Journal of Hydrology: Regional Studies 26 (2019) 100631

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Estimating impact of forest land on groundwater recharge in a humid subtropical watershed of the Lower Mississippi River Alluvial Valley

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ARTICLE INFO

Keywords:
Forest land
HSPF
Lower Mississippi River Alluvial Valley
Water recharge

ABSTRACT

Study region: Lower Mississippi River Alluvial Valley (LMRAV) is located in the humid subtropical region of mid-south USA, and Lower Yazoo River Watershed (LYRW) in Mississippi is within the LMRAV.

Study focus: Groundwater depletion due to anthropogenic activities is an issue of water resource concern in the LMRAV. Some studies suggested that forest lands reduce water recharge from land surface into aquifers as compared to agricultural lands. However, very few efforts have been devoted to investigating the relationship of water recharge and land use in the LMRAV. This study was designed to meet this need.

New hydrological insights for the region: Using the HSPF (Hydrological Simulation Program-FORTRAN) model along with the LYRW, we found that the annual average water recharge from the land surface into the deep aquifer over the 10-year simulation period for the three land uses was: agriculture < forest < wetland. Only 1.1, 1.2, and 1.4% of the precipitation water from the agriculture, forest, and wetland, respectively, recharged into the deep aquifer in the LYRW. Results demonstrated that forest land slightly increased rather than reduced water recharge from the land surface into the groundwater as compared to that of the agricultural land. These finding could change the traditional scientific view on how forests affect water recharge into groundwater in the humid subtropical region around the world.

1. Introduction

Groundwater depletion is a long-term water level decline due to the agricultural, domestic, and industrial water usages. Today many regions of the United States and the world are experiencing depletion of groundwater resources (Konikow, 2013; Doll et al., 2014). This is also true in the Lower Mississippi River Alluvial Valley (LMRAV), which is located in the floodplain of the Mississippi

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https://doi.org/10.1016/j.ejrh.2019.100631
Received 11 December 2018; Received in revised form 28 September 2019; Accepted 30 September 2019
Available online 17 October 2019

River and encompasses seven states (*i.e.*, Illinois, Missouri, Kentucky, Arkansas, Tennessee, Mississippi, and Louisiana). The desire by farmers to increase crop yields through irrigation has led to the overdraft of groundwater resources in the LMRAV (Ouyang et al., 2018a). From 1987 to 2014 the average loss of groundwater in the Mississippi Delta of the LMRAV is estimated to be about 493,000,000 m^3/y and has resulted in more than 7 m decline in groundwater level (Clark and Hart, 2009; YMD, 2015). To mitigate groundwater resource depletion in the LMRAV, management alternatives have been implemented including the construction of on-farm water storage ponds for irrigation (Ouyang et al., 2018a), the development of optimal irrigation strategies (Kebede et al., 2014), and the conversion of marginal agricultural lands into forests or afforestation (Stanturf et al., 1998; Ouyang et al., 2013).

Afforestation is the process of planting trees on a treeless lands to create a forest, which plays an integral role in sustaining water resources, protecting water quality, and attenuating river floods. More specifically, afforestation can absorb rainwater, disperse surface runoff, purify pollutant, and thereby reduce pollutant load into the rivers and streams and producing clean water (Ouyang et al., 2013). While afforestation on marginal agricultural lands in the LMRAV has advantages on reducing sediment erosion and nutrient load into streams, increasing forest areas, and mitigating groundwater depletion, numerous studies reported that forests reduce groundwater recharge (Allison et al., 1990; Favreau et al., 2002; Farley et al., 2005; Zhang and Schilling, 2006; Smerdon et al., 2009; Owuor et al., 2016; Adane et al., 2018). For instance, Allison et al. (1990) studied the land clearance and river salinization in the Western Murray Basin, a semi-arid region of southern Australia. Using the simple unsaturated chloride mass balance approach, these authors found that conversion of native vegetation to agricultural land increases groundwater recharge. Likewise, Favreau et al. (2002) investigated the groundwater recharge in a semi-arid southwest region of Niger using the isotope analysis and a simple model. They found that the conversion of native vegetation to agricultural land increased groundwater recharge by an order of magnitude. Zhang and Schilling (2006) argued that changing land cover from perennial vegetation to seasonal row crops would result in an increase in groundwater recharge and baseflow based on a study from Iowa, USA by Dinnes (2004). Owuor et al. (2016) reviewed the effects of land use and land cover on groundwater recharge in the semi-arid tropical and subtropical regions, and found that forests have lower groundwater recharges in the semi-arid tropical and subtropical regions. Adane et al. (2018) investigated the impact of grassland conversion to forests on groundwater recharge rate in the Nebraska Sand Hills using the HYDRUS 1-D model to simulate two plots, one representing grasslands and the other dense pine forest conditions. They found that the overall reduction of groundwater recharge rate for this conversion is nearly 17%. Scanlon et al. (2002) reviewed the global impacts of conversions of native vegetation into agricultural land on water quality and quantity and argued that increases in rain-fed cropland and pastureland during the past 300 years from forest lands decreased evapotranspiration (ET) and increased recharge (two orders of magnitude) and streamflow (one order of magnitude). In contrast, Ilstedt et al. (2016) developed an optimum tree cover theory and applied to a cultivated woodland in West Africa. These authors found that groundwater recharge is maximized or increased at the intermediate tree densities. In addition, Migliavacca et al. (2009) and Tricker et al. (2009) found that the water use of lands with poplars is similar to that of agricultural lands and grasslands. In general, these mixed results suggest that groundwater recharge in forest lands and that tree planting in the semi-arid regions are discouraged because of reducing groundwater resources. However, the effect of afforestation on groundwater recharge in the humid-subtropical region, especially in the LMRAV, remains relatively unexplored.

Because of the increasing groundwater depletion in the LMRAV and the conversion of marginal agricultural lands to forest lands, an understanding the effect of forest land on groundwater recharge is needed. Currently, little to no effort has been devoted to estimating water recharge from forest lands for the LMRAV. Since a direct measurement of water recharge is challenging, a modeling approach is employed in this study. The goal of this study was to assess water recharge from three land uses—agricultural land, forest land, and wetland—in the LMRAV using the HSPF (Hydrological Simulation Program-FORTRAN) model. Our specific objectives were to: (1) develop an HSPF model for the Lower Yazoo River Watershed (LYRW), a local watershed in the LMRAV; (2) calibrate and validate the model with field-observed data; and (3) apply the model to estimate the amount of water from land surface and vadose zone recharges into groundwater for the respective land uses.

