Rain Water Deficit and Irrigation Demand of Major Row Crops in the Mississippi Delta

Q. Tang, G. Feng, D. Fisher, H. Zhang, Y. Ouyang, A. Adeli, J. Jenkins

Abstract. *The Mississippi Delta is an important agricultural area, producing 67% of the soybean, corn, and cotton grown in the state of Mississippi. Because irrigation can stabilize and increase crop yields and economic returns, approximately 80% of the water withdrawn from the alluvial aquifer is used for irrigation. This region is experiencing severe declines in groundwater level, which threaten the sustainability of irrigated agriculture. Therefore, better irrigation management practices must be developed, but there is lack of knowledge regarding crop water requirements, rain water deficits, and irrigation demand to improve rain and irrigation water use efficiencies of these crops. The objective of this study was to determine the crop water requirements, rain water deficits, and irrigation demand of the three crops using the RZWQM2 model based on a 100-year representative weather data series from the Stoneville weather station for improving irrigation management in the Mississippi Delta. The analysis indicated that mean monthly precipitation in the crop non-growing season from November to the following April was 127 mm, while only 82 mm on average was received during the crop growing season. Soybean, corn, and cotton are typically planted in early May, late March, and late May and harvested in mid-September, late August, and late October, respectively. Rainfall during the growing seasons for soybean, corn, and cotton was 400, 510, and 435 mm and accounted for 31%, 40%, and 34% of annual rainfall, respectively, over the 100-year period. Early seeding can allow crops to receive more early season rainfall and reduce the number of days of water stress during the growing season. Average crop evapotranspiration of soybean, corn, and cotton was 546, 588, and 552 mm, respectively. Rainfall was found to be insufficient to meet the crop water requirements beginning in the 5th, 7th, and 6th weeks after planting. Weekly effective rain water deficits greater than 20 mm were found in weeks 7 through 16 (22 to 29 mm) for soybean, in weeks 11 through 20 (20 to 26 mm) for corn, and in weeks 11 through 16 (20 to 30 mm) for cotton. The RZWQM2 model estimated a range of annual effective rain water deficits in soybean of 0 to 622 mm, with an average deficit of 340 mm. Deficits in corn ranged from 32 to 685 mm, with an average deficit of 355 mm, while deficits in cotton ranged from 169 to 650 mm, with an average deficit of 395 mm. Results obtained from the 100-year historical weather data can be applied to improve irrigation scheduling, water resources planning, and design of irrigation and cropping systems in the Mississippi Delta.*

Keywords. *Corn, Cotton, Crop water requirement, Irrigation demand, Mississippi Delta, Rain water deficit, Soil water balance, Soybean.*

The Mississippi Delta region in northwestern Mississippi is an important agricultural area. As producers in this region have become increasingly reliant on supplemental irrigation to ensure adequate yields and reduce risks, the region has experienced as high as a 92% increase in irrigated farmland since 1998 (Vories and Evett, 2014). More than 1800 wells pump 9 million m^3 d^{-1} of groundwater for agriculture. An average loss of groundwater of 5.3×10^3 m^3 $year^{-1}$ has been reported between 1987 and 2014, resulting in the groundwater level declining by more than 6 m since the 1970s (YMD, 2015). To prevent further groundwater declines in the future, irrigation management practices must be evaluated and improved to better match crop water requirements and soil water-holding properties. Better estimates of rain water deficits and irrigation demand for major row crops are essential for improving irrigation management practices.

State-of-the-science process-based agricultural system models, such as the Root Zone Water Quality Model (RZWQM2), are capable of accounting for different types of weather conditions by using long-term weather data to estimate parameters critical for improved water management. RZWQM2 is a cropping system model developed to simulate the effects of soil type, weather conditions including precipitation, irrigation amount and timing, and crop management practices on water quantity and quality and crop production (Ahuja et al., 2000, 2014; Ma et al., 2000).

Submitted for review in April 2017 as manuscript number NRES 12397; approved for publication as part of the "Crop Modeling and Decision Support for Optimizing Use of Limited Water" collection by the Natural Resources & Environmental Systems Community of ASABE in August 2017.

Mention of company or trade names is for description only and does not imply endorsement by the USDA. The USDA is an equal opportunity provider and employer.

The authors are **Qiuxiang Tang,** Assistant Professor, College of Agronomy, Xinjiang Agricultural University, Xinjiang, China; **Gary Feng,** Research Soil Scientist, USDA-ARS Crop Science Research Laboratory, Mississippi State, Mississippi; **Daniel Fisher,** Agricultural Engineer, USDA-ARS Crop Production Systems Research Unit, Stoneville, Mississippi; **Huihui Zhang,** Agricultural Engineer, USDA-ARS Water Management Research Unit, Fort Collins, Colorado; **Ying Ouyang,** Research Hydrologist, USDA Forest Service, Mississippi State, Mississippi; **Ardeshir Adeli,** Soil Scientist, and **Johnie Jenkins,** Supervisory Research Geneticist, USDA-ARS Crop Science Research Laboratory, Mississippi State, Mississippi. **Corresponding author:** Gary Feng, USDA-ARS, 810 Highway 12 East, Mississippi State, MS 39762; phone: 662-320-7449; e-mail: Gary.Feng@ars.usda.gov.

Vol. 61(3): 927-935 2017 American Society of Agricultural and Biological Engineers ISSN 2151-0032 https://doi.org/10.13031/trans.12397

RZWQM2 has been used worldwide for row crop water management (Ahuja et al., 2016; Fang et al., 2014; Howden et al., 2007; Ma et al., 2012; Saseendran et al., 2008), with applications in irrigation optimization (Fang et al., 2010), irrigation scheduling (Saseendran et al., 2008; Fang et al., 2010), water percolation and tile drainage (Malone et al., 2014), and evapotranspiration (ET) demand (Fang et al., 2014). RZWQM2 has been calibrated and validated in the Great Plains (Johnsen et al., 1995; Ma et al., 2012; Qi et al., 2016; Saseendran et al., 2008), the upper Mississippi River basin (Kladivko et al., 2014), and the Mississippi Delta in the lower Mississippi River basin (Feng et al., 2015; Saseendran et al., 2016a) for managing water and nutrients in both rainfed and irrigated row crops across climates and soils in the U.S. These studies indicate that RZWQM2, as a system approach and scientifically sound method, provides reliable results by accounting for long-term climate variability at a given location. However, application of the model for simulation of row crops in the humid Mississippi Delta region is lacking (Saseendran et al., 2016a). Kebede et al. (2014) indicated that the Mississippi Delta experiences high intraseasonal variability of both the amount and temporal distribution of precipitation, which confounds the outcomes of agricultural water management for adoption by producers. They suggested that a solution to the problem would be to derive definite patterns of rain water deficit over the long term (30 years or more) to account for variations in precipitation and other climatic variables.

