



Accounting for Inter-Annual and Seasonal Variability in Assessment of Water Supply Stress: Perspectives from a humid region in the USA

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Received: 5 February 2020 / Accepted: 17 May 2020 /

Published online: 5 June 2020

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Abstract

Stresses on water systems can be quantitatively assessed through indices that account for water demand relative to water availability, e.g., the Water Supply Stress Index (WaSSI). However, as a result of adopting deterministic supply-driven approaches, limited attention is paid to the potential impacts of climatic variability on quantifying water stresses. The current study aimed to account for the impacts of inter-annual and intra-annual variability in the WaSSI stress index and to provide insights into potential opportunities for better water management practices. The results from our analysis indicate that looking only at average stresses can substantially mask the important impacts of climate variability. Louisiana, as a typical example of humid regions in the USA, is subjected to high levels of stresses (WaSSI exceeds 1.0) with higher inter-annual variability in watersheds where thermoelectric power plants exist and extensive water is used for cooling process. In addition, intra-annual variability in some watersheds shows periodicity in terms of seasonal stress distributions due to variability in surface water supply and water demand. Our analysis indicated that the stress variability grows as the median WaSSI increases but up to a certain threshold level and then the variability decreases for very high stress levels. For the annual and monthly scales, the peak variability, quantified as the width of the 2.5–97.5 stress percentiles, reached 68% for a median annual WaSSI of 1.00 and 100% for a median monthly WaSSI of 1.15, respectively. Various decisions related to water use and management can be driven by such variability, at both annual and intra-annual scales. Hence, these results have important implications for applied water resource studies aiming to formulate water management policies and improve water system sustainability under climate variability.

Keywords Water supply stress index · Climate variability · Water resources · Louisiana · HUC12

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1 Introduction

Water resource systems are faced with meeting the challenge of growing demands coupled with the potential for added stress from climate change, including increasing variability, in the coming decades (Jackson et al. 2001; Chen et al. 2010; Hall et al. 2014). Water supply is greatly impacted by climate variability, which may have substantial impacts on water system sustainability (Vörösmarty et al. 2000; Alcamo et al. 2003; Arnell and Lloyd-Hughes 2014). Addressing such variability in the analysis of water systems will be critical for building sustainable water infrastructure systems and enabling successful management of water resources (Brown and Lall 2006; Georgakakos et al. 2012).

Understanding such variability requires accounting for water supply and demand conditions at intra-annual (seasonal and monthly) and inter-annual (year-to-year) scales instead of annual average conditions. The latter has been the focus of most previous studies (e.g., Sun et al. 2008; Averyt et al. 2013; Tidwell et al. 2014; Eldardiry et al. 2016). Sun et al. (2008) compared the impacts of historical and future climate scenarios on the water system stresses. These scenarios accounted only for precipitation annual variability without examining the impacts of seasonal or intra-annual variability. Tidwell et al. (2014) mapped water availability in the western United States by examining a variety of water sources including unappropriated surface water, unappropriated groundwater, appropriated water, municipal wastewater, and brackish groundwater. However, the analysis was based on annual average estimates without including the seasonal variability in either the water supplies or demands. More recent investigations by Devineni et al. (2015) and Etienne et al. (2016) highlighted the importance of climate variability. These investigations applied two deficit-based risk metrics to assess droughts in the United States. While applied at a fairly coarse spatial resolution (county-scale), the risk metrics highlighted the need to include information on climate variability at fine temporal scales rather than the annual-average scales. Hence, with changing climate conditions, there is a clear need to extend water stress analysis to finer scales temporally (e.g., seasonal scales) as well as spatially. Unlike previous studies that addressed the stresses over coarse hydrological scales (e.g., HUC-8 watershed in Averyt et al. 2013 and Tidwell et al. 2014), our study explores the impacts of climate variability over a finer scale represented by the 12-digit Hydrologic Unit Code (HUC-12) watershed scale.

Louisiana, located in the humid southeastern U.S., is currently supplied with abundant surface water; however, recent studies showed a significant over-use of groundwater resources (Reilly et al. 2008; Liu et al. 2008; Famiglietti and Rodell 2013). For instance, water use in the Chicot aquifer in southwest Louisiana has been dominated by groundwater withdrawals, while less surface water is being used despite abundant surface water availability (Borrok and Broussard 2016). Eldardiry et al. (2016) highlighted these observations by investigating the average annual stresses on a HUC12 watershed scale in Louisiana. They identified considerable stresses on the groundwater system that were comparable to stresses previously identified by Averyt et al. (2013) in the drier areas of the Southwestern U.S. Such annual-average stresses on groundwater resources can be potentially exaggerated or underestimated by not considering the variability in water supply and demand. Effects from both natural (e.g., due to climate variability) and anthropogenic factors (e.g., anticipated population growth, industrialization, and changing land-use) are likely to add further stress to the water system. Examining stresses at small temporal and spatial scales can also highlight challenges (increased local stresses) as well as opportunities (harvesting excess surface water) for sustainable water management.

In this study, we use the foundation of our earlier study (Eldardiry et al. 2016) of annual water stress in Louisiana to investigate the effects of natural variability in surface water supply and seasonal variability in water demand on quantifying water stress levels in Louisiana using the water supply index (WaSSI). We applied the WaSSI index to assess the implications of climate variability, both at inter-annual and intra-annual scales, and identify areas with potential risk of meeting existing and future demands. Variability in the demand-side includes consideration of the agricultural uses of water where crops need to be irrigated only at periodic intervals during the growing seasons. We apply the analysis at a relatively small spatial scales (HUC-12 watersheds). Understanding the impacts of climate variability on water stress at finer temporal and spatial scales is crucial to water management and planning efforts that look for ways to efficiently manage water that may be available during time of low stress to offset groundwater pumping during drier periods. In addition, our analysis will provide insights on the opportunities to store excess flow in surface and subsurface reservoirs in typically wet states like Louisiana.

2 Data and Methodology

2.1 Surface Water Supply

We perform the water stress analysis at the HUC12 watershed scale. Due to the lack of long-term historical records of streamflow measurements at the HUC12 scale, and in order to capture the effect of natural variability in surface water availability, we rely on a retrospective record of streamflow simulations that goes back to 1979, which is produced by the second phase of the North American Land Data Assimilation System (NLDAS-2). The NLDAS-2 is a data assimilation system with uncoupled land surface models driven by atmospheric forcing fields, e.g., air temperature, wind, and precipitation (Cosgrove et al. 2003; Xia et al. 2012). The NLDAS-2 is currently running under four different land surface models (LSMs): (1) Noah, (2) Mosaic, (3) Sacramento Soil Moisture Accounting (SAC-SMA), and (4) Variable Infiltration Capacity (VIC) models. The four models produce streamflow estimates on a 1/8th-degree grid over central North America. According to the validation study conducted by Xia et al. (2012), the SAC-SMA and VIC models perform better than the other two models when compared with USGS observed streamflow. Therefore, the current study will use the streamflow record produced from the SAC-SMA model for the 35 years from 1979 to 2013. For the purposes of the current study, the NLDAS-2 streamflow records were spatially sampled by finding the specific NLDAS-2 grid that is closest to the HUC12 centroid. The streamflow values extracted from the NLDAS-2 grids were then used to represent the surface water availability for each HUC12. This was done for more than 1200 HUC12 watersheds in Louisiana. While the focus of our study is to account for the variability in surface water supply, we also accounted for groundwater as a source to mitigate stresses on water supply. However, due to the relatively lower natural variations in groundwater sources, and due to the lack of long-term and spatially distributed historical groundwater recharge dataset, the groundwater supply is set equal to the annual average recharge rate estimated by the USGS at 1-kilometer resolution grids (Wolock 2003).

