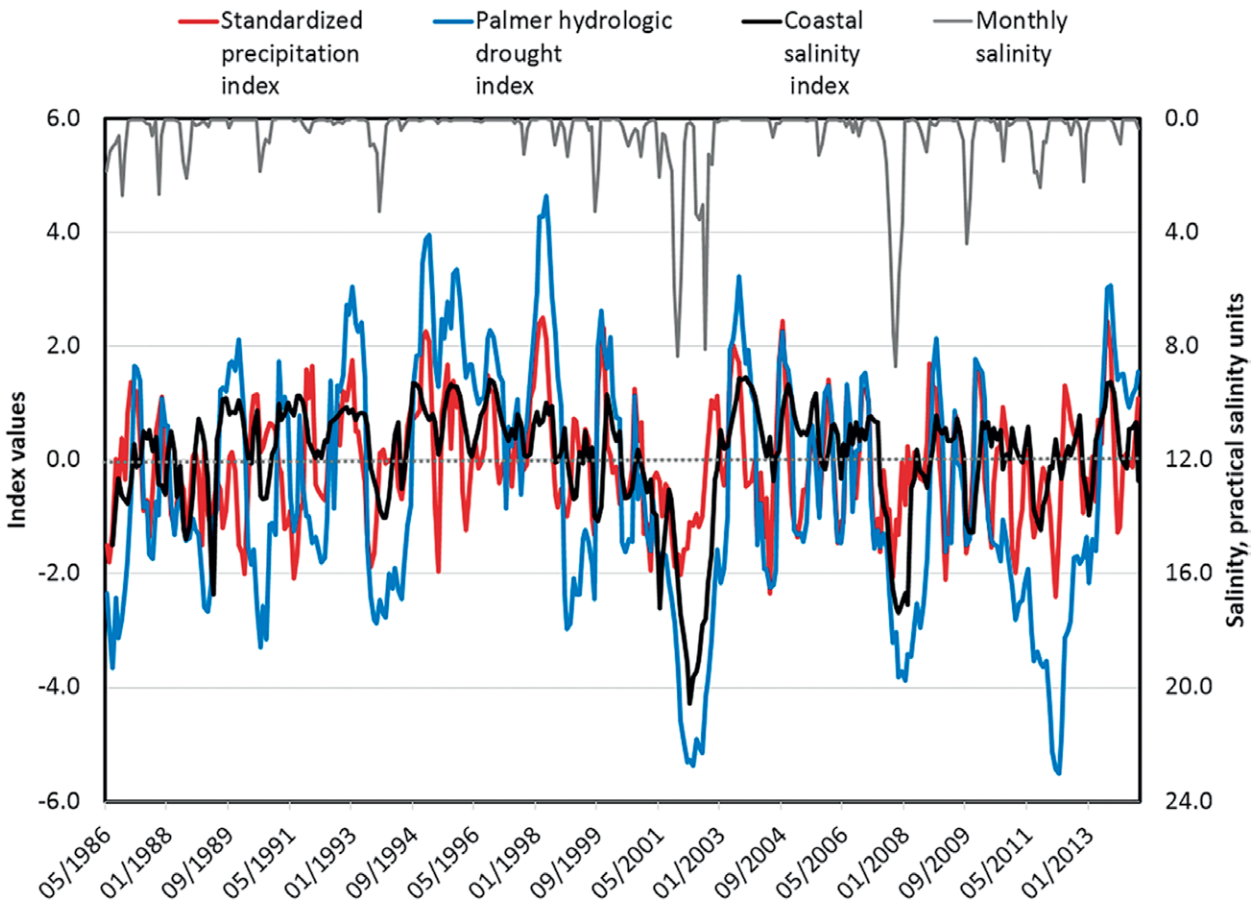


Fig. 5. The 3-month CSI and monthly salinity values for Hadley Landing and the SPI (3 months) and PHDI for the period May 1986–Jun 2014.

of how much "shared" information there is between two time series. The PHDI (R^2 = 0.44) shares more information with CSI than the SPI (R^2 = 0.10). Of the three indices, the CSI is most highly correlated with the monthly salinity (R^2 = 0.36). The SPI and PHDI often oscillate between wet and dry conditions, whereas the CSI is indicating only normal or fresh conditions. For example, from November 1990 to September 1993, July 1994 to November 1998, and January 2003 to May 2007 (Fig. 5), the CSI showed normal to fresh conditions that occurred during lower salinity values (generally less than 1.0 psu), whereas the SPI and PHDI showed drought conditions during these same periods. The most severe PHDI values occurred in March 2012 when monthly salinity values were not as high as periods in 2001–02 and 2007.

