Groundwater

Methods Note/

Relationships Between Water Table and Model Simulated ET

by Priyantha Jayakody[1], Prem B. Parajuli[2], Gretchen F. Sassenrath[3], and Ying Ouyang[4]

Abstract

This research was conducted to develop relationships among evapotranspiration (ET), percolation (PERC), groundwater discharge to the stream (GWQ), and water table fluctuations through a modeling approach. The Soil and Water Assessment Tool (SWAT) hydrologic and crop models were applied in the Big Sunflower River watershed (BSRW; 7660 km^2) within the Yazoo River Basin of the Lower Mississippi River alluvial plain. Results of this study showed good to very good model performances with the coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) index from 0.4 to 0.9, respectively, during both hydrologic and crop model calibration and validation. An empirical relationship between ET, PERC, GWQ, and water table fluctuations was able to predict 64% of the water table variation of the alluvial plain in this study. Thematic maps were developed to identify areas with overuse of groundwater, which can help watershed managers to develop water resource programs.

Introduction

Evapotranspiration (ET) and the underlying water table are strongly related (William 1994; Devitt et al. 2002; Nachabe et al. 2005), as shallow unsaturated soil and deep saturated groundwater are hydrologically connected through the process of ET (Thompson 2003). The strength of these relationships varies with depth to the water table from the land surface. Roots extract water from the unsaturated zone if the water table is deeper than the root zone, and the unsaturated soil zone is then replenished from the water table below (Jury et al. 1991). Moreover, high and low ET rates are associated with shallow and deep water tables respectively (Duell 1990; Nichols 1994). These interconnections among ET, unsaturated soil zone, and water table fluctuations help to derive useful relationships and functions which can be used to understand the water table dynamics (Nichols 1994, 2000).

Understanding seasonal fluctuations of the water table helps to plan crop calendars, irrigation schedules, and crop field maintenance operations. But lack of data availability and cost of the water table measurements hinder proper understanding of groundwater dynamics. As an alternative, groundwater models have become useful tools to investigate relationships between ET and water table. Semi-distributed hydrological models such as the Soil and Water Assessment Tool (SWAT; Arnold et al. 1993) can be used to investigate the groundwater status of large watersheds (Hu et al. 2010; Reshmidevi and Kumar 2012). Therefore, this study was designed to establish methodologies using hydrological outputs from the SWAT to explore observed water table fluctuations. The developed methodologies were then applied in groundwater irrigated croplands for improved water management.

Methodology

Study Area

This study was performed in the Big Sunflower River Watershed (BSRW; 7 660 km^2), which is the major subwatershed of the Yazoo river watershed in Mississippi

[1]Corresponding author: Department of Agricultural and Biological Engineering, Mississippi State University, Starkville, MS 39762; +1 662-617-9194; fax: +1 662-325-3853; jb2038@msstate.edu

[2]Department of Agricultural and Biological Engineering, Mississippi State University, Starkville, MS 39762.

[3]USDA-ARS Crop Production Systems Research Unit, Stoneville, MS 38776.

[4]USDA-FS, Center for Bottomland Hardwoods Research, Starkville, MS 39762.

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(Figure 1). Agriculture is the main land use (>80%) in the watershed, and soybean, corn, and rice are grown intensively. Crops are irrigated from groundwater wells with pumping capacity in excess of 7.5 cm^3/s; about 98% of the abstract groundwater is used for irrigation (Arthur 2001).

Soil, Land Use, and Elevation Data

Soil Survey Geographic Database (SSURGO) was incorporated into the model to parameterize soils in the watershed (USDA 2005). The cropland data layer, with a 30-m spatial resolution, was used to parameterize land use characteristics of the watershed (U.S. Department of Agriculture, National Agricultural Statistic Services [USDA/NASS] 2009). The 30 m × 30 m grid digital elevation model (DEM) data from the U.S Geological Survey (USGS 2010a, 2010b) was used as elevation data in this study.