In this study, RZWQM2 and long-term weather data were used to investigate the characteristics of rainfall patterns and soil water balance and its component on typical crops grown in the Mississippi Delta region. Temporal variations in rainfall, crop water requirements, soil moisture status, runoff, drainage, rain water deficit, and irrigation demand were analyzed as affected by the changing climate patterns. The objective was to evaluate the rain water deficit and irrigation demand for soybean, corn, and cotton during wet, normal, and dry years for a 100-year period in the Mississippi Delta region for use in water resource planning, cropping system and irrigation system design, and irrigation scheduling.

Methodology

Definitions of Technical Terms

Crop water requirement is the amount of water needed by a crop to achieve its optimal growth and economic yield, and it is often referred to as crop evapotranspiration (ET_c). Irrigation demand can be defined as the crop water requirement not met by precipitation, and its value depends on the irrigation scheduling method and soil physical and hydraulic properties. Rain water deficit is the difference between rainfall and crop evapotranspiration, while effective rain water deficit is the difference between rainfall and losses due to runoff and percolation plus evapotranspiration. Rainfall frequency refers to the percent likelihood of certain rainfall amounts being equaled or exceeded. Irrigation frequency is the percentage of the total number of days requiring irrigation during the crop season to the total numbers of the same days in 101 years.

Site Description

The simulation study was conducted based on data from Stoneville, Mississippi (33° 26′ 30.86″ N, -90° 53′ 26.60″ W), a location representative of agricultural conditions in the Mississippi Delta. Sharkey clay is the dominant soil type in the Mississippi Delta (fig. 1) based on the NRCS-SSURGO soil database (NRCS, 2015) and NASA land use dataset (Mississippi, 2014), with Sharkey clay soils accounting for 46% of crop land in this region. Corn, soybean, and cotton are the three main crops, accounting for 65% of total crop land in the state, with production in the Mississippi Delta accounting for 79%, 69%, and 69%, respectively, of the state's yield of the three crops (USDA-NASS, 2015).

RZWQM2 Overview and Input Parameters

RZWQM2 calculates components of soil water balance on a daily basis. The model simulates potential ET (PET) based on the Shuttleworth-Wallace method and separates total PET into transpiration from the canopy (PT) and evaporation from bare soil (PE) (Farahani and DeCoursey, 2000). The calculated PE and PT are used as the upper limits for actual evaporation (AE) and transpiration (AT), respectively, constrained by soil water supply. AE is estimated by the capability of the soil to deliver water as determined by the Richards equation, while AT is computed by the Nimah-Hanks approach adopted in the DSSAT crop models (Ritchie, 1998).

Infiltration is estimated with the Green-Ampt equation when rain or irrigation occurs, and runoff is calculated as the difference between rainfall and infiltration at each time step. RZWQM2 simulates downward water flow in 1 cm increments as each 1 cm of soil becomes saturated, and water movement below the wetting front during infiltration is assumed to occur according to unit gradient flow. Soil water movement below the root zone is considered drainage. If there is no rainfall or irrigation, soil water redistribution is

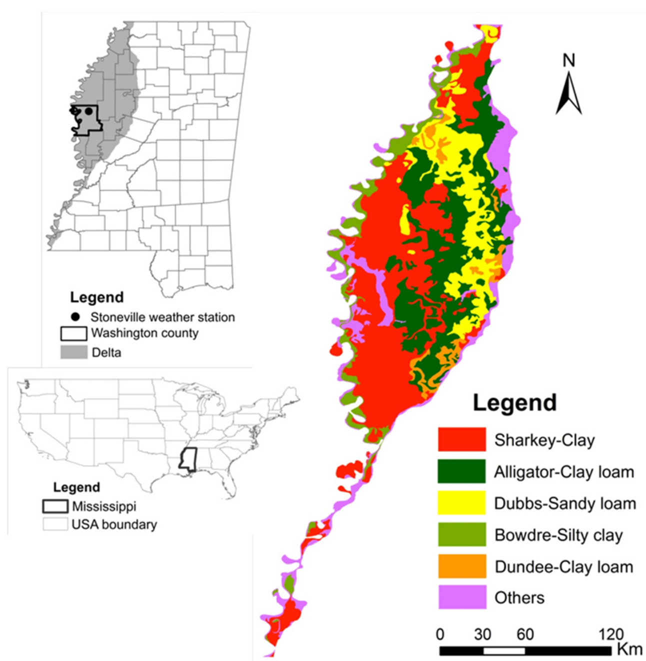

Figure 1. Soil types in the Mississippi Delta.

Table 1. Measured properties of Sharkey clay soil at Stoneville in the Mississippi Delta as input parameters required by RZWQM2.

Horizon Depth (cm)	Bulk Density (g cm^{-3})	Porosity	Silt (%)	Clay (%)	Field Water Capacity (cm^3 cm^{-3})	Wilting Point Water Content (cm^3 cm^{-3})	Saturated Hydraulic Conductivity (cm h^{-1})
15	1.35	0.49	33	28	0.39	0.17	1.98
30	1.36	0.49	31	30	0.39	0.17	1.82
60	1.37	0.48	29	28	0.36	0.21	1.64
90	1.38	0.48	25	27	0.38	0.23	0.93
120	1.39	0.48	32	29	0.40	0.25	0.82
150	1.40	0.47	32	28	0.41	0.26	0.78
180	1.40	0.47	32	28	0.39	0.27	0.83

estimated using the Richards equation. The Brooks-Corey equations are used to describe relationships between volumetric soil water content and matric suction head. Processes of water movement are described in detail by Ahuja et al. (2000).

RZWQM2 requires input parameters relating to the soil, crop, meteorology (low temperature, high temperature, wind speed, relative humidity, and solar radiation), and water and nutrient management activities. Soil input parameters for the Stoneville location are listed in table 1. Soybean, corn, and cotton are typically planted in early May, late March, and mid-May and harvested in mid-September, late August, and late October, respectively (Mississippi, 2014; USDA-NASS, 2015). In this simulation study, the growing seasons extended from day of year (DOY) 128 (8 May) to 260 (17 September) for soybean, from DOY 86 (27 March) to 236 (24 August) for corn, and from DOY 141 (12 May) to 296 (23 October) for cotton. Historical weather data from 1915 through 2015 were obtained and used in this study (https://beaumont.tamu.edu/climaticdata/StateMap.aspx?index=2_14_0_26&name=mississippi).