2. Materials and methods

2.1. Study site, HSPF model, and data acquisition

The LYRW was selected as the study area because it represented a typical watershed in the LMRAV. The watershed is 618 km^2 in size, consists of 61% forest land, 31% agriculture land, and 4% of wetland, and located in the humid subtropical region of the LMRAV (Fig. 1). The watershed is a highly productive agricultural area (MDEQ, 2008; Ouyang et al., 2018b) containing these major soil types: sand, loam, and clay.

HSPF is a watershed model developed by the U.S. Environmental Protection Agency (US-EPA) to simulate hydrologic processes and water quality. A detailed description of the HSPF model can be found elsewhere (Bicknell et al., 2001; https://www.epa.gov/ceam/hydrological-simulation-program-fortran-hspf). However, an overview is provided to familiarize the reader with the model and its components.

A schematic diagram illustrates the metrics, processes, and their linkages used in the HSPF model (Fig. 2). Precipitation is the principal driver of the model. Initially, it is intercepted by vegetation and other objects before falling to the ground or being evaporated. Once on the ground surface, multiple pathways exist for water movement. Subsequently only a small portion of precipitation actually recharges groundwater through infiltration, percolation, and lateral interflow, which are quantified in the subroutine LZONE. Processes are site-specific and depend on topography, land use/land cover, soil type, and geographical location. All of these watershed conditions are parameterized in HSPF.

We use LZONE to determine the quantity of infiltrated and percolated water which enters the lower soil zone. The fraction of

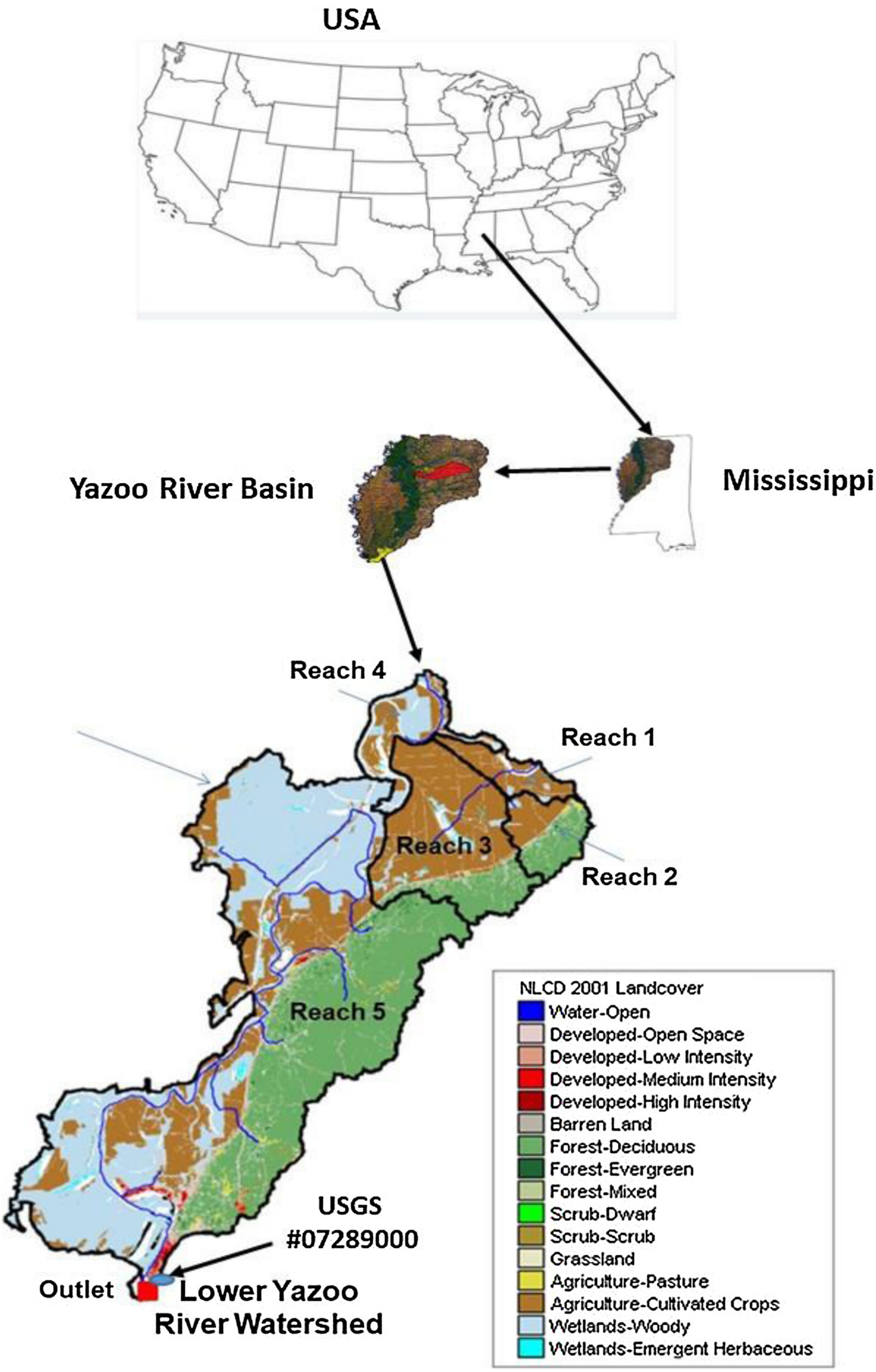

Fig. 1. Locations of Lower Mississippi River Alluvial Valley and Lower Yazoo River watershed used in this study.

water inflow into the lower soil zone is the sum of infiltration, percolation and lateral interflow, which is determined empirically by (as described in the HSPF Users' Manual):

$$\mathrm{LZFRAC} = 1.0 - \mathrm{LZRAT}(1.0/(1.0 + \mathrm{INDX}))^{\mathrm{INDX}} \tag{1}$$

