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A FRAMEWORK FOR INCORPORATING THE IMPACT OF WATER QUALITY ON WATER SUPPLY STRESS: AN EXAMPLE FROM LOUISIANA, USA[1]

David M. Borrok, Jian Chen, Hisham Eldardiry, and Emad Habib[2]

ABSTRACT: Water of poor quality can directly impact the budget of water available for key user groups. Despite this importance, methods for quantifying the impact of water quality on water availability remain elusive. Here, we develop a new framework for incorporating the impact of water quality on water supply by modifying the Water Supply Stress Index (WaSSI). We demonstrate the usefulness of the framework by investigating the impact of high salinity waters on the availability of irrigation water for agriculture in Louisiana. The WaSSI was deconstructed into sectoral components such that the total available water supply could be reduced for a particular demand sector (agricultural irrigation in this example) based on available water quality information. The results for Louisiana highlight substantial impacts on water supply stress for farmers attributable to the landward encroachment of saline surface water and groundwater near the coast. Areas of high salinity near the coast also increased the competition for freshwater resources among the industrial, municipal, and agricultural demand sectors in the vicinities of the municipal areas of Lake Charles, Lafayette, and Baton Rouge, Louisiana. The framework developed here is easily adaptable for other water quality concerns and for other demand sectors, and as such can serve as a useful tool for water managers.

(KEY TERMS: salinity; water supply; sustainability; irrigation; stress; index; coastal; quality.)

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INTRODUCTION

Both the quality and quantity of water must be considered for the sustainable management of freshwater resources. Globally, water quantity is being stressed by changes in climate, increased demand from growing populations, and an increased need of water for agriculture and industry (*e.g.*, Vörösmarty *et al.*, 2000; Wada and Bierkens, 2014). Water quality is similarly being stressed from pollutants associated with growing populations, land cover change, and irrigation and industrial effluents (*e.g.*, Kundzewicz *et al.*, 2008; Teixeira *et al.*, 2014). Water quality is fundamentally connected to water quantity by the fact that water of inferior quality effectively reduces the amount of available water for some users (or it can dramatically increase the cost of obtaining

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available water because of necessary treatment). Despite this important linkage, most investigations that evaluate water stress treat the problems of water quality and water quantity separately.

Water quality indices (WQIs) aggregate individual water quality parameters (*e.g.*, pH, temperature, dissolved oxygen, biological oxygen demand, total nitrogen, total phosphorous, fecal coliform counts, etc.) into a single, easily understood and easily communicated value (*e.g.*, Bordalo *et al.*, 2006; Lumb *et al.*, 2006; Sánchez *et al.*, 2007; Simsek and Gunduz, 2007; Ramakrishnaiah *et al.*, 2009; Gazzaz *et al.*, 2015; Whittaker *et al.*, 2015). In general, WQIs are constructed by identifying the key chemical or physical water parameters that lead to the targeted outcomes, converting the measurements to unitless subindex values and aggregating the subindex values to achieve a single overall index. The number of parameters considered, how much weight is assigned to each parameter, and the method of aggregation (linear, geometric, logarithmic, etc.) varies considerably among approaches (Tyagi *et al.*, 2013). Despite some variability, WQIs have been used effectively for many years by state and federal agencies to guide water management decisions (Gitau *et al.*, 2016). For example, for regulatory and monitoring purposes the U.S. Environmental Protection Agency uses a WQI comprised of six individual parameters (dissolved oxygen, biological oxygen demand, total nitrogen, total phosphorus, fecal coliform counts, and total suspended solids). These parameters are integrated for mapping pollution changes to human impacts and are part of the EPA's effluent limitation guidelines and standards for the construction and development point source category (USEPA, 2009). Modifications of the EPA's original WQI have been made to better adapt the approach for the assessment of surface waters in individual states (*e.g.*, USEPA, 2010). State environmental agencies have adopted similar practices. For example, the Oregon WQI has been used extensively for monitoring, reporting and informing water management decisions in that state (Cude, 2001). Similar WQIs have guided water management practices in Canada (*e.g.*, Lumb *et al.*, 2006) and parts of Europe (*e.g.*, Sánchez *et al.*, 2007).

Problems associated with the quantity of available freshwater have similarly been addressed through the construction of index values. These indices are based on the physical balance of water demand relative to water supply (or the cumulative deficits of this balance; Devineni *et al.*, 2013) in a given region or watershed. The exact methodology of the comparison, including time and spatial scales, data sources for water availability and water demand, and the assumptions made (*e.g.*, consumptive versus nonconsumptive water use) vary among individual studies (*e.g.*, Falkenmark, 1989; Alcamo *et al.*, 2000; Smakhtin *et al.*, 2004; Averyt *et al.*, 2013; Schlosser *et al.*, 2014; Boithias *et al.*, 2014; Tidwell *et al.*, 2014). One of the most basic and widely used water availability indices is the Palmer drought severity index (PDSI). The PDSI examines the water balance in a region and its impact on soil moisture over time (Palmer, 1965; Hayes *et al.*, 2007). It is used as a trigger for water management plans in response to drought. These plans impact water allocation strategies, irrigation allotments, and reservoir management. The Surface Water Supply Index (SWSI) builds on this approach, taking into account snowpack, streamflow, and reservoir storage in addition to precipitation (Doesken *et al.*, 1991). These additional considerations become important in the Western United States (U.S.), where much of the available surface water is derived from snowmelt. More recent approaches additionally address the water balance for groundwater. For example, Sun *et al.* (2008) developed the Water Supply Stress Index (WaSSI) and applied it to examine stress on water supplies in the Southeastern U.S. The WaSSI approach was later modified by Eldardiry *et al.* (2016) to explore smaller spatial and temporal scales and to incorporate environmental flow requirements into the water budget calculations.

The use of index or indicator values can be helpful in guiding water management decisions, but they are not without shortcomings (*e.g.*, as described in Sullivan, 2002; Brown and Matlock, 2011; Gitau *et al.*, 2016). In the simplest sense index values reduce complex interrelated datasets to one easily understood and communicated value. This has the advantage of establishing a uniform basis of comparison over periods of time and often from place to place. This is, however, a substantial oversimplification. Index values rarely consider all the relevant factors that might influence water scarcity in a given region. They often suffer from problems of scaling in that some of the individual components and data that comprise the index don't scale similarly despite being treated in a uniform fashion. Furthermore, individual water scarcity indices tend to be tailored to specific sectors of water demand (*e.g.*, industrial, power, municipal, agriculture) and often neglect the importance of ecological demand.

