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Seasonal precipitation pattern analysis for decision support of agricultural irrigation management in Louisiana, USA

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ABSTRACT

Rainfed agriculture is often a challenge in many humid regions due to the irregular distribution of precipitation events. Precipitation irregularity during crop growing seasons causes soil water deficits that negatively impact crop yields. To alleviate water stress, farmers are expected to compensate for water deficits through irrigation. Because irrigation consumes valuable water resources, it is critical to envision water management strategies that enhance precipitation water use and reduce irrigation water withdrawals. However, precipitation patterns generally vary depending on locations and seasons. Hence, a thorough understanding of crop exposure to water deficit in time and space is essential to improve agricultural water use efficiency. This study investigated both spatial and seasonal patterns of precipitation to elucidate the exposure of crops to water deficits at a regional scale. Specifically, a spatial regionalization technique was applied to a 33-year gridded time series of seasonal precipitation totals and numbers of events in Louisiana to determine two precipitation regions with distinct characteristics. Within each region, kernel density estimators were employed to approximate the actual probability distribution of seasonal precipitations. Estimates of crop water requirements for corn, soybean, cotton, grain sorghum, and sugarcane under both early and late planting scenarios were employed to evaluate the probabilities of crop exposure to water deficits during the growing seasons. The outcomes of this study include a distinction of precipitation regions for Louisiana and a detailed probabilistic evaluation of crops exposure to water deficits. These outcomes are intended to support irrigation management recommendations for farmers across the state of Louisiana.

1. Introduction

The spatial and temporal distributions of terrestrial water resources generally affect human activities and agriculture in particular (Bagatin et al., 2014; Gleick, 1996). In many agroecosystems, crop seasons rely on local precipitation patterns and available water resources. However, the absolute reliance on natural precipitation has become challenging in these agroecosystems due to precipitation irregularity. Indeed, the irregular distribution of precipitation events during crop seasons causes water deficits, affecting crop yield stability (Sohoulande et al., 2019). This is especially true in humid regions where the total annual precipitation is virtually sufficient to meet crop water requirements. Crops suffer differently from water stress during the growing seasons depending on their species and development stages. Hence, the decision to compensate water deficit through supplemental irrigation may not be a systematically profitable option for farmers, given the irrigation systems' costs (Adusumilli et al., 2016). Yet, to invest in irrigation infrastructure, farmers need a thorough understanding of crops exposure to water deficit based on the local climate and the types of crops. In addition, insights into crops exposure to water deficit may influence farmers' decision to consider an early or late planting given the reports of precipitation patterns' disturbance under climate change (Sohoulande and Singh, 2016). As a result, a thorough understanding of precipitation patterns during crop growing seasons is critical to improve water use efficiency and justify the value of irrigation systems in humid climates (Sohoulande et al., 2019; Kebede et al., 2014).

In many humid regions, farmers fail to utilize the existing water resources optimally by opting for less efficient irrigation systems and not taking enough advantage of seasonal precipitation distribution (Sohoulande et al., 2019; Kebede et al., 2014). This situation is real in

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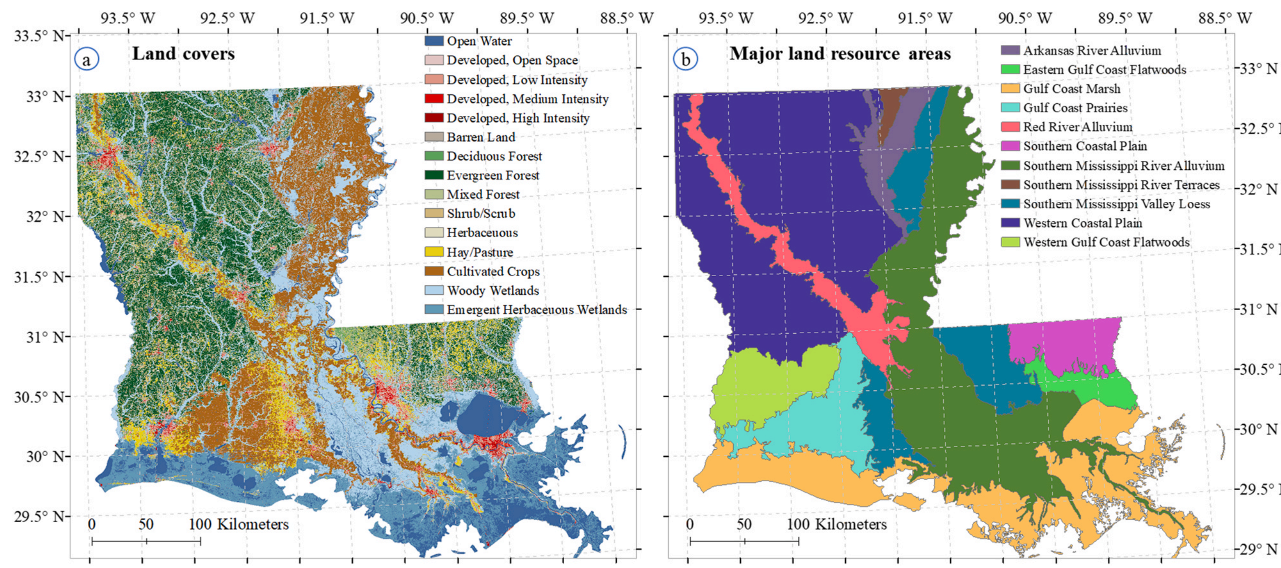

Fig. 1. Spatial distribution of land cover types and major land resource areas across the state of Louisiana.

Table 1
Summary of the percentage coverages of land cover types and major land resource areas in Louisiana.

Land Cover		Major land resource areas[a]		
Designation	Area covered (%)	Designation	Area covered (%)	Dominant soils
Open water	10.30	Arkansas River Alluvium	3.04	Vertisols, alfisols, inceptisols, and entisols.
Developed, open space	2.94	Eastern Gulf Coast Flatwoods	2.05	Alfisols, ultisols, entisols, spodosols, and histosols
Developed, low intensity	2.81	Gulf Coast Marsh	15.21	Entisols and histosols
Developed, medium intensity	0.73	Gulf Coast Prairies	5.88	Alfisols, mollisols, and vertisols
Developed, high intensity	0.34	Red River Alluvium	4.98	Vertisols, entisols, inceptisols, and alfisols
Barren land	0.26	Southern Coastal Plain	3.58	Ultisols, entisols, and inceptisols
Deciduous forest	1.50	Southern Mississippi River Alluvium	21.52	Alfisols, vertisols, inceptisols, and entisols
Evergreen forest	19.21	Southern Mississippi River Terraces	0.60	Alfisols
Mixed forest	2.11	Southern Mississippi Valley Loess	8.57	Alfisols, entisols, inceptisols, and ultisols
Shrub/Scrub	3.84	Western Coastal Plain	29.59	Alfisols and ultisols
Herbaceous	2.41	Western Gulf Coast Flatwoods	4.98	Alfisols and ultisols
Hay/pasture	6.54	TOTAL	100	
Cultivated crops	15.47			
Woody wetlands	20.85			
Emergent herbaceous wetlands	10.72			
TOTAL	100			

[a] Detailed description of the major land resource areas is reported by USDA-NRCS (2006).