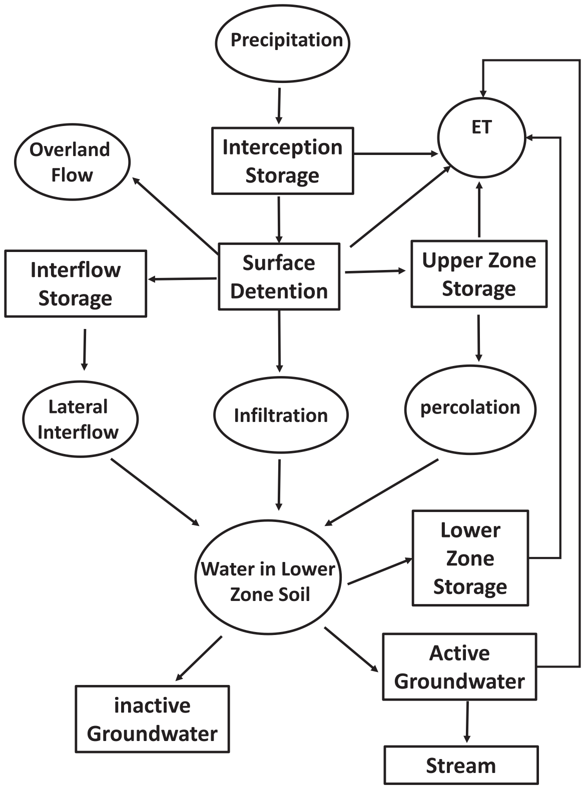

Fig. 2. A schematic diagram showing the processes on how the precipitation recharges into the groundwater through soil infiltration, percolation, and lateral interflow used in the HSPF model.

with

$$LZRAT = LZS/LZSN \tag{2}$$

and

$$INDX = 1.5ABS(LZRAT - 1.0) + 1.0 \tag{3}$$

where LZFRAC is the fraction of water stored in the lower soil zone due to infiltration, percolation and lateral interflow, LZS is the lower zone storage, LZSN is the lower zone nominal capacity, and ABS is the function for determining absolute value. The difference between the amounts of soil water supplies (i.e., precipitation and irrigation) and the amounts of water from runoff, ET, and upper zone and lower zone storages is the groundwater storage in either active zone or inactive zone.

The subroutine GWATER in HSPF is used to determine the amount of water outflow from the active zone (or groundwater baseflow) and the amount of water inflow into the inactive zone (deep aquifer). The active zone groundwater outflow (or baseflow) is estimated by:

$$AGWO = KGW(1.0 + KVARY \times GWVS)AGWS \tag{4}$$

where AGWO is the active groundwater outflow (baseflow), KGW is the coefficient for groundwater baseflow recession, KVARY is the coefficient characterizing nonlinear relationship between active groundwater storage and its baseflow, GWVS is the index to groundwater slope, and AGWS is the initial active groundwater storage. The fraction of the groundwater inflow into the inactive aquifer is determined by the parameter DEEPER (Table 1). Detailed explanations of the parameters in Eq. (4) and DEEPER can be found in the HSPF Users' Manual.

In HSPF model, the land-use editor enables users to modify or convert one land use to the other within different catchments. This editor enables us to convert agricultural lands into forest lands (i.e., afforestation) or *vice versa*. In addition, there are several input parameters such as FOREST, AGWRC, INFILT, BASETP, AGWETP, CEPSC, and LZETP in the PWATER modular, which can be used to adjust ET under different land uses and land covers (Table 1). It should be noted that effects of land uses such as agricultural land, forest land, and wetland on surface and ground (to a small degree) water hydrology in HSPF are simulated by its PERLND (pervious land segment) module. This module groups the same land use (e.g., wetland) into a land segment and then calculates the hydrological processes and water budget. An elaborate description of the calculations can be found in HSPF Users' Manual.

Other input data for land use, soil type, topography, precipitation, air temperature, solar radiation, stream network, and discharge

Table 1
Input parameter values from model calibration as well as pertaining to land uses and groundwater recharge in HSPF model.

Parameter	Variable definition	Agricultural Land	Barren Land	Forest Land	Urban or Built-up	Wetlands/Water	Reference
PWAT-PARM2 (Second group of PWATER Parameters)							
FOREST	Fraction of land covered by forest	0.05	0.01	0.9	0.1	0.3	Based on LYRW observation
LZSN	Lower zone nominal storage	4	4	6	7	8	Calibrated; US-EPA, 2000
AGWRC	Basic groundwater recession rate (1/day)	0.96	0.96	0.98	0.96	0.97	US-EPA, 2000
INFILT	An index to the infiltration capacity of the soil	0.68	0.1	0.88	0.05	0.77	US-EPA, 2000
PWAT-PARM3 (Third group of PWATER Parameters)							
BASETP	Fraction of remaining potential E-T which can be satisfied from baseflow	0.03	0.01	0.1	0.01	0.07	Calibrated; US-EPA, 2000
AGWETP	Fraction of remaining potential E-T which can be satisfied from active groundwater storage	0.01	0.01	0.1	0.01	0.1	US-EPA, 2000
DEEPER	Fraction of the groundwater inflow into the inactive (or deep) aquifer	0.05	0.05	0.05	0.05	0.05	Calibrated and based on Clark and Hart, 2009
PWAT-PARM4 (Fourth group of PWATER Parameters)							
CEPSC	Interception storage capacity	0.1	0.01	0.18	0.01	0.1	US-EPA, 2000
LZETP	Lower zone ET and an index to the density of deep-rooted vegetation	0.6	0.3	0.7	0.4	0.8	US-EPA, 2000
ICR	Interflow recession parameter (1/day)	0.3	0.3	0.3	0.3	0.3	Calibrated; US-EPA, 2000
UZSN	(upper zone nominal storage (inch)	0.5	0.2	0.4	0.2	0.6	Calibrated; US-EPA, 2000