2.2 Monthly Water Withdrawals

Surface and groundwater use data are collected by the U.S. Geological Survey (USGS) in cooperation with the Louisiana Department of Transportation and Development (DOTD) and

published as water withdrawal estimates aggregated at the county level on a five year basis since 1960 (Sargent et al. 2011). In our study, we used the USGS water withdrawals estimated in 2010 for different sectors (irrigation, industrial, public supply, and power generation) and spatially disaggregated them to the HUC12 watershed scale. The disaggregation of water withdrawals is based on weighting factors that account for the use at a finer resolution. These factors include: (1) the percentage of crop acreage in each HUC12 unit (for irrigation demand); (2) The maximum order of stream lines located inside each HUC12 unit (for irrigation and industrial demands); and (3) The ratio of urbanized area in each HUC12 unit compared to the total urbanized area in the county containing the HUC12 (for industrial and public supply demands). A geometric weighting formula is used to account for the weighting factors in the disaggregation of surface water use for each demand sector from the county level to the HUC12 scale. The reader is referred to Eldardiry et al. (2016) for more details on the disaggregation method of water withdrawals from the county scale to the HUC12 unit. In this study, we assumed constant weighting factors throughout the study period, for water withdrawal disaggregation. This assumption is reasonable for the scope of our study since the focus is on exploring the impacts of surface water supply variability on the water stress. However, future analysis of water stresses can be augmented to consider varying weighting factors that account for future developments in economy, social behavior, and technological innovations. Figures (1) shows the total water withdrawal calculated at HUC12 scale by all demand sectors excluding the agricultural sector (left panel) and when considering only the agricultural sector (right panel). Figures (1) highlights two key points: (1) the spatial variability in the water withdrawal is very evident at the HUC12 scale which would be masked when using the raw USGS data at county scale (see for example Acadia and Jefferson Davis counties in southwestern Louisiana); and (2) the irrigation water withdrawals (the right panel in Fig. 1) are spread over most of the HUC12s closer to major rivers (e.g., Mississippi River in southeastern Louisiana) and in southwestern Louisiana where rice irrigation is more dominant.

In addition to accounting for the seasonal variability in surface water availability, seasonal variations in water demands should also be considered, especially for agricultural uses where crops are irrigated only during specific seasons. Agriculture in Louisiana is one of this state's most important economic resources and about 11% of the total water withdrawals in Louisiana are used for crop irrigation (Sargent et al. 2011). For the current analysis, we only consider the most dominant types of irrigated crops grown in Louisiana. These include rice, corn, cotton, sugarcane, sorghum, and soybeans. Using the 30 × 30 m cropland data layer (Fig. 2) available from the United States Department of Agriculture/National Agricultural Statistics Service Information (USDA/NASS), the dominant crop type for each county is defined. The county crop type is then used to calculate the monthly irrigation water withdrawals for all HUC12 watersheds located within the county. The spatial distribution of the six dominant crops in Louisiana (Fig. 2) depicts a significant density of rice farms in southwestern Louisiana, while soybeans fields are mostly located in the northeastern counties along the Mississippi river. Moreover, other crop types such as corn, cotton, and soybeans, characterize the agriculture lands along the banks of the Red River in northwestern to central Louisiana. In the southwest region, rice farming is often combined with aquaculture (crawfish) use. Therefore, in our analysis, we distinguished between irrigation water demand for rice-only (irrigation season beginning in March and continuing through July) and demand for combined rice and crawfish (irrigation extends through November). The current study decomposes annual irrigation water withdrawals into a monthly basis using the percentages of the total withdrawals for each crop (Fig. 3).

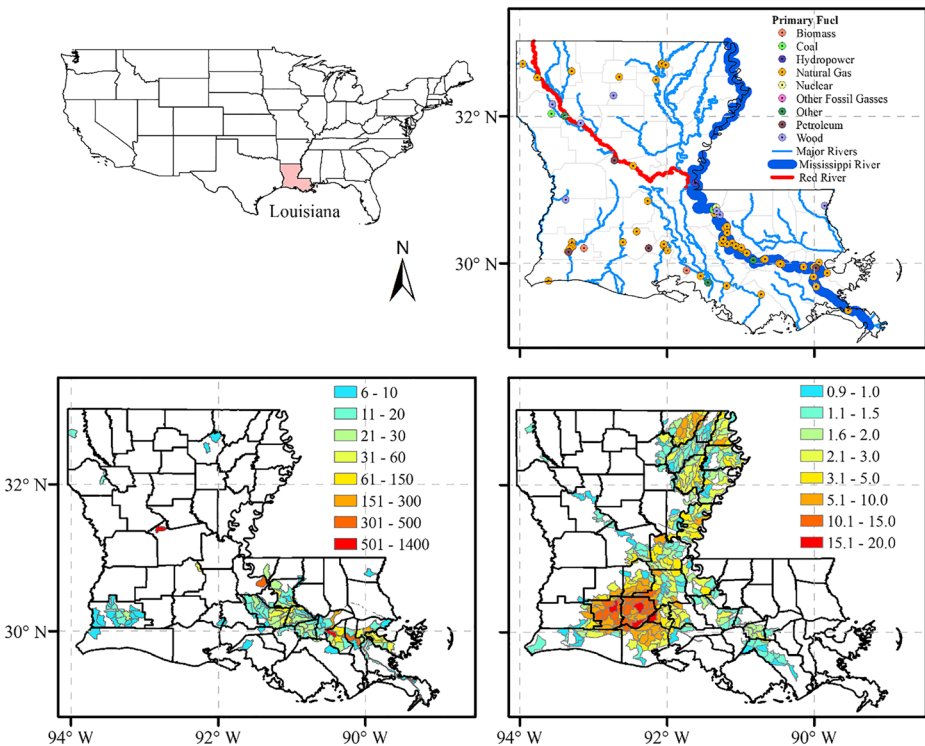


Fig. 1 Upper Right Panel: Location of power plants in Louisiana (Source: US Energy Information Administration (EIA)). The red and blue thick lines indicate the Red river and Mississippi river in Louisiana, respectively. Lower Left Panel: Total water withdrawal (in Million Gallon per Day; MGD) by all demand sectors (as estimated in 2010) excluding the agricultural sector for each HUC12 unit. Lower Right Panel: same as the left panel but for only the agricultural sector

These percentages were derived from estimates of monthly water requirements for different crop types provided by the United State Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Louisiana Irrigation Guide (Durga Poudel, Personal Communication). It is worth noting that these values are based on estimates in central Louisiana during a year with normal rainfall conditions. Due to the absence of more detailed information at a statewide scale, we assume the same pattern of water requirements for all years and for the whole state.

