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The role of changing land use and irrigation scheduling in groundwater depletion mitigation in a humid region

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ABSTRACT

Many agricultural production regions in the world have been experiencing groundwater resource depletion, which threatens water and food security if mitigation practices are not developed and implemented. To understand how changing land use and irrigation schedule impact groundwater, a coupled SWAT-MODFLOW model was applied to determine groundwater depletion mitigation strategy in a humid region, the Big Sunflower River Watershed (BSRW) in Mississippi, USA. It was found that converting grasslands to forests contributed to reducing groundwater declining. Simulated results indicated that the watershed lost 749, 586, and 381 mm yr^{-1} of water through surface runoff in the wet, normal and dry years, respectively. The amount of groundwater that moved into the vadose zone to help satisfy crop water demand ranged from 700 to 750 mm yr^{-1}. Precipitation increased the groundwater recharge during the rainy season from fall to spring. Annual recharge rate was only 34–50 mm. Groundwater level dropped 0.2–0.5 m in crop irrigation seasons (May to August). Land use dataset showed 81 % of the area is cropland, with soybean, corn, rice, and cotton accounting for 64 % of the total cropland area in BSRW. The planted area of corn and soybean significantly increased while the area of cotton area was tremendously reduced. Corn, soybean, and rice consumed approximately 96 % of the total amount of groundwater irrigation. This study indicated that irrigation scheduling based on plant water demand could save 47 % of groundwater currently used by conventional irrigation. The improved irrigation schedule could reduce groundwater decline by 0.01–2.05 m across the watershed, and mitigate the declines by 1.35–2.05 m in the depression cone in the central east part of the watershed. The results can assist with planning land and water use and developing sustainable groundwater management practices focused on locations of high groundwater withdrawals in other regions around the world.

1. Introduction

Water and food security are two of the major challenges across the world in the future. Agricultural production is sustained by irrigation, more than 40 % of the global yields relies on irrigated fields (FAO, 2022a; b). Approximately 70 % of the global blue water withdrawal from groundwater and surface water is used for agriculture (Census of Irrigation, 2023; Dieter et al., 2018; Siebert et al., 2010), in some regions the share can be over 90 % in Asia, Middle East (Meier et al., 2018) or North America, such as the Lower Mississippi River Basin of the United States (NASS, 2018; Reba and Massey, 2020; Vories and Evett, 2014). However, over 80 % of irrigated lands is under a gravity or other surface irrigated systems, with irrigation system efficiencies often below 50 % (Jägermeyr et al., 2015; Reba and Massey, 2020). The majority of growers, even in developed counties, still feel for soil water or use a calendar to schedule irrigation (Feng et al., 2018). As a result, many agricultural production regions in the world, Africa, Middle East, Asia, China, North America, and Australia, have been experiencing groundwater resource depletion (Dalin et al., 2017; Doll et al., 2014; Feng et al., 2013; Garduño et al., 2010; Konikow and Kendy, 2005; Ouyang et al., 2019; YMD, 2015). The regional declining groundwater level threatens water and food security across the world if mitigation practices are not developed and implemented (Aeschbach-Hertig and Gleeson, 2012; Gleeson et al., 2012). There is little potential for increasing irrigation or

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expanding cropland (Gerten et al., 2013). For example, irrigated farmland area increased by only 1 % from 2013 to 2018 in the United States (Steffen et al., 2015). Thus, global water and food should be secured by reducing groundwater withdrawals while increasing crop water productivity.

Some states with major irrigated agriculture production in the United States, such as Colorado, California, and Florida, experienced large decreases in irrigated area (NASS, 2018). Pumping from aquifers for irrigation is clearly not sustainable, and further groundwater declines in irrigated area are expected. The state of Mississippi experienced the largest increases in irrigated area at 92 % from 1988 to 2008, and more increase in irrigated area and further groundwater declines are expected (NASS, 2018). Over 70 % of row crops were irrigated by using groundwater (Massey, 2010). Approximately 4.58×10^7 m^3 per day of water are withdrawn from the Mississippi River Valley alluvial aquifer, withdrawal for irrigation was 6.06×10^6 m^3 per day from the state of Mississippi alone (Lovelace et al., 2020). It was forecasted that there will have a groundwater supply gap of 27 Mm^3 d^{-1} by 2050, the current and projected groundwater demands are not sustainable (ANRC, 2014, 2016). Konikow (2015) and Siebert et al. (2010) estimated that global groundwater reserves are being depleted very rapidly to meet irrigation demand for crop production at a withdrawal rate of 545 km^3 per year, and this rate is expected to increase. For example, the Mississippi River Alluvial Plain (MRAP), the second most used aquifer in the United States, has been facing a severe groundwater level decline due to irrigation extraction (Barlow and Clark, 2011; Lovelace et al., 2020). The Mississippi Delta in MRAP, once a floodplain to the Mississippi River covered with hardwoods and marshland, is now a highly productive agricultural region of large economic importance to the state of Mississippi. Over 4.48 million acres in the region represent irrigated cropland and 90 % of those acres rely on the groundwater supply. Increased water withdrawals and low recharge jeopardize the long-term water availability of the aquifer and place irrigated agriculture in the region on an unsustainable path. The Big Sunflower River Watershed (BSRW) which is the major agriculture production watershed in the region, experiences subtropical weather. Droughts in the summer frequently cause large yield losses, even short droughts can greatly affect crop growth and production due to either small water holding capacities or slow infiltration rate of many soils in the watershed. Irrigation was motivated and widely adopted for stabilizing or increasing yields. However, limited irrigation related research is available which could guide farmers and other stakeholders (Feng et al., 2018; Vories and Evett, 2014). The major irrigation system type in Mississippi is low efficiency, gravity surface irrigation (93 %) (Lo and Pringle, 2021; NASS, 2018,). Pumping groundwater for excessive irrigation using flooding irrigation system and inappropriate irrigation scheduling has resulted in serious groundwater declines (Ouyang et al., 2018, 2021). The groundwater level has declined greater than 7 m since 1970 (Vories and Evett, 2014; YMD, 2015). BSRW has become one of the fastest groundwater depletion regions in the U.S. (Konikow, 2015; Ouyang et al., 2021; Reba et al., 2017), and will continuously decline if conservation practices that promote reductions in groundwater withdrawals are not employed (Barlow and Clark, 2011). It is believed that improving cropping systems by using more efficient irrigation methods and scheduling is one of the sustainable groundwater management practice. However, little is known on whether or how much groundwater depletion could be reduced if land use is changed or science-based water-saving irrigation scheduling is implemented. It is essential to investigate the impacts of cropping systems and improved irrigation schedule on mitigating groundwater level declines.

Mathematical process-based models have the promising potential to explore solutions to groundwater management problems. The Soil and Water Assessment Tool (SWAT) was developed for simulating water quantity and quality as affected by land use and management practices including irrigation under historical weather conditions and future climate changes (Arnold et al., 2012; Baffaut et al., 2015; Neitsch et al., 2011; Tuppad et al., 2011). It has been applied to the BSRW for evaluating best management practices (Dakhlalla et al., 2016; Nepal and Parajuli, 2022; Ni and Parajuli, 2018; Risal et al., 2021), determining the amount of surface water as an alternative to groundwater for irrigation (Gao et al., 2019a; b), and assessing water quality (Barlow and Coupe, 2014; Jayakody et al., 2013; Ouyang et al., 2018; Risal et al., 2020). SWAT was designed focusing on surface and vadose zone hydrological process. The USGS Modular Groundwater Fine-Difference Flow model (MODFLOW), instead, was developed to simulate groundwater level, recharge, discharge, storage and flow in the saturated zone defined by three-dimensional cells (groundwater domain), as affected by anthropogenic activities, environmental and hydrogeological conditions (Harbaugh, 2005). The well package in MODFLOW is designed to simulate wells that withdraw water from or add water to the aquifer at a constant rate during a stress period. MODFLOW can represent multiple aquifer conditions such as confined, unconfined, leaky, delayed yield, and variably confined/unconfined conditions. Both steady state and transient conditions can be simulated. The USGS used MODFLOW to construct a large-scale regional model for the Mississippi Embayment Regional Aquifer Study (MERAS). The description and calibration of the MERAS model were reported by Clark and Hart (2009).