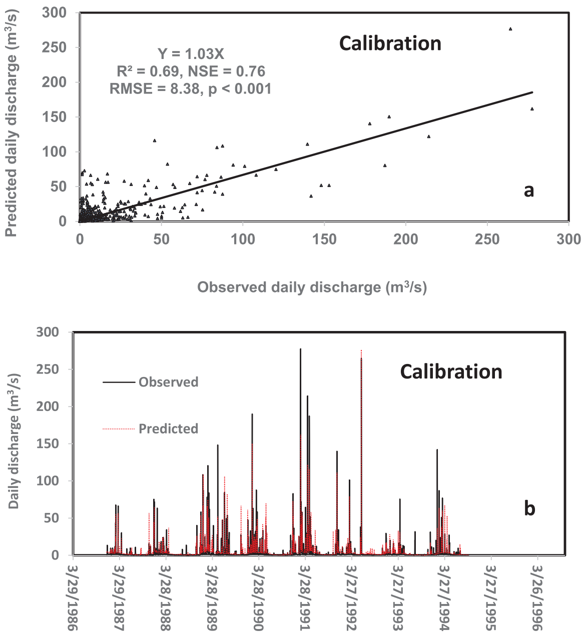

Fig. 3. Comparison of the observed and predicted daily discharge during model calibration.

were obtained from the National Hydrography Dataset, US Geologic Survey (USGS) National Water Information System, and the 2001 National Land Cover Data. These data were downloaded from the Metadata Section of BASINS.

2.2. Model calibration, validation, and scenario

Model calibration was adjusted to input parameters' values within a reasonable range until the model predictions match the field observations. In this study, the following five input parameters' values were adjusted during the model calibration: LZSN, BASETP, DEEPER, ICR, and UZSN (Table 1). These parameters were selected because they are most sensitive to the HSPF model predictions (Donogian et al., 1984). Because very few observed discharge data were available at the LYRW outlet for model calibration we used the observed data collected around the watershed outlet and recalculated the data to represent the average LYRW conditions. More specifically, the observed data from the nearby USGS (e.g., #07289000 at Vicksburg, MS) and Army Corps of Engineer monitoring stations (http://rivergages.mvr.usace.army.mil/WaterControl/new/layout.cfm) were selected and were further aggregated and/or disaggregated to better represent the watershed average conditions.

Fig. 3 compared the observed and predicted daily stream discharges for the period from 1987 to 1995 during the model calibration. As the values of R^2, NSE (Nash-Sutcliffe Efficiency), RMSE were 0.69, 0.68, 8.38 m^3/s, respectively, and $p < 0.001$ (Fig. 3a), a good agreement was gained between the model predictions and the field observations. The goodness-of-fit was also estimated graphically by comparing the peaks and valleys of daily discharge (Fig. 3b). The daily peaks and valleys from the model predictions matched reasonably well visually with the field observations during the model calibration.

Model validation was verified by comparing the model predictions with another independent set of field observations. During the model validation, none of the input parameters' values used during the model calibration were modified. Fig. 4 shows the observed and predicted daily stream discharges for the period from 1994 to 2002 during the model validation. The values of R^2, NSE, and RMSE were 0.65, 0.82, 5.64 m^3/s, respectively, and $p < 0.001$ (Fig. 4a), indicated a reasonable agreement between the model predictions and field observations. Fig. 4b further revealed that the daily peaks and valleys from the model predictions matched reasonably well with the field observations visually during the model validation.

We developed a simulation scenario to compare how much water from the land surface recharged into the underlying groundwater in the agricultural land, forest land, and wetland over the 10-year simulation period from 2000 to 2009 at the LYRW. The input data used in this scenario were the same as those used for model validation above except for climate data. The values of the key input parameters pertaining to the groundwater recharge calculation in the HSPF model are given in Table 1.

3. Results and discussion

3.1. Daily processes

Daily changes in measured precipitation, simulated surface water runoff, and precipitation interception among the three land uses (*i.e.*, agriculture, forest, and wetland) over the 10-year (2000–2009) simulation period are shown in Fig. 5. In general, the peaks of

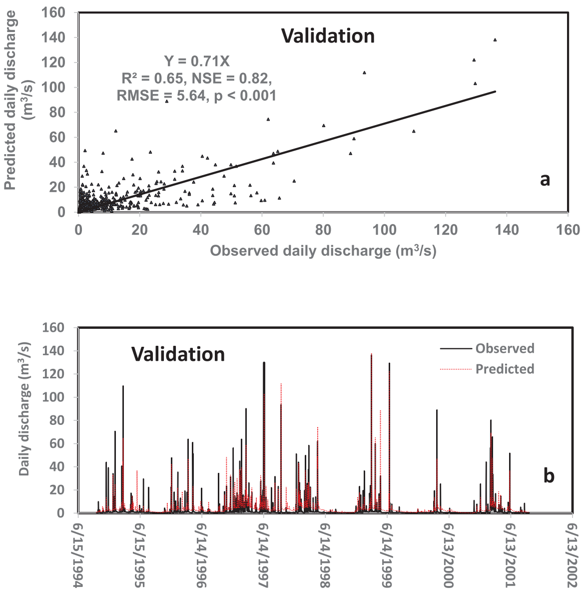

Fig. 4. Comparison of the observed and predicted daily discharge during model validation.

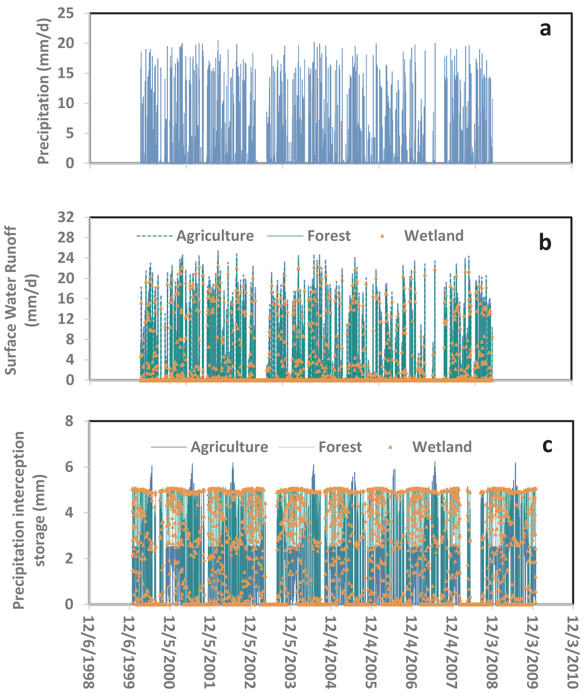

Fig. 5. Daily precipitation, surface runoff, and precipitation interception during the 10-year simulation period from 2000 to 2009.