Weather, Stream Flow, and Groundwater Data

Observed daily rainfall and temperature data from the National Climatic Data Center (National Climatic Data Center [NCDC] 2010) were used in this study. Monthly stream flow data from three USGS gauge stations (Merigold in sub-watershed 5; Sunflower in sub-watershed 16; Leland in sub-watershed 26) from 2001 to 2009 were used for stream flow calibration and validation. Two types of observed water table data were used. Discrete water table measurements, collected by the Yazoo Management District (YMD), were available for 108 locations within the watershed (USGS 2010a, 2010b). The discrete water table measurements only reported the extreme conditions

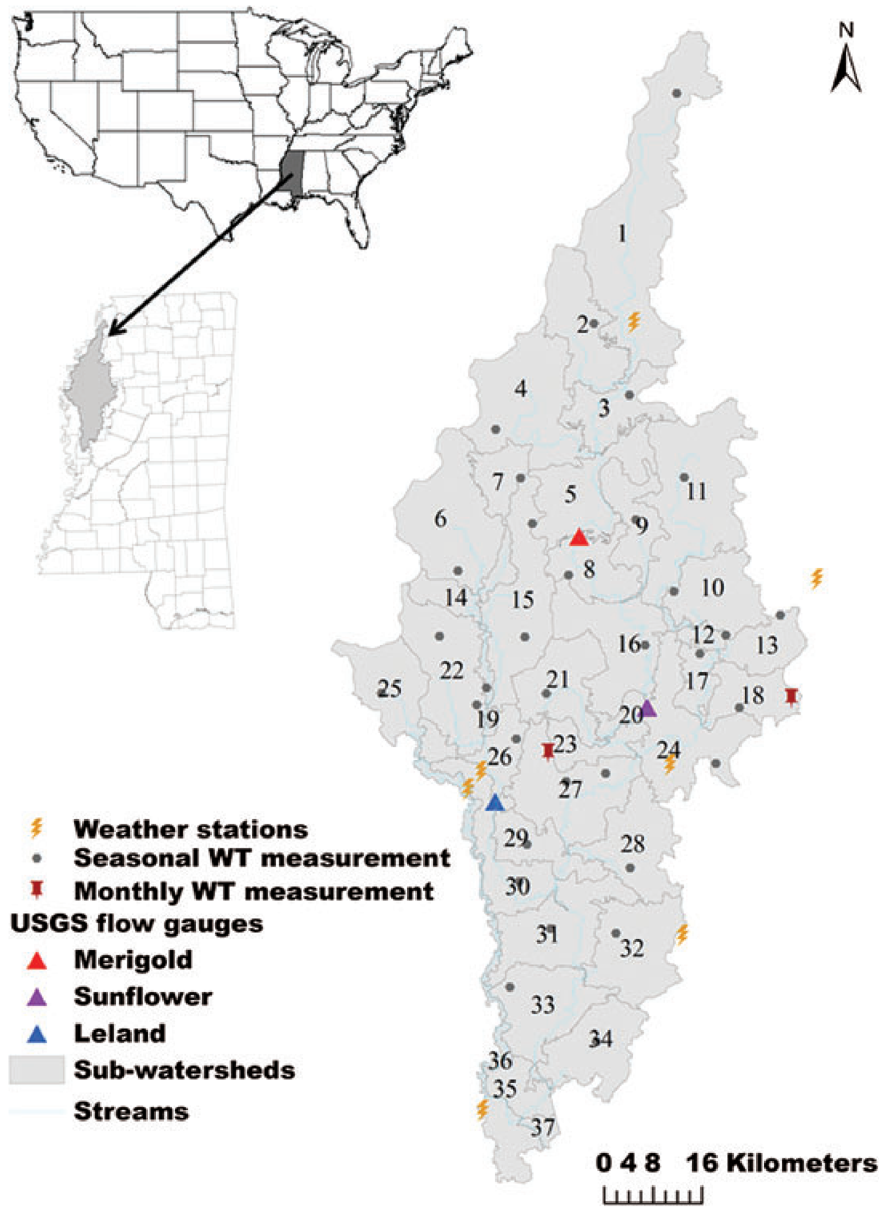

Figure 1. Big Sunflower River watershed showing locations of weather stations, measurement sites for water table and flow measurements, and the sub-watersheds.

of the water table during a year and were available from 1990 to 2009. Measurements taken from April represented the lowest depth to the water table, whereas August measurement represented the highest. Once the primary crop growing season begins in May, intensive groundwater abstraction begins and continues through the growing season. The highest drawdown is commonly observed in August following peak irrigation demand. Out of 108 discrete water table measurement locations, only 33 locations were selected by overlaying with the sub-watersheds map to represent each sub-watershed by one well. Over the measurement area, depth to the water table changed from a minimum depth of 4.8 m in sub-watershed 01 in the northern Delta to a maximum depth of 14.1 m in sub-watershed 16, located in the mid-Delta. In addition to these discrete water table measurements, two continuous time-series data measurements were taken at two locations within the watershed: sub-watershed 27 (Sunflower station) and sub-watershed 18 (Leflore station) (Figure 1). These two stations reported monthly water table measurements from Jan 1990 to September 1994.