A coupled SWAT-MODFLOW model can overcome the limitations of either model. SWAT passes its deep percolation to MODFLOW as recharge in each grid cell, and MODFLOW provides groundwater discharge to SWAT in each sub-basin. Therefore, the coupled model is capable of modeling water flow and transport in both unsaturated and saturated zones as well as interactions between surface water, vadose water and groundwater. Coupled SWAT-MODFLOW model has been applied to different studies (Bailey et al., 2016; Bejranonda et al., 2007; Guzman et al., 2015; Ni and Parajuli, 2015). For example, Sophocleous and Perkins (2000) applied it to assess the impacts of land use, irrigation, and climate change on both surface and groundwater resources at three agriculture-dominated watersheds in Kansas, USA. Guzman et al. (2015) employed the coupled model to simulate dynamic interactions between the surface and groundwater in an agroecosystem at the Fort Cobb Reservoir watershed of southwestern Oklahoma, USA. Chunn et al. (2019) used the coupled model to study the influence of climate change on the interactions between surface and groundwater in West-Central Alberta, Canada. The coupled model was also applied to BSRW for determining surface and groundwater resources (Gao et al., 2019b; Ni and Parajuli, 2015) and the effects of climate change (Ouyang et al., 2021). Limited or no effort has been devoted to employing the coupled SWAT- MODFLOW model for assessing cropping systems and irrigation management in an attempt to reducing groundwater withdrawals in the BSRW. Barlow and Clark (2011) warned the current rate of water use from the Mississippi River Valley alluvial aquifer is not sustainable. A better understanding of how changing land use and irrigation schedule impact groundwater level and recharge is needed. The goal of this study was to apply the coupled model and determine how changing land use, crop rotation and irrigation schedule impact groundwater recharge and level. The specific objectives were to: 1) compare the changes in land use area and determine the change trend; 2) investigate the effect of land use change on groundwater level and their relationships; 3) determine the change range and spatiotemporal variation of groundwater level; 4) identify the location where groundwater was over drafted for crop irrigation; 5) compare the amount of groundwater used between conventional growers' irrigation schedule and plant water-demand scheduling method; and 6) assess the impacts of the two different irrigation schemes on change in groundwater level.

2. Materials and methods

2.1. Study area

The BSRW is in the alluvial plain located in northwestern Mississippi which encompasses 10,488 km^2 from latitude 32° to 35° N and longitude

91° to 90° E (Fig. 1). The BSRW is bordered by the Mississippi River levee on the western boundary and the Bluff Hills on the eastern boundary (Coupe et al., 2012). The Big Sunflower River meanders over the flat flood plain as a slow-moving river and flows through an ecologically rich landscape (Parajuli and Jayakody, 2012). It covers eleven Mississippi counties, including Coahoma, Bolivar, Tallahatchie, Sunflower, Leflore, Washington, Humphreys, Sharkey, Issaquena, Yazoo, and Warren. The watershed is relatively flat with a slope of 6–7 cm km^{-1}. Its elevation ranges from 15 m to 60 m above mean sea level. The majority soils are silty clay of Alligator, Sharkey, Dowling, Forestdale, and Dundee (Soil Survey Staff, 2023). These soils account for over 90 % of the soil types in the watershed and are classified as hydrologic soil groups C and D, which allow for high runoff potential.

The subtropical region has a long growing season, its annual mean temperature is 18 °C with 90 days above 32 °C. It is a highly productive agricultural region in the state. The dominant crops are cotton, soybean, corn, and rice. The average annual precipitation ranged from 1200 mm in the north to 1400 mm in the south of the watershed, however, only 30 % of the annual rainfall occurs during those crop growing seasons from April to October (Tang et al., 2017). Therefore, irrigation is needed for stabilizing or increasing yields, and as high as 87–95 % of the irrigation water was from groundwater wells (NASS, 2018; Vories and Evett, 2014). The thickness of the shallow aquifer averages about 30 m, it is the main source of water for irrigation (Reba et. al, 2017). As of 2018, there have been 14,684 irrigation wells in the BSRW (Lo and Pringle, 2021).

The empirical frequency analysis was conducted to classify rainfall category year according to annual rainfall amount (Zhang et al., 2016). The procedures were to: 1) rank rainfall in descending order with a total of n values (number of years); 2) assign each descending order as a rank m, from the largest value as 1 and the smallest as n; 3) calculate the empirical probability (P) by Weibull equation: $P = m/(n+1) \times 100$ %; 4) if $P \leq 25$ %, it is categorized to 'wet' year; if 25 % $< P < 75$ %, it is categorized to 'normal' year; and if $P \geq 75$ %, it is categorized to 'dry' year. In order to obtain better rainfall statistical Weibull pattern in this region, we expanded analysis for the years earlier than 2000, from 1990 to 2018, though the period of time that the study was conducted mainly from 2000 to 2018.

2.2. Data source for model inputs

The input data for the model consist of a Digital Elevation Model (DEM), land use, soil physical and hydrological properties, weather data (daily precipitation, maximum and minimum air temperature, solar radiation, average daily wind speed, and daily relative humidity), and land management and operation information (Table 1). USGS daily and monthly observed streamflow data at 3 gauge stations: Merigold (07288280), Sunflower (07288500), and Leland (07288500) (Fig. 1) were used.

The calibrated parameters were used (Gao et al., 2019a, 2019b) in this study: CH_N2 (the Manning's roughness coefficient for the main channel, 0.3); CN2 (curve number, −0.015); SURLAG (the surface runoff lag time, 9.5); SOL_K (the saturated hydraulic conductivity of the soil layers, 0.1); GWQMN (the threshold depth of water in the shallow aquifer for baseflow to occur, 1075).

Impact of changes in land use on water balance components were simulated and compared from 2000 to 2018. Two scenarios of irrigation from pumping shallow aquifer groundwater were simulated by the coupled SWAT-MODFLOW model (Table 5): one is the currently used