surface water runoff corresponded very well with those of precipitation among the three land uses with an increase in precipitation normally increasing surface water runoff. For example, the rates of precipitation were 20.52 and 29.97 mm/d on May 12, 2009 and May 14, 2008, respectively, while the rates of surface runoff from the agricultural land were 15.52 and 23.39 mm/d for those two days, respectively. A 46% increase in the rate of precipitation resulted in an increase in the rate of surface runoff from agricultural land by 51%. There was more water loss from surface runoff in the agricultural land than in the forest land and wetland (Fig. 5b). The rates of surface water runoff were 14.6 mm/d in the agricultural land, 13.3 mm/d in the forest land, and 12.1 in the wetland on June 27, 2004. Overall, the rate of surface runoff was: agriculture > forest > wetland. This ranking occurred because the agricultural land was covered by crops primarily during the growing season, whereas the forest and wetland were covered by trees, herbaceous vegetation, grasses, and organic matter (*e.g.*, recently fallen organic material, litter layer, and humus) the entire year, which mitigated surface water runoff. In addition, wetlands typically reduced surface water runoff since they were normally located in lower

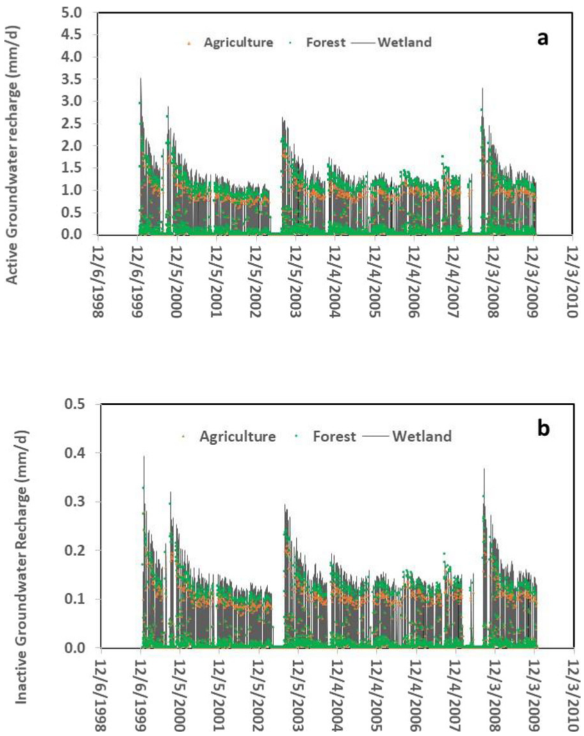

Fig. 6. Daily active and inactive groundwater recharges during the 10-year simulation period from 2000 to 2009.

topographic land with a lower relief and greater surface storage than typically exhibited by the other land uses and therefore reduced surface water runoff.

In contrast, the daily precipitation interception was lower in the agricultural land than in the forest land and wetland. However, a distinct pattern in precipitation interception was observed in the agricultural land. That is, the highest daily precipitation interception was found in the agricultural land during earlier summer for most of the years (Fig. 5c). For instance, the daily precipitation interceptions were 1.55 mm in the agricultural land, 4.11 mm in the forest land, and 4.17 mm in the wetland on December 29, 2000. By comparison, the daily precipitation interceptions were 6.05 mm in the agricultural land and 4.90 mm in both the forest land and wetland on June 28, 2000. These seasonal discrepancies in precipitation interception among the three land uses occurred because of the seasonal changes in the agricultural land. Most of the agricultural lands in Mississippi were heavily covered by crops during early summer and thereby intercepted more precipitation during this period. In addition, the daily precipitation interception was somewhat larger in the wetland than in the forest land (Fig. 5).

Daily variations in simulated active and inactive groundwater recharges varied among the three land uses over the 10-year (2000–2009) simulation period (Fig. 6). In HSPF model, water recharges into active groundwater (or baseflow) can be outflowed into streams and loss to the atmosphere through ET, whereas water recharges into inactive groundwater is stored in the deep aquifers. In general, daily active groundwater recharge was low in the agricultural land and high in the wetland (Fig. 6a). For example, the rates of daily active groundwater recharge on August 22, 2008 were 2.39, 2.79, and 3.30 mm/d in the agricultural land, forest land, and wetland, respectively. This finding was consistent with the general consensus that wetland and grassland increase groundwater recharge as compared to that of agricultural and forest lands but contradicted other studies that reported agricultural land has more groundwater recharge than forest land (Zhang and Schilling, 2006; Owuor et al., 2016). Zhang and Schilling (2006) concluded that conversion of perennial vegetation to seasonal row crops would result in increasing groundwater recharge. The conclusion is drawn based on the studies in Iowa, USA (Schilling and Libra, 2003; Dinnes, 2004) that the annual water loss from ET is generally smaller in crop land than in forest land (although how the annual soil evaporation was estimated during the non-growing season was not elaborated in their studies). However, groundwater recharge is not only dependent on ET but also on watershed hydrogeological conditions. In addition, Iowa is located in the Midwest climate region, whereas the LYRW is the located in humid-subtropical region. Owuor et al. (2016) reviewed the impacts of pre- and post-land use changes on groundwater recharge in semi-arid environment and concluded that conversion of forest land to crop land increases groundwater recharge by 3.4%. Their conclusion is primarily based on the study reported by Allison et al. (1990), who estimated groundwater recharge rate after clearing of native vegetation in a semi-arid region of southern Australia. These authors estimated groundwater recharge using chloride mass balance approach in the unsaturated soil zone with the assumption that surface water runoff is negligible. This approach would not be appropriated because several hydrological processes such as surface water runoff, soil water interflow, and ET from vegetation interception and land surface, were not included. We attributed the discrepancies between our finding and the one from Allison et al. (1990) to the following two reasons: (1) our study was focused on a humid subtropical region, while Allison and other's study was for a semi-arid region; and (2) our finding was based on more hydrological processes included in the modeling. Additionally, there was more precipitation available for groundwater recharge in the humid subtropical region than in the semi-arid region.