The USGS estimates of water withdrawals in the agriculture sector don't only represent water use for crop irrigation, but also include non-crop irrigation uses such as horticulture practices, water used in golf courses, parks, and other self-supplied landscape-watering uses. Hence, the current study assumes 90% of withdrawals are distributed based on the water requirements of the individual crop types and patterns (Fig. 3), while 10% of the water is allocated for non-crop use. Moreover, due to lack of information on the monthly distribution of the water withdrawals by other sectors, i.e., industrial, public supply, and power generation, we assumed an even distribution of the water demand across the entire year for these sectors. This assumption is reasonable because, compared to irrigation use, a more uniform distribution of monthly water use is expected for these water sectors.

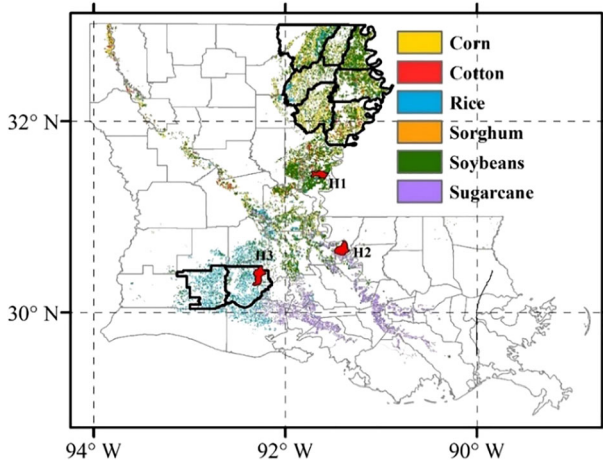


Fig. 2 Spatial distribution of dominant types of crops in Louisiana using the 30 × 30 m USDA/NASS data. The thick black line and red HUC12 units delineate the selected counties and watersheds, respectively, considered in our WaSSI analysis

2.3 Water Supply Stress Index (WaSSI)

Different indicators have been developed to assess water scarcity and the impact on meeting demands by different sectors (see Liu et al. 2017 for a summary of water scarcity indicators). In our study, the stress on the water system is quantified using the water supply stress index (WaSSI) originally developed by Sun et al. (2008). The WaSSI equation is expressed as a ratio of annual water withdrawals from surface water and groundwater sources ($WW_{SW} + WW_{GW}$) to annual water supplies ($WS_{SW} + WS_{GW}$) for each individual basin, which is defined in this case at the HUC12 watershed scale. The WaSSI formula was modified to include an environmental flow requirement (ENV) requirement (Eldardiry et al. 2016; Habib et al. 2018). The ENV factor accounts for the fraction of flow in rivers and streams that is necessary to support a healthy ecosystem in each watershed. Following the same threshold adopted by

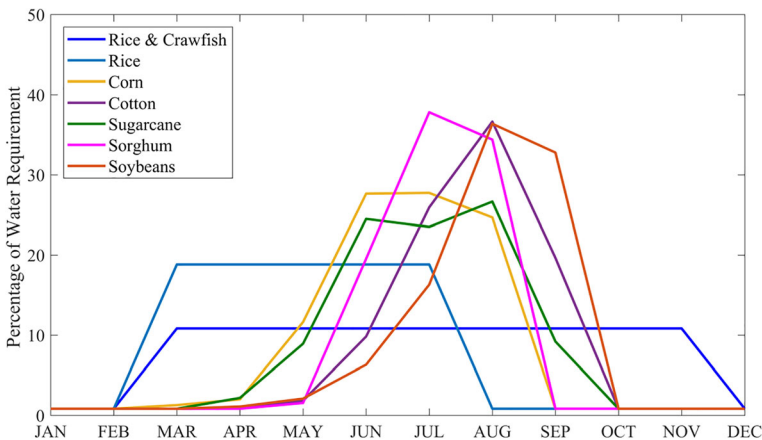


Fig. 3 Monthly distribution of water requirements (expressed in percentages of annual values) for irrigation demands of different crop types in Louisiana

Tidwell et al. (2014), the environmental flow factor in the WaSSI formula is chosen as 50%, which is a more conservative ratio compared to an average value of 37% concluded by Pastor et al. (2014) in their global water assessments. The WaSSI equation is described as follows:

$$WaSSI = \frac{WW_{SW} + WW_{GW}}{(I - ENV) * WW_{SW} + WW_{GW}} \quad (1)$$

The WaSSI formula has been typically applied using annual-average supply and demand values. In order to investigate both inter- and intra-annual stress variability, we calculated the annual and monthly stress in each HUC12 during the 35 years of our study period (1979–2013). While the monthly estimates of water withdrawals and groundwater supply are assumed constant from one year to another throughout our period of analysis, the inter-annual variability in the WaSSI stresses were accounted for by using the NLDAS streamflow simulations. To statistically characterize the inter- and intra-annual variability in the stresses, we calculated the median and the 97.5th and 2.5th percentiles of the WaSSI stress for each HUC12 over the 35-year record. The percentile difference (97.5%-2.5%) for annual and monthly WaSSI is used to indicate how wide the stress can vary across different years (inter-annual variability) and between months (intra-annual variability), respectively.

3 Results and Discussion

3.1 Inter-annual Variability in Water Stresses

To facilitate the discussion of results, we classified the stress levels into three categories: low ($WaSSI < 0.5$); medium ($0.5 < WaSSI < 1.0$); and high ($WaSSI > 1.0$). The median annual WaSSI for each HUC12 unit is displayed in the left panel in Figure (4) and shows relatively higher stresses in the southeastern part of the state where most of water use is by industrial facilities. In addition, some HUC12 units experience higher stresses in southwestern Louisiana, where water use for irrigation prevails. For instance, the median stress averaged over Acadia county is 0.18 with 7 of 23 total HUC12 watersheds having WaSSI greater than 0.2. The median results, which are based on a record of 35-year streamflow estimates, are

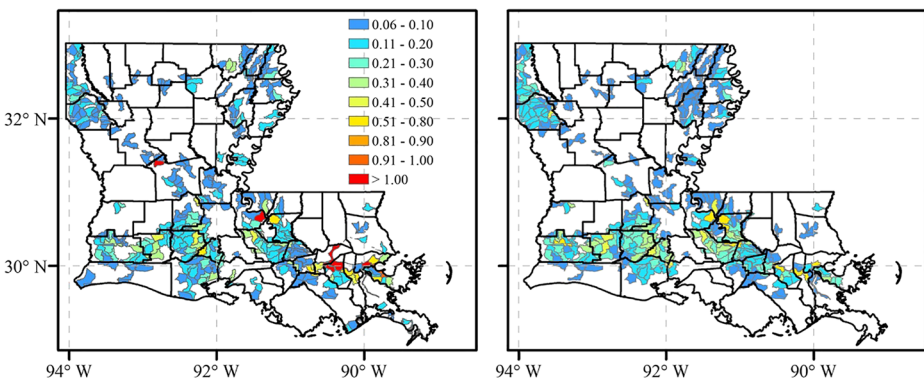


Fig. 4 Left panel: Spatial distribution of median annual WaSSI at the HUC12 scale during the period 1979–2013. Right panel: Inter-annual variability in WaSSI expressed as difference of the (97.5%-2.5%) percentiles

comparable to those of Eldardiry et al. (2016) who relied on a mean-annual record of streamflow to represent surface water availability.