Louisiana, where the predominant irrigation methods are furrow and flood systems (Kebede et al., 2014; Gautam et al., 2020). A significant paradox noted in Louisiana is the depletion of the state's aquifers due to an overdraft of groundwater for irrigation, despite an abundance of precipitation and surface water (Eldardiry et al., 2016; Adusumilli et al., 2016). Indeed, Louisiana produce a wide variety of humid-climate adapted crops such as corn, soybean, cotton, grain sorghum, and sugarcane. Because these crops are essential for the Louisiana economy, it is necessary to promote water management practices that sustain environmental integrity across the state. Especially in Louisiana, agricultural practices aiming to maximize precipitation water use and enhance irrigation efficiency are likely to contribute to environmental sustainability. Hence, the scope of this study is to investigate both spatial and seasonal patterns of precipitation and elucidate the exposure of crops to water deficits based on farm locations across Louisiana.

The study used a combination of principal component analysis (PCA) and cluster analyses to conduct a spatial regionalization based on both precipitation totals and number of precipitation events (Sohoulande et al., 2019). The Food and Agriculture Organization (FAO) CropWAT 8.0 (Smith et al., 2002) was used to estimate the water requirement of various seasonal crops including corn, soybean, cotton, grain sorghum, and sugarcane under early and late planting scenarios in Louisiana. The estimates were used to evaluate the probability of seasonal precipitation exceeding the amount needed to meet crop water requirements under average Louisiana climate conditions. The outcomes of this evaluation are intended to help farmers become better informed about crop water management decisions that can contribute to the propensity for enhancing crop water use efficiency. This evaluation's outcomes seek to help farmers become better informed about crop water management decisions that can contribute to improved crop water use efficiency.

2. Data and method

2.1. Data and study region

The study region is the state of Louisiana which is characterized by diverse land resource areas and land covers (Fig. 1). Fig. 1 presents the spatial distribution of land covers and the major land resource areas across Louisiana as demarcated by the Natural Resources Conservation Service at the United States Department of Agriculture (USDA-NRCS, 2006). Table 1 summarizes their coverage percentages retrieved from the 2016 National Land Cover Database (Jin et al., 2019). Louisiana encompasses a large part of the Mississippi River delta but the climate

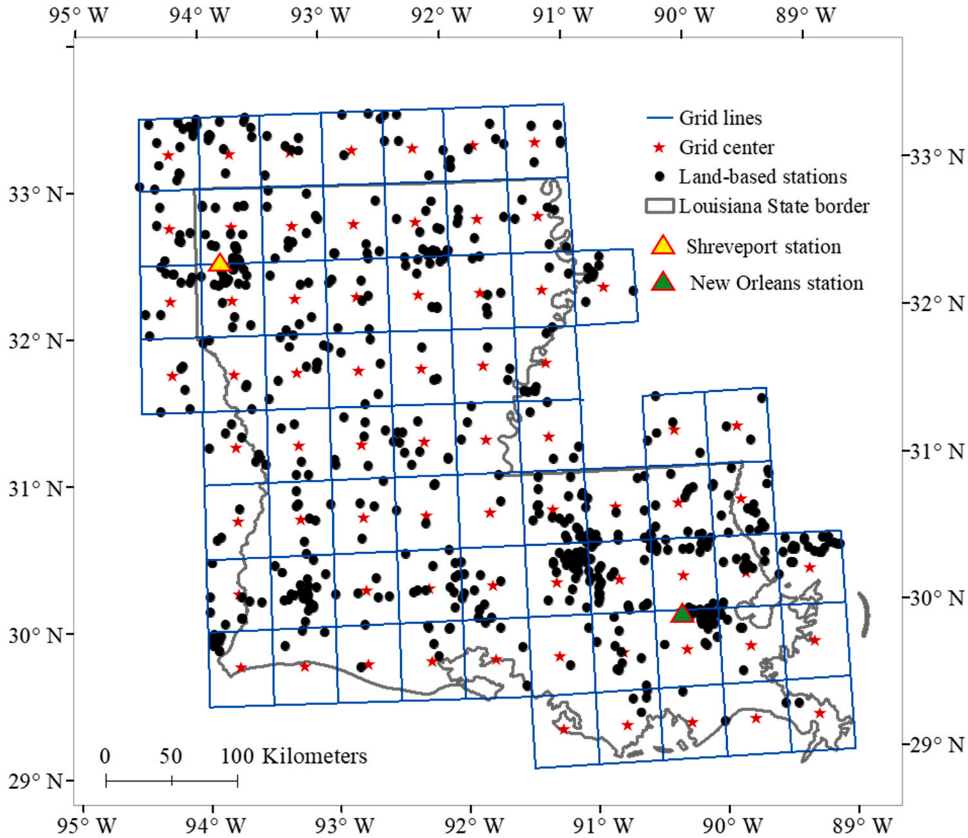

Fig. 2. Gridding precipitation data to cover Louisiana based on historical records from 635 land-based stations. Shreveport station (Northern Louisiana) and New Orleans station (Southern Louisiana) are represented by the yellow and green triangles respectively.

and lands resources across the state, allow farmers to grow a wide variety of seasonal crops. In 2018, corn, soybean, cotton, grain sorghum, and sugarcane represented 73.4% of the harvested acreage of field crops in Louisiana (USDA-NASS, 2021). Annually, the spatial distribution of these crops varies depending on a variety of factors including current crop prices, winter weather conditions, expected droughts during the crop season, and possibly the need to rotate for allelopathic reasons. As shown in Table 1, the combination of wetlands (i.e., woody wetlands, emergent herbaceous wetlands) and open water areas represent approximately 42% of Louisiana land covers, while cultivated crop areas represent 15.5%. Hence, water resources are relatively abundant in many parts of Louisiana, but this abundance created a propensity for poor agricultural water management practices. Indeed, Kebede et al. (2014) reported low water use efficiencies in southern Louisiana agriculture. They associated groundwater depletion with the continuous overdraft of water for irrigation. Wiser management of agricultural water in both rainfed and irrigated systems would enhance crop water use efficiency defined as the ratio between the crop evapotranspiration and the amount of water supplied by both irrigation and precipitation (Fernández et al., 2020).

In addition to the land covers and major land resource data used to generate Fig. 1 and Table 1, the analyses in this study used two categories of data: precipitation and crop water requirements. The precipitation data were 0.5° gridded time series of seasonal precipitation totals and number of events with 71 grids created to cover the state. For each grid, the associated precipitation data spanned from 1988 to 2020 encompassing a standard climatological normal length (i.e., 30 years) (WMO, 2017). Historical daily precipitation data from 635 land-based stations were retrieved from the National Oceanic and Atmospheric Administration (NOAA) database to generate the gridded time series (Fig. 2). Data from stations falling within the same grid were averaged daily to generate the grid-level time series. Note that these land-based stations generally present gaps in their historical precipitation records. Thus, for each date of the time-series, the grid-level daily precipitation calculation only considers the land-based stations having a record for that date. When none of the stations within a grid contained a record for a given day, a weighted distance average of the nearest three stations outside the grids was used to fill the gap. This process generated71 gap-free gridded daily time series. The grid-level daily precipitation data were summed to obtain time series of seasonal precipitation totals based on the seasonal periods defined as December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON). With some exceptions, annual row crops grown in Louisiana are planted in MAM and harvested in SON with critical growth periods typically occurring in JJA. Thresholds of 5 mm, 12.7 mm (half inch), and 25.4 mm (1 in.) were used to generate gridded time series of seasonal numbers of precipitation events according to Sohoulande et al. (2019, 2014).