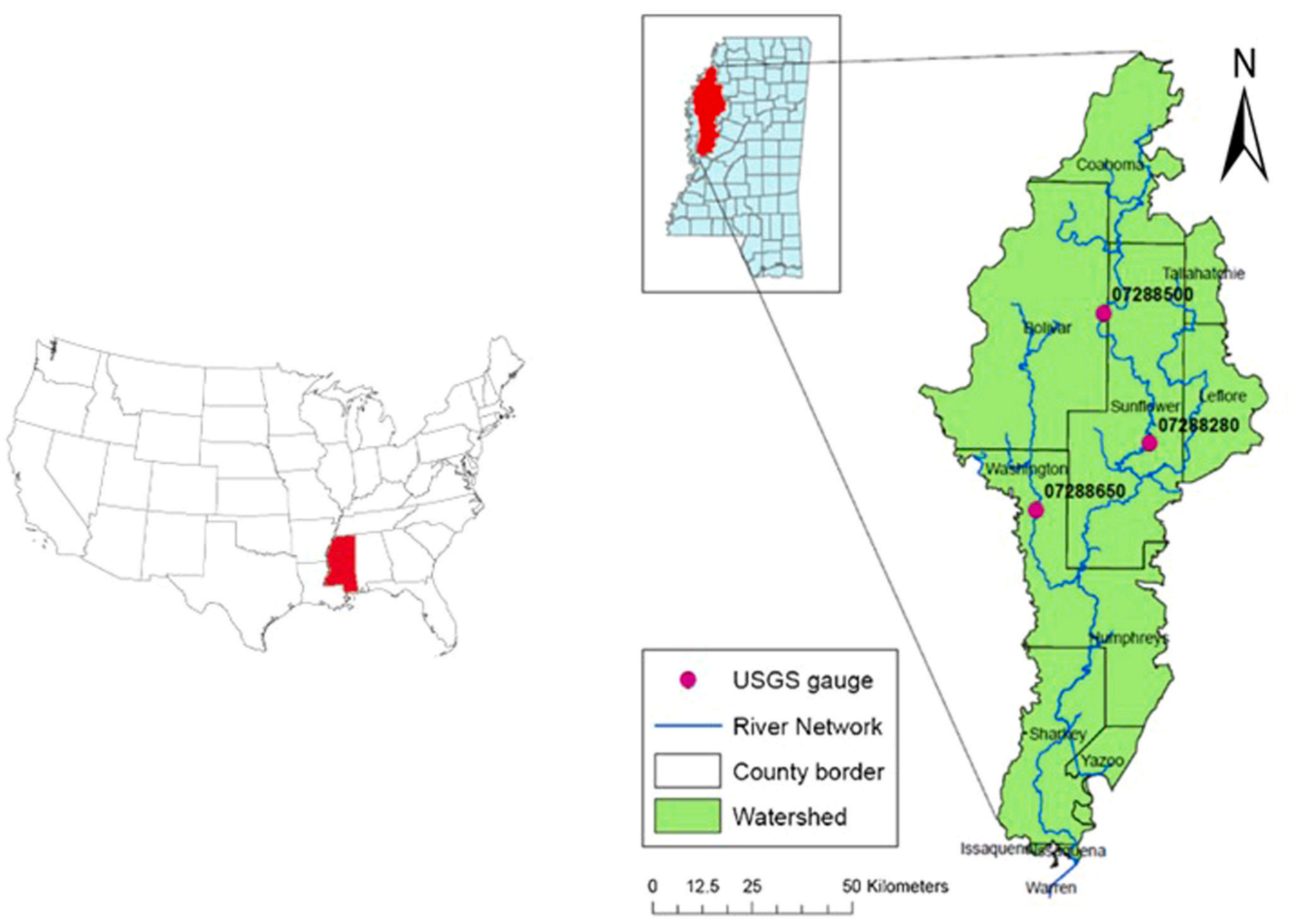

Fig. 1. The location of Big Sunflower River Watershed (BSRW).

Table 1
The coupled SWAT-MODFLOW model input data and sources.

Data	Source	Period of time	Resolution (m)
Land use	USDA National Agricultural Statistics Service https://nassgeodata.gmu.edu/CropScape/	2000–2018	30
Groundwater Level	Yazoo Mississippi Delta Joint Water Management District (YMD) http://www.ymd.org/	2003–2013	
DEM	United States Geological Survey (USGS) http://viewer.nationalmap.gov/downloader	2000–2018	10
Soil properties	the soil survey geographic (SSURGO) database from the Natural Resources Conservation Service (NRCS) andClark et al. (2011) https://gdg.sc.egov.usda.gov/GDGOrder.aspx	2000–2018	30
Weather	NRCS National Water and Climate Center http://wcc.sc.egov.usda.gov/nwcc	1990–2018	
Land management & operation	Dates of planting and harvest; timing, types and amount of fertilization; tillage types and depth, etc. http://www.ymd.org/,Dakhlalla et al. (2016)	2000–2018	
River stage, water quantity & quality	U.S. Corps of Engineers www.rivergages.com	2000–2018	

Table 2
The percentage of land use types in the subbasins with the amount of runoff greater than 87 mm as shown in Fig. 5b.

Year	Corn (%)	Cotton (%)	Rice (%)	Soybean (%)	Others (%)
2000	6	23	6	31	35
2018	23	2	10	42	24
Total change	17	–21	4	11	–11

conventional irrigation scheme by most growers in the watershed, another one was to schedule irrigation amount based on plant water demand (evapotranspiration, ETc). Water balance components such as the amount of irrigation and groundwater recharge, and change in ground water level were compared.

We applied geographic information system and geo-statistical methods (ArcMap 10.4.1, Esri, Redlands, CA), the semi-variogram model and Kriging interpolation method (Wang et al., 2016), to analyze the response of land use/land cover change to spatiotemporal variations of the groundwater level in the BSRW, further investigated which land use pattern will lead to the rapid decline of groundwater. Transition matrix of land use types with respect to different change range of groundwater depth was obtained by comparing the land use maps of 2003 and 2013. The relations between different regions of change in groundwater level and the land use/land cover type were simultaneously analyzed.

The MERAS model has been rigorously calibrated and validated by USGS (Barlow and Clark, 2011; Barlow and Leake, 2012; Barlow and Coupe, 2014; Clark and Hart, 2009; Clark et al., 2011, 2013; Harbaugh, 2005; Ouyang et al., 2021) in this region. In addition, Gao et al. (2019b) calibrated and validated the SWAT-MODFLOW model. The calibrated hydraulic parameters and boundary conditions used in these studies were adopted in this study. Areal recharge is applied throughout the MERAS model area using the MODFLOW-2005 Recharge Package (Harbaugh, 2005) and represents net recharge. A total of 19 recharge zones were classified for the MERAS model, three of these zones cover the alluvial aquifer within Mississippi state. USGS daily and monthly observed streamflow data were obtained at 3 gauge stations (Fig. 1): Merigold (07288280), Sunflower (07288500), and Leland (07288500). The specific values of these parameters can be found in the literature reported by Clark et al. (2011).

3. Results

3.1. Land use

The BSRW is an intensively cultivated and highly productive crop production region in Mississippi state, southeast USA. Nearly 81 % of the area is cropland, soybean, corn, rice, and cotton are dominant row crops, accounting for 64 % of the total cropland area in BSRW (Figs. 2 and 3). The planted area of those crops has significantly changed over time. For example, from 2003 to 2013, corn area increased by 1179 km^2 (366 %), cotton and rice planting area showed a downward trend, decreasing 89 % and 42 %, respectively, in 2013. The change in rice area is relatively less, the largest area of soybean was always found since 2003, increased 28 % in 2013. As of 2021, soybean was increased up to 3574 km^2 while corn was reduced to 627 km^2. Cotton and rice area continuously decreased, down to 106 and 169 km^2. Compared with 2000, soybean plant area increased by 337 %, whilst cotton decreased by 86 % in 2018. There were 2606, 1179, 192, and 790 km^2 for soybean, corn, cotton, and rice in 2018, respectively (Figs. 2 and 3).

3.2. Runoff as affected by landuse

In order to investigate the impacts of land use on runoff, we simulated two land use scenarios in 2000 and 2018 under different rainfall and other weather conditions from 2000 to 2018 (Fig. 4). As Fig. 4 shown, the total amount of runoff and rainfall in the entire BSRW was positively correlated (R^2 =0.93) and consistent for both land use scenarios. When we fit the linear model with both land use year (binary variable; 2000 or 2018) and rainfall as predictors, the R^2 was increased to 0.95. The inclusion of land use year into the model results in a better model fit than rainfall alone (delta-AIC = 8.7). This suggests that land use did play a role in the runoff variation. The amount of runoff was constantly larger for 2018 land use scenarios than 2000 regardless the amount of rainfall, the runoff difference ranged from 30 to 130 mm in the entire watershed.

Considering its 26 individual subbasins, more runoff did not always occur in the subbasins receiving more rainfall (Fig. 5). For example, the area with the most rainfall was located in subbasins 13, 15 and 19, while a larger amount of runoff was simulated in subbasin 2, 4, 6, 10, 16, 18, and 24. Instead, it is consistent with the increase in soybean area and the decrease in cotton area (Fig. 2, Table 2). Overall, the runoff was associated with the increase in the area of corn and soybean in those subbasins. The area increased in 2018 was mainly from the fields where cotton was planted (Table 2).

3.3. Groundwater level as affected by landuse

Cotton, corn and soybean are high-water-demand crops in terms of their rainwater deficit and irrigation demand in the region (Tang et al., 2017). Groundwater was pumped for irrigation to those crops (Fig. 3), which resulted in a decrease in groundwater level both spatially and temporally (Figs. 6 and 7). The 0–2 m of groundwater level drop was observed in most regions of the watershed (Fig. 6). The significant decline of groundwater level as shown in Fig. 6, ranging from 2 to 4 m, occurred in the east central regions (Fig. 7). Groundwater level in BSRW declined from 36.97 m in the northeast to 25.75 m in the southeast, and 34.1 m in the northwest to 23.72 m in the northeast between 2003 and 2013. A funnel-shaped zone of groundwater was found, Sunflower County is located in the center of the zone (Fig. 7). The groundwater level in the depression cone was 27.01 m in 2003 and 24.85 m in 2013.