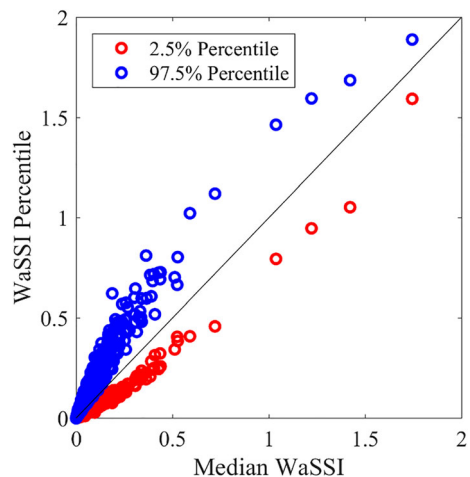
Examining the inter-annual variability results provides new insights into the impact of natural variability in water availability. The right panel in Figure (4) shows the variability in the water stress expressed in terms of the percentile difference (97.5%-2.5%) of the annual WaSSI calculated over the 35 years of historical data. High stresses (WaSSI > 1.0) with wider percentile differences (i.e., higher inter-annual variability) are noticed in watersheds where thermoelectric power plants exist and use extensive water for cooling processes. For example, a median WaSSI of 1.22 and percentile width of 0.65 (about 53% of the median WaSSI) is noticed for HUC12 80703000101 (highlighted as H2 in Fig. 2).

The inter-annual stress variability results are further summarized in Figure (5). The results reveal a clear dependency pattern where the inter-annual variability increases as a function of median WaSSI. Watersheds with smaller (larger) bounds of variability are associated with low (high) median levels of stress. Identifying the bounds of annual stress variability provides a more detailed representation of the water stress in a watershed, especially with those HUCs that show medium to high stresses. Such impacts of climate variability are masked when only showing the average (or median) stresses as in previous studies (e.g., Averyt et al. 2013; Tidwell et al. 2014; Eldardiry et al. 2016). increased stress revealed by natural variability in water supply, higher levels of WaSSI stresses in southern Louisiana can be further intensified when accounting for the quality of water (e.g., higher-salinity areas near the coast). For example, Borrok et al. (2018) showed higher stresses in Louisiana when considering limitations imposed by saline and brackish waters in coastal areas.

3.2 Intra-annual Variability in Water Stresses

In addition to the inter-annual variability in water stress, it is also crucial to understand the variability between months within the year (or intra-annual variability). In our analysis, such monthly variations in water stress reflect the variability in both surface water supply and irrigation demands. Monthly stresses were calculated for all HUCs over Louisiana and displayed spatially as shown in Figures (6) and (7). The high median stresses in southeastern

Fig. 5 Annual WaSSI (median vs. percentile) for all HUC12 watersheds in Louisiana



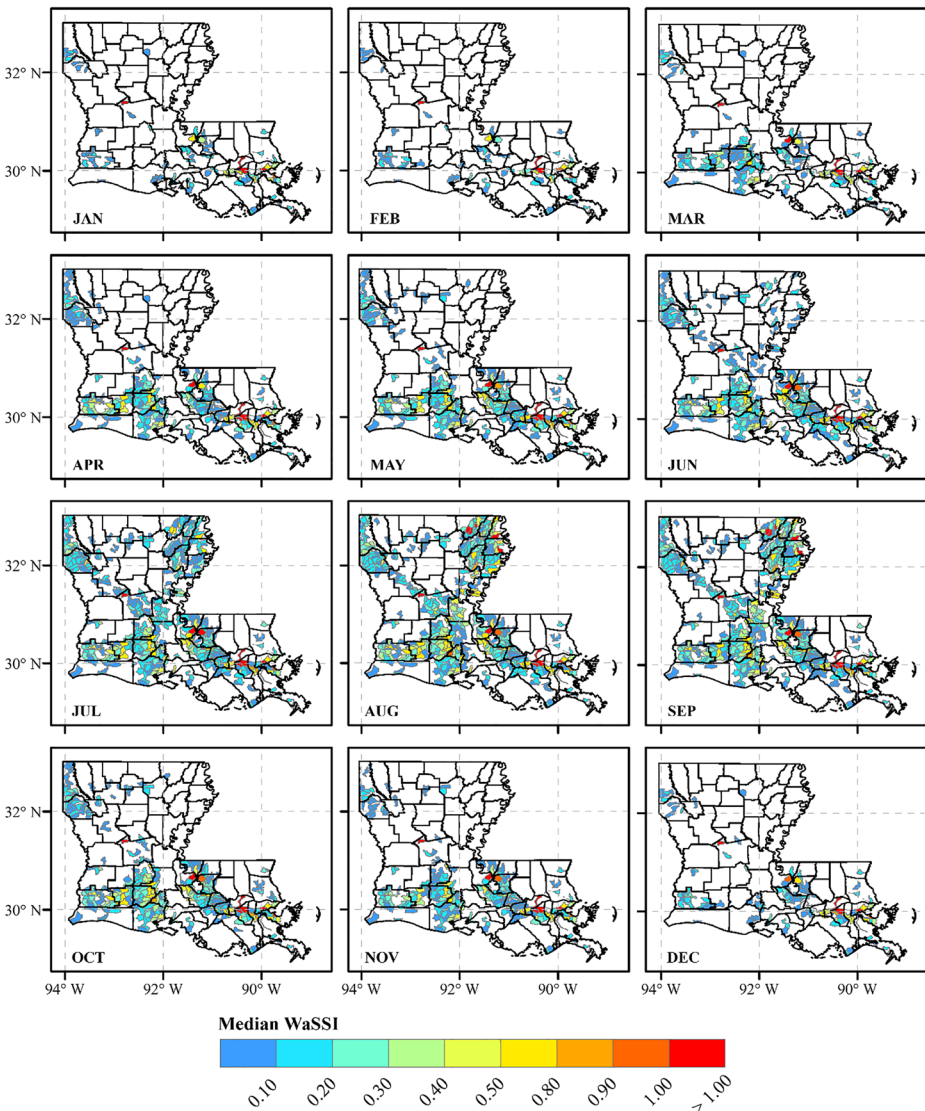


Fig. 6 Median Monthly WaSSI in each HUC12 during the period 1979–2013

Louisiana (e.g., HUC12 units with $WaSSI > 1.0$) are still present across all months, which is expected given that the stress in these HUCs is dominated more by the water demand from thermoelectric power plants, which was assumed constant across the months, than by the natural variability in streamflow. However, the results changed significantly for the irrigation areas in southwestern and northeastern Louisiana where water demand was allocated by monthly irrigation demand. In these areas, the effect of streamflow variability also plays a significant role and is not necessarily overwhelmed by high demands. The WaSSI in these areas mirrored the cropping pattern in Figure (3). For instance, the northeastern counties, where soybeans is the dominant crop type, are subjected to much higher stresses (with larger variability) during the peak irrigation seasons of July through September. Within each month,