2.2. Precipitation regionalization

The study's method included a spatial regionalization approach and a probability assessment of seasonal crop water requirements. The spatial regionalization aimed to optimally determine regions that capture seasonal precipitation patterns across Louisiana. The regionalization approach was reported in detail by Sohoulande et al. (2019) and consisted of a combined PCA and cluster analyses. Used as a variable reduction technique, PCA was applied separately to the 33-year gridded time series of seasonal precipitation totals and the number of precipitation events > 5 mm. The first six principal components (PCs) were retained as their eigenvalues (i.e., the total amount of variance explained by a given PC) were greater or equal to 1.0 (Kaiser, 1958). For each of the 71 grids, the six loading factors associated with the first six PCs were retained for the cluster analysis. Calculation of the loading

Table 2
Summary of the crop coefficient K_c values for corn, soybean, cotton, grain sorghum, and sugarcane. Values reported in this tables are the weight average based on the length of the crop growth stages in CropWAT 8.

Region	Growth stage	Corn	Soybean	Cotton	Grain sorghum	Sugarcane
Northern Louisiana (Shreveport)	Initial	0.30	0.40	0.35	0.30	0.93
	Development	0.74	0.66	0.78	0.63	0.89
	Mid	1.24	1.17	1.23	1.03	1.33
	Late	0.74	0.88	0.89	0.78	1.04
Southern Louisiana (New Orleans)	Initial	0.30	0.40	0.35	0.30	0.93
	Development	0.73	0.65	0.77	0.58	0.89
	Mid	1.22	1.16	1.20	0.99	1.32
	Late	0.74	0.87	0.87	0.77	1.04

factors, given by Eq. (1), is based on both the eigenvalue and eigenvector.

$$Loading\ factor = eigenvector * \sqrt{eigenvalue} \tag{1}$$

K-means cluster analysis was conducted on the 71 grids, with each grid having six loading factors. To determine the optimum number of clusters (k), Jaccard similarity indices were calculated for different values of k ($2 \leq k \leq 12$). Given two clusters X and Y, the Jaccard index formula given by Eq. (2) was used to evaluate the similarity between the clusters obtained based on seasonal precipitation totals and those obtained based on seasonal number of precipitation events.

$$Jaccard\ index = \frac{X \cap Y}{X \cup Y} \tag{2}$$

The higher Jaccard index value corresponded to the optimum number of clusters and identified the precipitation regions. A comparative analysis of seasonal precipitation patterns was carried out to evaluate differences between precipitation regions. A paired-wise Student *t*-test was conducted to compare DJF, MAM, JJA, and SON precipitation totals and number of events > 5 mm, > 12.7 mm, and > 25.4 mm.

The probability analyses used a non-parametric kernel density estimator to approach the probability density function of seasonal precipitation. Probabilities of exceedance were thereafter calculated for different values of seasonal crop water requirements estimated using CropWAT 8.0 under the climate conditions of the precipitation regions in Louisiana. The kernel density estimator $\hat{f}(\,)$ for a seasonal precipitation time series P with n elements was given by Eqs. (3), (4), (5), (6), (7), and (8).

$$\hat{f}(p) = \frac{1}{n * h_{opt}} \sum_{i=1}^{n} K\left(\frac{p - P_i}{h_{opt}}\right) \tag{3}$$

$$K(u) = \frac{1}{\sqrt{2\pi}} Exp\left(-\frac{u^2}{2}\right) \tag{4}$$

$$u = \frac{p - P_i}{h_{opt}} \tag{5}$$

$$h_{opt} = 1.06 * \sigma * n^{-1/5} \tag{6}$$

$$\int K(u)\, du = 1 \tag{7}$$

$$\int \hat{f}(p)\, dp = 1 \tag{8}$$

Where h_{opt} was the optimal band width (i.e., smoothing parameter) of the kernel density estimator, P_i was any value within the range of P, σ was the standard deviation of P, p was the center of any bin with h_{opt} width, and *K(.)* was the gaussian kernel.

2.3. Crop water requirement estimates

The study addressed crop water requirement estimates for five major crops grown in Louisiana: corn, soybean, cotton, grain sorghum, and sugarcane. For each crop, the water requirement and irrigation need during the growing season were estimated using CropWAT 8.0 (Smith et al., 2002). The estimates from CropWAT 8.0 used soil, climate, and crop data. The climate in Southern and Northern Louisiana were represented by the New Orleans station (Latitude: 29.98 N, Longitude 90.25 W), and Shreveport station (Latitude: 32.46 N, Longitude 93.81 W), respectively (Fig. 2). Note, input climate variables required for CropWAT 8.0 (i.e. precipitation, minimum temperature, maximum temperature, relative humidity, wind speed, sunshine duration, solar radiation, and potential evapotranspiration) are available for both the New Orleans and Shreveport stations. The CropWAT 8.0 estimation of crop water requirement was based on crop evapotranspiration (ET_c) and it assumed no limitations (e.g. salinity, pests, diseases, weed, fertility, density) on the crop growth. For each crop, the ETc values at different growth stages were determined using the crop coefficient K_c approach, which established ET_c as the product of the potential evapotranspiration (ET_o) and K_c as shown by Eq. (9).

$$ET_c = K_c * ET_0 \tag{9}$$

A summary of the K_c values for corn, soybean, cotton, grain sorghum, and sugarcane in CropWAT 8.0 estimates is presented by Table 2. Given the diversity of soils in Louisiana, CropWAT 8.0 was set using a medium soil condition (i.e. loam soil) which is given by the default CropWAt 8.0 medium soil. Note, CropWAT 8.0 was set with no irrigation system allowing the estimate of irrigation water need as the difference between effective precipitation and crop water requirement. Effective precipitation estimates of CropWAT 8.0 used USDA soil conservation service method which is based on the Eq. (10).

$$\begin{cases} \mathrm{Pre}_{eff} = \mathrm{Pre}\left(125 - 0.2\alpha\mathrm{Pre}\right) \Big/ 125 \quad for \quad \mathrm{Pre} \leq \dfrac{250}{\alpha}\, mm \\ \mathrm{Pre}_{eff} = 125 \Big/ \alpha + 0.1\mathrm{Pre} \quad for \quad \mathrm{Pre} > \dfrac{250}{\alpha}\, mm \end{cases} \tag{10}$$

Where Pre is the actual precipitation depth, Pre_{eff} is the effective precipitation, and $\alpha = 3$ is the 10 days CropWAT 8′s correction factor. The crop water requirements were estimated at a daily scale then totaled seasonally. With each crop, two planting scenarios including an early and late planting were considered based on common planting recommendations in Louisiana. The crop water requirement values were estimated separately for these two scenarios then used in a probability analysis.