The 6-month SPI is more correlated with the 1-month CSI (R^2 = 0.43) than with the 6-month CSI (R^2 = 0.26) (Fig. 6a), indicating that there may be an inherent timing difference in the inputs of precipitation and salinity to characterize climate conditions. Moving window averages (MWAs) and time delays were applied to the 6-month SPI values to try and increase the correlation with the 6-month CSI. Applying an optimum time delay of zero months and a MWA of 8 months increased R^2 from 0.26 to 0.54 (Fig. 6b), which also indicated that the precipitation

Table 2. Cross-correlation matrix of coefficients of determination R^2 for the CSI (3 months), SPI (3 months), PHDI, and monthly salinity values.

	CSI	SPI	PHDI	Standardized streamflow index	Monthly salinity
CSI	1.00	0.10	0.44	0.48	0.36
SPI	0.10	1.00	0.31	0.18	0.07
PHDI	0.44	0.31	1.00	0.46	0.15
Standardized streamflow index	0.48	0.18	0.46	1.00	0.20
Monthly salinity	0.36	0.07	0.15	0.20	1.00

and salinity dynamics are occurring over different time scales. It appears that the CSI contains unique information on coastal conditions with respect to salinity that are not captured by the SPI or PHDI.

The CSI addresses the issue of differences in the temporal scale of the response variable in a similar manner to the SPI by being computed for different averaging intervals. Depending on the interval selected for evaluating salinity conditions, the CSI can be used for short-, medium-, and long-term coastal evaluations. The CSI was computed for Hagley Landing for 1–24-month intervals and the color ramp thresholds are shown for the period 2000–14 (Fig. 7). The vertical axis shows increasing time intervals (duration) for the CSI from 1 to 24 months. The warm color (reds) ramp indicates increasing saline conditions and the cool color (blues) ramp is for increasing wet or "fresh" conditions. The greater the vertical extent of a color ramp, the longer the duration of either a drought or freshwater conditions. One can see more variability in the shorter intervals and the persistence of either drought or wet conditions with the longer intervals. Depending on the short- and long-term intervals, the system may be experiencing coastal drought or freshwater conditions at the same time. For example, during September 2003, the 1–12-month CSI intervals indicate some degree of coastal wet conditions, whereas the 13–24-month intervals indicate the persistence of coastal drought conditions that began in previous years (Fig. 7).