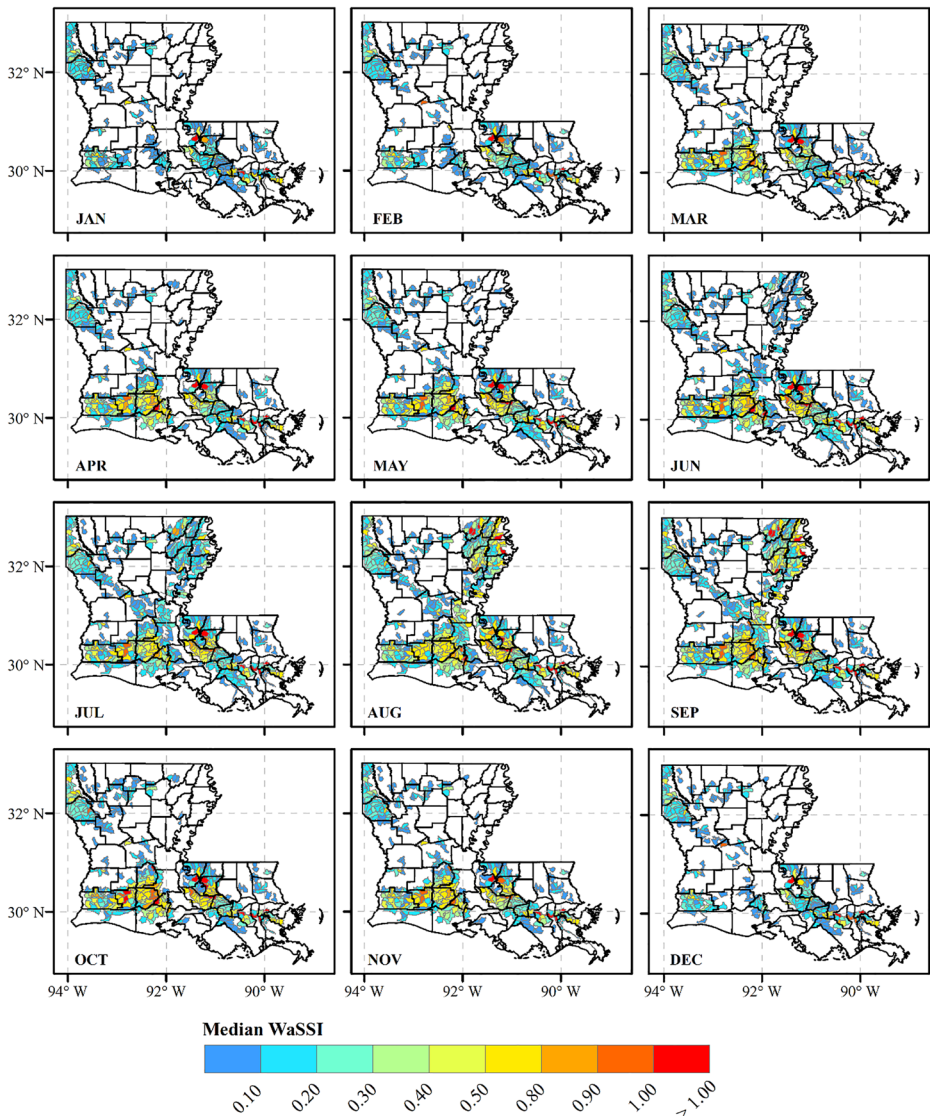


Fig. 7 Inter-annual variability in monthly WaSSI, expressed as percentile difference (97.5%-2.5%), for each HUC12 during the period 1979–2013

the effect of climate variability is also evident as illustrated by the relatively wide percentile differences, indicating the potential for high water stresses in areas that don't necessarily report such risk when evaluated at annual or monthly-average scales.

To further examine the WaSSI variability, we selected seven counties in northeastern Louisiana with a high density of cropped area (Fig. 2). Monthly WaSSI values for the individual HUC12 units located in the seven selected counties are shown in Figure (8). The spread across the different months (bars) represents the effect of inter-annual variability, while the spread within each month (circles) represents the effect of intra-annual variability. This figure illustrates that water stresses are mostly impacted by the irrigation demands where the

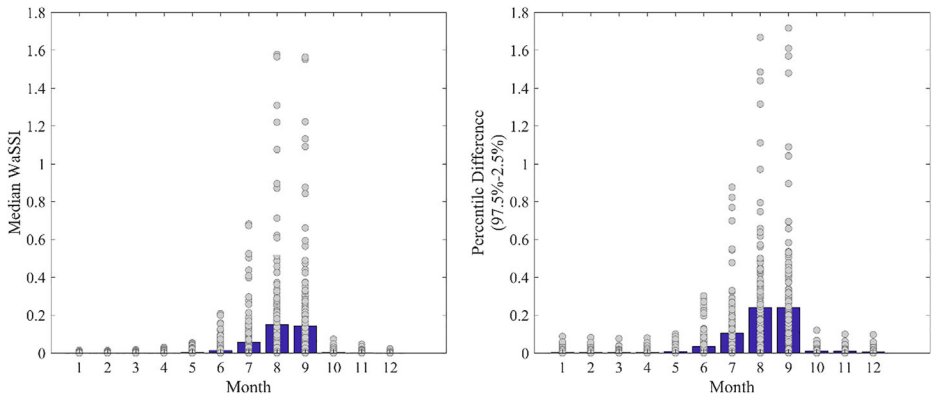


Fig. 8 Median (Left Panel) and percentile difference (Right Panel) of WaSSI stress index for HUC12 units within the seven counties in northeastern Louisiana (Fig. 2). The grey circles indicate the individual WaSSI statistics for the HUC12 units within the selected counties and the blue bars represent their medians

median WaSSI reaches as high as 0.15 in August with a variability of 0.24. About 20% (33 out of 168) of the HUC12 units in the northeastern region experience a stress level of more than 0.50 during the year. Such stress levels are reached during the soybean irrigation season in July (6 HUCs), August (14 HUCs), and September (13 HUCs). Similar patterns are also noticed in southwestern Louisiana where rice irrigation occurs primarily from March through November. Figures (9) shows a statistical summary of the monthly WaSSI index over two counties in southwestern LA (Acadia and Jefferson Davis). The effect of the variability in surface water supply on the WaSSI is apparent in both counties where the stress index decreases as more surface water supply become available (e.g., WaSSI in Acadia county decreases from 0.30 to 0.25 between August and September). The largest percentile difference for the two counties is noticed in October with about 0.60 and 0.37 over Acadia and Jefferson Davis, respectively. Higher stresses in these two counties were also indicated by Devineni et al. (2015) using risk metrics that capture the effects of within-year dry periods (Normalized Deficit Index, NDI) and droughts over multiple years (Normalized Deficit Cumulated, NDC). For instance, they