Several factors affected daily active groundwater recharge among the three land uses (Fig. 2). These factors included surface water runoff (over land flow), precipitation interception, interflow storage and lateral interflow, and ET from precipitation interception, surface detention, upper zone soil, and lower zone soil. Under normal conditions in the humid subtropical region, forest lands record less surface runoff than agricultural lands because of contiguous vegetation cover and the presence of ground litter the entire year Agricultural lands were under crops only during the growing season. In addition, forest land has less surface evaporation than agricultural land because forest land has lower soil surface temperature than agricultural land. Soil surface temperature was one of the driving forces for surface evaporation. In addition, more soil water losses to the atmosphere occurred in forest land than in agricultural land due to leaf transpiration. Groundwater recharge differences between agricultural land and forest land depended also on such factors as geographical locations, watershed conditions, and tree and crop species.

Active groundwater discharge (or baseflow) need to be calibrated to obtain more accurate simulation results on deep groundwater recharge. Although no measured baseflow data were available at the LYRW, we found the baseflow estimations within the LMRAV near the LYRW by USGS (Killian and Asquith, 2019). The minimum, mean, and maximum values of the basesflows estimated by these authors were, respectively, 0.0, 1.24, and 3.3 mm/d from 2000 to 2009, while the minimum, mean, and maximum values of the basesflows predicted by our simulations were, respectively, 0.0, 0.92, and 3.5 mm/d for the same time period. Results revealed that our predicted baseflows (or active groundwater recharge) agreed well with those reported by Killian and Asquith (2019).

Similar results were obtained for the inactive groundwater recharge. That is, the daily inactive groundwater recharge was low in the agricultural land and high in the wetland (Fig. 6b). What deserves further investigation was the difference between the active and inactive groundwater recharges. More specifically, the active groundwater recharge was one order of magnitude larger than that of inactive groundwater recharge. For instance, the active and inactive groundwater recharges were 0.79 and 0.08 mm in forest land on May 16, 2004, respectively. The former was about 10 times larger than the latter. Results indicated that the rate of groundwater recharge into the deep aquifer in this watershed was very small. This was attributed to the deep aquifer, which is about 50 m below the ground surface and the presence of a thick clay layer (Clark and Hart, 2009; Dyer et al., 2015).

3.2. Annual processes

Annual variations in measured precipitation and simulated surface runoff and total ET among the three land uses over the 10-year (2000–2009) simulation period are shown in Fig. 7. Similar to daily surface runoff, the order of annual surface runoff was: agriculture > forest > wetland (Fig. 7b). This was attributed to the same reasons as for the case of daily surface runoff discussed in the previous section.

Unlike the case of daily surface runoff, an increase in annual precipitation did not always lead to an increase in annual surface runoff (Fig. 7a and b). For example, the annual precipitations on agricultural land were 526 and 1326 mm, respectively, in 2007 and

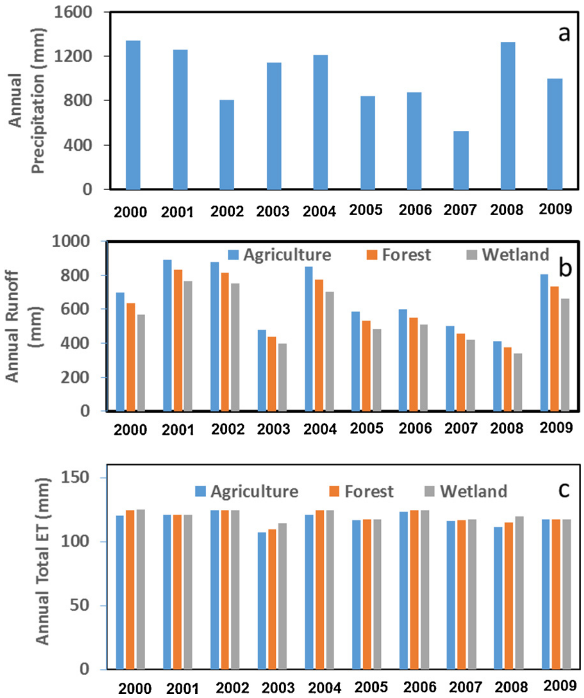

Fig. 7. Annual precipitation, surface runoff, and total ET during the 10-year simulation period from 2000 to 2009.

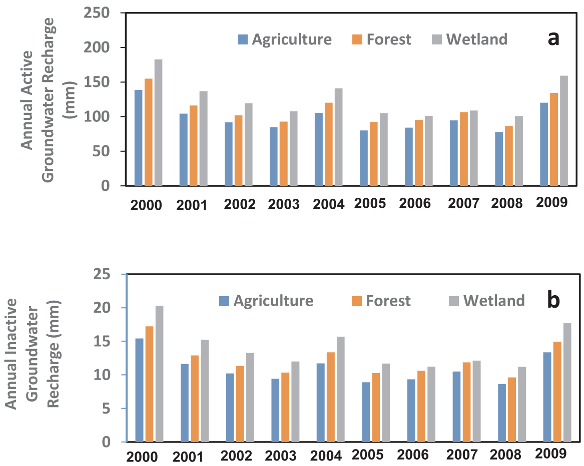

Fig. 8. Annual active and inactive groundwater recharges during the 10-year simulation period from 2000 to 2009.

2008 (Fig. 7a), while the annual surface runoffs from the same agricultural land were 510 and 412 mm, respectively, for those two years (Fig. 7b). A 2.5-fold increase in the annual precipitation decreased the annual surface runoff by 19%. Apparently, the annual surface runoff depended not only on the annual precipitation but also on the antecedent watershed conditions. If the antecedent soil water content was low due to the low precipitation from the previous years, an increase in annual precipitation in the current year did not increase surface runoff. Because more waters was needed to alleviate soil moisture deficiency, surface runoff occurred only when the soil surface was saturated and the surface water ponding follows.

There were only slightly differences in annual total ET among the three land uses with somewhat less ET from agricultural land in certain years (Fig. 7c). In the HSPF model, the total ET included the ETs from interception storage, surface detention, upper soil zone, lower soil zone, and active (shallow) groundwater. In general, the annual ET from the upper soil zone was high in agricultural land because the soil surface evaporation was high during the non-growing season, whereas the annual ET from the low soil zone was high in forest land because the tree root water uptake occurred in this zone (data not shown).