SWAT Model Setup

The SWAT 2005 currently runs in ArcGIS 9.2 and needs three main geospatial data inputs to parameterize physical properties of the watershed: elevation, soil, and land use (Neitsch et al. 2005). The BSRW boundary and sub-watershed boundaries were delineated using the 30 m × 30 m DEM data. The 30-m cropland layer and SSURGO soil data layer were overlaid with sub-watersheds to create a number of hydrological response units (HRUs) required for the study. In this study, 37 sub-watersheds were delineated, and 1900 HRUs were created during overlay operations. After creating HRUs, the weather data were incorporated. The model was run from 2000 to 2009 in monthly time steps.

Stream Flow Calibration and Validation

Simulated monthly stream flows from three sub-watersheds (5, 16, and 26), corresponding to observed monthly stream flows from USGS (Merigold, Sunflower, and Leland), were compared for the calibration and validation of the model. The SWAT hydrologic model was manually calibrated using data from January 2002 to December 2005, and validated from January 2006 to December 2009. Calibration was performed iteratively until acceptable model performance statistics were achieved. Mean, correlation coefficient (R^2), and Nash-Sutcliffe efficiency (NSE) are some of the commonly used model performance indexes (Moriasi et al. 2007; Parajuli et al. 2009). The SWAT model performance can be described by six ranking levels (Parajuli 2010) varying from excellent to unsatisfactory.

Corn and Soybean Yield Simulation

Accurate simulation of crop growth is essential to correctly determine ET from the land surface. Crop management data was collected from field research plots at two agricultural experimental stations, Clarksdale and Stoneville, located within sub-watersheds 1 and 30 respectively. Corn and soybean are common crops in the Delta (NASS 2011), and often planted in rotation. In the SWAT crop simulations, auto irrigation and auto fertilization were implemented to minimize water stress and nutrient stress, which represent field conditions.

SWAT Outputs and Water Table Relationships

The SWAT simulates percolation (PERC), ground-water discharge to the stream (GWQ), and ET for each sub-watershed. These simulated variables were utilized with continuous time-series water table depths from sub-watershed 27 to develop a descriptive relationship. The relationship was validated using continuous time-series water table depths from the Leflore station at sub-watershed 18. The developed relationship was then used to analyze discrete water table measurement to investigate the groundwater usage in the BSRW.

Results and Discussions

Monthly stream flow calibration and validation results showed good to very good model performances (Table 1), similar to the results reported by previous studies in the region (Arnold et al. 2000; Jha et al. 2006; Parajuli 2010). The R^2 and NSE were varied from 0.73 to 0.86 and 0.67 to 0.85 respectively.

Crop yield simulation showed good to very good model performances for corn ($R^2 = 0.5$ and NSE = 0.8–0.9), and fair model performances for soybean ($R^2 = 0.4–0.6$ and NSE = 0.4–0.6). Similar results have been reported by a previous study in the region

Table 1
Model Performance Statistics for the SWAT Hydrological Calibration and Validation

Process	Parameter	Sub-Watershed 5; Merigold	Sub-Watershed 16; Sunflower	Sub-Watershed 26; Leland
Calibration 2002–2005	R^2	0.82	0.73	0.73
	NSE	0.78	0.67	0.67
Validation 2006–2009	R^2	0.86	0.85	0.73
	NSE	0.85	0.83	0.71

Process	Crop	Observed (Mt/ha)	Simulated (Mt/ha)
Calibration-Stoneville	Corn	9.7	9.8
	Soybean	3.0	2.66
Validation-Clarksdale	Corn	9.1	8.6
	Soybean	3.2	2.6

Table 2
Observed and Simulated Average Corn and Soybean Yield for the Stoneville and Clarksdale Experimental Stations

(Srinivasan et al. 2010). Observed and simulated average yield for the study period showed that the model was able to accurately predict observed crop yields (Table 2). The model very slightly (1%) over-simulated the corn yield at Stoneville and under-simulated yield at Clarksdale. Soybean yield was under-simulated by 10 and 18% at the Stoneville and Clarksdale stations, respectively.