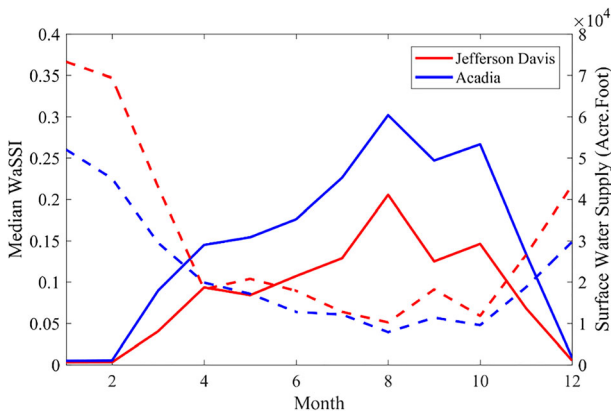


Fig. 9 The Median WaSSI (solid lines) considering all HUC12 units located in the two selected counties in southwestern Louisiana (Jefferson Davis and Acadia). The right axis is used to indicate the surface water supply in each county (dashed lines)

showed a multiyear cumulative deficit index NDC (cumulative deficit normalized by average annual rainfall) of more than 5 over Acadia county (see Fig. 2 in Devineni et al. 2015).

The percentile difference (97.5%-2.5%) as a function of the median WaSSI at a monthly scale (Fig. 10) have a similar pattern to that observed for the annual WaSSI (Fig. 5) in that higher percentile differences are associated with larger median WaSSI. This behavior is persistent across all months. However, it is important to note that this pattern changes when the median WaSSI becomes very high and the variability starts to decrease. To further characterize this pattern, we regressed the percentile difference (97.5%-2.5%) of the WaSSI relative to the median WaSSI for all HUC12 units in Louisiana. Figures (11) shows the percentile difference as a function of the median WaSSI (here a quadratic function is used for smoothing) at both monthly and annual scales. The figure reveals a pattern that could be generalized spatially (across all HUCs) and temporally (across all months). According to this pattern, the stress variability grows as the median WaSSI increases but up to a certain threshold

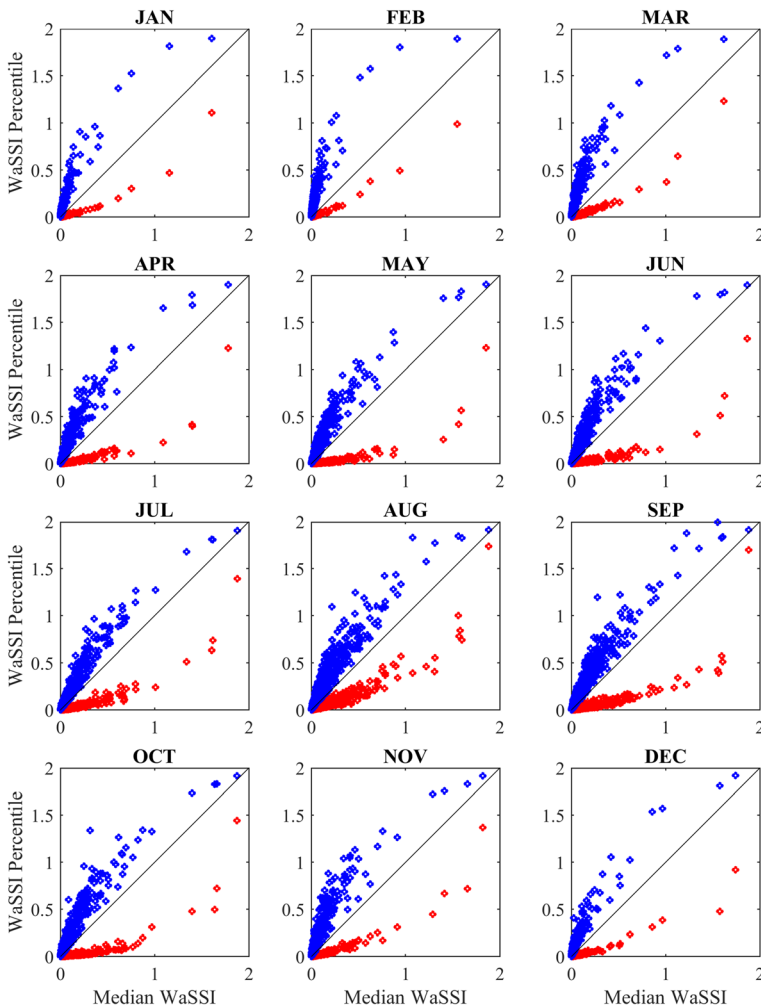


Fig. 10 Monthly WaSSI (median vs. percentile difference) for all the HUC12 units in Louisiana. Red and blue circles represent the 2.5 and 97.5 percentile for each HUC12, respectively

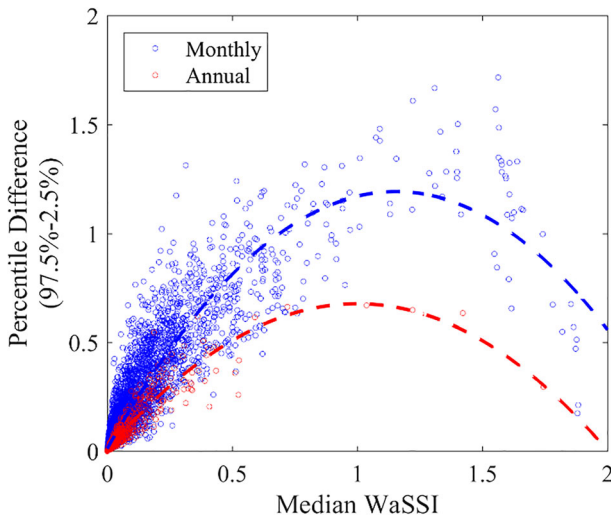


Fig. 11 Regression of the percentile difference (97.5%-2.5%) on the median WaSSI at annual and monthly scales for all the HUC12 units in Louisiana

level and then the variability decreases at very high stress levels. For instance, at annual and monthly scales, the peak variability was reached at a median WaSSI of 1.00 (corresponding to percentile difference of 0.68) and 1.15 (corresponding to percentile difference of 1.19), respectively. This pattern is likely attributable to the fact that modest changes in supply and demand that occur in watersheds with a low median annual stress do not have a big overall impact, simply because the stress in these watersheds is controlled by the low demands, or by high water availability, or by both. However, when watersheds are highly-stressed, changes in supply and demand can lead to large changes in the water stress regime. These watersheds are sensitive to changes in both climate variability and seasonal variability in demands. Finally, at the very highest levels of median water stress, changes in supply and demand no longer matter much as the water stress is already maximized due to very high demands, very low water availability, or both. Figure (11) shows the importance of considering WaSSI at monthly time scales as opposed to annual WaSSI that can veil high levels of WaSSI stress attributable to seasonal variability. Such variations in stress levels are highly important when dealing with water management practices in light of different climate conditions.