From 2003–2013, 410 and 540 km^2 of cotton fields were converted

Table 3
The transition matrix of land use types with respect to different change range of groundwater level from 2003 to 2013. The second column displays the land use types in 2003, while the first row lists the land use types in 2013. The values in the table show the percentage changes of each land use type from 2003 to 2013 in different range of changes in groundwater level (the first column) during the same period of time in the Big Sunflower River Watershed.

Range of Change in Groundwater Level	2013 / 2003	Corn (%)	Cotton (%)	Rice (%)	Soybeans (%)	Grass/Pasture (%)	Woody wetland/Forest (%)	Water (%)	Total (%)
> 0 m	Corn	0.8	0.0	0.0	0.9	0.0	0.4	0.1	2.3
	Cotton	**9.3**	3.9	0.1	**11.5**	0.0	1.4	0.6	26.9
	Rice	0.2	0.0	0.0	0.9	0.0	0.5	0.1	1.7
	Soybeans	4.2	1.3	0.1	11.1	0.0	2.2	1.0	20.0
	Forest	0.4	0.1	0.0	0.8	0.0	4.0	0.2	5.4
	Grass/ Pasture	1.9	0.4	0.1	5.7	0.1	**25.8**	1.5	35.6
	Water	1.2	0.2	0.2	3.0	0.0	0.7	2.8	8.0
	Total								100.0
0 to − 2 m	Corn	1.9	0.1	0.0	2.2	0.0	0.3	0.0	4.6
	Cotton	**9.1**	2.2	0.5	**12.1**	0.0	0.7	0.2	24.8
	Rice	1.4	0.0	1.4	5.1	0.0	0.2	0.1	8.3
	Soybeans	7.0	0.7	2.6	21.4	0.0	1.5	0.3	33.5
	Forest	0.4	0.0	0.1	0.9	0.0	2.1	0.1	3.5
	Grass/ Pasture	2.4	0.3	0.5	6.2	0.0	**11.3**	0.6	21.5
	Water	0.4	0.0	0.1	1.1	0.0	0.5	1.6	3.8
	Total								100.0
< −2 m	Corn	2.9	0.1	0.1	3.0	0.0	0.3	0.0	6.3
	Cotton	**12.6**	1.4	0.5	**14.3**	0.0	0.3	0.1	29.2
	Rice	1.7	0.0	1.0	4.5	0.0	0.2	0.0	7.5
	Soybeans	8.1	0.5	1.7	**18.3**	0.0	1.4	0.4	30.4
	Forest	0.3	0.0	0.1	0.6	0.0	1.3	0.1	2.3
	Grass/ Pasture	3.2	0.2	0.7	6.7	0.0	**8.7**	0.6	20.1
	Water	0.3	0.0	0.1	1.2	0.0	0.5	1.9	4.1
	Total								100.0

Table 4
Major components and interactions of surface, vadose and ground water under conventional water management conditions in the Big Sunflower River Basin from 2000 to 2018.

Year category	Mean annual values from 2000 to 2018 (mm)					
	PREC	SURQ	GWQ	RECH	GWET	SW
Dry	1083	381	102.5	33.5	751	205
Normal	1342	586	106.2	42.1	710	219
Wet	1706	749	106.7	49.8	697	223

PREC: precipitation (mm), SURQ: surface runoff; GWQ: ground water discharge to stream; RECH: recharged to the groundwater; GWET: groundwater moved to vadose zone for plant uptake; SW: water stored in 0–2 m soil profile.

to corn and soybean in the region where groundwater declined 0 – 2 m. Table 3 displays the acreage percentage of the four major crops rotated to other crops with respect to different range of change in groundwater level over the 10-year period from 2003 to 2013. The planting area of cotton was significantly reduced (25–29 %), mainly replaced by soybean and corn in all regions with different drops of groundwater level. The greatest change in cotton to soybean (14 %) and corn (13 %) was found in the regions where groundwater level declined more than 2 m. Grasslands which were converted to crop lands accounted for 11 % in the regions within <–2 m groundwater level change, followed by 9 % in 0 to –2 m regions and 8 % in >0 m regions. Grassland was largely converted to forest, ranging from 9 % to 26 %. The woody wetland/ forest land accounted for 26 %, 11 %, and 9 % in the regions where groundwater level raised (>0 m), declined 0–2 m, and more than 2 m, respectively.

3.4. Comparison of groundwater recharge and associated components

Empirical frequency analysis was applied to classify rainfall category years (Zhang et al., 2016). Fig. 8 shows dry, normal and wet years in terms of the range of rainfall from 1990 to 2018. In dry years, annual precipitation ranged from 822 to 1163 mm; in normal years, ranged from 1186 to 1496 mm; and in wet years from 1535 to 1897 mm. Average annual precipitation of dry years, normal years and wet years were 1083 mm, 1342 mm and 1706 mm, respectively.

As shown in Fig. 8 and Table 4, the BSRW in the subtropical region had at least 1083 mm mean annual precipitation. Annual runoff ranged from 274 to 432 mm (mean 379 mm, median 407 mm) in dry years, 420–670 mm (mean 587 mm, median 603 mm) in normal years, and 698–1041 mm (mean 740 mm, median 795 mm) in wet years. There

Table 5
Conventional irrigation amounts from Dakhlalla et al. (2016) and the Mississippi Delta annual report summarized by the Yazoo Mississippi Delta Joint Water Management District (http://www.ymd.org/) and the plant demand irrigation amounts scheduled by SWAT model for soybean, corn, cotton, and rice production in the Big Sunflower River Watershed from 2000 to 2018.

	Irrigation amount ($\times 10^7$ m^3)							
	May		June		July		August	
Crops	Conve-ntion	Plant demand	Conven-tion	Plant demand	Conven-tion	Plant demand	Conven-tion	Plant demand
Corn	6.73	2.02	13.46	2.34	6.73	4.20	0.00	2.22
Cotton	0.00	3.26	1.10	0.24	1.64	0.56	0.54	0.61
Rice	22.56	15.08	27.07	1.77	24.86	3.16	2.22	2.53
Soybean	7.32	23.44	29.76	5.98	22.20	10.06	22.20	8.50

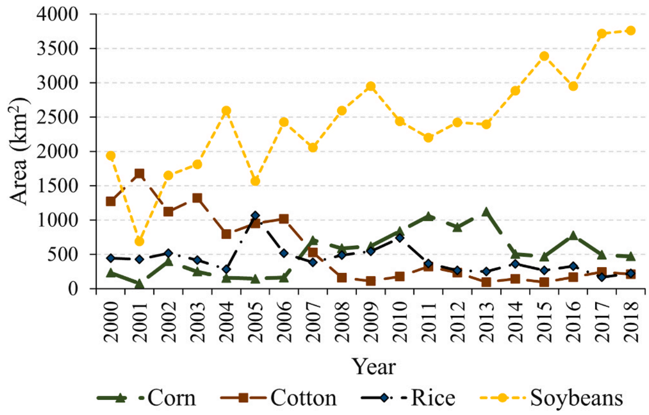

Fig. 2. Planted area of four major crops in the Big Sunflower River Watershed from 2000 to 2018.

were 513 and 259 mm more annual rainfall in the wet and normal years than the dry years. The BSRW lost 749, 586 and 381 mm of water through surface runoff in the wet, normal and dry years, respectively (Table 4). Little difference was found among all years for water stored in soil profile. Approximately 105 mm of groundwater was discharged to streams. The amount of groundwater moved into vadose zone ranged from 700 to 750 mm. The range was 633–918 mm (median 754 mm) in dry years, 439–939 mm (median 748 mm) in normal years, and 617–978 mm (median 657 mm) in wet years. The groundwater recharge range was 26.5–37.4 mm (median 34.2 mm) in dry years, 36.7–46.5 mm (median 42.1 mm) in normal years, and 48.0–59.2 mm (median 54.0 mm) in wet years.