SWAT Hydrological Outputs and Water Table Relationship

The change in water table showed a strong inverse correlation to the simulated monthly ET, PERC, and GWQ (Figure 2). A relationship was developed to describe the correlation (Equation 1).

$$\Delta GW = -6.1452\ (ET - (PERC - GWQ)) + 440.17 \quad (1)$$

where ΔGW is the water table fluctuations (mm) compare to the previous month, ET the evapotranspiration (mm), PERC the percolation (mm), and GWQ the amount of groundwater discharge to the stream (mm).

Both linear and exponential decay have been proposed in previous studies to describe the relationship between ET and depth to the water table (McDonald and Harbaugh 1988; Nachabe et al. 2005). Our results indicate a linear relationship between ET and monthly water table fluctuations (Figure 2a). Although the water table was below 7.9 m from the land surface, model outputs and water table fluctuations still showed a good relationship. Previous studies have reported similar relationships for the shallow water tables (Nichols 2000; Devitt et al. 2002; Sophocleous 2002). This may be due to regular pumping of groundwater into the surface that acts as a linkage between water table and ET. Moreover, unrestricted groundwater pumping allows farmers to abstract water as required. Crops always received adequate irrigation water from the aquifer in the simulation, as the model was set for the auto irrigation mode, and simulated ET was mainly controlled by crop types and weather parameters. Model simulated ET was able to explain 32% ($R^2 = 0.32$) of the water table fluctuations. After incorporating model simulated PERC and GWQ, the groundwater model was able to explain 64% ($R^2 = 0.64$) of the water table variation for the study period. Similar results have been reported by a study in Muscatatuck river basin in southeast Indiana (Vazquez-Amábile and Engel 2005). The groundwater model may not be able to capture the entire observed variation because of differences of actual irrigation efficiencies and timing of irrigations. The developed empirical relationship was evaluated using monthly data from sub-watershed 18 (Leflore station). The results showed that the developed groundwater model was able to simulate water table fluctuations of sub-watershed 18 with a reasonable accuracy ($R^2 = 0.6$). From January 93 to June 93, the model over-simulated the water table by a maximum of 0.4 m, and under-simulated from August 93 to January 94 by a maximum of 0.9 m (Figure 2b).

The water table has been shown in previous studies to be hydrologically connected with ET in shallow groundwater systems (Thompson 2003). When the water table is deeper than the root zone, roots extract water from unsaturated zones and replenish from the water table based

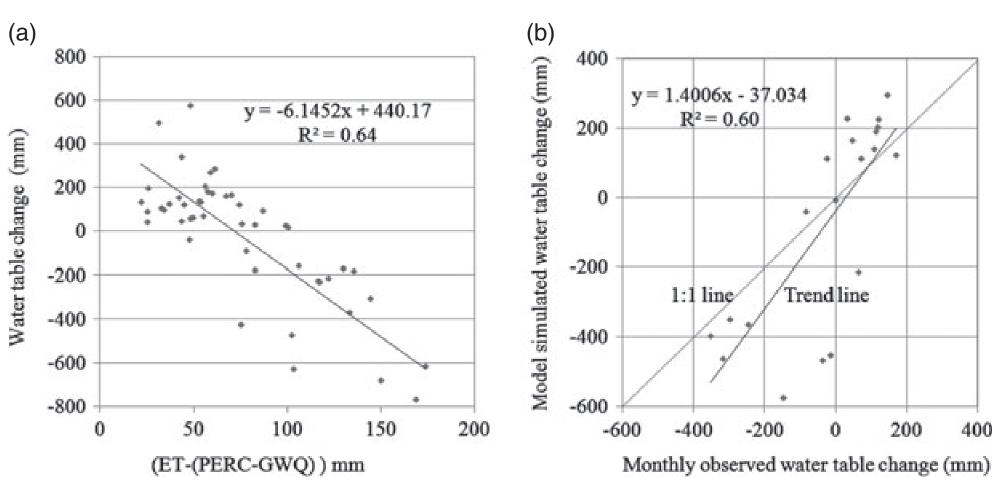

Figure 2. (a) Relationship between model simulated variables (ET − (PERC − GWQ)) with observed monthly water table changes (difference between consecutive months) for the period from 1990 to 1994. (b) Observed vs. simulated water table changes at the Leflore station.