Irrigation was triggered when the AET/PET ratio was less than 90%, irrigation water was added to recharge the root zone soil profile to field capacity, and no nutrient deficit was assumed to occur for the three crops during the simulation, based on calibration and validation by Feng et al. (2015) and Saseendran et al. (2016a) for locations in the state of Mississippi. Because growers often schedule irrigations on a weekly basis, information on total and weekly rainfall, crop evapotranspiration (ET_c), and rain water deficit were estimated for the three crop systems.

Classification of Wet, Normal, and Dry Years

Zhang et al. (2016) classified 14 years of a study as wet, normal, or dry years for analysis of soybean production under various weather conditions. This approach was used to classify the 100 years in this study as wet, normal, or dry years in order to quantify rain water deficit for satisfying crop water requirements and to determine irrigation demand. Total rainfall amounts during the crop growing seasons were sorted from largest to smallest values and assigned numbers 1 to n in descending order. The probability of exceeding a rainfall amount (P, %) was then calculated for any year m as $P = m/(n + 1) \times 100$. A year was then classified as a wet year if P was less than 25%, a normal year if $25\% < P < 75\%$, and a dry year if P was ≥75%. Details of this method are described by Zhang et al. (2016).

Results and Discussion

Rainfall and Frequency

Based on the weather data for the 100-year period from 1915 to 2015, the average annual rainfall amounted to 1306 mm, with a maximum of 1884 mm and a minimum of 776 mm. The majority of the annual rainfall was in the range of 1000 to 1500 mm, as shown in figure 2a. Based on the rainfall probabilities, shown in figure 2b, 25 years were classified as wet years, with rainfall ranging from 1485 to 1884 mm, 51 years were normal years, with rainfall ranging from 1125 to 1480 mm, and the remaining 25 years were dry years, with annual rainfall ranging from 776 to 1125 mm. Figure 2b provides estimates of the annual rainfall at any design frequency. For example, annual rainfall at 4% design frequency is 1806 mm; alternatively, the probability of occurrence of annual rainfall ≥1806 mm is 4%, or ≥1806 mm could be expected to occur four times in 100 years.

Mean monthly rainfall ranged from 68 to 137 mm, as shown in figure 2c. Most rainfall occurred in the months of January to April and November to December, with mean monthly rainfall of 124, 123, 130, 137, 120, and 133 mm for those months, respectively. Less rain was received during the crop growing seasons, averaging 81 mm in May, 90 mm in June, 94 mm in July, 68 mm in August, 80 mm in September, and 81 mm in October. While average annual rainfall totaled approximately 1306 mm, only 30% occurred during the growing seasons of most crops.

From June to August, when corn, soybean, and cotton require large quantities of water, only 19% of the annual rainfall occurred. Rainfall during the summer months frequently includes heavy rainfall events that increase runoff from cropland, resulting in only a portion of the rainfall infiltrating into the soil profile and available for plant use. Bennett (2002) noted that, while Mississippi enjoys rainfall in excess of 1000 mm per year on average, most of the rainfall occurs outside the growing season, unlike other areas of the southern U.S., and lack of adequate soil moisture lowers crop yields and profits.

Crop Evapotranspiration (ET_c)

The mean water requirement, or ET_c, for soybean, corn, and cotton during the growing seasons (fig. 3a) totaled 580, 606, and 649 mm, respectively. The ET_c of soybean, corn, and cotton ranged from 500 to 800 mm $year^{-1}$ (figs. 3a and 3b), and a slightly declining pattern was observed from 1915 to 2015. Cotton had the highest ET_c, followed by corn and soybean (fig. 3a). As shown in figure 3b, soybean ET_c varied from 450 to 700 mm $year^{-1}$, and 80% of its ET_c was within 450 to 600 mm $year^{-1}$. The ET_c of corn ranged from 500 to

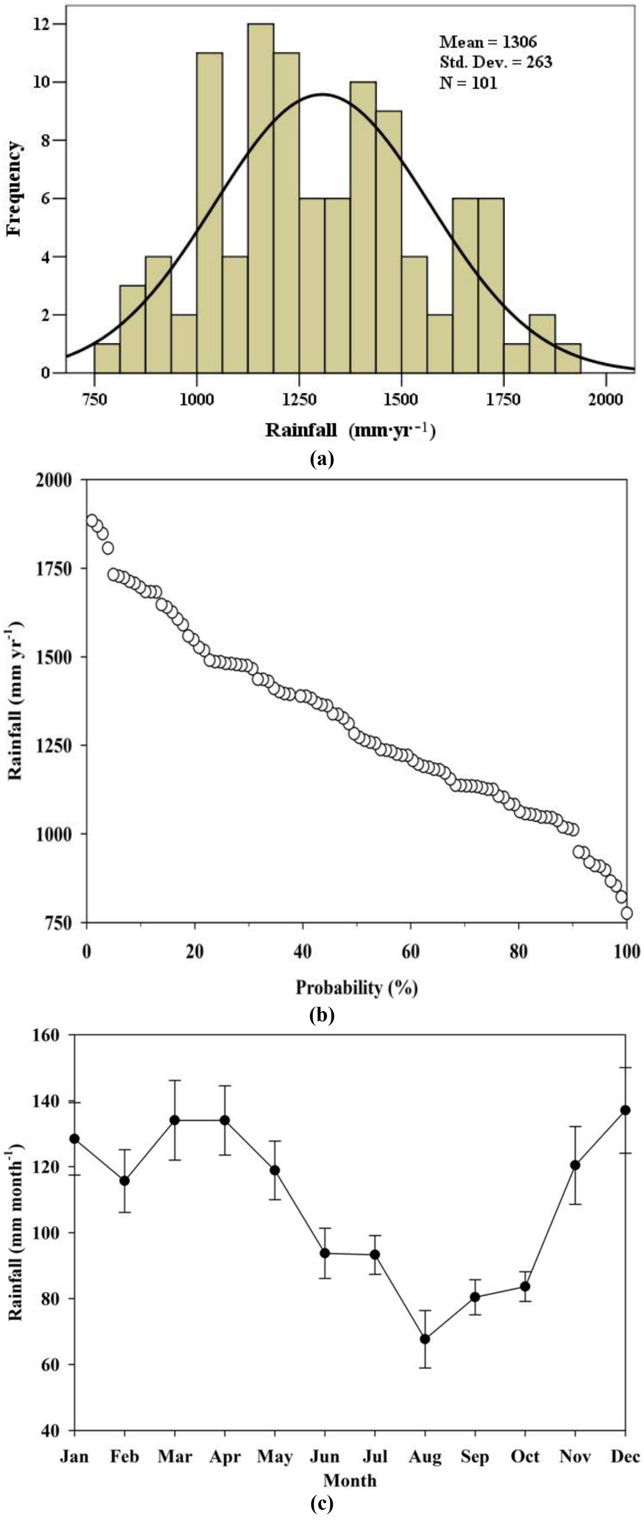

Figure 2. (a) Annual rainfall frequency, (b) probability of annual rainfall, and (c) monthly rainfall at Stoneville in the Mississippi Delta.