Pumping to meet irrigation demands occurs from May through August of each year, the irrigation season is then followed by an 8-month period of no withdrawals. Fig. 9 displays a clear pattern of shallow groundwater storage from 2000 to 2013, it was increased 0.2–0.6 m in rainy seasons (October to April), decreased 0.2–0.5 m after crop irrigation season (May to August). Therefore, reducing irrigation pumpage could stop groundwater level decline.

3.5. Comparison of irrigation schemes and the impact on groundwater level

Table 5 shows the conventional grower irrigation schedule data obtained from Dakhlalla et al. (2016) and the Mississippi Delta annual report summarized by the Yazoo Mississippi Delta Joint Water Management District (http://www.ymd.org/).

The amount of groundwater used by growers' irrigation scheduling method (1.9×10^9 m^3) was 2.2 times that of the plant water-demand method (0.9×10^9 m^3). Cotton, soybean, corn and rice which were sowed on 64 % of the total area in BSRW (Figs. 2 and 3) consumed approximately 96 % of total amount of groundwater irrigation. Growers applied 43 %, 41 %, 14 % and 2 % of pumped groundwater to irrigate soybean, rice, corn and cotton, respectively. While irrigation for meeting plant water demand scheduled 56 %, 26 %, 13 % and 6 % to those crops (Table 5).

Fig. 10 shows that groundwater was greatly over pumped in Bolivar, Sunflower and Leflore Counties in BSRW as compared with plant water demand scheduling method. Irrigation based on plant water demand could reduce groundwater usage up to 976 mm, to 230 mm averaged in the entire Delta region. It could potentially save 55 % of groundwater currently used by conventional grower's calendar irrigation scheduling method. The groundwater saving was greatly attributed to the reduction of irrigation for rice (saved 71 %), corn (saved 60 %), and soybean (41 %) (Table 5). Consequently, the conventional irrigation schedule resulted in 0.01–2.05 m more drop of groundwater level than the plant water demand irrigation schedule (Fig. 10). The most difference in groundwater level decline was found in subbasin 8, 9, 13, 14 ranging from 1.35 to 2.05 m. Plant water demand irrigation scheduling contributed to more groundwater recharge in corn and cotton fields in Sunflower, Bolivar, and Humphreys County, recharged 0–50 mm yr^{-1} greater than grower irrigation schedule.

4. Discussion

Our results indicated that the surface runoff changed with rainfall fluctuation (Fig. 4), approximately 35–47 % of annual rainfall was lost through runoff (Table 2). The previous simulation also indicated that

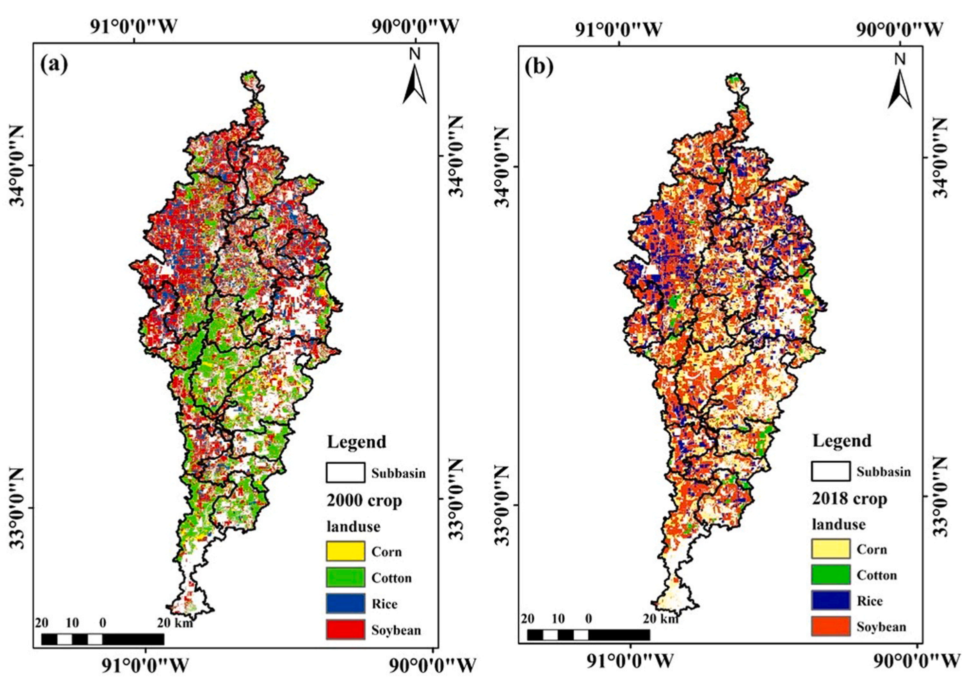

Fig. 3. Dominate row crops, corn, cotton, rice and soybean of spatial distribution in 2000 (a) and 2018 (b) in the Big Sunflower River Basin.

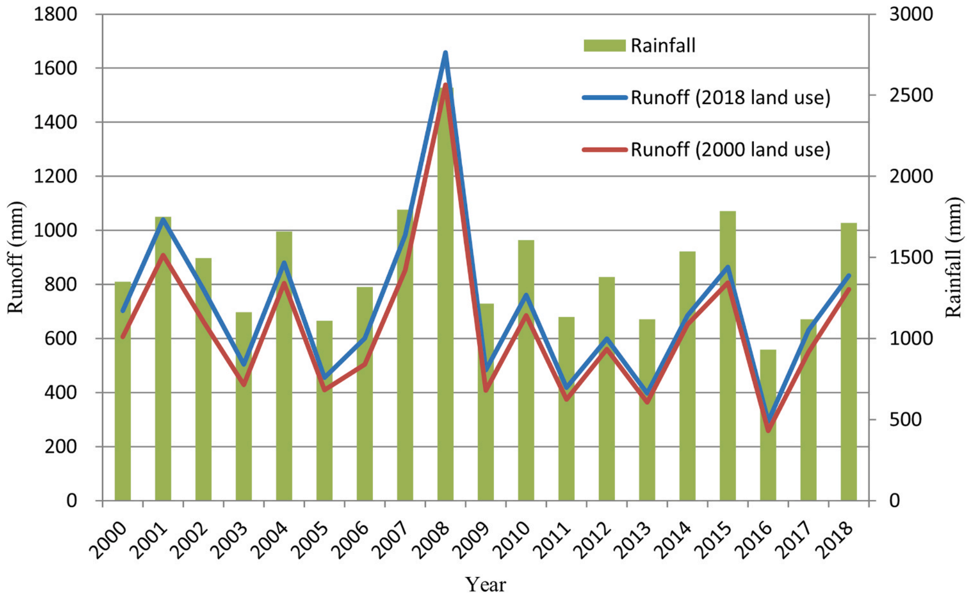

Fig. 4. Total amount of rainfall and runoff occurred under land use in 2000 and 2018 and weather condition from 2000 to 2018 in the entire Big Sunflower River Watershed.