on the hydraulic conductivity of the soil (Jury et al. 1991). The ET rates are higher when the water table is shallow (<1.2 m); deep water tables (3.2 to 4.7 m) correspond to low ET rates (Duell 1990). When depth to the water table increases, the ET rates are decreased exponentially (Nichols 1994). This study showed an opposite trend, and sub-watersheds with deep water tables showed higher annual ET during 2000 to 2009 (Figure 3a and 3b). This trend was observed in two depth categories. The sub-watersheds which have a water table less than 8 m below the land surface (14 sub-watersheds) and water table between 10 and 13 m (10 sub-watersheds) showed a linear relationship with R^2 of 0.62 and 0.5 respectively between depth to the water table and annual ET. The remaining sub-watersheds were not shown to have any relationship between depth to the water table and annual ET rate. Sub-watersheds in which water table levels were more than 10 m below the land surface showed more than 700 mm of ET. Conversely, for those sub-watersheds in which water table levels were between 6 and 10 m, ET was less than 700 mm. This proved that ET rates were not solely governed by the depth to the water table in BSRW, and other crop management practices such as crop, cultivar, tillage, planting dates, and irrigation scheduling may influence the ET rates.

Seasonal ET and Groundwater Consumptions

Long-term differences between average groundwater abstractions for the growing season and model simulated variables (ET − (PERC − GWQ)) for two decades were analyzed; 1990 to 1999 and 2000 to 2009 (Figure 4). This helps to identify the areas of the underlying aquifer where frequent over-abstraction occurs. The zones with values below zero represent good water management or possible recharge during the growing season as a result of influent stream (recharge to the aquifer) or excessive rainfall. The zones with positive values indicate overuse of groundwater or effluent stream (abstraction from aquifer).