Arguably the most challenging issue associated with the index approach is describing the related yet dissimilar concepts of water quality and water availability using a single index value. Effectively integrating WQIs and water stress indices remains a challenge in part because water supply stress is an issue of physical water scarcity, while water quality is an issue of economic water scarcity. In other words, the water supply component of the water balance equation is dictated by climatic and natural biophysical interactions and is intransient in a given region. On the other hand, it is possible to convert water of poor quality to useable, high-quality water via economic investment in treatment and/or new infrastructure. The extent to which water will require treatment depends on the use of the water and the availability of alternate supply. Despite this challenge several previous attempts have been made to integrate these concepts. The Water Poverty Index (Sullivan, 2002) attempts to quantify water scarcity by combining socioeconomic factors, water quantity, and access to safe drinking water as a single index. However, despite acknowledging the importance of water quality on the availability of safe drinking water, there is no explicit accounting for the potential impact of water quality on the available water budget. Zeng *et al.* (2013) attempted to overcome this problem by combining a WQI based on the footprint of "grey water" with a WaSSI by adding the two indices together. Although this approach results in a single index value, it does not explicitly account for the loss of water availability (or the cost of potential water treatment) due to water quality concerns as a part of the WaSSI.

In this study, we build on the framework described by Eldardiry *et al.* (2016) and develop a methodology for integrating water quality data into the existing WaSSI framework. We explicitly account for the change in the budget of available freshwater caused by water that is not currently usable due to its poor quality. This approach treats poor water quality like a physical water scarcity problem and does not directly address the potential for water treatment and its associated costs. A logical next step, however, would be to correlate the water supply stress attributable to poor water quality with a monetary valuation of the water. Our method is also necessarily user-specific in that different users demand water with different physiochemical characteristics. We choose to explore an example case of salinity-imposed requirements for the agricultural irrigation in Louisiana, U.S. The framework we develop is easily adoptable for other water use sectors and for other water quality parameters or WQIs.

METHODS

Water Quality Threshold Ratio

High levels of salinity in surface water and groundwater impact available water supplies for the irrigation of crops, which ultimately results in increased stress on available freshwater. Here we examine the use of chloride (Cl), specific conductivity (SC), and total dissolved solids (TDS) as parameters to express salinity. We develop a fractional relationship, f, where the numerator is the number of individual water quality measurements above a certain user-chosen threshold value and the denominator is the sum of all the individual measurements. This approach is summarized in Equation (1).

$$f_X = \frac{\text{Number of measurements with } X > \text{threshold}}{\text{Total number of measurements}} \tag{1}$$

where X is the water quality parameter of choice (*e.g.*, Cl, SC, or TDS in this case). The threshold value is chosen based on the identified water quality parameter and water use sector as described further below. The threshold ratio is calculated for surface water (f_{X_sw}) and groundwater (f_{X_gw}) separately within a given watershed. In this study, we separately analyze f_X where X is TDS, SC, and Cl, for surface water and groundwater for the 1,276 HUC12-scale watersheds in the state of Louisiana. The HUC classification system was developed by the U.S. Geological Survey to subdivide the U.S. into successively smaller hydrologic watershed units and HUC12 is the smallest. In cases where insufficient water quality data were available to solve for f_X on this small scale, we reverted to the larger HUC8 scale. In this case, we assigned the f_X for the larger HUC8 watershed that encompasses the smaller HUC12 unit to the HUC12 watershed that had insufficient data coverage. In order to achieve the highest spatial resolution we used all of the available chemical data in the calculation of f_X. By lumping chemical data collected at different time periods, we are in essence sacrificing temporal resolution for increased spatial resolution in this example analysis. We believe this is a reasonable approach because an initial comparison of the f_X in each watershed for different time periods (not shown) suggests that locations of high salinity surface water and groundwater have remained relatively consistent in Louisiana over time. The amount of available data and good spatial coverage are critical aspects of this approach, as they are for the calculation of any WQI. It may be possible to adapt satellite imagery or other remote sensing approaches to expand data coverage for some WQIs. However, in the case of salinity, there appears to be no substitute for physical measurements.

The calculated value of f_X increases as a larger percentage of the total water quality measurements in a given watershed exceed the threshold value. Assuming that water above the chosen threshold value is no longer available for the chosen water use sector, the fraction of remaining water available can be estimated using the relationship $(1 - f_X)$.

Water Quality Data and Crop Yield Thresholds

Water quality data for Louisiana were downloaded from the U.S. Geological Survey's National Water Information System (NWIS) database. For this initial effort, all available data, spanning a range from the early 1940s to present (2016), were used. We preferred maximum spatial coverage over temporal resolution for this initial assessment. The database included 29,723, 32,301, and 18,718 individual measurements of Cl, SC, and TDS, respectively, for surface water and 33,600, 22,073, and 8,679 measurements of Cl, SC, and TDS, respectively, for groundwater. Future work could also explore the addition of data from the EPA Storage and Retrieval (STORET) database. However, we neglected these data for this study because of the higher potential for spatial bias, as many of the EPA water quality datasets focus on contaminated sites.

Irrigated agriculture in Louisiana is dominated by the production of soybeans, rice, aquaculture (crawfish production), corn, and cotton. Rice and aquaculture production are dominant in the southwest part of the state, while soybeans and mixed crop types are present within a large agricultural area of the Mississippi Valley in northeastern Louisiana (Figure S1). Brackish surface water near the coast can often extend inland through canals, channels and estuaries, impacting the availability of surface water for irrigation. The availability of groundwater is also limited near the coast by the location of the saltwater-freshwater interface within the underlying coastal aquifers (*e.g.*, Borrok and Broussard, 2016). Areas of high-salinity groundwater also exist within the Mississippi River Alluvial Aquifer in Northeast Louisiana (and in Southeast Arkansas), which are thought to be impacted by the upward migration of deeper brines (Huff and Bonk, 1993).