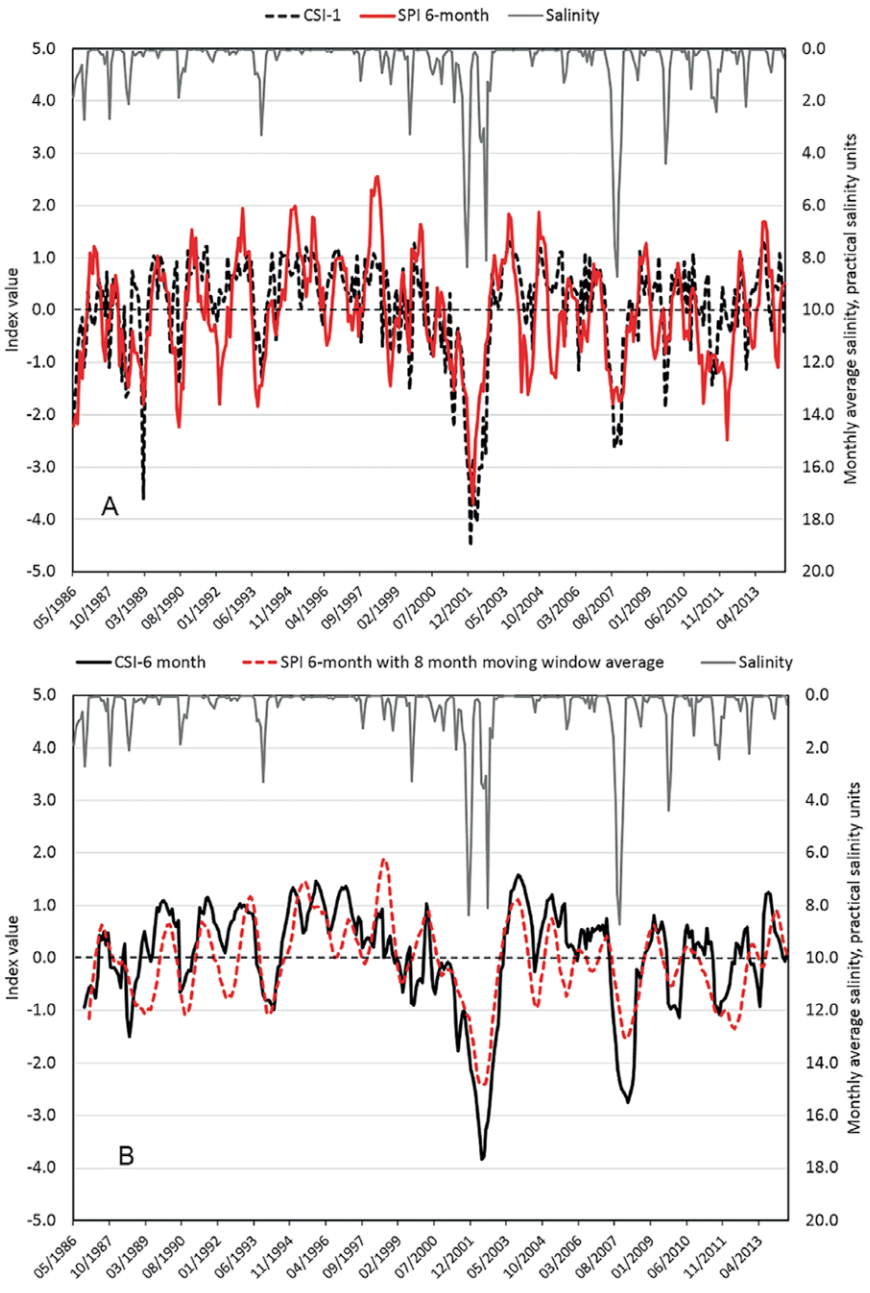
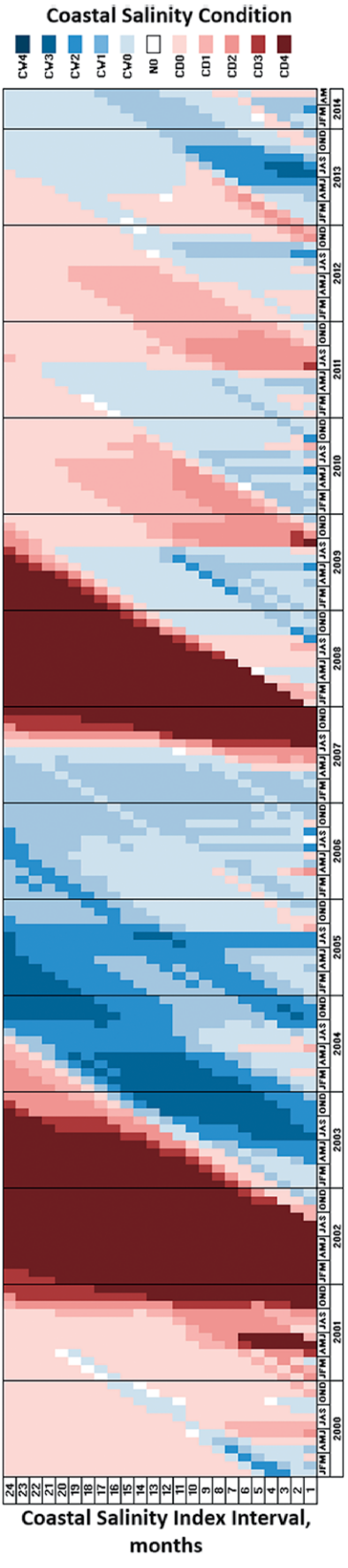


Fig. 6. (a) The 1-month CSI, 6-month SPI, and the monthly salinity, and (b) the 6-month CSI, the 8-day moving-window average of the 6-month SPI, and the monthly salinity at Hagley Landing for the period May 1986–Jun 2014.

An important issue with the CSI is whether the index would be site specific or whether it can be used to compare coastal locations. To evaluate the ability of CSI to compare coastal conditions along coastlines, the CSI was computed for the Luchnow Canal and Hagley Landing for a concurrent 20-yr (1994–2014) period. The 6-month CSI values and the USDM categories for the two sites are shown in Fig. 8. The plots and USDM categories show similar drought and wet trends, with the main differences being in the intensities and the timing of the conditions. To evaluate the regional intensities of the drought, the



◂ Fig. 7. Computation of a CSI for 1–24-month intervals (vertical axis) for Hagley Landing during the period 2000–14. The warm color ramp indicates increasing coastal drought conditions and the cool color ramp indicates increasing wet or "fresh" conditions.