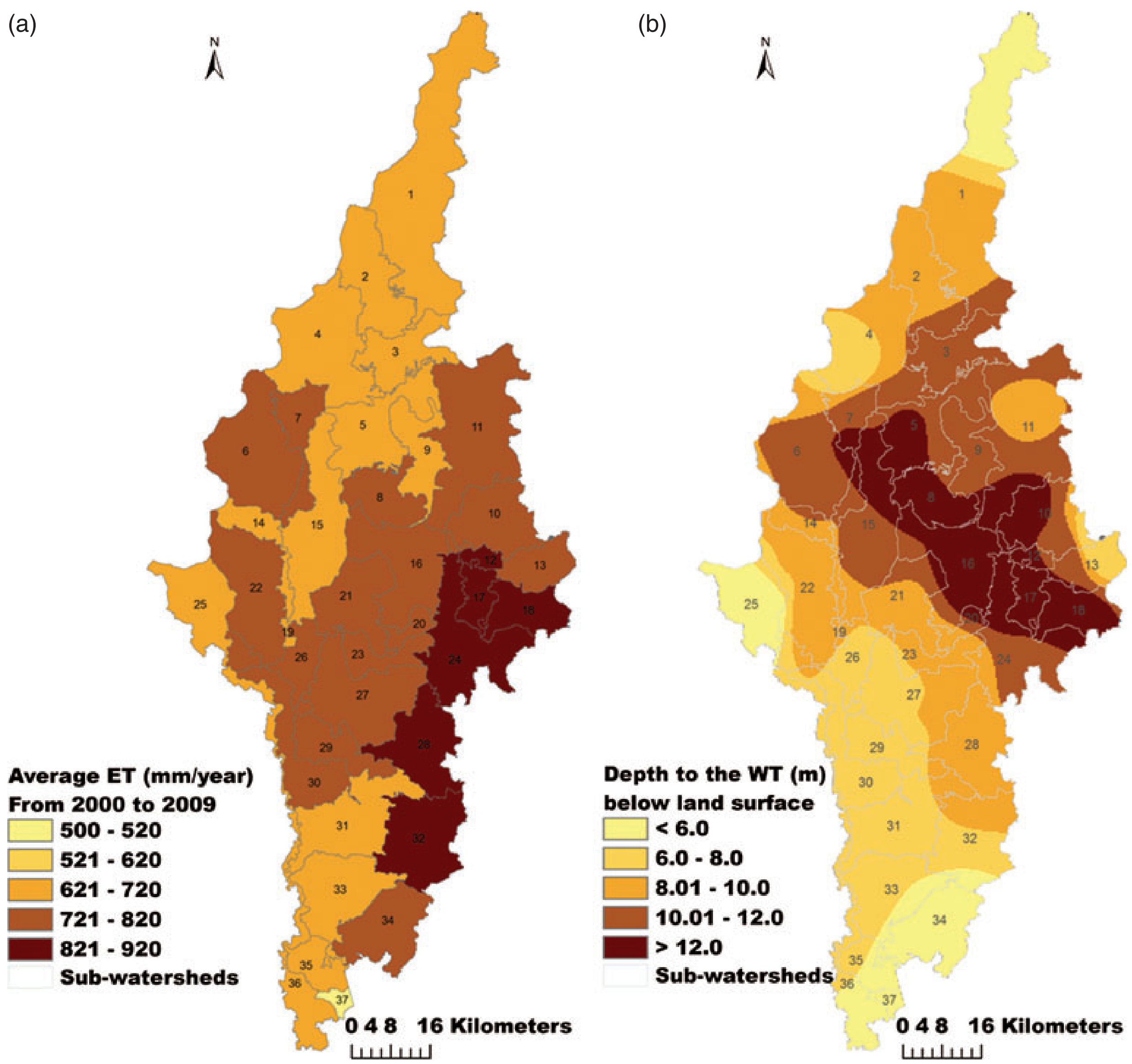

Figure 3. Model simulated average annual ET and average depth to the water table.