The thresholds above which the concentrations of Cl, SC, and TDS in irrigation water can harm crops are not universal. They depend on the type of crop, its growth stage, and soil conditions. Moreover, thresholds can be set at different levels depending upon how much loss of yield is acceptable in a given region. For this investigation, we reviewed a number of studies that examined salt tolerances for crops including rice, soybeans, and corn (*e.g.*, Ayres and Westcot, 1976; Maas *et al.*, 1983; Maas, 1985; Grattan and Grieve, 1999; Fipps, 2003; Hanson *et al.*, 2006). Based on these analyses, we chose a salt threshold level of 1,100 µS/cm (for SC) above which the yield for corn is negatively impacted (Maas *et al.*, 1983). When the SC is below 5,000 µS/cm it is commonly converted to TDS (in mg/L) by multiplying by 0.64 (*e.g.*, Fipps, 2003). Hence, we set the TDS threshold value at 704 mg/L, using this conversion to conform to the chosen value for SC. Finally, assuming an end-member case in which all the salt is comprised of NaCl, the equivalent threshold concentration of Cl that conforms to the TDS concentration is 457 mg/L. For this example, we apply these threshold values to surface water and groundwater for the whole state of Louisiana regardless of crop types in the different regions. This approach is very sensitive to the choice of threshold value, which must be chosen carefully based on specific user requirements. Because of this specificity, the resultant water stress calculations apply only to the user group (agriculture in this case) for which the threshold was established.

Integrating Water Quality and Water Stress

The WaSSI was originally introduced by Sun *et al.* (2008) and modified by Eldardiry *et al.* (2016). As described in Equation (2), the WaSSI is formulated as the ratio of total annual water withdrawal, which includes withdrawal from surface water ($\mathrm{WW_{SW}}$) and groundwater ($\mathrm{WW_{GW}}$) separately, relative to the total annual water supply, which is the sum of the groundwater supply ($\mathrm{WS_{GW}}$) and surface water supply ($\mathrm{WS_{SW}}$) less an environmental flow requirement (ENV).

$$\mathrm{WaSSI} = \frac{\mathrm{WW_{SW}} + \mathrm{WW_{GW}}}{(1 - \mathrm{ENV}) \times \mathrm{WS_{SW}} + \mathrm{WS_{GW}}} \qquad (2)$$

The environmental flow term represents the fraction of flow in streams that is necessary to support a healthy ecosystem in each watershed. Eldardiry *et al.* (2016) chose a conservative fraction of 0.5 for environmental flow in their study and we adopt the same value here. This value is arbitrarily chosen, allowing us to isolate changes in stress attributable to the other factors. A great deal of additional work would be necessary to define environmental flow values for individual watersheds.

Because we are concerned with evaluating the impact of salinity on water stress relative to the agriculture water usage sector only, the WaSSI must be broken down into its individual components. The $\mathrm{WW_{SW}}$ and $\mathrm{WW_{GW}}$ terms in Equation (2) represent the sum of water withdrawal for all of the important water usage sectors, including agriculture ($\mathrm{WW_i}$), industry ($\mathrm{WW_j}$), power generation ($\mathrm{WW_k}$), municipal ($\mathrm{WW_l}$), and rural domestic ($\mathrm{WW_m}$) sectors. The $\mathrm{WS_{SW}}$ and $\mathrm{WS_{GW}}$ terms in Equation (2), however, cannot similarly be broken down into individual components because water withdrawal from one sector reduces the available water in another. Hence, for this formulation we use, as a starting point, the case where the water withdrawal for all other use sectors is met before water is available for the agricultural sector. Using this approach, the total water available for the agricultural sector (WS_i) is described by adding both the surface and groundwater components of water availability as shown in Equations (3) and (4), respectively.

$$\mathrm{WS_{iSW}} = [(1 - \mathrm{ENV}) \times \mathrm{WS_{SW}}] - (\mathrm{WW_{SWj}} + \mathrm{WW_{SWk}} + \mathrm{WW_{SWl}} + \mathrm{WW_{SWm}}) \tag{3}$$

$$\mathrm{WS_{iGW}} = [\mathrm{WS_{GW}} - (\mathrm{WW_{GWj}} + \mathrm{WW_{GWk}} + \mathrm{WW_{GWl}} + \mathrm{WW_{GWm}})] \tag{4}$$

Inherent in this analysis is the assumption that water is of a sufficient quality to meet the needs of all the other water use sectors. The $\mathrm{WS_{SW}}$ term in Equation (3) is set to the average annual streamflow in each HUC12 watershed plus $\mathrm{WW_{SW}}$, as the water that was withdrawn in each watershed must be added back to determine the natural streamflow. Annual average streamflow volumes from 1971 to 2000 were obtained from the National Hydrography Dataset (NHDPlus) (McKay *et al.*, 2012). Return flows to surface water were not considered in this formulation. The $\mathrm{WS_{GW}}$ term in Equation (4) is calculated as the amount of groundwater recharge in each HUC12 watershed, which was estimated using an existing USGS dataset with a grid resolution of 1 km. We aggregated the data from this scale to fit the HUC12 scale. The USGS estimated recharge by multiplying a grid of baseflow index values by a grid of mean annual runoff values as described by Gebert *et al.* (1987). The framework for calculating WS_i is not meant to suggest that in practice water demand for the other usage sectors is prioritized over the agricultural sector. This is simply a starting point that can later be changed to evaluate tradeoffs in water prioritization. Using this framework, we develop a Sectoral WaSSI (SWaSSI) which is expressed in Equation (5).

$$\mathrm{SWaSSI} = \frac{\mathrm{WW_{iSW}} + \mathrm{WW_{iGW}}}{\mathrm{WS_{iSW}} + \mathrm{WS_{iGW}}} \tag{5}$$

The threshold ratio approach described above can now be integrated into the SWaSSI to consider the impact of salinity as presented in Equation (6).

$$\mathrm{SWaSSI} = \frac{\mathrm{WW_{iSW}} + \mathrm{WW_{iGW}}}{(1 - f_{X\_\mathrm{SW}}) \times \mathrm{WS_{iSW}} + (1 - f_{X\_\mathrm{GW}}) \times \mathrm{WS_{iGW}}} \tag{6}$$

The SWaSSI with and without consideration of salinity was evaluated for all the HUC12 watersheds in the state of Louisiana. Additional details regarding data sources, disaggregation techniques, assumptions, and the calculations for WW and WS can be found in Eldardiry *et al.* (2016).

RESULTS AND DISCUSSION

Data Distribution and Water Quality Threshold Ratios

The distributions of the available water quality data for surface water and groundwater are presented as a function of sample date in Figure 1. The numbers of Cl and SC measurements collected in Louisiana's surface waters peaked around 1975, with subsequent peaks for SC data in 1994 and 2010. The lower numbers of TDS measurements for surface water formed a broad peak between about 1965-1985 (Figure 1a). The numbers of Cl and SC measurements for groundwater were greatest between about 1960 and 1980, while the substantially lower number of TDS measurements for groundwater peaked from around 1965 to 1980 (Figure 1b).