3.3 Examples from HUC12 Watersheds

In this section we further examine the inter-annual and intra-annual variability of the WaSSI stress index and its components (i.e., water supply and demand) in three example HUC12 watersheds. The selected watersheds are (see Fig. 2 for the locations of the three HUCs): H1: 80403060201, H2: 80703000101, and H3: 80802010203. The two watersheds (H1 and H3) were chosen in areas where water withdrawals for irrigation are dominant and thereby variability is influenced by both water supply and demands, while watershed H2 is representative of a water system where most water is withdrawn for cooling of thermoelectric power plants (Table 1) so water supply is the driver of variability. To better assess the impact of climate variability, both from intra-annual and inter-annual perspectives, we estimate the

Table 1 Water supply and demand for the three representative HUC12 watersheds highlighted in Fig. 2 (Supply and demand units are in Acre-Foot/Year; AFY)

HUC12	SW Supply	GW Supply	Agriculture	Industrial	Power Generation	Public Supply	Dominant Crop
80403060201	376667	12597	3512	0	0	156	Soybeans
80703000101	42691	12433	1370	324	411116	853	Soybeans
80802010203	112303	14875	16681	101	0	261	Rice

WaSSI stress at different temporal scales by using a moving-window with a size of T months (where T is set to 1, 3, 6, and 12 month intervals).

Figures 12, 13, and 14 show time series of water supply, demand, and corresponding stresses at different temporal scales. This illustrative analysis reinforces the picture revealed in the previous sections on the importance of quantifying the variability in the water stress at temporal scales that are relevant for water management operations. For instance, while the average stress in watershed H1 is classified as low stress (WaSSI = 0.15), considering the stress at monthly or three-month scales, this HUC can encounter higher stresses that fall in the medium stress category (WaSSI > 0.50). In this case, 54 and 28 out of 420 months were highly stressed when using a scale of one- and three- months, respectively. Similar patterns are present in H3 where the average WaSSI (1.25) masks the inter-annual and intra-annual variability that can worsen the stresses to a level greater than 1.70 (February through May of 2000). The stress increase in 2000 is attributed to the sudden drop in the surface water supply due to a major drought reported in the region as indicated in the upper panel of Figure (13).

The periodicity in the WaSSI is evident in every HUC, but is more pronounced for some of the HUC's (e.g., H1 and H3), where irrigation derives the demand variability. In these HUCs,

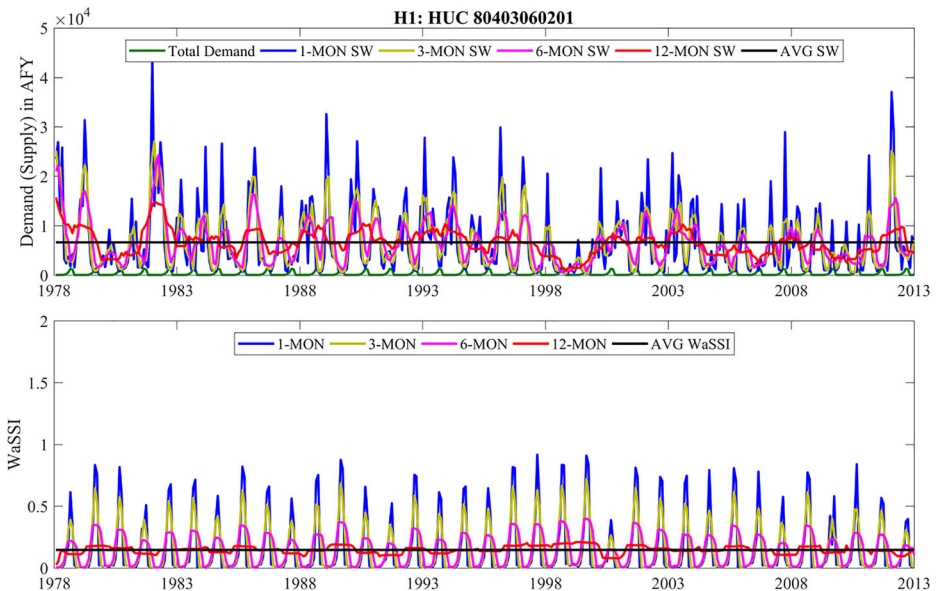


Fig. 12 Upper panel: Time series of monthly demand and surface water supply (in Acre-Foot/Year; AFY) at different time scales over HUC unit (H1). Lower panel: Time series of the WaSSI at different time scales (See Fig. 2 for the location of the HUC unit H1)

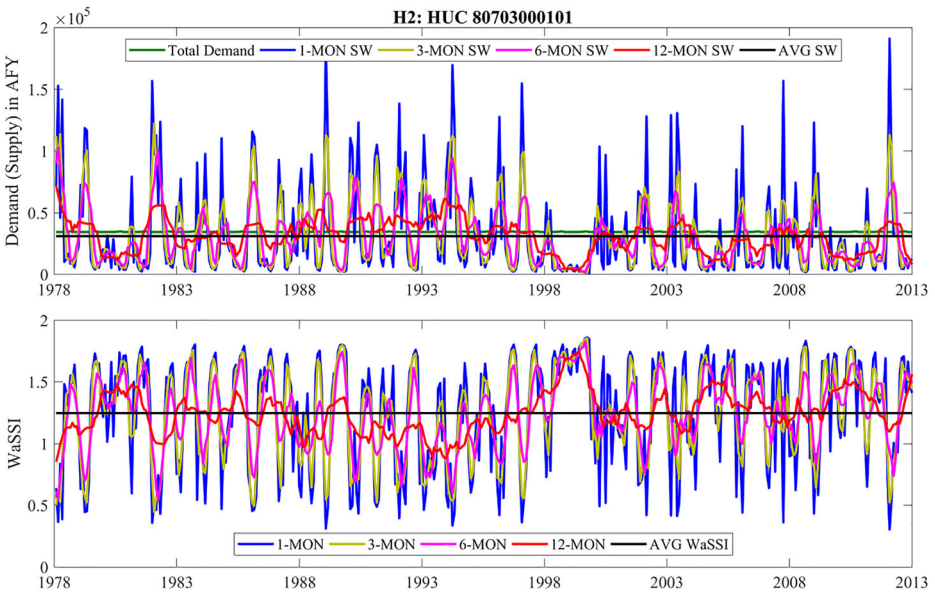


Fig. 13 Upper panel: Time series of monthly demand and surface water supply (in Acre-Foot/Year; AFY) at different time scales over HUC unit (H2). Lower panel: Time series of the WaSSI at different time scales (See Fig. 2 for the location of the HUC unit H2)

the annual demand is distributed over the months based on agricultural uses and produces peak demands from July to September. This variability in demand can be easily detected in the one- or three-month scales and is repeated every year, while in the larger window sizes (6 and 12