700 mm year^{-1}, and 80% of its ET_c was between 500 and 650 mm year^{-1} (fig. 3b). The ET_c of cotton ranged from 500 to 800 mm year^{-1}, with 80% between 600 and 700 mm year^{-1} (fig. 3b).

ANNUAL EFFECTIVE RAIN WATER DEFICIT

Total rainfall often cannot be fully used by the crop, as rainfall intensity above the soil infiltration rate, or excess rainwater after soil saturation, is lost as surface runoff or percolation below the root zone. The components of daily water balance, including runoff, percolation, crop evapotranspiration, effective rainfall, and required irrigation, were calculated by the RZWQM2 model. Estimates of these water balance components during the growing seasons were sorted in descending order of rainfall from wet to dry years and are shown in figure 4.

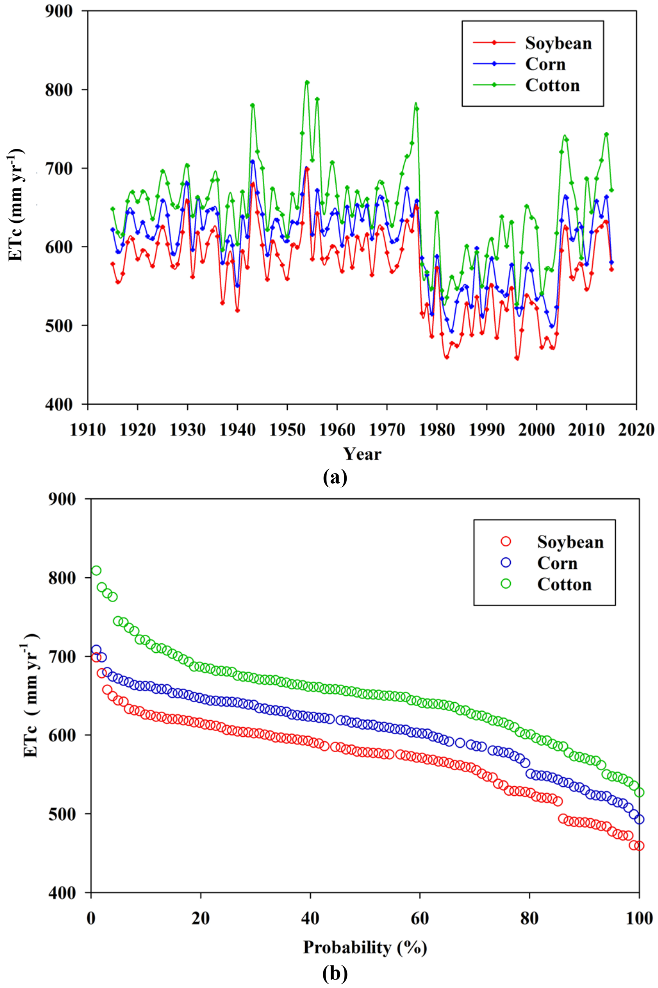

Figure 3. (a) crop water requirements (ET_c) of soybean, corn, and cotton and (b) ET_c at different levels of probability over 100 years.

During soybean seasons, water deficit ranged from 128 to 524 mm (328 mm average) in normal years, from -36 to 401 mm (235 mm average) in wet years, and from 353 to 622 mm (468 mm average) in dry years. During corn growing seasons, the water deficit and irrigation amounts increased, in general, from wet years to dry years. In wet years, runoff and drainage were higher than in normal and dry years. The rain water deficit ranged from 128 to 588 mm (349 mm average) in normal years, from 32 to 499 mm (222 mm average) in wet years, and from 293 to 685 mm (502 mm average) in dry years. During cotton growing seasons, the rain water deficit ranged from 178 to 547 mm (383 mm average) in normal years, from 169 to 480 mm (319 mm average) in wet years, and from 386 to 650 mm (469 mm average) in dry years. Overall, soybean experienced less water deficit than