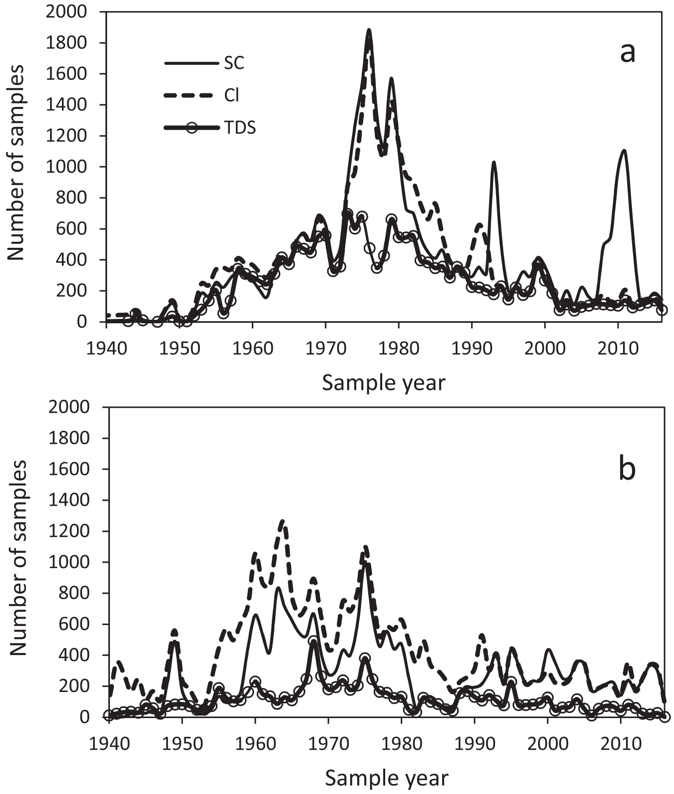

FIGURE 1. The Amounts of Surface (a) and Groundwater Samples (b) Analyzed for Chloride (Cl), Specific Conductivity (SC), and Total Dissolved Solids (TDS) in Louisiana from 1940 to 2016. Data were compiled from the U.S. Geological Survey's National Water Information System (NWIS) database.

The distributions of sampling stations/locations for surface water and the calculated f_X values for Cl, SC, and TDS in Louisiana are presented in Figure 2. Individual sampling locations may have been sampled multiple times and all sample measurements were used to calculate f_X. Surface water data were present for 46.7%, 46.2%, and 38.4% of the HUC12 watersheds in the state of Louisiana for Cl, SC, and TDS, respectively. In cases where data were not present for a HUC12 watershed, the f_X calculated at the larger HUC8 scale containing the watershed was applied. Data were available at the HUC8 level in 100% of the cases. The calculated f_X values for Cl, SC, and TDS for surface water were remarkably consistent (Figure 2), demonstrating that the approach itself is robust and that the threshold values chosen for the different constituents were roughly equivalent. Furthermore, the salinity of surface water in Louisiana is primarily a problem for irrigation for surface waters near the Gulf Coast (Figure 2). Several smaller isolated areas of higher salinity surface water exist in central and north central Louisiana within the Ouachita River Basin (Figure 2; Figure S2).

The distributions of sampling locations for groundwater and the calculated f_X values for Cl, SC, and TDS in Louisiana are presented in Figure 3. As with the surface water samples, individual sampling locations may have been sampled multiple times and all sample measurements were used to calculate f_X. Groundwater data were present for 79.3%, 74.8%, and 70.5% of the 1,270 HUC12 watersheds in the state for Cl, SC, and TDS, respectively. The f_X values for Cl, SC, and TDS for groundwater were generally consistent in delineating areas of groundwater impacted by salt water intrusion near the Gulf Coast (Figure 3). However, the f_X for SC additionally identified many areas of higher salinity groundwater in parts of the Red River alluvial aquifer, Mississippi River alluvial aquifer, and the Sparta, and Carrizo-Wilcox aquifers (Figure 3 and Figure S2). One explanation of why the f_X values for SC are higher than those for Cl and TDS is that the threshold concentration relationships among Cl, SC, and TDS could be less consistent for groundwater as compared to surface water. Many of the groundwater systems in Louisiana contain water with elevated concentrations of bicarbonate as opposed to Cl (*e.g.*, Hanor and McManus, 1988; Borrok and Broussard, 2016). Water dominated by sodium and bicarbonate is classically thought to form from the dissolution of carbonates followed by ion exchange of sodium for calcium in clay minerals (*e.g.*, Foster, 1950). In this situation, the SC of groundwater could be high, while the concentration of Cl could be lower than expected because of the evolution of the groundwater chemistry away from the NaCl endmember during water rock interaction. If this were the case we might also expect more values above the threshold established for TDS since the mass of TDS would be greater in cases where bicarbonate replaced Cl since the atomic mass of bicarbonate is higher than that of Cl. Indeed, the f_{TDS} does show higher values in more HUC12 watersheds than f_{Cl}, but it is still less than the extent of higher salinity identified by f_{SC}. We also examined the distribution of SC analyses relative to Cl and TDS to determine whether the results could be skewed based on unique sample locations for SC that did not include measurements for Cl or TDS. Although there were 318 unique groundwater sample locations for SC, a map of their locations (not shown) suggested that these measurements were not responsible for the full extent of increased f_{SC} relative to f_{Cl} or f_{TDS}. Although it is beyond the scope of this contribution, a more thorough examination of the groundwater chemistry in each aquifer could help to better inform threshold values for SC relative to Cl and other proxies for salinity.

Water Supply Stress for Agriculture

The SWaSSI for the agriculture water demand sector in Louisiana prior to considering the impact of salinity on water availability (Equation 5) is presented in Figure 4. Most of the areas of water stress for agricultural users occur in southwest and northeast Louisiana. Most of this stress is low, as 1,212 of the 1,276 HUC12 watersheds in Louisiana have an SWaSSI < 0.1. Only two watersheds had a SWaSSI > 0.5, signifying substantial water stress (Table 1; Figure 4). The SWaSSI including the impact of salinity calculated considering f_{Cl}, f_{SC}, and f_{TDS} is presented in panels a, b, and c of Figure 5, respectively. The left side of each panel shows the SWaSSI calculated using Equation (6), while the right side shows the difference in SWaSSI relative to the original SWaSSI in Figure 4 (*i.e.*, results from Equation 6 minus the results from Equation 5). The results are largely consistent whether using Cl, SC, or TDS as proxies for salinity (Figure 5), demonstrating that the methodology is robust regardless of the chosen parameter. When considering the impact of salinity based on SC, water stress increased for 23 watersheds in Louisiana and the number of watersheds under high stress (>0.5) increased by six (Table 1). Three watersheds increased to stress levels greater than one, indicating that the use of freshwater for agricultural purposes is unsustainable in these watersheds. Most of the increases in water stress attributable to salinity occurred in watersheds adjacent to the coast in southwest and southcentral Louisiana (Figure 5). A few isolated watersheds in northeast and northwest Louisiana showed increased stress attributable to salinity, but only when considering SC and TDS calculations (Figures 5b and 5c).