3. Results

3.1. Louisiana precipitation regions

The combined PCA and cluster analyses were conducted separately on the time series of seasonal precipitation total and number of

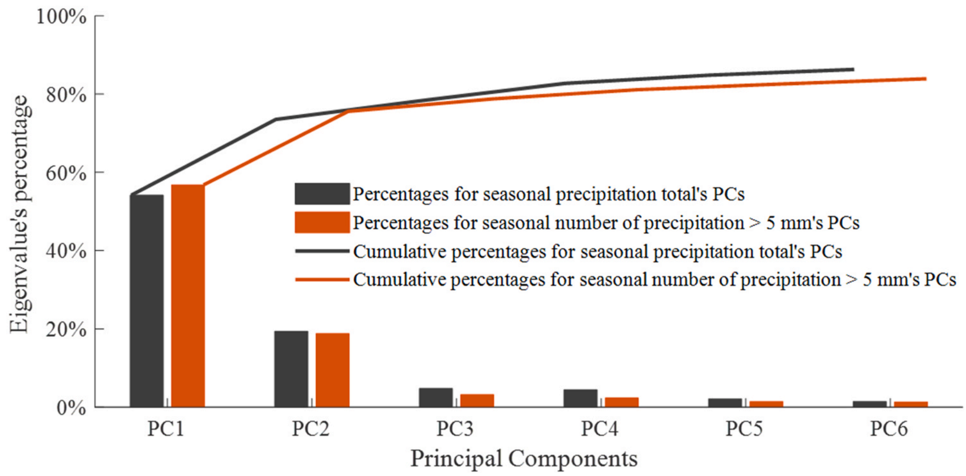

Fig. 3. Scree-plot of the eigenvalues percentages of the selected principal components (PCs). PCA were conducted separately on seasonal precipitation total and the seasonal number of events > 5 mm.

Table 3
Jaccard similarity index values between clusters derived from precipitation totals and clusters derived from number of events > 5 mm. The maximum value of Jaccard index corresponds to the optimal number of clusters.

Number of clusters k	Grids distribution within the clusters		
	Clusters based on total precipitation	Clusters based on the number of events > 5 mm	Jaccard index
2	36, 35	36, 35	0.99[a]
3	36, 19, 16	35, 21, 15	0.93
4	36, 16, 13, 6	21, 19, 16, 15	0.63
5	19, 17, 16, 10, 9	19, 16, 15, 14, 7	0.72
6	36, 13, 7, 6, 6, 3	16, 15, 14, 10, 9, 7	0.56
7	19, 17, 10, 9, 7, 5, 4	16, 15, 10, 9, 7, 7, 7	0.48
8	17, 13, 10, 9, 7, 6, 5, 4	15, 14, 10, 9, 7, 6, 5, 5	0.58
9	14, 13, 11, 9, 9, 8, 3, 2, 2	19, 15, 14, 6, 5, 5, 4, 2, 1	0.49
10	13, 10, 9, 8, 7, 6, 6, 5, 4, 3	15, 14, 10, 7, 7, 6, 5, 3, 2, 2	0.45
11	10, 9, 9, 8, 7, 6, 6, 5, 4, 4, 3	14, 9, 8, 7, 6, 6, 5, 5, 5, 4, 2	0.45
12	11, 10, 9, 8, 6, 6, 5, 4, 4, 3, 3, 2	16, 9, 7, 7, 7, 6, 5, 5, 5, 2, 1, 1	0.38

[a] Maximum value of Jaccard index indicating the optimal number of clusters.

precipitation events. Fig. 3 show the eigenvalue's percentages of the first six PCs retained for the cluster analysis. The PCs captured 86% and 84% of the variances in the seasonal precipitation total and number of precipitation events respectively. Table 3 summarizes the k-means cluster analyses carried out with different values of k (i.e., $2 \leq k \leq 12$). For each value of k, the similarity between the clusters based on total precipitation and those based on the number of events was estimated and reported as Jaccard index values in Table 3. The highest similarity was reached at the Jaccard index of 0.99, which was the maximum value and corresponded to $k = 2$. This outcome suggests that there are two distinct precipitation patterns for the state that emerged when independently considering both daily precipitation totals and number of events. Fig. 4 presents the spatial distribution of the grids associated with the clusters based on the total precipitation (i.e., clusters 1 and 2, Fig. 4a) and those based on number of events (i.e., clusters A and B, Fig. 4b). In both cases, one can associate one cluster to Northern Louisiana and the other to Southern Louisiana, leading to the identification of two distinct precipitation regions for Louisiana.

3.2. *Comparative Analysis of the seasonal precipitation patterns*

Fig. 5 presents the two Louisiana precipitation regions with an overlay of contours that show the spatial distribution of annual precipitation totals (Fig. 5a), annual number of precipitation events > 5 mm (Fig. 5b), events > 12.7 mm (Fig. 5c), and events > 25.4 mm (Fig. 5d). The contours of annual precipitation totals (Fig. 5a) show higher values in region 2. However, these annual values often shade critical seasonal patterns which need to be elucidated for water management purposes. Hence, a paired student *t*-test was used to evaluate the statistical differences between the two regions' seasonal precipitation patterns (Table 4). The results show significant differences for JJA precipitation totals and number of events (i.e., events > 5 mm, > 12.7 mm, > 25.4 mm) between the two precipitation regions. However, the statistical differences were not significant for DJF, MMA, and SON precipitation variables between the two regions. Therefore, one can assert that the JJA precipitations drive the significant differences observed with the annual precipitation total and numbers of events (i.e., > 5 mm and > 12.7 mm).

Overall, the Northern Louisiana precipitation region receives less precipitation during JJA (in average 319.8 mm, 16 events > 5 mm, 8 events > 12.7 mm, and 3 events > 25.4 mm) compared to the Southern Louisiana precipitation region (in average 511.2 mm, 26 events > 5 mm, 13 events > 12.7 mm, and 5 events > 25.4 mm). This disparity between the two regions is likely to have critical impact on crop production because the growing period of major crops such as corn, soybean, cotton, grain sorghum, and sugarcane overlap partially or entirely in the JJA season. Further analyses needed to comprehend the exposure to water deficit for these crops, include a probability assessment of the seasonal precipitation.

Figs. 6 and 7 present the kernel density estimates of precipitation totals and the number of events for the seasons defined as DJF, MAM, JJA, and SON. From a visual prospect, the curves differ in shape (skewness and kurtosis) depending on the precipitation region and the season. The curves corroborate the discrepancies reported in Table 4. Figs. 6c and 8c highlight apparent differences in the shape of the JJA precipitation variables' distribution. In Fig. 6c and c, the JJA curves of region 1 are relatively skewed and shifted to the left compared to region 2. These kernel density curves are approximations of the actual probability distributions of the seasonal precipitation and they will thereby be used to evaluate the crops exposure to water deficit in each of the two precipitation regions in Louisiana.