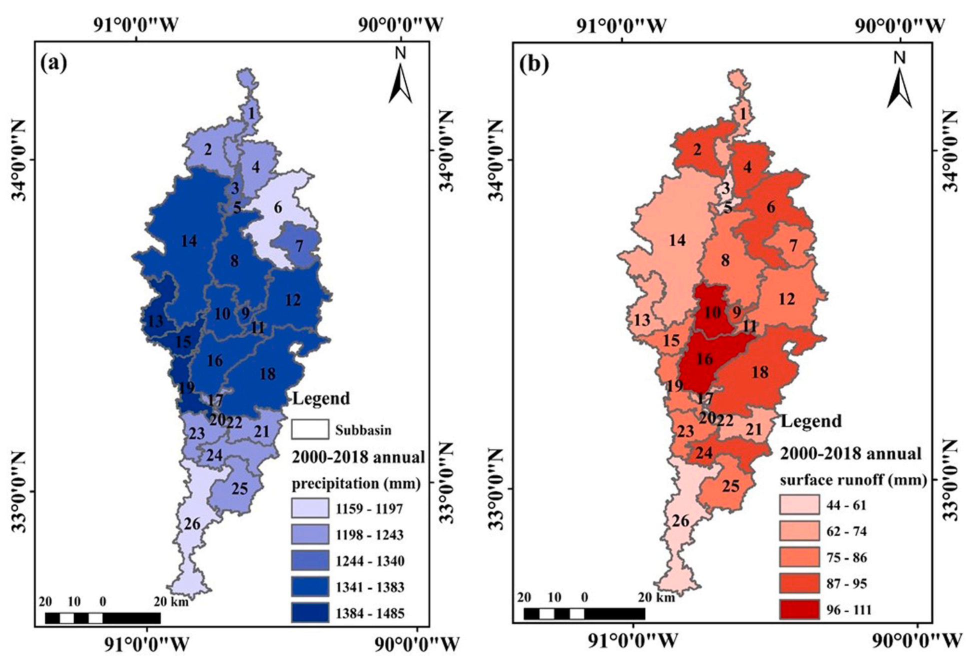

Fig. 5. The averaged annual rainfall from 2000 to 2018 (a) and the difference in runoff between the two years (b) in the 26 subbasins of the Big Sunflower River Basin. Number 1–26 are only for distinguishing the subbasins.

runoff caused up to 31–42 % of rainfall loss in the same region (Tang et al., 2017). The rainfall is mainly concentrated in the west and the central region (Fig. 5), however, the areas with the largest increase in surface runoff were in the central and north area (Fig. 5). Therefore, it was not fully consistent with the spatial pattern of rainfall. It is widely known that rainfall is not the only factor that affects runoff. Surface roughness, soil characteristics, infiltration rate, slope, plant cover, and soil moisture can greatly affect runoff and other hydrological processes (Baffaut et al., 2015; Parajuli et al., 2012). Land use change has significant impact on surface water runoff and groundwater consumption (Dakhlalla et al., 2016). Runoff in 2018 was always greater than that in 2000 under any amount of rainfall and other weather conditions (Fig. 4), which resulted from the great increase in the area of high irrigation demand corn, soybean, and rice, and the decrease in cotton and other land use (Table 2). In particular, soybean occupied approximately three fifths of irrigated cropland, the portion of soybean and corn have been increased by 0.014 y^{-1} and 0.178 y^{-1}, while the water stress tolerant crops such as cotton decreased by 0.045 y^{-1} (Figs. 2 and 3, Lo and Pringle, 2021). A negative correlation was found between runoff and crop leaf area index (LAI), soybeans LAI is generally less than maize (Gao et al., 2020).

A previous study found that converting grassland to cropland over a 100-year period reduced groundwater recharge due to the changes in irrigation and evapotranspiration (Huang et al., 2012). Our results support the statement. The greater decline of groundwater was found in the regions where more grasslands were converted to croplands

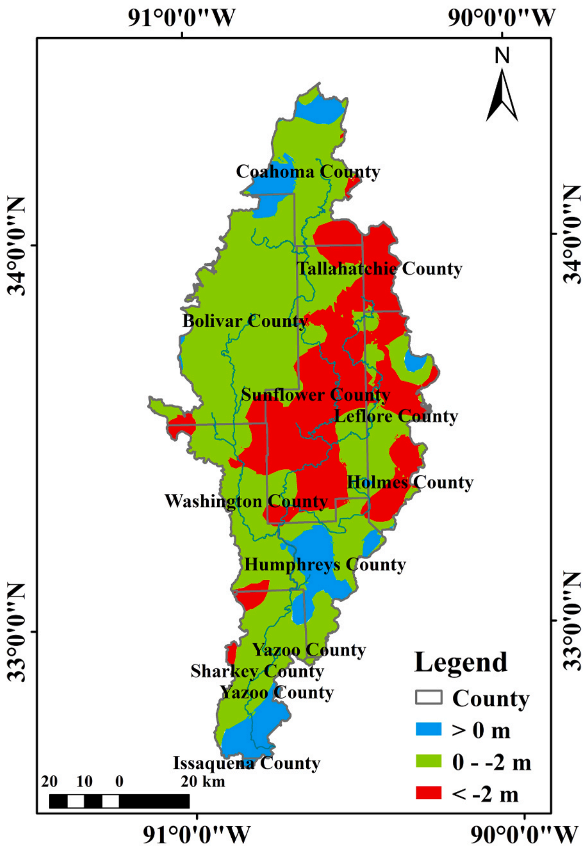

Fig. 6. The groundwater level variation across the Big Sunflower River Basin and the difference from 2003 to 2013.

(Table 3, Roosmalen et al., 2009). Analysis for the last century in the region revealed that the annual effective rainwater deficits (rainfall-runoff-evapotranspiration) in soybean, corn, and cotton was up to 650 mm, with an average deficit of 360 mm (Tang et al., 2017). The crops did not need irrigation for only 15 of 122 years (Feng et al., 2018). In addition, the region has experienced as high as a 92 % increase in irrigated farmland since 1998 (Vories and Evett, 2014). In the irrigated fraction of harvested croplands among full-Delta counties, the growth rate ranged from 0. 1–1.8 % each year (Lo and Pringle, 2021).

In 2018, there were 14,684 wells pumped 9 million m^3 d^{-1} of groundwater for irrigation. An average groundwater loss 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 6.5 m since the 1970s (YMD, 2015). Another SWAT-MODFLOW modeling research and observation indicated that the change in groundwater level ranged from 4 to 6 m (27–40 cm per year) in the agriculture region due to water consumption of those crops from 1998 to 2012 (Ni and Parajuli, 2015). Killian et al. (2019) revealed that the difference in groundwater level between 1980 and 2016 was up to 12 m, equivalent to 33 cm decline each year. In general, the reported depletion rate is 15–60 cm per year (Dyer et. al., 2015). We calculated that groundwater level dropped 4 m over 10 years, equivalent to 40 cm decline each year. The degree of changes in groundwater level corresponded to changes of those crop areas both spatially and temporally (Table 3, Figs. 6 and 7). Though decline in water level of the region has gained widespread attention, those studies did not characterize the different land use changes in the three ranges of groundwater level drop as shown in Table 3. Changes in land use from cotton to corn (12.6 %) and soybean (14.3 %) greatly contributed to the decline of ground water level (<–2 m) (Table 3). It is because more groundwater was pumped to irrigate large areas of higher water-demand corn and soybean fields (Tables 2 and 3; Feng et al., 2018; Tang et al., 2017;).

Soybean planted areas steadily increased since 2005 (Figs. 2 and 3), Lo and Pringle (2021) also reported that irrigated soybean fields were larger than any other crops. A 12-year study in Mississippi found that irrigation applications by producers averaged 160 ± 90 mm, 220 ± 160 mm, and 330 ± 200 mm for center pivot sprinkler, border and contour flooding, and furrow methods, respectively (Massey et al., 2017). The greatest portion of groundwater was pumped to irrigate soybean fields, therefore, more groundwater could have been saved by applying the soybean water-demand irrigation scheme. The largest area of woody wetland/Forest was found in the regions where groundwater level did not drop (>0 m) or had less decrease (<–2 m) (Table 3). Ouyang (2021) suggested that converting grasslands to forests could contribute to reducing groundwater declines, probably because of reducing groundwater discharge including irrigation (Huang et al., 2012; Ouyang et al., 2019, 2021). However, Roosmalen et al. (2009) did not find such conversion attributed to increasing groundwater recharge in the western part of Jutland, Denmark. They attributed to climate change causing CO_2 effects on transpiration which resulted in a relatively large increase in recharge. This study reported that the average recharge is reduced from 1389 to 1349 mm per hectare as grass is