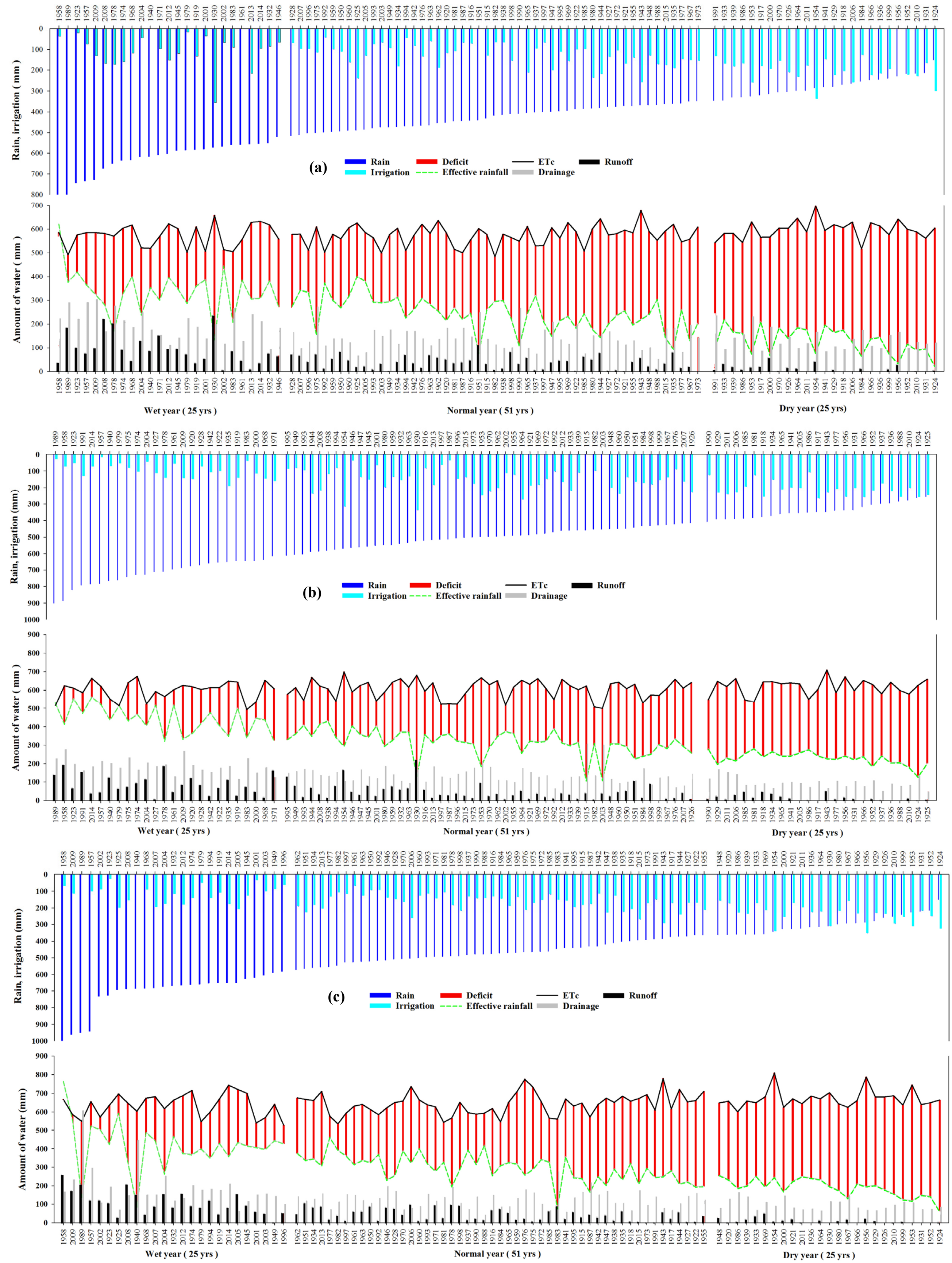

Figure 4. Water balance components sorted by rainfall amount during (a) soybean, (b) corn, and (c) cotton growing seasons at Stoneville in the Mississippi Delta.

cotton and corn over the 100-year period. Mean total effective rain water deficits were 344, 358, and 390 mm for soybean, corn, and cotton production, respectively. Christ et al. (2015) found similar water deficits in cotton (348, 267, and 319 mm) in Georgia, while Pote and Wax (1986) estimated rain water deficits for soybean and corn of 430 and 444 mm, respectively, in the Mississippi Delta. Their estimation was based on an 80% level of probability, and the losses due to runoff and percolation were not taken into consideration in calculating rain water deficit.

WEEKLY EFFECTIVE RAIN WATER DEFICIT

Weekly effective rainfall was calculated with the RZWQM2 model, as shown in figure 5. Soybean and cotton are typically planted in May, with corn planted seven to eight weeks earlier in April (Mississippi, 2014). As winter and spring are rainy seasons in this region, it was wet in April and May, and ET_c was lower during the early growth stages. Rainfall surpluses were found in the first five, seven, and six weeks for soybean (fig. 5a), corn (fig. 5b), and cotton (fig. 5c), respectively, and corn had a longer rain surplus due to its earlier planting. Thereafter, rain water deficit was observed during the later vegetative and reproductive growth stages for all three crops (fig. 5b). Saseendran et al. (2016a) studied planting windows for cotton in terms of long-term climate conditions and found that optimum planting windows under both rainfed and irrigated conditions extended from mid-March to mid-June in the Mississippi Delta. Early planting of these row crops can reduce days of rain water deficit and improve rain water use efficiency in this region. Saseendran et al. (2016b) found that planting cotton six weeks earlier than the normal historical planting date boosted irrigated cotton yields. As shown in figure 5, the weekly effective rainfall deficit during periods of high water requirement was 22 to 29 mm in weeks 7 through 16 for soybean, 20 to 26 mm in weeks 11 through 20 for corn, and 20 to 30 mm in weeks 11 through 16 for cotton. Pote and Wax (1986) estimated similar peak weekly irrigation requirements of 34 mm for soybean, 39 mm for corn, and 35 mm for cotton at the 80% level and 26, 29, and 30 mm, respectively, at the 50% level in Mississippi.

IRRIGATION DEMAND

The RZWQM2 model triggered irrigation at 90% of PET to estimate the amount of supplemental irrigation needed to fully satisfy water requirements of the three crops. Simulated soybean irrigation demand was 0 to 257 mm year^{-1} (122 mm average) in normal years, 0 to 216 mm year^{-1} (98 mm average) in wet years, and 124 to 337 mm year^{-1} (195 mm average) in dry years (table 2 and fig. 6a). Sassenrath et al. (2010) estimated soybean requirements of 186 mm year^{-1}, while Heatherly (2014) found soybean irrigation requirements of 263 and 414 mm, which are within the ranges determined in the RZWQM2 study. The different results were due to differences in weather conditions (wet, normal, or dry years).

Corn irrigation requirements ranged from 16 to 183 mm year^{-1} (110 mm average) in wet years, from 0 to 256 mm year^{-1} (141 mm average) in normal years, and from 107 to 315 mm year^{-1} (213 mm average) in dry years, as shown in