Variations in simulated annual active and inactive groundwater recharges varied among the three land uses over the 10-year (2000–2009) simulation period (Fig. 8). In general, the annual active (shallow) groundwater recharge was low in the agricultural land and high in the wetland with the forest land in-between (Fig. 8a). For example, the annual active groundwater recharges in 2004 were 105, 120, and 141 mm, in agricultural lands, forest lands, and wetlands respectively. Under the normal conditions in this humid-subtropical region, less surface runoff and more soil water reservation occurred in the forest land than in the agricultural land. As previously stated, forest land was covered by trees, grasses and soil organic matter year-round, while the agricultural land was covered by crops only during the growing season. In addition, the forest land had less surface evaporation than the agricultural land because of the lower soil surface temperatures in forest lands. Soil surface temperature is a driving force for surface evaporation and is usually lower in the forest land than in the agricultural land. Water in active groundwater was lost to the atmosphere through ET or outflowed into the streams. Also, more water loss occurred in the forest land than in the agricultural land due to the leaf water transpiration. Overall, the groundwater recharge for a given soil type depended not only on surface runoff and ET but also on vegetative coverage (type, degree and seasonality), stage of organic matter-mediated soil structure, and topography. All of which influenced soil water infiltration, percolation, and lateral interflow.

Similar results were obtained for the inactive groundwater recharge. That is, the annual inactive groundwater recharge was low in agricultural land and high in wetland (Fig. 8b). Comparison of annual active and inactive groundwater recharges among the three land uses, however, revealed that the amount of inactive groundwater recharge was one order of magnitude lower than that of active groundwater recharge (Fig. 8a and b). Water in inactive groundwater was stored in the deep aquifer that is normally used for crop irrigation in Mississippi. An annual groundwater recharge of 20 mm or less (Fig. 8b) was the case for all of the three land uses, which was very small in the LYRW.

3.3. Precipitation and recharge

Annual average precipitation, surface runoff, total ET, and water recharge into active and inactive groundwater over the 10-year period and their percentages based on precipitation varied among the three land uses (Table 2). The average annual surface runoff was high (669.8 mm) in the agricultural land but was low (559.82 mm) in the wetland. About 64.92, 59.5, and 54.26% of the precipitation were lost to surface runoff from the agricultural land, forest land, and wetland, respectively. Results indicated that more precipitation water was runoff in the agricultural land because this land was not covered during the non-growing season. Little differences in annual average total ET existed among the three land uses, demonstrating that land uses had minimal effects on total ET in this watershed. As discussed in Section 3.1 above, our findings were opposite to those reported by Zhang and Schilling (2006) and Owuor et al. (2016). We attributed the discrepancies to the differences in climatic settings at different regions and the approaches

Table 2
Precipitation, surface runoff, total ET, and active and inactive groundwater recharges over a 10-year simulation period.

Parameter	Annual Average (mm)	% Based on precipitation	Annual Average (mm)	% Based on precipitation	Annual Average (mm)	% Based on precipitation
Land use	Agriculture		Forest		Wetland	
Precipitation	1031.75		1031.75		1031.75	
Runoff	669.80	64.92	613.92	59.50	559.82	54.26
Total ET	117.88	11.43	119.41	11.57	120.47	11.68
Active groundwater recharge	98.17	9.52	110.13	10.67	126.31	12.24
Inactive groundwater recharge	10.91	1.06	12.24	1.19	14.03	1.36

used in calculation of groundwater recharge. In this study, we were focused on the humid subtropical region, whereas the cited researchers were focused on the semi-arid region. Additionally, we have included more hydrological processes for the calculation of groundwater recharge than the cited researchers.

Only a small portion of precipitation contributed to the inactive (or deep aquifer) groundwater recharge (Table 2). More specifically, only 1.06, 1.19, and 1.36% of precipitation from the agricultural land, forest land, and wetland, respectively, entered into the deep aquifer in this watershed. Although the exact reasons for this phenomenon needs to be investigated, a possible explanation was that the aquifer is deep (about 50 m) and has a thick clay layer (Clark and Hart, 2009; Dyer et al., 2015). Other hydrological processes such as stream inflow and outflow were not included in this discussion because they were beyond the scope of this study. In the HSPF model, the water balance was automatically checked at each time step of a run resulting in balanced water budget for the study.

3.4. Sensitivity analysis

When insufficient measured data to calibrate and validate the important simulation results exist, sensitivity analyses of the model simulations to input parameters need to be conducted. In this study, we used three input parameters—AGWRC, INFILT, and ICR—(see Table 1 for their definitions), for the sensitivity analysis. These parameters were highly related to the groundwater recharge estimation, which was the major purpose of this study. Simulations were conducted by varying the values of the three input parameters for the agricultural and forest lands (Table 3). Results show that the decreases of AGWRC by 20 and 40% from the base value in the forest land increased the average annual groundwater recharges by 1.3 and 1.35%, respectively. Apparently, AGWRC (or the basic groundwater recession rate) was slightly sensitive to groundwater recharge estimation. A much less sensitivity was obtained for the agricultural land. That is, the decreases of AGWRC by 20 and 40% from the base value in the agricultural land only increased the average annual groundwater recharges by 0.4 and 0.44%, respectively (Table 3). Our simulation further revealed that ICR (or interflow recession parameter) was not sensitive to groundwater recharge in both the agricultural and forest lands by either increased or decreased the base ICR value by 20% (Table 3).

By comparison, increasing the INFILT 20% from the base value in the forest and agricultural lands, the average annual groundwater recharges were 14.05% and 12.17% higher, respectively. Result demonstrated that INFILT (or an index to the infiltration capacity of the soil) was highly sensitive the groundwater recharge estimation. This was reasonable because soil water infiltration is a major pathway for water recharge into groundwater. These results point to the need for field measurement of soil water infiltration rate so that more accurate model simulations can be obtained.

4. Conclusions

Modeling study suggested that the effects of land uses on daily and annual surface water runoff were: agriculture > forest > wetland. This could occur because the agricultural land was only covered by crops during the growing season, whereas the forest land and wetland were covered by trees, scrubs and herbaceous vegetation, litter, grasses, and other organic materials year round, which mitigated surface water runoff.

Our simulation also showed that daily precipitation interception was, in general, less in the agricultural land than in the forest land and wetland. The maximum daily precipitation interception was observed in the agricultural land during early summer in comparison to the forest land and wetland rest of the year because of the densely crop cover.