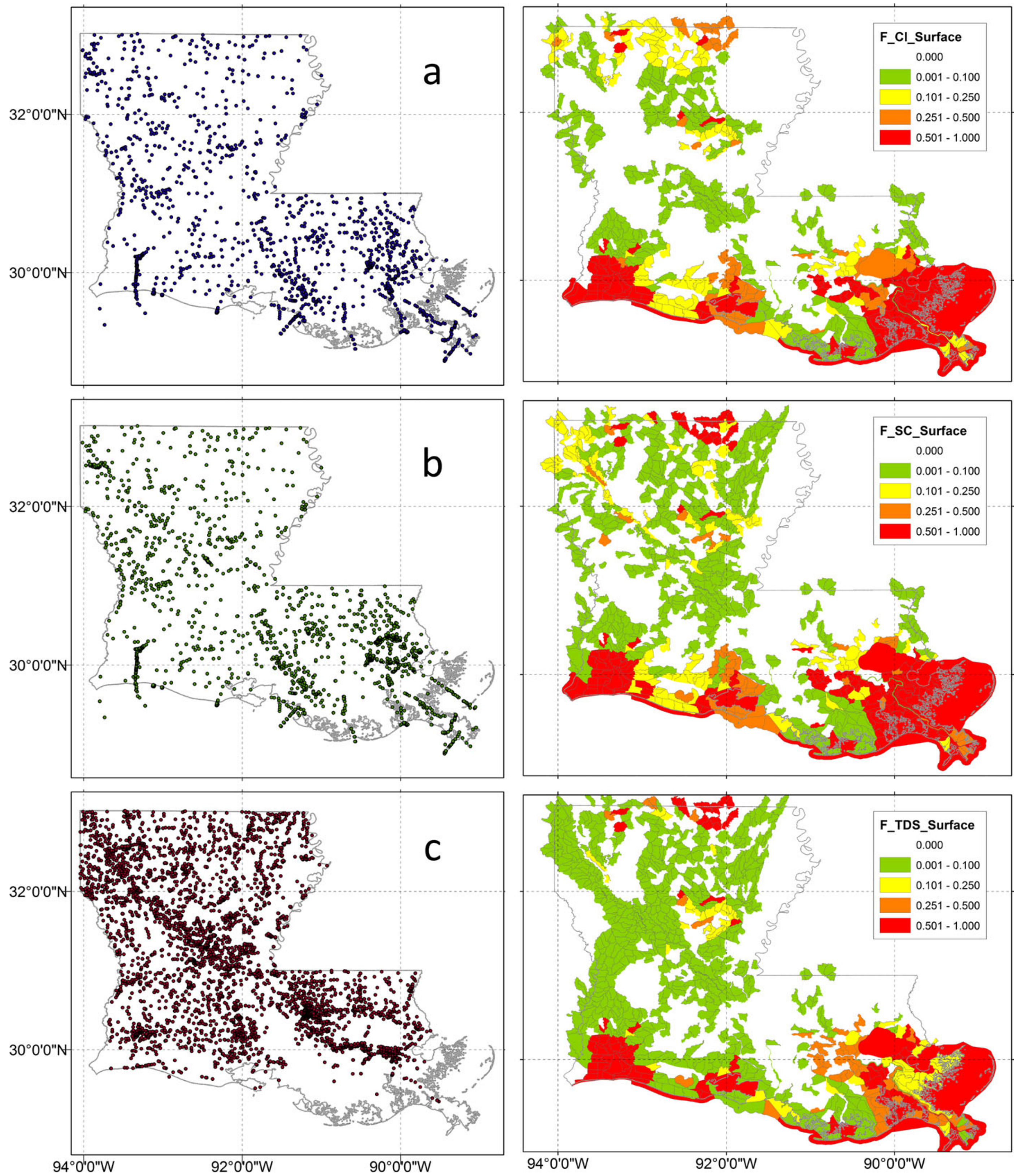

FIGURE 2. Surface Water Sample Locations (Left) and Calculated f_X (Right) in the State of Louisiana for Chloride (Cl), Specific Conductivity (SC), and Total Dissolved Solids (TDS) in Panels a, b, and c, Respectively. f_X is a unitless ratio representing the number of water samples in a given watershed where X is greater than a chosen threshold (see text) relative to the total number of water samples in that watershed.