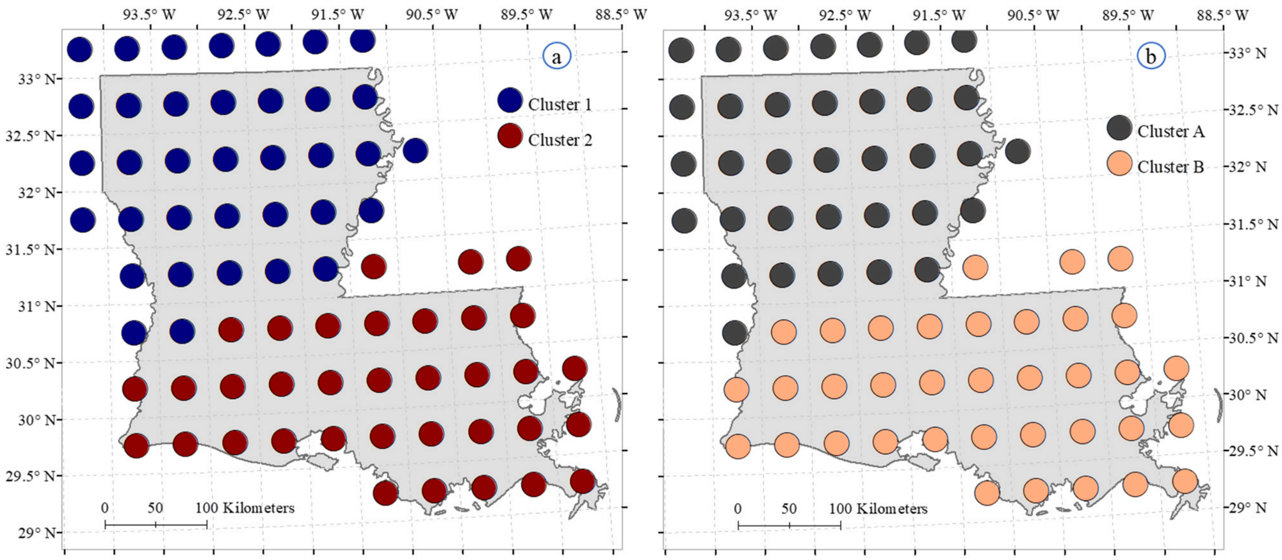

Fig. 4. Spatial distribution of precipitation grids across Louisiana for k-means clustering (k = 2) based on seasonal precipitation totals (a), and seasonal number of precipitation events > 5 mm (b).

3.3. Crops water requirements and probabilistic assessment of seasonal precipitation

Fig. 8 summarizes crop water requirements and irrigation needs estimated using CropWAT 8.0 in each precipitation region based on the scenarios of early and late planting of corn, soybean, cotton, grain sorghum, and sugarcane. The irrigation needs are the differences between the effective precipitation and crop water requirement estimates. However, in practice the actual irrigation water needs will be affected by the efficiency of the irrigation method. In all cases, crop water requirements are slightly higher in region 1, compared to region 2 and this can be explained by an overall higher atmospheric water demand in North Louisiana (average annual $ET_0 \approx 4.2$ mm d^{-1}) compared to South Louisiana (average annual $ET_0 \approx 3.8$ mm d^{-1}). However, discrepancies in irrigation need (i.e., water deficit) are more the consequences of lower precipitation rates and higher atmospheric water demand in region 1 compared to region 2.

During the growing season, the crop water requirements vary depending on the plant's growth stage (expressed by K_c) and ET_0 variation. This allowed an evaluation of the magnitude of the crop water demand with more details by using daily, weekly, or monthly time scales. Table 5 reports detailed estimates of the crop water demand based on seasonal periods DJF, MAM, JJA, and SON. These estimates were used as thresholds in the kernel density functions of precipitation totals (described in Fig. 6) to determine the probabilities of exceeding based on different values of crop water requirements. These probabilities indicate the chance that total precipitation exceeds crop water requirements in each region. For individual crop, lower probability values can be interpreted as a high exposure to crop water deficit and a requirement for irrigation when considering general field location and planting window. Fig. 8 shows that both crop water requirement and water deficits (i.e., irrigation need) for each region vary depending on the planting scenario (i.e., early, late planting). Likewise, the analysis presented in Table 5 shows that the probability of crop exposure to water deficit depends on the planting scenario and not only the precipitation region.

4. Synthesis and discussion

The study used principal component and cluster analyses to identify two significant precipitation regions in Louisiana. Regionalization was based on seasonal precipitation totals and the number of events over the period 1988–2020. From a geographic standpoint, the two precipitation regions were opposed as one location covers Northern Louisiana and the other region spans Southern Louisiana (see Fig. 5). Further statistical analyses of the seasonal precipitation patterns have exposed critical dissimilarity of both precipitation total and distribution of events in the two regions. Explicitly, JJA precipitation totals and distribution of events showed critical dissimilarities between the two regions. These dissimilarities have implications on agricultural water management because the growing period of most common Louisiana crops such as corn, soybean, cotton, grain sorghum, and sugarcane overlap the JJA season. Estimates of crop water requirements and irrigation needs for these crops under early and late planting scenarios confirmed the dissimilarities between the regions. Further analyses based on kernel density estimators elucidated crop exposure to water deficits. Overall, the results enlighten crops exposure to water deficit across the state of Louisiana.

The crop water deficit analyses can be used to inform farmers considering an investment in expanding irrigation capacity or increasing crop diversification. Over the last decade, the fluctuation of agricultural commodities' prices have led producers to try different crops in unconventional locations that have immediate implications for water management. For instance, sugarcane's production which was traditionally restricted to Southwest Louisiana, has noticeably expanded northward and eastward due to the availability of irrigation capacity for drought periods. This expansion is somewhat true for corn, soybean, cotton, and sorghum which are often incorporated in crops rotation. Thus, supplying a regionally specific evaluation of precipitation and crop water requirements including probabilities for requiring irrigation of major crops based on planting date was applicable to all farmers across the state.