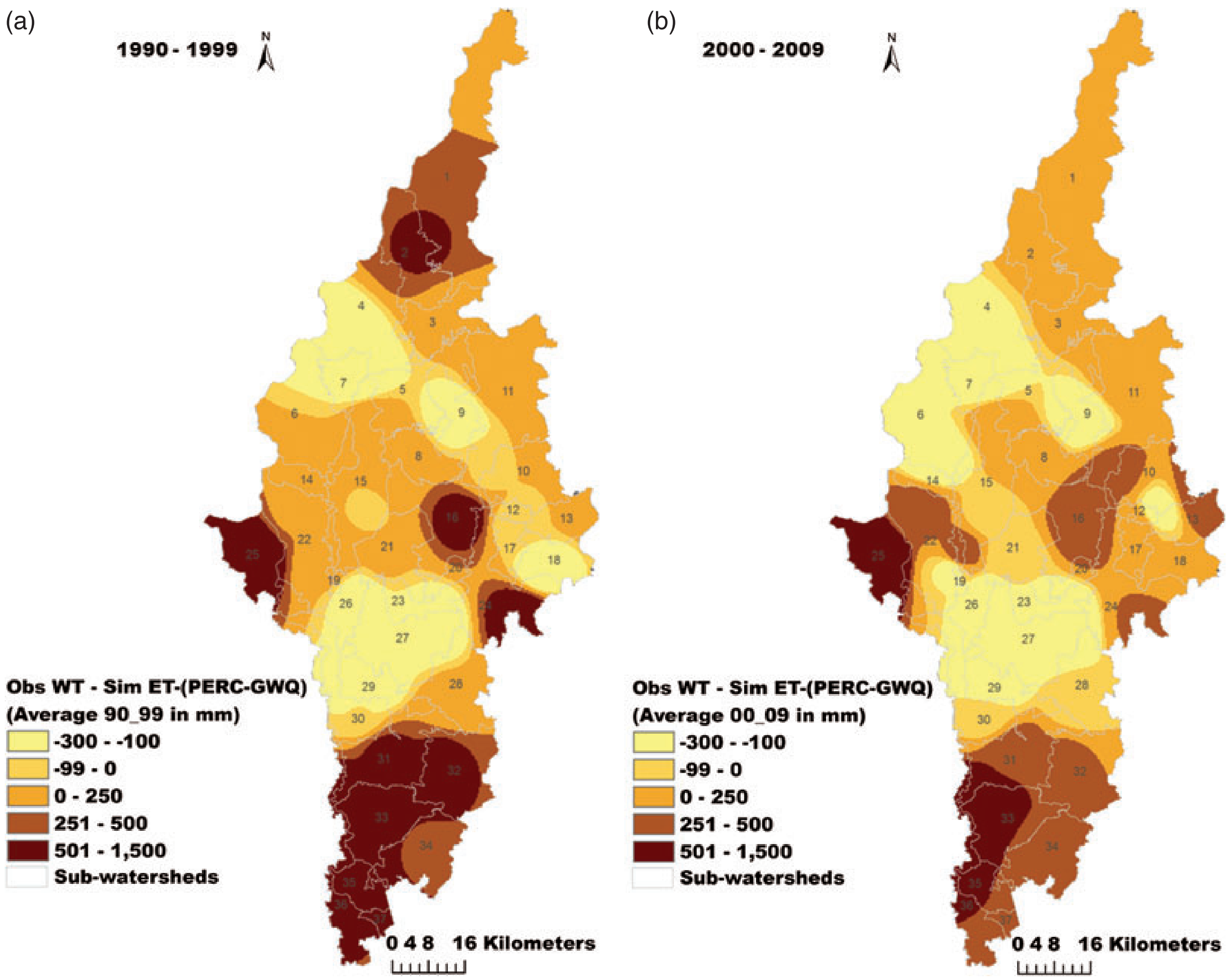

Figure 4. Differences between observed average seasonal water table fluctuations (mm) and model simulated average seasonal variables (ET – (PERC – GWQ)) in millimeters.

Compared with the period from 1990 to 1999, water management from 2000 to 2009 improved. More than 500 mm of groundwater per season was overused in 10 sub-watersheds (2, 16, 24, 25, 31, 32, 33, 35, 36, and 37) from 1990 to 1999, but only 5 sub-watersheds (25, 31, 33, 35, and 36) showed overuse of groundwater during the subsequent decade. Careful investigation of darker areas will help to improve water management and conserve the groundwater resources in the Mississippi Delta.

Groundwater abstractions for irrigation were influenced by crop management activities of farmers. Some farmers may over irrigate their field, while others may under irrigate. On the other hand, variable (ET – (PERC – GWQ)) as calculated by the model was only influenced by climatic forcing, crop types, and field management. We have compared those two (groundwater abstraction and variable [ET – (PERC – GWQ)]) to identify the areas where proper water management occurs. It has been reported that ET-based irrigation scheduling is important for proper water management (Jonghan and Piccinni 2009; Migliaccio et al. 2010). Currently, irrigation applications in the Delta are based on farmer observations. This study proved the inefficiency of such a system to protect the groundwater resources. Field level investigation of causes for the differences may help to improve the Delta water management.

Conclusions

This study demonstrated the use of a modeling tool and water table measurements to identify the areas where over-abstraction of groundwater occurred in Mississippi Delta. Calibrated and validated SWAT model simulations can be used to develop hydrological relationships with observed water table depths. Both hydrological and crop models showed good to very good model performance during calibration and validation. The R^2 and NSE varied from 0.4 to 0.9 respectively during both hydrologic and crop model calibration and validation. This study was able to develop an empirical relationship between groundwater consumption and model simulated ET, percolation, and groundwater movements to the streams. This relationship explains 64% of the water table fluctuations. Variable (ET – (PERC – GWQ)) increases when depth to the water table increases, which is consistent for 24 sub-watersheds. Groundwater abstraction in Mississippi Delta is spatially and temporally changing. Seasonal differences between groundwater abstraction and variable (ET − (PERC − GWQ)) indicate the years of groundwater over-abstraction. Results from this study are useful to develop water management plans to protect groundwater resources of the Mississippi Delta.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Relationships Between Water Table & Model Simulated ET.

Table S1. Soil properties of the study area, averaged over soil textural classes, based on SSURGO databases (USDA 2005).

Table S2. Observed water table changes minus (−) simulated water balance (ET-(PERC-GWQ)) at sub-watershed level.

Figure S1. Groundwater process in SWAT (Neitsch et al. 2005).

Figure S2. Generalized section of the hydrogeologic and geologic units of the study area (after Hart et al. 2008).

Figure S3. Annual monthly cumulative observed and predicted water yield and annual monthly cumulative rainfall for the station. (a) Merigold, (b) Sunflower, and (c) Leland.

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