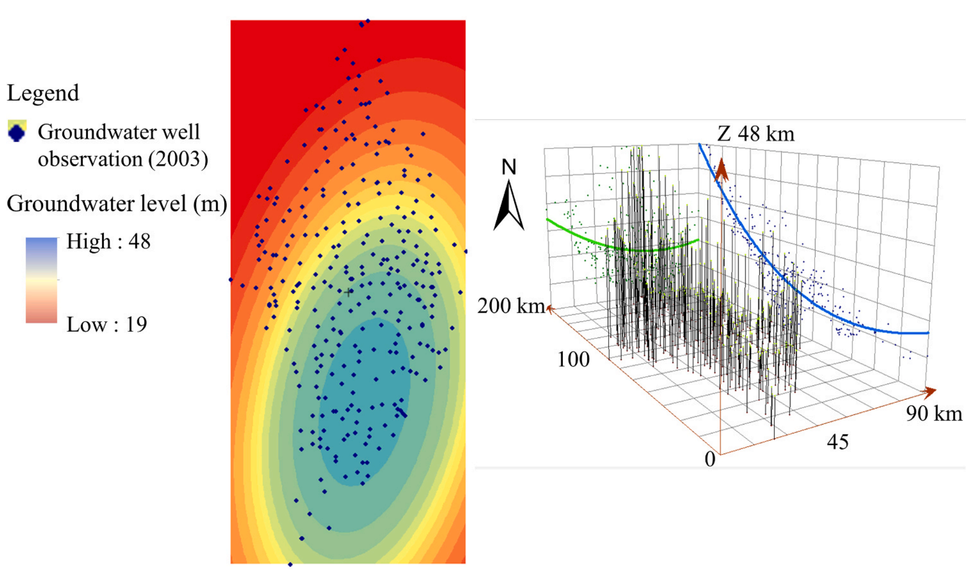

Fig. 7. Three-dimensional groundwater levels and its change tendency in the Big Sunflower River Basin from 2003 to 2013.

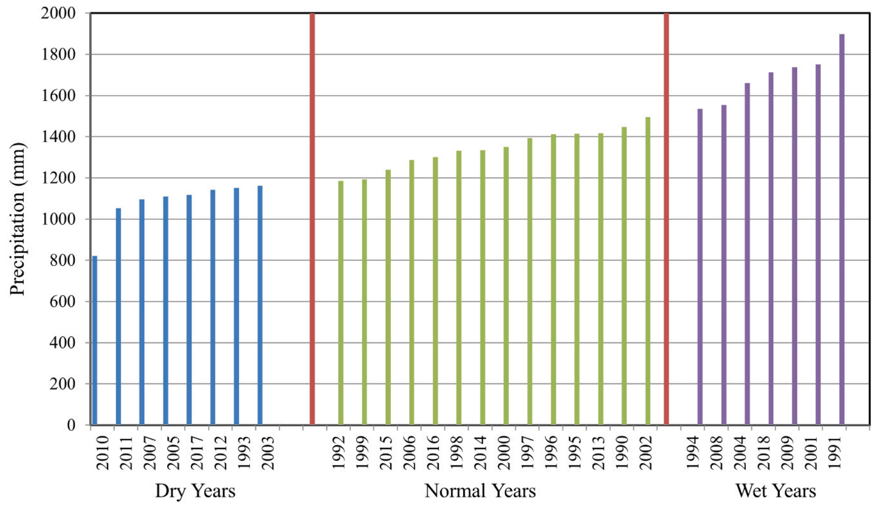

Fig. 8. The amount of rainfall in dry, normal, and wet category years from 1990 to 2018 in the Big Sunflower River Basin.

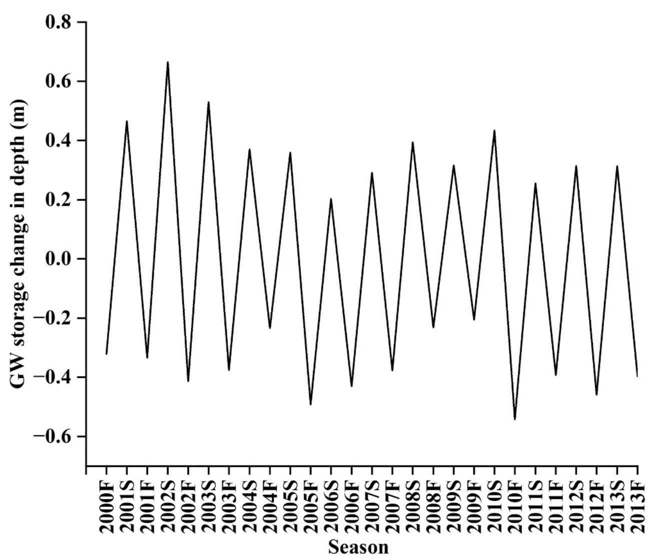

Fig. 9. Fluctuation of groundwater storage in depth each year was recorded in the beginning of April (s) and October (f) from 2000 to 2013. GW: groundwater.

changed to forest. Our results showed a spatial distribution of groundwater levels in BSRW, for example in the Fall of 2013, it was higher in the northeast of BSRW than in the Southwest, ranging from 24 to 37 m (Fig. 7) which is in the other reported range of 14–36 m (Barlow and Clark, 2011). It is because the most groundwater was abstracted in the south for irrigation, groundwater level gradient dropped from north to south, the groundwater storage loss has reached up to 1.8×10^8 m^3 per year (Clark et al., 2013). The largest declines occurred at the central east part of the watershed (Fig. 6 and Fig. 7), which is consistent with the area identified by Barlow and Clark (2011), Killian et. al. (2019), and Ni and Parajuli (2015). The large cone of depression in the central watershed (Fig. 7), formed as a result of groundwater pumping for irrigation intercepting the regional groundwater flow path (Arthur, 2001; Chen et al., 2023). Reba and Massey (2020) reported that a regional cone of depression in the Mississippi River Valley Alluvial Aquifer started forming in the 1980 s as withdrawals continued at unsustainable rates. It has become deeper and wider and will continue if current irrigation management is not improved (Clark et al., 2013). Therefore, groundwater conservation has to be implemented in the depression cone area. Crop rotation and land use alteration strategies, to some degree, could alleviate the problems as our results indicated.

The groundwater yearly recharge rate was 26.5–59.2 mm from dry to wet years, 9 and 16 mm more in normal and wet years than dry years from 1990 to 2019 (Table 4). Recharge was very sensitive to rain season, irrigation season and the amount of rainfall (Fig. 9), averaging approximately 3 % of annual rainfall. Broom and Lyford (1981) reported that recharge range from 10 to 50 mm y^{-1}. Arthur (2001) and Welch (2010) estimated a recharge rate of 64 mm y^{-1} in the same region, about 5 % of the average annual rainfall. It is close to the rate we calculated in wet years. For comparison, Scanlon et al. (2012) showed that groundwater recharge rate was 9–32 mm y^{-1} in the US High Plain and Central Valley and Vories and Evett (2014) reported that the Ogallala aquifer recharge is at lower rate of approximately 25 mm y^{-1} in the semiarid region, which is similar to the situation for the alluvial aquifer in Mississippi during the dry years as shown in Table 4. Arthur (2001) indicated that the upper part of the aquifer is extensive silt and clay layer, therefore, recharge from infiltration through vadose zone typically is low in the region (Barlow and Clark, 2011). They consider the most likely scenarios of recharge rate are 5, 52 and 61 mm y^{-1}, which are equivalent to only 0.3 %, 3.8 %, and 4.5 % of annual rainfall. Regardless of loss through runoff, it is beneficial to find that the amount of groundwater moved to the vadose zone for plant uptake (GWET) was as great as 44–69 % of precipitation (Table 4). Nearly 30 times of annual recharged groundwater was pumped to croplands (Tables 4 and 5), which is not sustainable for irrigated agriculture in the region. Barlow and Clark (2011) reported that irrigation pumpage accounts 88 % of total groundwater outflow, the maximum withdrawal rate could be 3785 m^3 per day. The aquifer has shown sensitive response to irrigation which has significantly reduced groundwater level after any crop growing season in the region (Fig. 9). Groundwater sources were often over extracted and exploited (Fereres and Soriano, 2006). The conventional irrigation scheme pumped approximately twice the amount of groundwater that crops need. Half amount of groundwater, approximately 900 mm (Table 5), was saved by applying the plant demand irrigation scheduling method. Bryant et al. (2017) indicated that improved irrigation scheduling such as using soil water sensors, were used in production soybean fields in Arkansas and Mississippi, seasonal irrigation applications were reduced by an average of 21 % relative to conventional furrow irrigation controls. Scanlon et al. (2012) suggested that groundwater depletion can be reduced in most irrigated areas by improved irrigation scheduling. Lo and Pringle (2021) reported that Sunflower and Bolivar Counties had the largest irrigated croplands which consumed more groundwater compared with other Counties in the region, which is consistent with our results (Fig. 10a). Plant demand irrigation scheduling method significantly mitigated groundwater decline by 1.35–2.05 m in subbasins 8, 9, 13 and 14, mainly in the two