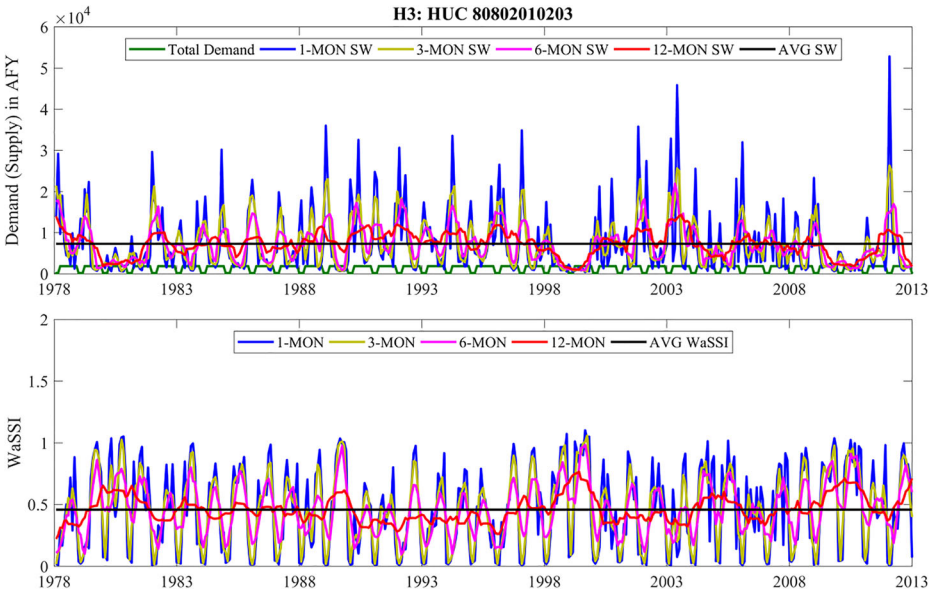


Fig. 14 Upper panel: Time series of monthly demand and surface water supply (in Acre-Foot/Year; AFY) at different time scales over HUC unit (H3). Lower panel: Time series of the WaSSI at different time scales (See Fig. 2 for the location of the HUC unit H3)

months) this periodic stress behavior is dampened. On the other hand, the stress behavior is different in the H2 watershed, which is dominated by industrial and power plant uses (Fig. 14). In this HUC, the variability in WaSSI is driven only by monthly streamflow variability since it was assigned a constant monthly distribution of annual demand for the industrial and power generation sectors. Using these different temporal scales further illustrates that relying on an aggregated WaSSI (i.e., based on average conditions) can be misleading since it hides climatic impacts on the system's ability to meet water demands, and may also mask opportunities for water harvesting during lower than average stress periods. In addition, exploring the stresses at small watershed scales (HUC12) highlighted important spatial variations that would be masked when performing the analysis at coarser scales. For instance, Greve et al. (2018) calculated the water stress globally at a gridded scale of 0.5° over the US (for the period between 2006 and 2015). They showed very low stresses in Louisiana with few grids that experience relative high stresses (greater than 0.1) in southwestern Louisiana.

4 Conclusions

This study investigated the inter-annual and intra-annual variability in water stress in Louisiana and provided insights into the importance of accounting for such variability when assessing water system sustainability. The analyses are based on incorporating historical records of streamflow estimates and annual changes in water demand into the Water supply stress index formula (WaSSI) to reflect the variability in the surface water supply. The key conclusions of our study are as follows:

- 1 The year-to-year variability in surface water supply can substantially ameliorate (wet years) or exacerbate (dry years) water stress, particularly in watersheds already subjected to high average annual stress.
- 2 A large number of HUC12 watersheds in Louisiana that exhibit low average water stresses are subjected to much higher seasonal stresses throughout the year due to seasonal variability in water supply and the demand for irrigation.
- 3 Our analysis quantifies what is likely a geographically HUC-independent pattern in the relationship between water stress variability and the median annual stress. The pattern shows that the variability in intra- and inter-annual stresses are lowest in watersheds with the lowest annual median stresses and increase with increasing annual median stress. However, at a threshold annual median stress value of about 1.0, the pattern reverses and the variability decreases with increasing average annual stress. This pattern shows that climate variability is most important to consider in the watersheds that are under medium to high annual stress, while the situation does not change as much at the highest and lowest ends of the spectrum.

The results highlighted the need for assessing the water stresses at spatial and temporal scales that are relevant for water management operations. These scales reveal challenges (e.g., drought management) as well as opportunities (e.g., managed aquifer recharge) for sustainable water management. This is significant in wet regions like Louisiana where abundant surface water exists and there is an opportunity for storing high magnitude flows in surface or subsurface reservoirs through strategies such as Aquifer Storage and Recovery (ASR). The value for such strategies was recently illustrated by Yang and Scanlon (2019) who showed the

potential of ASR in capturing peak flows during Hurricane Harvey in Houston, Texas. While integration of data on water supply and demand from various sources and models revealed key patterns in the stress variability at annual and monthly scales, one caveat related to our analysis is that it does not address different sources of uncertainties associated with such data. For instance, such uncertainties can stem from parametrization of the LSM to simulate streamflow (surface water supply), monthly decomposition of water withdrawals, and socio-economic demand drivers (Gleick 2003; Jury and Vaux 2005). Thus, future research needs to be carried out to further quantify the uncertainty in both water supply and demand. Furthermore, our WaSSI analysis is important for water managers to assess alternative measures for mitigating water stresses, including: the use of non-traditional sources of water (e.g., desalination of brackish groundwater and reuse of treated wastewater) to supplement peak demand and improving the efficiency of existing power plants through less water-intensive cooling technology and fuel types.

Acknowledgements This study was funded by the National Science Foundation (NSF) grant for study of water sustainability and climate (NSF-USDA/NIFA 2014 WSC-Category 1 Collaborative, Award # 1360398) and by the Program Project ID R/CRM-02 through the Louisiana Sea Grant College Program under NOAA Award NA18OAR4170098. The NLDAS-2 streamflow estimates used in this study were acquired as part of the mission of NASA's Earth Science Division and archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC). The authors acknowledge the valuable inputs provided by Durga Poudel (School of Geosciences, University of Louisiana at Lafayette) regarding the seasonal water requirements for different crop types in Louisiana.

Compliance with Ethical Standards

Conflict of Interest The authors declare that there are no conflicts of interest.

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Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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