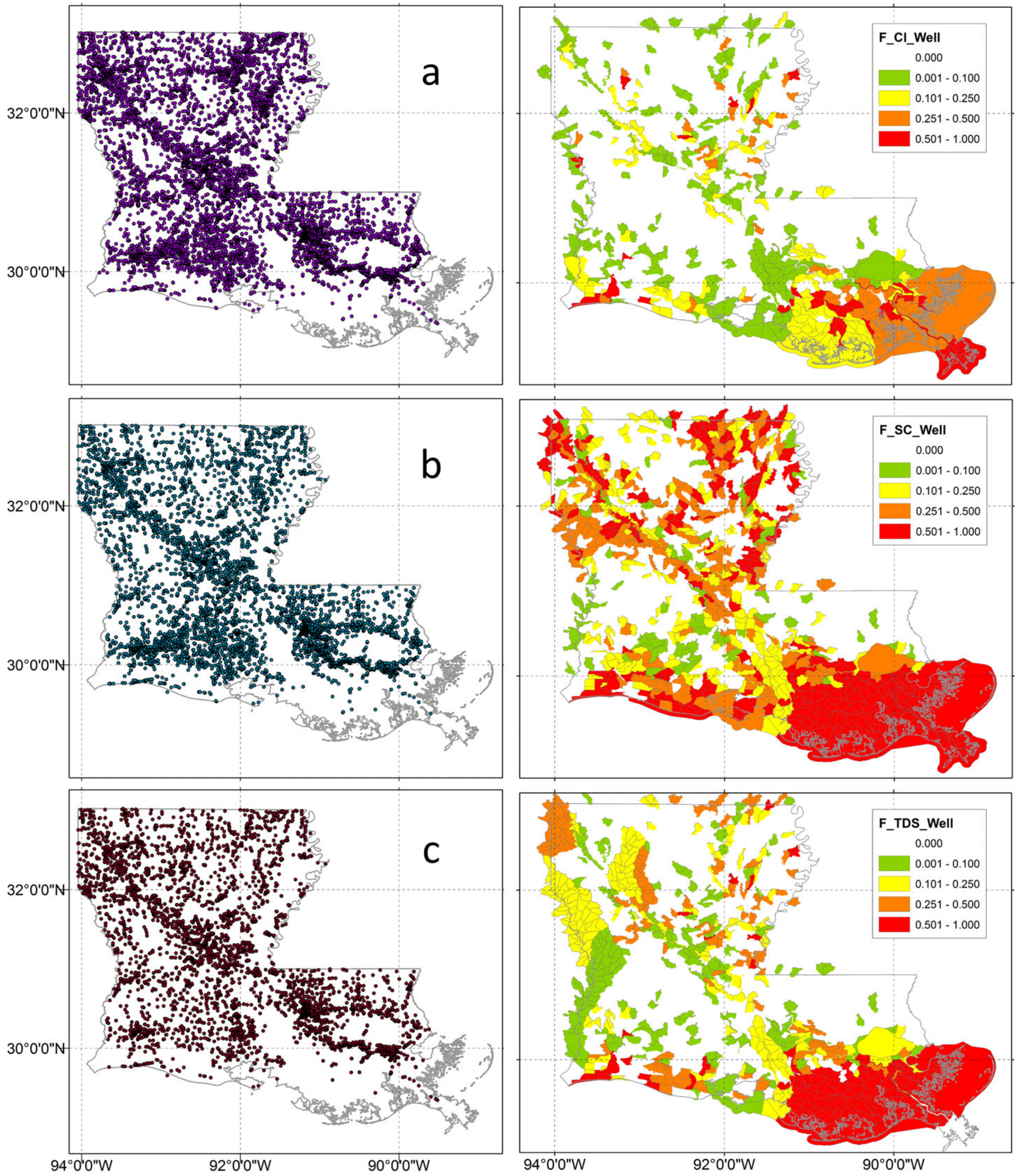

FIGURE 3. Groundwater Sample Locations (Left) and Calculated f_X (Right) in the State of Louisiana for Chloride (Cl), Specific Conductivity (SC), and Total Dissolved Solids (TDS) in Panels a, b, and c, Respectively. f_X is a unitless ratio representing the number of water samples in a given watershed where X is greater than a chosen threshold (see text) relative to the total number of water samples in that watershed.

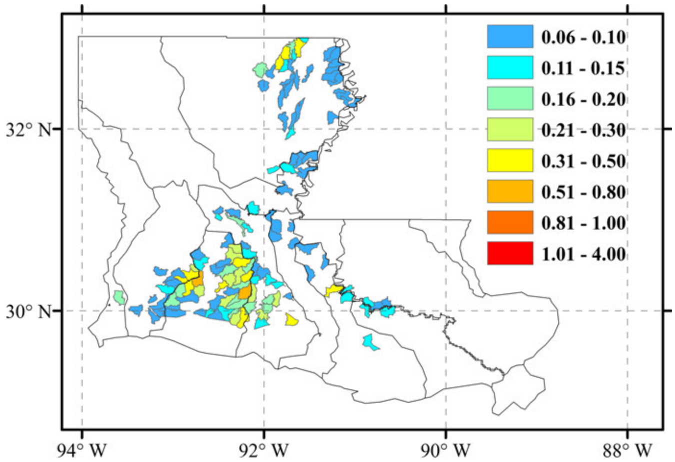

FIGURE 4. SWaSSI for the Agriculture Water Demand Sector in Louisiana Prior to Considering the Impact of Salinity on Water Availability. SWaSSI is a unitless formula developed to represent water supply relative to demand (see Equations 5 and 6 in text). Values <0.06 are not shown.

We also examined the impact of salinity on the SWaSSI for surface water and groundwater systems separately by considering only the surface water or groundwater terms in Equations (5) and (6). The results from this analysis, using Cl as a proxy for salinity, are illustrated in Figure 6. The majority of additional stress attributable to salinity in surface waters occurred along the coast and can probably be linked to the landward encroachment of salt water in the Sabine, Calcasieu, and Vermillion-Teche Basins (Figure 6a, Figure S2). This result emphasizes the need for thoughtful water management of Louisiana's coastal systems. The balance of freshwater and saltwater in the coastal zone is delicate and can be disrupted by changes in water use in the upstream catchments, as well as by built infrastructure such as canals that might provide conduits for the migration of brackish water landward. This analysis could also guide the implementation of potential sustainable water management solutions that involve mixing different proportions of brackish and freshwater to produce water of acceptable salinity. The majority of additional stress from salinity in groundwater occurs in the Mississippi River Alluvial Aquifer system in northeast Louisiana with isolated pockets in the Chicot and/or Evangeline aquifers in southwest Louisiana (Figure 6b, Figure S2). This result emphasizes the need to closely monitor the impact of increases in groundwater pumping, particularly in the Lower Mississippi River Alluvial Aquifer, on the migration and possible expansion of salt-rich groundwater. Note that the stress from salinity on groundwater in Figure 6b is largely masked by the abundance of available surface water when considering the combined availability of both surface and groundwater (as seen in Figure 5).

The SWaSSI considering salinity was also evaluated based on the effect of prioritization of the water needs of the various demand sectors. Our original formulation effectively gave agriculture the lowest priority for water withdrawals. We explored the opposite case in which the agriculture sector had the highest priority for water withdrawals. This approach assumes all the surface water and groundwater is available for agriculture such that Equations (3) and (4) simplify to Equations (7) and (8).

$$\mathrm{WS_{iSW}} = [(1 - \mathrm{ENV}) \times \mathrm{WS_{SW}}] \tag{7}$$

$$\mathrm{WS_{iGW}} = \mathrm{WS_{GW}} \tag{8}$$

Giving agriculture priority over the other water demand sectors served to lessen the stress

TABLE 1. Number of HUC12 Watersheds in Louisiana Impacted by Different Levels of Water Stress.