USDM maps for the Southeast were compared with CSI plots for the two sites. Three dates are shown in Fig. 8 for comparison. In May 2001, the USDM showed more intense drought in the Savannah River basin than in the Yadkin–Pee Dee River basin and the CSI showed a similar response with coastal drought conditions just beginning at Hagley Landing and more persistent coastal drought conditions at Luchnow Canal. In October 2007, the reverse conditions occurred, with more-intense drought conditions in the Yadkin–Pee Dee River basin than the Savannah River basin. The CSI showed a similar response with CD3 and CD4 conditions for Hagley Landing and CD0 and CD1 conditions at Luchnow Canal. In May 2012, there was more intense drought in the Savannah River basin than in the Yadkin–Pee Dee River basin. The CSI for Hagley Landing shows no drought conditions whereas the CSI for Luchnow Canal shows CD2 conditions.

DISCUSSION AND CONCLUSIONS.

The phenomenon of coastal drought has a different dynamic than upland droughts, which are typically characterized by agricultural, hydrologic, meteorological, or socioeconomic drought. For coastal drought, change in salinity is the primary environmental stressor across the gradient of estuarine types. There is not a drought or standardized index that uses coastal salinity data. This is a major information gap in the existing indices for evaluating coastal conditions. The CSI, on the other hand, is based on a direct measure of the primary stressor of salinity, whereas other drought indices use other parameters that essentially are surrogates or indirect measures for the salinity response. The two sites presented in this article are large coastal rivers where streamflow is a component of the salinity dynamics. Although there was an apparent inverse relation between the upland streamflow and USDM drought categories for the Yadkin–Pee Dee basin and the salinity response at Hagley Landing on the Waccamaw River, there were obvious timing and magnitude issues with using an upland drought index or input parameter for coastal drought declarations. There are many coastal sites, such as tidal sloughs and bays, with limited drainage areas that are dominated by tidal exchanges, not streamflow.