The study aligns with previous studies which highlighted the need to enhance crop water use efficiency in Louisiana (Gautam et al., 2020; Adusumilli et al., 2016; Kebede et al., 2014). Many farmers in Louisiana adopted furrow irrigation because water availability was not an apparent issue in the state. However, furrow irrigation generally exacerbates nutrient runoff from fields to stream networks and nutrient leaching from the soil profile into the ground water (Yu et al., 2008). Poor water quality can directly impact aquatic life and water availability for other domestic, recreational, and industry uses besides agriculture (Borrok et al., 2018; Eldardiry et al., 2016). In the long-term, the environmental impacts of poor water management practices may outweigh the marginal crop yield gains. Hence, the tools reported in this study can

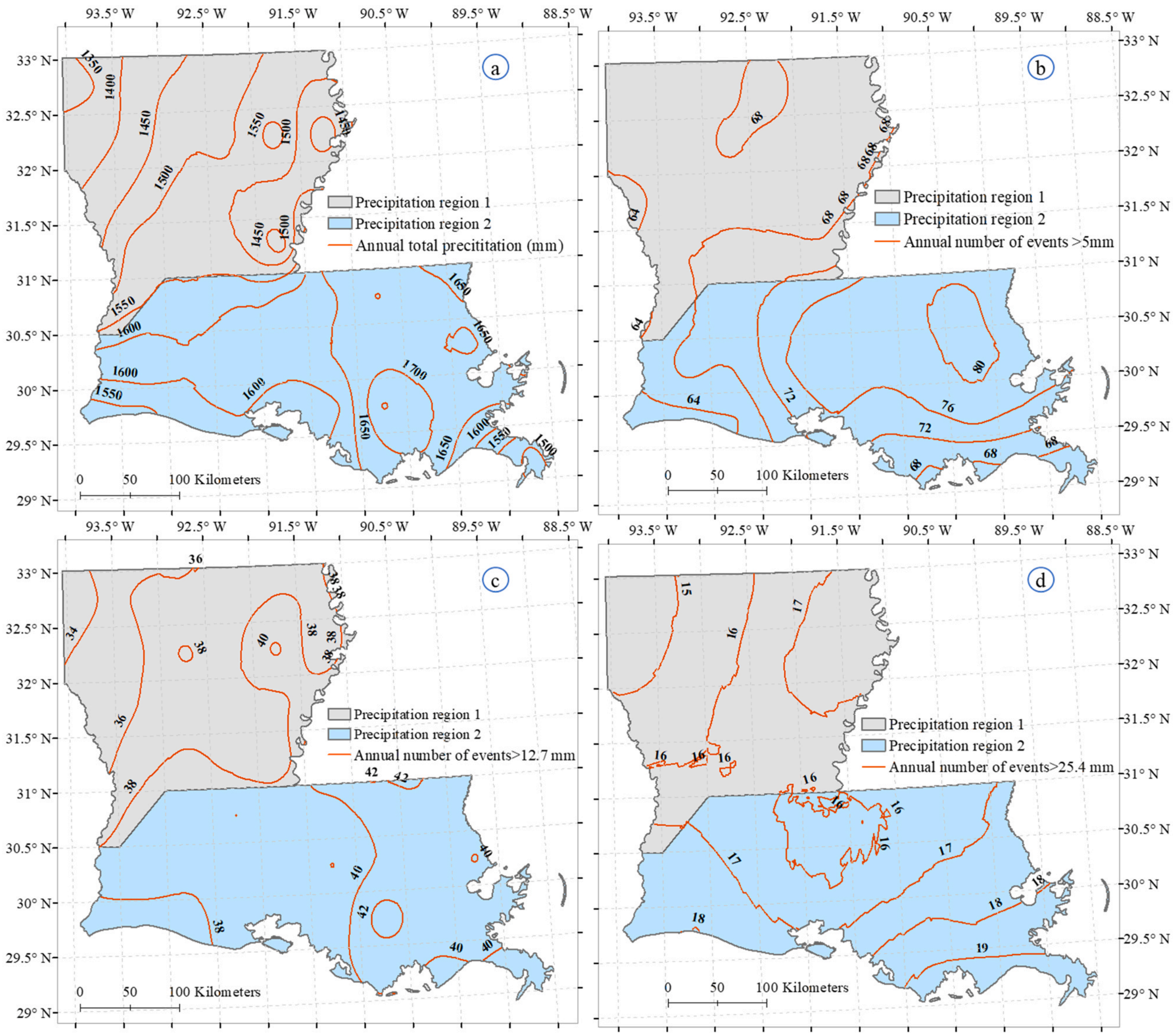

Fig. 5. Louisiana's precipitation regions with (a) the contours of annual precipitation total, (b) annual number of precipitation events > 5 mm, (c) > 12.7 mm (c), and (d) > 25.4 mm.

be useful to enhance water resource management at the farm, watershed, and state levels. At farm level, understanding the probabilities of crops exposure to water deficit during the growing season could help a farmer to properly ponder the cost and benefits of adopting irrigation systems. Particularly, the crop water deficit assessment can be used to inform farmers considering an investment in irrigation systems. Analyses of Table 5 and Fig. 8 showed that the crops' exposure to water deficit depended primarily on the precipitation region but also on the planting scenarios (i.e., early, late planting). The farmer may consider the water need differences associated with the planting scenarios to enhance their water management practices. At the watershed and state level, the map of precipitation regions (Fig. 4) could be a useful tool for implementing programs or propose policies aiming to promote environmental equity and water resources conservation. These points of view align with previous studies which foresaw the seasonal fluctuation of surface water resources in Louisiana as a key factor to consider for developing water management plans that promote agriculture sustainability in the state (Eldardiry et al., 2016; Kebede et al., 2014). From another angle, it is essential to recall that Louisiana is prone to natural disasters such as short-term and long-term drought, excessive rains, and hurricanes that have caused substantial damages to state agriculture (Rahman et al., 2017; Guidry and Pruitt, 2012). During the past two decades, each of these disasters has affected Louisiana agriculture by causing crops failure and lowering productivity. Nevertheless, these natural disasters are very unpredictable and beyond the scope of this study.

As fore-indicated in the method section, the precipitation regionalization procedure was first reported by Sohoulande et al. (2019), who developed and successfully applied it on the Southeastern Coastal Plain of the United States. The same procedure in this study showed its consistency since the disparities between the resulting precipitation regions were confirmed by statistics detecting significant differences between seasonal precipitation patterns. A potential application of the results from this study include the ability to inform Louisiana farmers on how their farm management decisions such as crop selections, planting dates, irrigation system investments can help to work toward sustainable crop production practices through enhanced crop water use efficiency in Louisiana.

Table 4
Comparing Louisiana precipitation regions using a paired-wise *t*-test. Seasonal precipitation totals and number of events were compared between precipitation region 1 (Northern Louisiana) and region 2 (Southern Louisiana).

Precipitation variables		Precipitation regions		Paired *t*-test	
		Region 1	Region 2	Significance	P-value
Total precipitation (mm)	DJF	409.9	389.7	ns	0.47
	MAM	395.4	374.1	ns	0.51
	JJA	319.8	511.2	**	< 0.01
	SON	328.5	354.9	ns	0.38
	ANN	1453.2	1629.3	**	< 0.01
Number of events > 5 mm	DJF	18.2	17.3	ns	0.35
	MAM	17.0	15.3	ns	0.12
	JJA	16.3	25.8	**	< 0.01
	SON	13.7	15.2	ns	0.18
	ANN	65.2	73.6	**	< 0.01
Number of events > 12.7 mm	DJF	10.7	9.9	ns	0.27
	MAM	10.0	9.0	ns	0.21
	JJA	8.0	12.5	**	< 0.01
	SON	8.0	8.4	ns	0.59
	ANN	36.8	39.8	*	0.04
Number of events > 25.4 mm	DJF	5.0	4.6	ns	0.34
	MAM	4.7	4.5	ns	0.77
	JJA	3.1	4.7	**	< 0.01
	SON	3.9	3.9	ns	0.99
	ANN	16.6	17.7	ns	0.25