SWaSSI	Number of HUC12 Watersheds						
Stress Levels	SWaSSI for Ag Sector[1]	SWaSSI for Ag Sector + Cl[2]	SWaSSI for Ag Sector + SC[2]	SWaSSI for Ag Sector + TDS[2]	SWaSSI for Ag Sector SW[3]	SWaSSI for Ag Sector GW[3]	SWaSSI for Ag Sector + Cl (priority)[4]
<0.1	1,212	1,196	1,189	1,191	1,235	1,011	1,204
0.1-0.15	24	26	21	21	15	36	25
0.15-0.2	15	12	15	20	7	32	13
0.2-0.3	11	20	20	17	8	39	16
0.3-0.5	12	14	19	18	6	51	13
0.5-0.8	2	6	8	5	4	31	3
0.8-1.0	0	1	1	0	0	14	1
>1.0	0	1	3	4	1	62	1

[1] Shown in Figure 4.
[2] SWaSSI considering salinity calculated using Cl, SC, and TDS shown in Figure 5.
[3] SWaSSI for surface water and groundwater separately shown in Figure 6.
[4] SWaSSI prioritizing agriculture water demand (Figure 7).

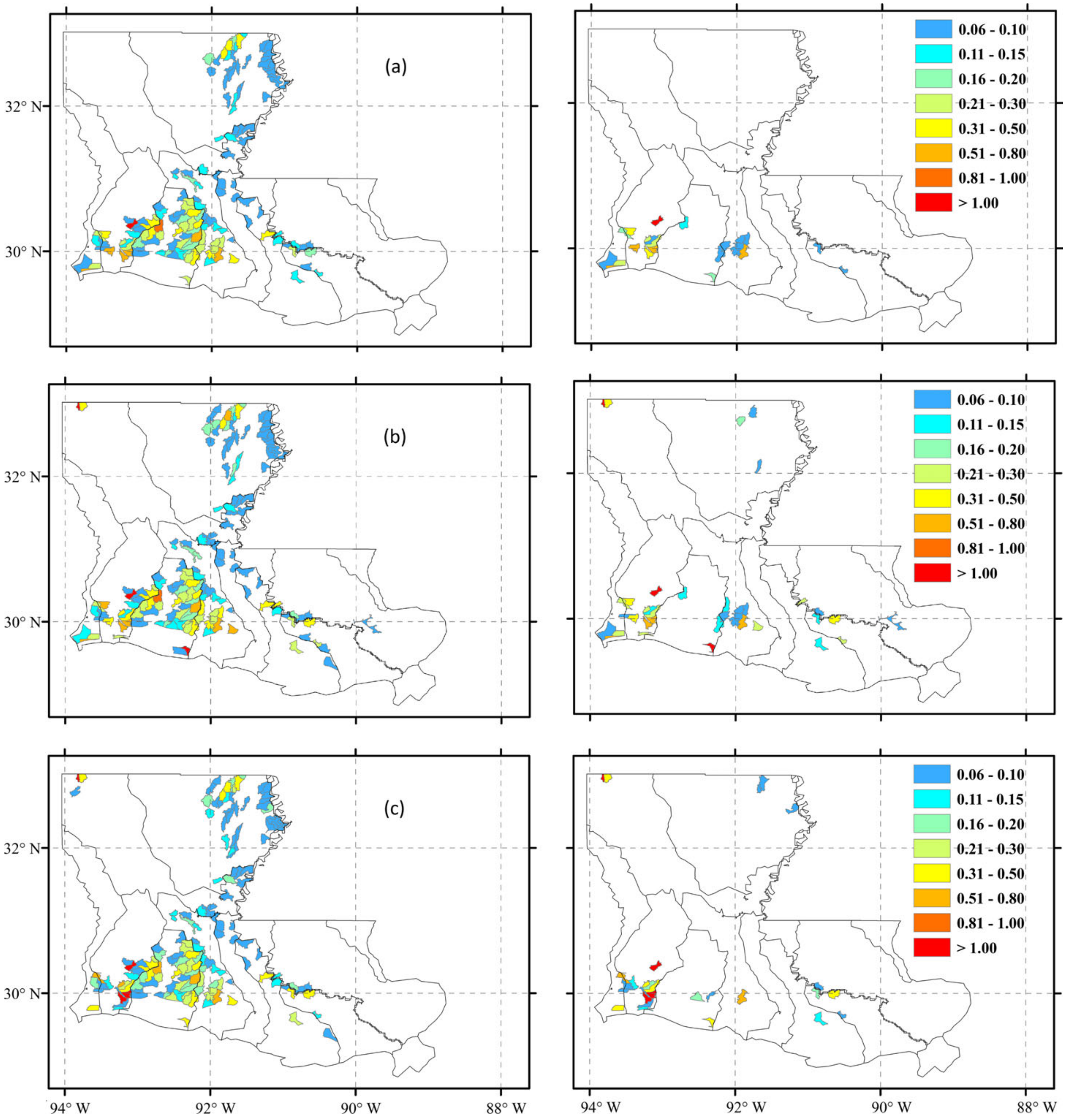

FIGURE 5. SWaSSI Including the Impact of Salinity Calculated Considering (a) f_{Cl}, (b) f_{SC}, and (c) f_{TDS} (where Cl, SC, and TDS are chloride, specific conductivity, and total dissolved solids, respectively). The left side of each panel shows the SWaSSI (calculated using Equation 5), while the right side shows the difference in SWaSSI relative to the original SWaSSI in Figure 4. SWaSSI is a unitless formula developed to represent water supply relative to demand. Values <0.06 are not shown.

measurably in some watersheds (Table 1; Figure 7). For example, the number of watersheds stressed at levels >0.2 decreased from 42 to 34 when prioritizing water for agriculture. The watersheds that showed the most alleviation in stress due to changing water use prioritization occurred in southwest and south-central Louisiana near the cities of Lake Charles, Lafayette, and Baton Rouge. These are the