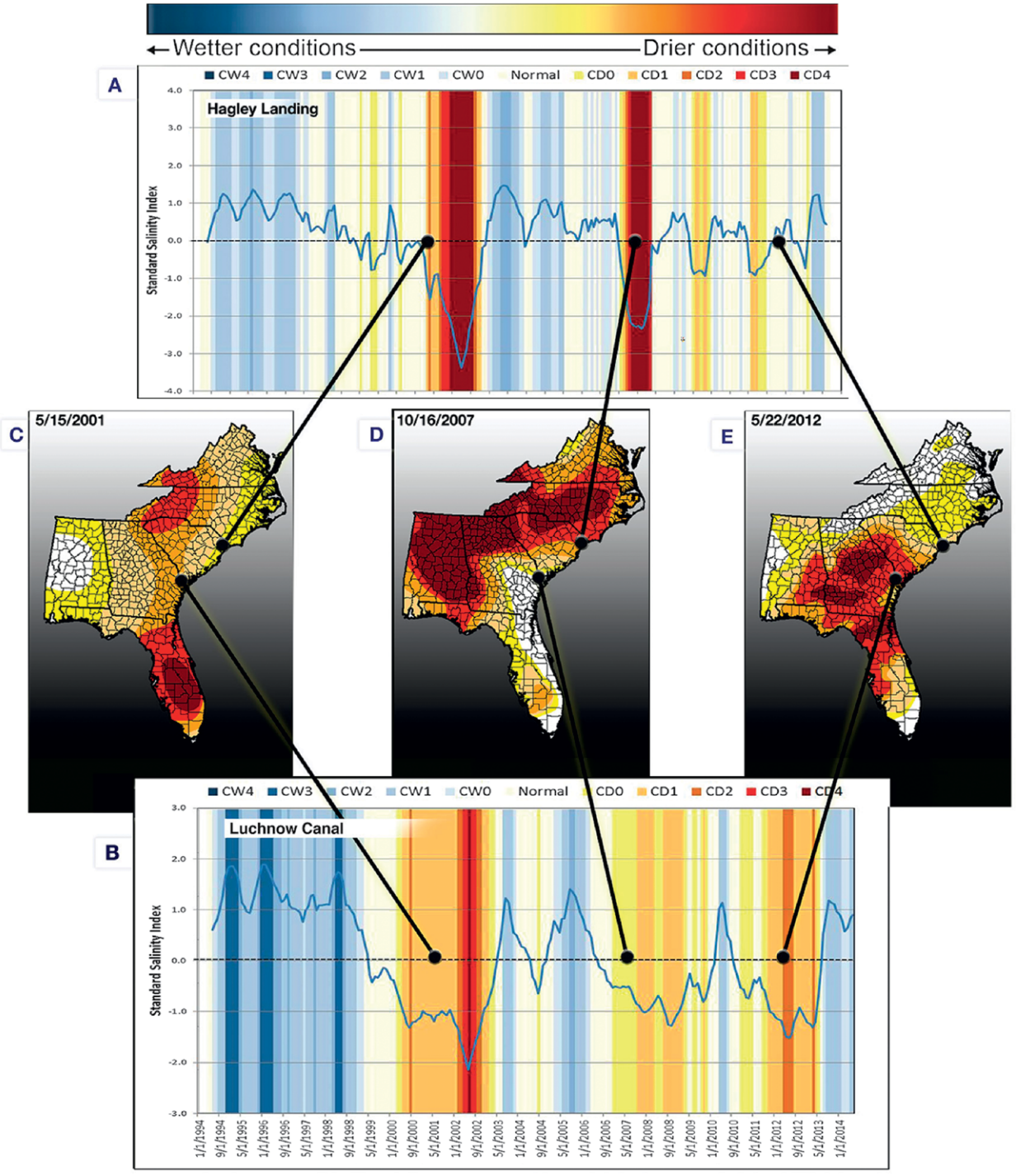


Fig. 8. The 6-month CSI for (a) Hagley Landing and (b) Luchnow Canal and the USDM maps for (c) 15 May 2001, (d) 16 Oct 2007, and (e) 22 May 2012.

Long-term salinity time series data can be leveraged to compute a unique coastal index.

There are many more salinity gauging stations along the coast than there are tidal-flow gauging stations and the majority of salinity stations do not measure tidal flow. This is true of the USGS sites and the National Estuarine Research Reserve System-Wide Monitoring Program sites. Long-term salinity time series data can be leveraged to compute a unique coastal index. Salinity data are relatively inexpensive to collect compared to tidal-flow data, which involves more expensive acoustic instrumentation, the development of stage-area and index-velocity ratings, and streamflow measurements over

tidal cycles to maintain the ratings for the stations (Levesque and Oberg 2012; Oberg et al. 2005). The long-term USGS flow monitoring sites are upstream from tidal-backwater flow conditions and not proximal to the coastal salinity sites. In summary, there are a number of advantages for computing a coastal drought index using salinity. One, salinity is a direct measure of the major environmental drought stressor along the coast. Two, salinity is a relatively inexpensive parameter to collect, as compared to turbidity or tidal streamflow. Three, tidal systems integrate forcing functions of tides, tidal range, precipitation, and flow differently depending on their geomorphic settings and salinity dynamics is a natural integrator of these various forcing functions.

The modification of the SPI approach by using salinity data instead of precipitation appears to be an effective approach for developing a unique coastal salinity index that can be used to more adequately assess the timing and magnitude of coastal drought conditions and for comparison along coastlines of coastal drought. The approach resulted in a CSI that provides categories for drought (higher saline conditions) and freshwater conditions. The computation of the index for various time intervals enables the CSI to be linked with coastal responses that occur on temporal intervals. The approach meets the five criteria of a drought index that were identified by Friedman (1957) and Heim (2002).

It is important that a CSI be correlated to coastal salinity response parameters to show the importance of a unique coastal index. There is a challenge in identifying potential coastal salinity-response datasets. Coastal drought is a relatively new concept and existing datasets may not have been collected or understood as "drought response" datasets. Potential drought-response datasets could include tree growth and litter fall in tidal marshes (Krauss and Duberstein 2010; Cormier et al. 2013), harmful algal bloom occurrences (Gilbes et al. 1996), Vibrio infection occurrence (Deeb 2013), shellfish harvesting data (Childress and Parmenter 2012), and shark attacks (Rice 2015). Coastal salinity could be an important explanatory variable for understanding the dynamic variability of the coastal drought response variable. An ongoing NIDIS drought early-warning project in the Carolinas is developing ecological linkages to the CSI and is evaluating the effectiveness of the CSI as a prediction tool for adaptation planning for future drought. Future work on the CSI will include assessing these kinds of datasets, as well as integrating the CSI into NIDIS drought early warning activities. Such work will make the CSI available in near–real time on the Internet, expand the CSI to sites beyond the two in South Carolina and Georgia, and connect CSI values to biological responses that further aid in the assessment of drought severity in coastal regions.

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