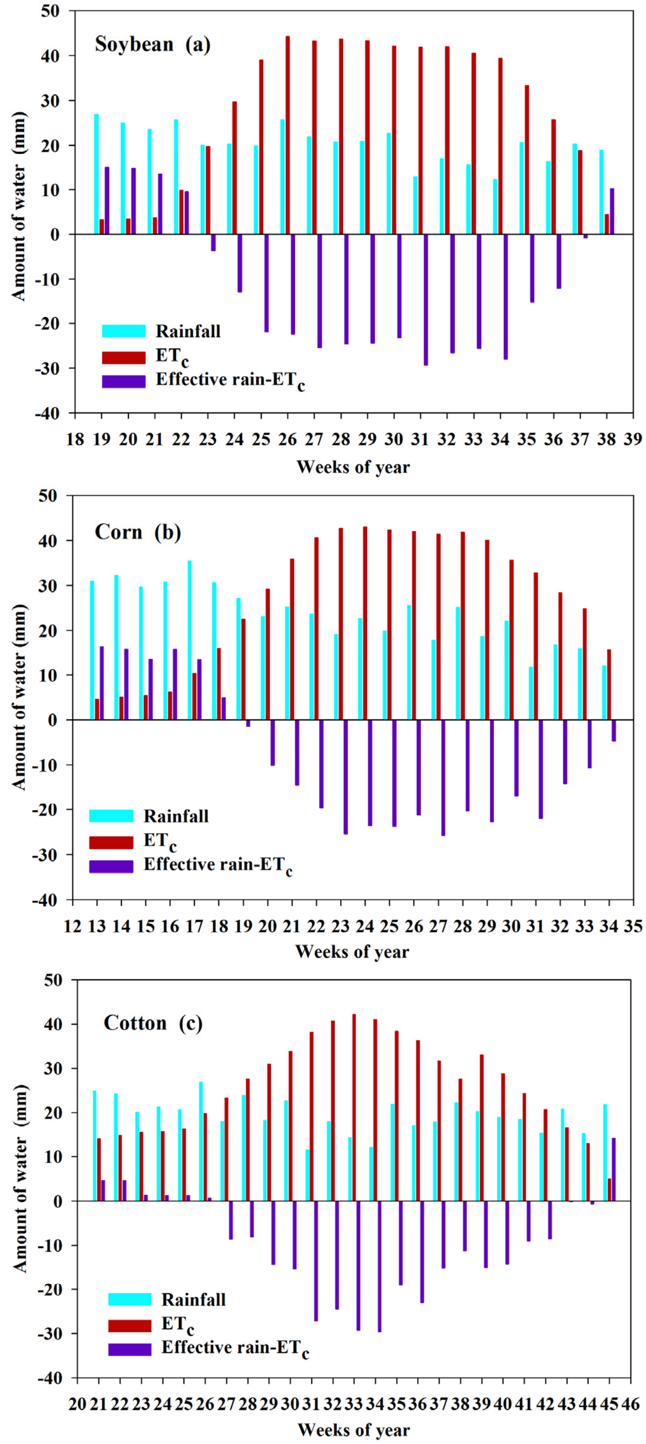

Figure 5. Weekly effective rainfall surplus or deficit for production of (a) soybean, (b) corn, and (c) cotton during the growing seasons at Stoneville on the Mississippi Delta.

Table 2. Yearly mean and range of irrigation required by soybean, corn, and cotton grown at Stoneville in the Mississippi Delta.

Type of Year	Irrigation (mm year^{-1}) Soybean Range	Soybean Mean	Corn Range	Corn Mean	Cotton Range	Cotton Mean
Wet	0-216	98	16-183	110	0-202	118
Normal	0-257	122	0-256	141	62-293	163
Dry	124-337	195	107-315	213	144-352	233

et al. (2016a) reported an irrigation requirement of 150 mm for cotton, while Powers (2007) stated that the average groundwater applied to cotton across a number of years was 183 mm. Averaged over all wet, normal, and dry years, we obtained a cotton water requirement of 171 mm.

The simulated daily irrigation amount and irrigation frequency depended on the crop type and year-to-year weather variability (fig. 6). Irrigation demand and frequency, in general, followed the same increasing and decreasing pattern. This suggests that frequent irrigation is needed to satisfy the crop water demand. As shown in figure 6, the daily amounts of irrigation required by corn varied between 10 and 20 mm from DOY 130 to 230, with maximum values found between DOY 150 and 220. Soybean daily irrigation was similar to corn between DOY 180 and 200, with maximum water demand between DOY 230 and 240. Daily amounts of irrigation for cotton ranged between 5 and 20 mm from DOY 210 to 250, with maximum values between DOY 210 and 240.

These curves could serve as guidance for irrigation planning and scheduling in this region. This study demonstrated that the RZWQM2 model, along with long-term historical weather data, can be used to determine patterns, trends, and magnitudes of crop water requirements, rain water deficits, and irrigation demand in wet, normal, and dry years for a given region.

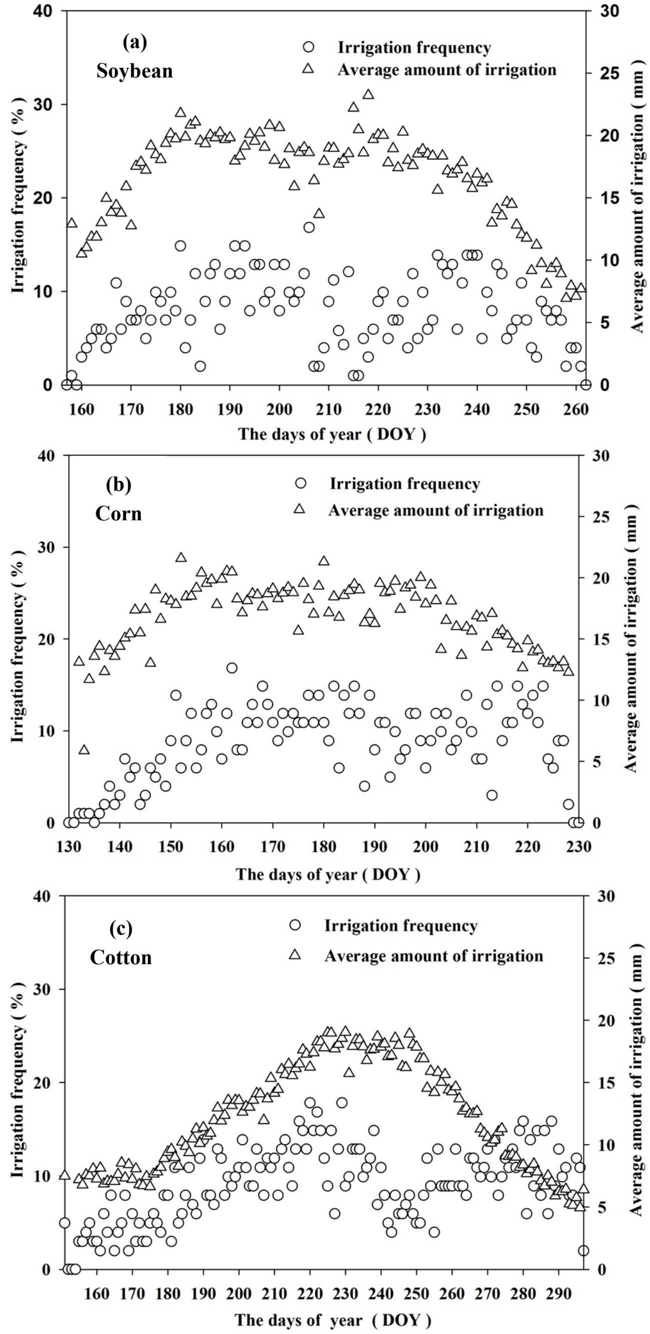

Figure 6. Frequency and amount of irrigation required by (a) soybean, (b) corn, and (c) cotton grown at Stoneville in the Mississippi Delta.

table 2 and figure 6b. Salazara et al. (2012) applied the CSM-CERES model and estimated that the amount of irrigation required by corn ranged from 136 to 281 mm year^{-1}, with an average of 227 mm, in the southeastern U.S. Those results are consistent with our RZWQM2 estimates for dry years.