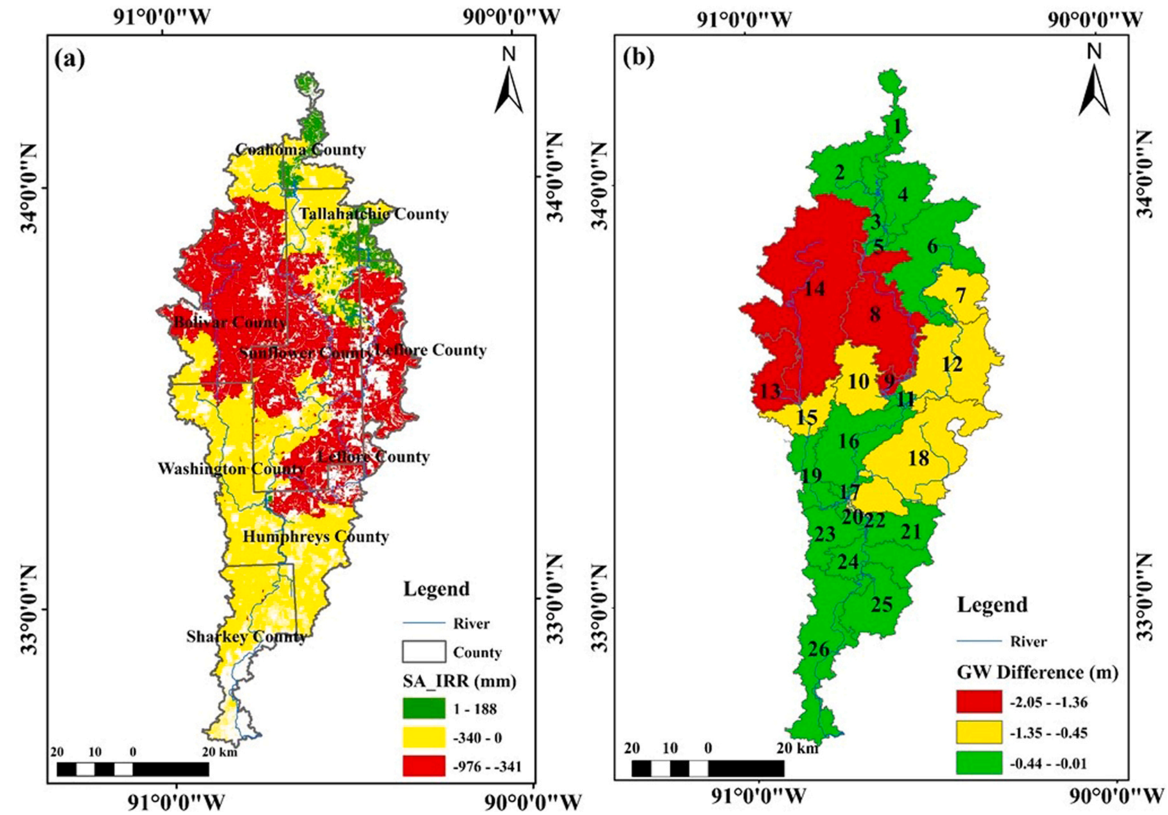

Fig. 10. The difference in irrigation amount of water pumped from shallow aquifer (a) and groundwater level (b) between plant water demand and the grower conventional irrigation scheme from 2000 to 2018. Number 1–26 are just for distinguishing the subbasins in plot (b).

counties (Fig. 10), where the depression cone was located (Fig. 7). Groundwater conservation strategy and practice should be implemented with more attention in the two counties where depletion was higher than recharge rate. Since 1985, Mississippi has also.

required permits for all agricultural irrigation wells with groundwater withdrawal limit: up to 460 mm ha-1 of irrigation may be applied to soybean, maize, and cotton and up to 910 mm ha-1 may be applied to rice (Bryant et al., 2017; Reba and Massey, 2020). In addition to reducing groundwater usage by improved irrigation schedule and required permit, using surface water directly or indirectly as source water for managed aquifer recharge in another option for conjunctive use. Gao et al. (2019a) estimated that surface water in streams and ponds in BSRW could be sufficient for replacing groundwater pumping to mitigate groundwater depletion. The alternate surface water sources include tailwater recovery, on-farm storage, and stream diversion. Currently, surface water provides only 6–7 % of the irrigation used in the region (Reba and Massey, 2020). The high energy price and the groundwater sustainability emphasis may enhance the expansion of pumping from streams or ponds on adjacent lands, which usually requires less energy to lift water.

5. Conclusions

Withdrawals in many aquifers throughout the world have led to significant groundwater-level declines, resulting in growing concerns about sustainability of groundwater supply. The BSRW is of international interest as a less common example of a sub-tropical humid region that has experienced rapid irrigation development and considerable groundwater level decline. The SWAT-MODFLOW model was applied to investigate the impact of change in land use and irrigation schedule on groundwater level and consumption in the BSRW.

Land use change has significant impact on surface water runoff and groundwater consumption. Converting grasslands to forests could contribute to reduce groundwater declining. However, crop lands consumed the majority of groundwater. Nearly 81 % of the BSRW was croplands, soybean, corn, rice, and cotton are dominant row crops, accounting for 64 % of the total croplands in the BSRW. Soybean occupied approximately three fifths of irrigated cropland, the portion of soybean and corn have been increased by 1.4 % y^{-1} and 17.8 % y^{-1} from 2000 to 2018 while the water stress tolerant crops such as cotton decreased by 4.5 % y^{-1}.

The largest surface runoff was found in the central and north area, approximately 35–47 % of annual rainfall was lost through runoff. Groundwater level was extremely sensitive to irrigation season, rain season and amount of rainfall, its recharge was approximately 3 % of annual rainfall. Groundwater levels were higher in the northeast of BSRW than in the southwest, ranging from 24 to 37 m. The largest declines occurred at the central east part of the watershed, and irrigation pumping of groundwater has resulted in a depression cone in the central watershed. The groundwater yearly recharge rate was only 27–59 mm from dry to wet years. However, crop water uptake, equivalent to 44–69 % of precipitation, from groundwater moved through the vadose zone. Crop water demand required more water than could be supplied by upward flow through the vadose zone, resulting in nearly 30 times of annual recharged groundwater being pumped to irrigate crops. Annual total groundwater usage for each of the four major crops was 396 mm. Crop water demand irrigation scheduling method could save 900 mm groundwater pumping for the four major crops compared with the current conventional irrigation scheme. The improved method could reduce groundwater level decline by 1.35–2.05 m, particularly in subbasins 8, 9, 13 and 14, in Sunflower and Bolivar Counties, where the depression cone was located.

The limitation of this study is we were not able to obtain measured data of groundwater level in the entire watershed beyond 2013. Coupled SWAT-MODFLOW model help us to determine it as affected by land use and irrigation schedule up to 2018. This research will facilitate the understanding and application of land use and crop water-demand irrigation scheduling for the benefit of groundwater issues in other regions around the world. Furthermore, this study provided results which can be used to compare and contrast with those in other humid regions.

CRediT authorship contribution statement

Huang Yanbo: Writing – review & editing. **Ouyang Ying:** Methodology, Software, Validation, Writing – review & editing. **Jin Wei:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation. **Feng Gary:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Gary Feng reports financial support was provided by The Mississippi Soybean Promotion Board (62–2023).

Data Availability

Data will be made available on request.

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