5. Conclusion

Over decades, irrigation infrastructure in humid regions such as Louisiana was selected based on the assumption of an abundance of water resources. However, this conception has led to poor water management practices with potential impacts on the environment. As a result, several authors raised sustainability concerns including overdrafting water for irrigation, groundwater depletion, and decline of water quality (Borrok et al., 2018; Eldardiry et al., 2016; Kebede et al., 2014). Strategies to improve irrigation efficiency in agriculture are now needed to sustain water resources conservation in Louisiana. From that prospective, this study sought to develop data driven tools to support decision making in irrigation management across the state of Louisiana. These tools include a precipitation regionalization for Louisiana and a detailed probabilistic assessment of crop exposure to water deficits based on scenarios of early and late planting. The study discussed the potentiality of using these tools for decision support in crop water management at the farm, watershed, and state levels. Specifically, the precipitation regions map and the probabilistic analyses can be used by extension services to inform farmers about crops exposure to water deficit depending on the location in Louisiana. In addition, these decision support tools can be useful when making farm management decisions and implementing water management plans that reduce irrigation water use and enhance water resources conservation at the state level.

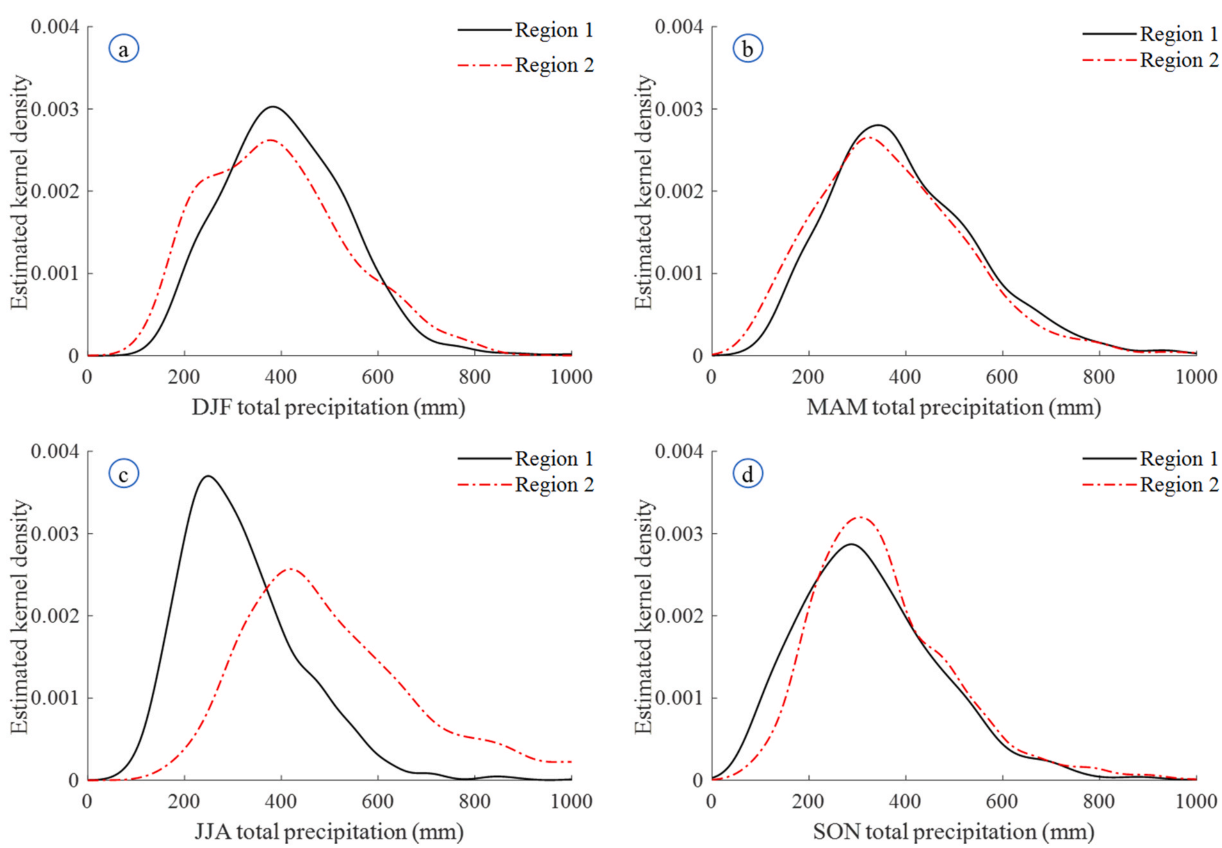

Fig. 6. Distribution of total precipitation using kernel density estimates for the two precipitation regions for seasons (a) DJF, (b) MAM, (c) JJA, and (d) SON.