For cotton, irrigation requirements ranged from 62 to 293 mm year^{-1} (163 mm average) in normal years, from 0 to 202 mm year^{-1} (118 mm average) in wet years, and from 144 to 352 mm year^{-1} (233 mm average) in dry years (table 2 and fig. 6c). Christ et al. (2015) reported that cotton required 311 mm of irrigation in Georgia in an experiment conducted in a dry year. In the Mississippi Delta, Sassenrath et al. (2010) indicated that cotton needs 146 mm of irrigation, Saseendran

CONCLUSIONS

A simulation study was undertaken to analyze rain water deficits and irrigation demand for the three major crops (corn, soybean, and cotton) grown in the Mississippi Delta. Based on historical weather data for Stoneville, Mississippi, from 1915 to 2015, annual rainfall ranged from 777 to 1884 mm, with a mean value of 1306 mm year^{-1}. Annual rainfall varied between 1000 and 1500 mm in most years. While there was abundant total annual rainfall in Mississippi, only 19% of the rainfall occurred from June to August during the critical water-sensitive stages of the crops, and 30% occurred between May and October in the normal crop growing seasons. The water requirement (or ET_c) of soybean, corn, and cotton during the growing seasons ranged from 500 to 800 mm, with mean values of 580, 606, and 649 mm, respectively.

The RZWQM2-estimated effective rain water deficits for soybean ranged from 128 to 524 mm (328 mm average) in normal years, from -36 to 401 mm (235 mm average) in wet years, and from 353 to 622 mm (468 mm average) in dry years. The range and average of deficits for corn were 128 to 588 mm (349 mm average) in normal years, 32 to 499 mm (222 mm average) in wet years, and 293 to 685 mm (502 mm average) in dry years. The ranges and average deficits for cotton were 178 to 547 mm (383 mm average) in normal years, 169 to 480 mm (319 mm average) in wet years, and 386 to 650 mm (469 mm average) in dry years.

The irrigation amounts required by soybean ranged from 0 to 257 mm year^{-1} in normal years, from 0 to 216 mm year^{-1} in wet years, and from 124 to 337 mm year^{-1} in dry years, with daily amounts of 10 to 20 mm during DOY 180 and 200. Corn irrigation demand was 0 to 256 mm year^{-1} in normal years, 16 to 183 mm year^{-1} in wet years, and 107 to 315 mm year^{-1} in dry years, with peak daily irrigation demand ranging from 10 to 20 mm from DOY 150 to 220. Cotton required irrigation amounts of 62 to 293 mm year^{-1} in normal years, 0 to 202 mm year^{-1} in wet years, and 144 to 352 mm year^{-1} in dry years, with peak daily irrigation amounts ranging from 5 to 20 mm during DOY 210 to 240. Results from this study can be used for the design of irrigation and cropping systems, and irrigation scheduling for production of the three row crops in this region. The approach applied in this research serves as a demonstration for other regions around the world to conduct similar studies and obtain similar results for sustainable management of limited water resources to improve rain and irrigation water use efficiencies.

ACKNOWLEDGEMENTS

This work was supported in part by the National Science Foundation of China (31460143) and the Mississippi Soybean Promotion Board (62-2017).

REFERENCES

Ahuja, L. R., Rojas, K. W., Hanson, J. D., Shafer, M. J., & Ma, L. (2000). *Root Zone Water Quality Model: Modeling management effects on water quality and crop production*. Highlands Ranch, CO: Water Resources Publications.

Ahuja, L. R., Ma, L., Fang, Q. X., Saseendran, S. A., Islam, A., & Malone, R. W. (2014). Computer modeling: Applications to environment and food security. In N. van Alfen (Ed.), *Encyclopedia of agriculture and food systems* (pp. 337-358). New York, NY: Elsevier. https://doi.org/10.1016/B978-0-444-52512-3.00246-1

Ahuja, L. R., Ma, L., & Lascano, R. J. (Eds.). (2016). *Practical applications of agricultural system models to optimize the use of limited water*. Madison, WI: ASA, CSSA, SSSA. Retrieved from https://portal.sciencesocieties.org/resources/files/Downloads/pdf/B40818.pdf

Bennett, D. (2002). Balancing demands for water. *Delta Farm Press* (16 April 2002). Retrieved from http://www.deltafarmpress.com/balancing-demands-water

Christ, E. H., Webster, P. J., Collins, G. D., Toma, V. E., & Byrd, S. A. (2015). Using precipitation forecasts to irrigate cotton. *J. Cotton Sci., 19*(3), 351-358.

Fang, Q. X., Ma, L., Yu, Q., Ahuja, L. R., Malone, R. W., & Hoogenboom, G. (2010). Irrigation strategies to improve the water use efficiency of wheat-maize double-cropping systems in North China Plain. *Agric. Water Mgmt., 97*(8), 1165-1174. https://doi.org/10.1016/j.agwat.2009.02.012

Fang, Q. X., Ma, L., Flerchinger, G. N., Qi, Z., Ahuja, L. R., Xing, H. T., ... Yu, Q. (2014). Modeling evapotranspiration and energy balance in a wheat-maize cropping system using the revised RZ-SHAW model. *Agric. Forest Meteorol., 194*, 218-229. https://doi.org/10.1016/j.agrformet.2014.04.009

Farahani, H. J., & DeCoursey, D. G. (2000). Evaporation and transpiration processes in the soil-residue-canopy system. In L. R. Ahuja, K. W. Rojas, J. D. Hanson, M. J. Shaffer, & L. Ma (Eds.), *Root Zone Water Quality Model* (pp. 51-80). Highlands Ranch, CO: Water Resources Publications.

Feng, G., Tewolde, H., Ma, L., Adeli, A., Sistani, K. R., & Jenkins, J. N. (2015). Simulating the fate of fall- and spring-applied poultry litter nitrogen in corn production. *SSSA J., 79*(6), 1804-1814. https://doi.org/10.2136/sssaj2015.06.0211

Heatherly, L. (2014). Soybean irrigation guide for the midsouthern U.S. Canton, MS: Mississippi Soybean Promotion Board. Retrieved from http://mssoy.org/wp-content/uploads/2012/04/IRRIG-WHITE-PAPER-MAR-2012.pdf.