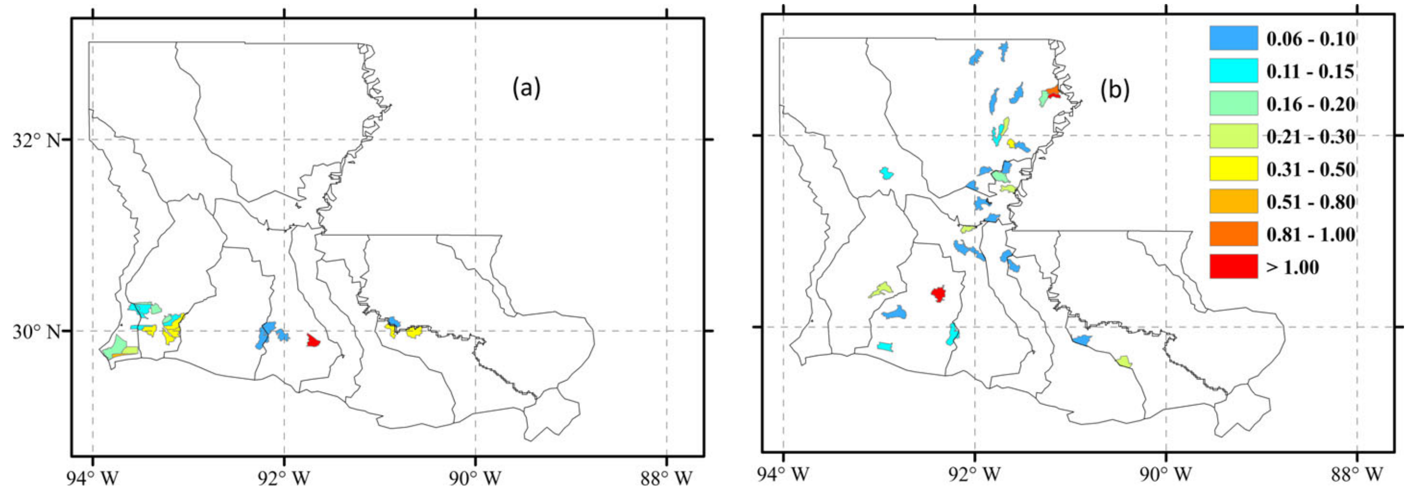

FIGURE 6. Difference in SWaSSI for the Agriculture Water Demand Sector in Louisiana after Considering the Impact of Salinity on Surface Water (a) and Groundwater (b) Separately. Values <0.06 are not shown. SWaSSI is a unitless formula developed to represent water supply relative to demand (see Equations 5 and 6 in text).

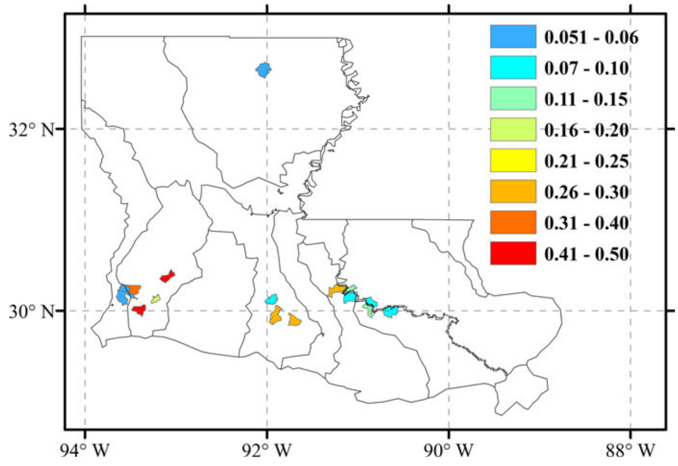

FIGURE 7. Difference in SWaSSI for the Agriculture Water Demand Sector when Prioritizing Water Allocation for Agriculture Over the Other Sectors Using the Chloride (Cl) Parameter as an Example. The differences represented reflect how much water stress was alleviated due to changing prioritization. SWaSSI is a unitless formula developed to represent water supply relative to demand (see Equations 5 and 6 in text).

watersheds where competing demands from other sectors, particularly industry and municipal water are highest. This example demonstrates how the SWaSSI approach can be used to investigate water stress under different scenarios of water prioritization in addition to water quality stress. An evaluation framework that integrates water quality as part of water allocation can be particularly useful in cases where water resources of poor quality may limit water demand for one sector but not another. This is not meant to suggest the need for top-down water allocation/prioritization policies, but is an approach that could be used by stakeholders of all kinds to support decision making by identifying the most efficient (and likely economical) ways to utilize available water resources in terms of water quality and quantity.

CONCLUSIONS

The framework developed here accounts for the effect of water quality on the available water supply and results in a single index value. The current framework is universal, in that similar relationships between water quality and water quantity can be quantitatively established for a broad range of conditions. Example applications may include the impact of suspended sediments on water availability for the industry sector or the impact of salinity, chemicals, or microorganisms on water availability for drinking water. It is also possible to integrate existing WQIs into this framework. Once a threshold ratio for the existing WQI is established a f_{WQI} can be calculated and integrated into the existing framework. Although this initial effort does not consider the economic implications of water quality changes and potential tradeoffs, this would be a logical next step. A large body of research already exists regarding the valuation of water quality in terms of individual perceptions, willingness-to-pay, and tradeoff costs (*e.g.*, Bockstael *et al.*, 1987; Van Houtven *et al.*, 2007; Egan *et al.*, 2009; Gibbons, 2013; Young and Loomis, 2014). It is likely that some of these previously established valuation concepts can be correlated with the water stress attributable to water quality calculated using our approach.

The application of this framework to agricultural water demand in the state of Louisiana demonstrates that salinity can substantially contribute to water supply stress, particularly in areas near the coast. Despite its importance, this additional stress on the water supply has not been previously quantified in Louisiana or in other locations. We also find that changes in prioritization of water among demand sectors has a large impact on water supply stress in watersheds with abundant municipal and industry water needs. Hence, both water quality and water prioritization should be carefully considered by all stakeholders in the overall allocation of water resources. The salinity of water in Louisiana is a particularly important example case because similar pressures from salinization of water resources are occurring globally (*e.g.*, Williams, 2001). The expansion of arid and semiarid landscapes, as well as anthropogenic forcing has led to increases in the salinity of many river systems (Reynolds *et al.*, 2007; Cañedo-Argüelles *et al.*, 2013; Borrok and Engle, 2014). Moreover, growing populations in coastal regions coupled with relative sea-level rise has increased the amount of salt water encroachment impacting both surface water and groundwater (Frederick and Major, 1997; Anderson and Al-Thani, 2016). In many cases the use of energy-intensive (and expensive) desalination technologies has become necessary to alleviate water stress in these regions (*e.g.*, Ghaffour *et al.*, 2013). In this context, the SWaSSI framework can be used to calculate the impact of salinity on water availability and to test scenarios of future water use, water prioritization, and the economic value of lower quality water.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Maps of cropping distributions, surface water basins, and aquifer locations within the state of Louisiana.

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