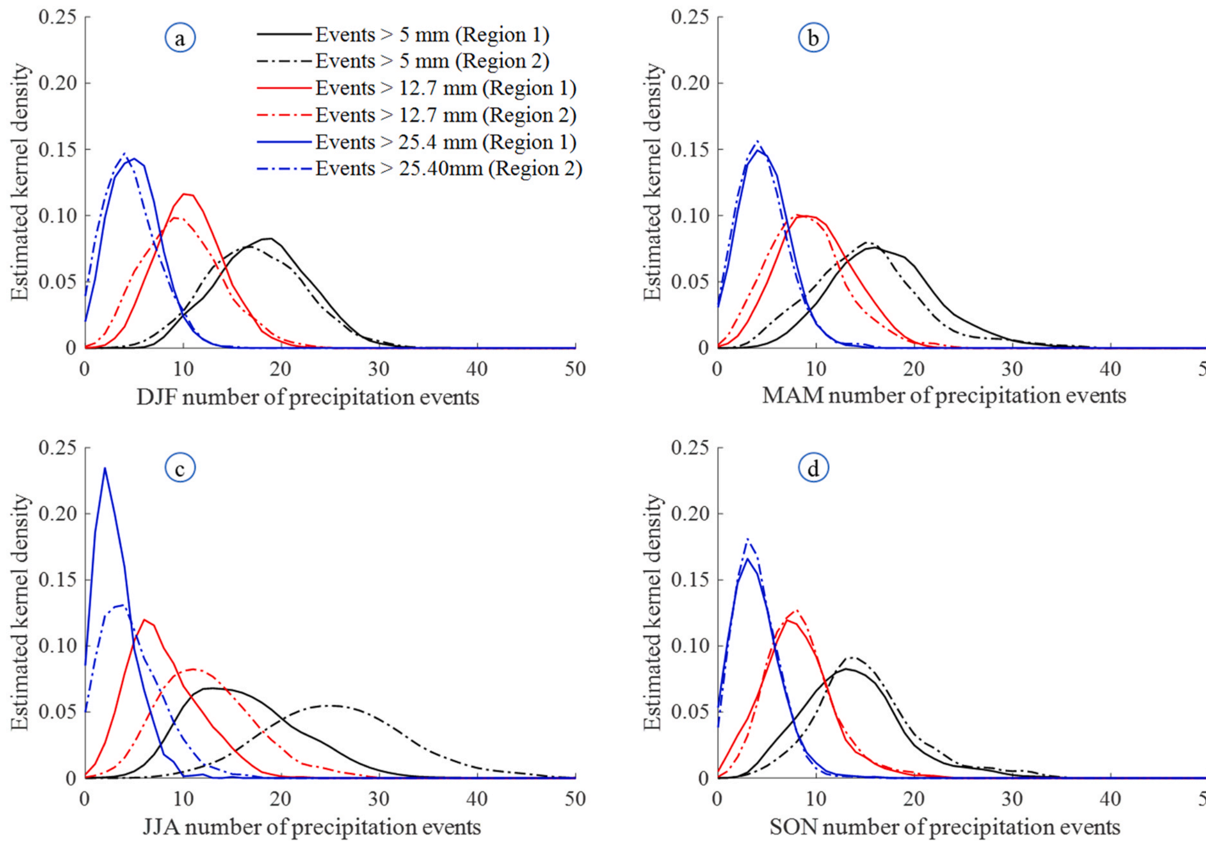

Fig. 7. Description of number of precipitation events using kernel density estimates for the two precipitation regions for seasons (a) DJF, (b) MAM, (c) JJA, and (d) SON.

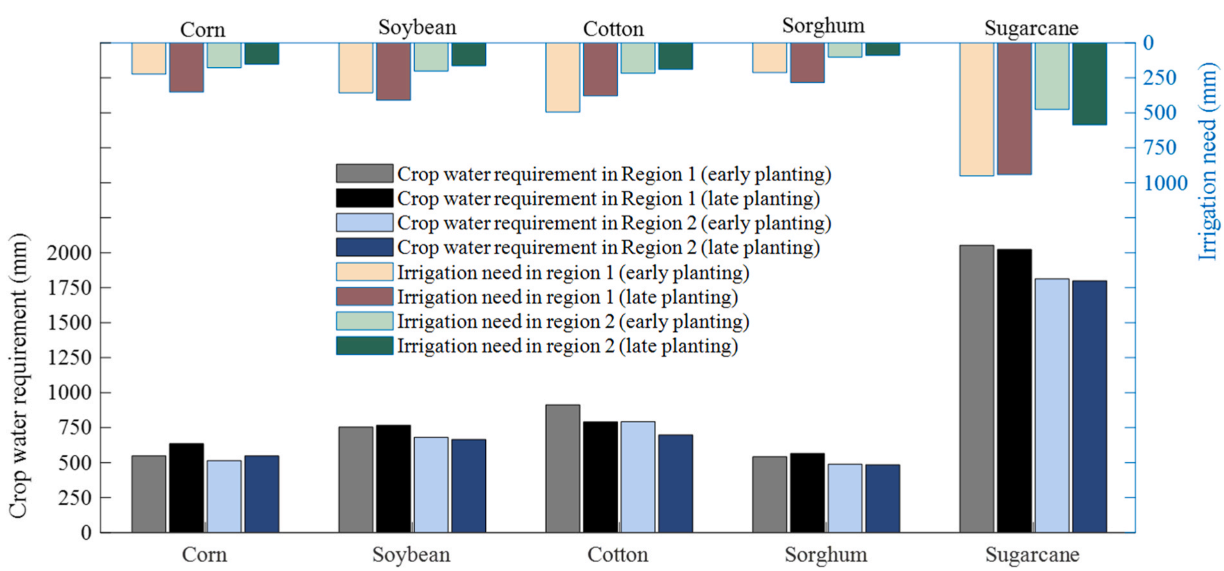

Fig. 8. Estimates of crop water requirement and supplemental irrigation needed for different crops typically grown in the two precipitation regions of Louisiana.

Table 5
Estimated crop water requirements and the corresponding probabilities of exceedance during the seasonal growing periods in both Region 1 and 2. Crops Water requirements were estimated using the CropWAT 8.0. South Louisiana condition used as inputs, weather data from New Orleans station (Lat: 29.98 N, Lon: 90.25 W). North Louisiana condition used as inputs, weather data from Shreveport station (Lat: 32.46 N, Lon: 93.81 W).

Crops	Growing period				Precipitation Region 1		Precipitation Region 2	
	Season	Planting	Harvest	Duration (months)	Crop water requirement (mm)	Probability of exceeding	Crop water requirement (mm)	Probability of exceeding
Corn (early plant)	DJF							
	MAM	Begin March		3	385.6	0.47	365	0.48
	JJA		End June	1	162.3	0.93	148.6	0.99
	SON							
Corn (late plant)	DJF							
	MAM	Begin May		1	58.2	0.99	56.6	0.99
	JJA		End August	3	572.6	0.04	487.4	0.47
	SON							
Soybean (early plant)	DJF							
	MAM	Begin April		2	276.9	0.77	266.8	0.73
	JJA		End August	3	476.8	0.11	413.4	0.65
	SON							
Soybean (late plant)	DJF							
	MAM	Mid-May		0.5	37.4	0.99	36.5	0.99
	JJA			3	593.5	0.03	508.7	0.42
	SON		Mid-October	1.5	135.6	0.92	120.9	0.98
Cotton (early plant)	DJF							
	MAM	Mid-April		1.5	98	0.99	94.4	0.98
	JJA			3	629.3	0.02	533.3	0.37
	SON		Mid-October	1.5	185	0.83	164.8	0.94
Cotton (late plant)	DJF							
	MAM							
	JJA	Begin June		3	397.1	0.23	336.9	0.83
	SON		End November	3	393.8	0.30	360.3	0.41
Grain Sorghum (early plant)	DJF							
	MAM	Begin April		2	121.3	0.98	108.9	0.97
	JJA		End July	2	419.4	0.19	379.3	0.73
	SON							
Grain Sorghum (late plant)	DJF							
	MAM	Begin May		1	56.2	0.99	54.6	0.99
	JJA		End August	3	502.4	0.09	424.9	0.62
	SON							
Sugarcane (early plant)	JJA[a]	Begin August		1	173.3	0.91	142.8	0.99
	SON[a]			3	371.8	0.34	340.9	0.47
	DJF			3	274.4		232.6	0.84

(continued on next page)

Table 5 (*continued*)

Crops	Growing period				Precipitation Region 1		Precipitation Region 2	
	Season	Planting	Harvest	Duration (months)	Crop water requirement (mm)	Probability of exceeding	Crop water requirement (mm)	Probability of exceeding
						0.84		
	MAM			3	547.4	0.16	506.8	0.19
	JJA			3	584.6	0.03	501.2	0.44
	SON		End September	1	101.3	0.96	88.8	0.99
Sugarcane (late plant)	SON[a]	Begin October		2	182.1	0.84	167.6	0.94
	DJF			3	258.6	0.87	218.4	0.87
	MAM			3	554.7	0.15	513.8	0.18
	JJA			3	700.1	0.01	602.6	0.26
	SON		End November	3	326.9	0.45	296.5	0.61

[a] Season of the previous year.

Disclaimer

Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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