Howden, S. M., Soussana, J. F., & Tubiello, F. N. (2007). Adapting agriculture to climate change. *Proc. Natl. Acad. Sci., 104*(50), 19691-19696. https://doi.org/10.1073/pnas.0701890104

Johnsen, K. E., Liu, H. H., Dane, J. H., Ahuja, L. R., & Workman, S. R. (1995). Simulating fluctuating water tables and tile drainage with a modified Root Zone Water Quality Model and a new model WAFLOWM. *Trans. ASAE, 38*(1), 75-83. https://doi.org/10.13031/2013.27814

Kebede, H., Fisher, D. K., Sui, R., & Reddy, K. N. (2014). Irrigation methods and scheduling in the Delta region of Mississippi: Current status and strategies to improve irrigation efficiency. *American J. Plant Sci., 5*(20), 2917-2928. https://doi.org/10.4236/ajps.2014.520307

Kladivko, E. J., Kaspar, T. C., Jaynes, D. B., Malone, R. W., Singer, J., Morin, X. K., & Searchinger, T. (2014). Cover crops in the upper midwestern United States: Potential adoption and reduction of nitrate leaching in the Mississippi River basin. *J. Soil Water Cons., 69*(4), 279-291. https://doi.org/10.2489/jswc.69.4.279

Ma, L., Ahuja, L. R., Ascough II, J. C., Shaffer, M. J., Rojas, K. W., Malone, R. W., & Cameira, M. R. (2000). Integrating system modeling with field research in agriculture: Applications of the Root Zone Water Quality Model (RZWQM). *Adv. Agron., 71*, 233-292. https://doi.org/10.1016/S0065-2113(01)71016-4

Ma, L., Hoogenboom, G., Ahuja, L. R., Ascough II, J. C., & Saseendran, S. A. (2006). Evaluation of the RZWQM-CERES-Maize hybrid model for maize production. *Agric. Syst., 87*(3), 274-295. https://doi.org/10.1016/j.agsy.2005.02.001

Ma, L., Trout, T. J., Ahuja, L. R., Bausch, W. C., Saseendran, S. A., Malone, R. W., & Nielsen, D. C. (2012,). On calibration of RZWQM2 for maize responses to irrigation water and use of the model for irrigation scheduling. *Agric. Water Mgmt., 103*, 140-149. https://doi.org/10.1016/j.agwat.2011.11.005

Malone, R. W., Jaynes, D. B., Kaspar, T. C., Thorp, K. R., Kladivko, E., Ma, L., ... Searchinger, T. (2014). Cover crops in the upper midwestern United States: Simulated effect on nitrate leaching with artificial drainage. *J. Soil Water Cons., 69*(4), 292-305. https://doi.org/10.2489/jswc.69.4.292

Mississippi. (2014). Mississippi agriculture, forestry, and natural resources factbook. Mississippi State, MS: Mississippi State University. Retrieved from http://www.dafvm.msstate.edu/factbook.pdf.

NRCS. (2015). Geospatial Data Gateway. USDA Natural Resource Conservation Service. Retrieved from https://gdg.sc.egov.usda.gov/.

Pote, J. W., & Wax, C. L. (1986). Climatological aspects of irrigation design criteria in Mississippi. BOR-20324310. Mississippi State, MS: Mississippi Agriculture and Forestry Experiment Station.

Powers, S. (2007). Agricultural water use in the Mississippi Delta. Stoneville, MS: Yazoo Water Management District. Retrieved from http://www.ymd.org/pdfs/wateruse/Agricultural%20Water%20Use%20Presentation.pdf

Qi, Z., Ma, L., Bausch, W. C., Trout, T. J., Ahuja, L. R., Flerchinger, G. N., & Fang, Q. X. (2016). Simulating maize production, water and surface energy balance, canopy temperature, and water stress under full and deficit irrigation. *Trans. ASABE, 59*(2), 623-633. https://doi.org/10.13031/trans.59.11067

Ritchie, J. T. (1998). Soil water balance and plant water stress. In G. Y. Tsuji, G. Hoogenboom, & P. K. Thornton (Eds.), *Understanding options for agricultural production* (pp. 41-54). Dordrecht, The Netherlands: Kluwer Academic. https://doi.org/10.1007/978-94-017-3624-4_3

Salazar, M. R., Hook, J. E., Garcia y Garcia, A., Paz, J. O., Chaves, B., & Hoogenboom, G. (2012). Estimating irrigation water use for maize in the southeastern USA: A modeling approach. *Agric. Water Mgmt., 107*, 104-111. https://doi.org/10.1016/j.agwat.2012.01.015

Saseendran, S. A., Ahuja, L. R., Nielsen, D. C., Trout, T. J., & Ma, L. (2008). Use of crop simulation models to evaluate limited irrigation management options for corn in a semiarid environment. *Water Resour. Res., 44*(7), W00E02. https://doi.org/10.1029/2007WR006181

Saseendran, S. A., Pettigrew, W. T., Reddy, K. N., Ma, L., Fisher, D. K., & Sui, R. (2016a). Climate-optimized planting windows for cotton in the lower Mississippi Delta region. *Agronomy, 6*(4), 46. https://doi.org/10.3390/agronomy6040046

Saseendran, S. A., Fisher, D. K., Reddy, K. N., Pettigrew, W. T., Sui, R., & Ahuja, L. R. (2016b). Vulnerabilities and adapting irrigated and rainfed cotton to climate change in the lower Mississippi Delta region. *Climate, 4*(55), 1-20. https://doi.org/10.3390/cli4040055

Sassenrath, G. F., Pringle III, H. C., Fisher, D. K., Samson, S., Schmidt, A. M., & Shrestha, B. (2010). Development of irrigation scheduling tools for the humid, high-rainfall environment of the lower Mississippi Delta. *Proc. 5th Natl. Decennial Irrigation Conf.* St. Joseph, MI: ASABE.

USDA-NASS. (2015). USDA's National Agricultural Statistics Service Mississippi Field Office. Washington, DC: USDA National Agricultural Statistics Service. Retrieved from http://www.nass.usda.gov/Statistics_by_State/Mississippi/Publications/Crop_Releases/

Vories, E. D., & Evett, S. R. (2014). Irrigation challenges in the sub-humid U.S. mid-south. *Intl. J. Water, 8*(3), 259-274. https://doi.org/10.1504/IJW.2014.064220

YMD. (2015). Fall 2015 water level survey report. Stoneville, MS: Yazoo Mississippi Delta Joint Water Management District. Retrieved from http://ymd.org/publications.htm

Zhang, B., Feng, G., Read, J. J., Kong, X., Ouyang, Y., Adeli, A., & Jenkins, J. N. (2016). Simulating soybean productivity under rainfed conditions for major soil types using APEX model in east central Mississippi. *Agric. Water Mgmt., 177*, 379-391. https://doi.org/10.1016/j.agwat.2016.08.022