Unlike the case of daily surface runoff, an increase in annual precipitation did not always increase the annual surface runoff. In other words, the annual surface runoff depended not only on the annual precipitation but also on the antecedent watershed conditions. If the antecedent soil water content was low due to the low precipitation from the previous years, an increase in annual precipitation in the current year would not necessarily increase surface runoff due to the soil water deficient conditions.

In general, the annual active (baseflow) and inactive (deep) groundwater recharges were less in the agricultural land than in the forest land. This finding was opposite to others' observations that forest land reduces groundwater recharge more than agricultural land. We attributed the discrepancies to the different climate regions (humid-subtropical versus semi-arid) and approaches used in the groundwater recharge calculation (inclusion of more detailed hydrological processes versus not).

Our modeling study further revealed that the amount of inactive groundwater recharge was one order of magnitude lower than

Table 3
Sensitivity analysis of three key input parameters (*i.e.*, AGWRC, INFILT, and ICR) to deep groundwater recharge in agricultural and forest lands.

Year	AGWRC					INFILT					ICR				
	Base (AGWRC = 0.98)	AGWRC decreased by 20%	Difference from Base (%)	AGWRC decreased by 40%	Difference from Base (%)	Base (INFILT = 0.88	INFILT decreased by 20%	Difference from Base (%)	INFILT increased by 20%	Difference from Base (%)	Base (IRC = 0.3)	IRC decreased by 20%	Difference from Base (%)	ICR increased by 20%	Difference from Base (%)
Annual Groundwater Recharge in Forest Land (mm)															
2000	16.46	16.46	0.00	16.46	0.00	16.46	14.5542	−11.57	18.14	10.19	16.46	16.46	0.00	16.46	0.00
2001	13.64	13.77	0.93	13.77	0.93	13.64	11.8364	−13.22	15.29	12.10	13.64	13.64	0.00	13.64	0.00
2002	12.09	12.34	2.10	12.34	2.10	12.09	10.414	−13.87	13.67	13.03	12.09	12.09	0.00	12.09	0.00
2003	9.83	9.88	0.52	9.88	0.52	9.83	8.6106	−12.40	10.95	11.37	9.83	9.83	0.00	9.83	0.00
2004	14.43	14.50	0.53	14.50	0.53	14.43	12.3952	−14.08	16.28	12.85	14.43	14.43	0.00	14.43	0.00
2005	10.59	10.74	1.44	10.74	1.44	10.59	9.1694	−13.43	11.86	11.99	10.59	10.59	0.00	10.59	0.00
2006	11.51	11.96	3.97	11.99	4.19	11.51	9.9568	−13.47	12.88	11.92	11.51	11.51	0.00	11.51	0.00
2007	12.01	12.27	2.11	12.27	2.11	12.01	10.541	−12.26	13.31	10.78	12.01	12.01	0.00	12.01	0.00
2008	9.22	9.25	0.28	9.27	0.55	9.22	8.0772	−12.40	10.24	11.02	9.22	9.22	0.00	9.22	0.00
2009	15.95	16.13	1.11	16.13	1.11	15.95	13.843	−13.22	17.86	11.94	15.95	15.95	0.00	15.95	0.00
Average	12.57	12.73	1.30	12.74	1.35	12.57	10.94	−12.99	14.05	11.72	12.57	12.57	0.00	12.57	0.00

Year	AGWRC					INFILT					ICR				
	Base (AGWRC = 0.96)	AGWRC decreased by 20%	Difference from Base (%)	AGWRC decreased by 40%	Difference from Base (%)	Base (INFILT = 0.68)	INFILT decreased by 20%	Difference from Base (%)	INFILT increased by 20%	Difference from Base (%)	Base (IRC = 0.3)	IRC decreased by 20%	Difference from Base (%)	ICR increased by 20%	Difference from Base (%)
Annual Groundwater Recharge in Agricultural Land (mm)															
2000	14.5288	14.53	0.00	14.53	0.00	14.5288	12.78	−12.06	16.05	10.49	14.5288	14.5288	0.00	14.5288	0.00
2001	11.8872	11.94	0.43	11.94	0.43	11.8872	10.34	−13.03	13.36	12.39	11.8872	11.8872	0.00	11.8872	0.00
2002	10.4902	10.54	0.48	10.54	0.48	10.4902	9.07	−13.56	11.84	12.83	10.4902	10.4902	0.00	10.4902	0.00
2003	8.6868	8.71	0.29	8.71	0.29	8.6868	7.62	−12.28	9.68	11.40	8.6868	8.6868	0.00	8.6868	0.00
2004	12.1666	12.17	0.00	12.17	0.00	12.1666	10.46	−13.99	13.74	12.94	12.1666	12.1666	0.00	12.1666	0.00
2005	8.89	8.94	0.57	8.94	0.57	8.89	7.72	−13.14	10.01	12.57	8.89	8.89	0.00	8.89	0.00
2006	9.779	9.91	1.30	9.91	1.30	9.779	8.48	−13.25	10.97	12.21	9.779	9.779	0.00	9.779	0.00
2007	10.3886	10.46	0.73	10.49	0.98	10.3886	9.09	−12.47	11.56	11.25	10.3886	10.3886	0.00	10.3886	0.00
2008	8.0772	8.08	0.00	8.08	0.00	8.0772	7.06	−12.58	8.99	11.32	8.0772	8.0772	0.00	8.0772	0.00
2009	13.8176	13.84	0.18	13.87	0.37	13.8176	11.99	−13.24	15.49	12.13	13.8176	13.8176	0.00	13.8176	0.00
Average	10.91	9.82	0.40	10.92	0.44	10.87	9.46	−12.96	12.17	11.95	10.87	10.87	0.00	10.87	0.00

that of active groundwater recharge (or baseflow). Only a small portion of precipitation (about 1%) contributed to the inactive groundwater (or deep aquifer) recharge. Although the exact reasons for this phenomenon remain to be investigated, a possible explanation would be that the aquifer is deep (about 50 m) with a thick clay layer.

Finally, our modeling showed that forest land slightly increased groundwater recharge as compared to agricultural land for LYRW. Additional research and modeling, with appropriate field measurements, need to be conducted to investigate the role of forest land on groundwater recharge in the humid-subtropical region.

Declaration of Competing Interest

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

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