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Impacts of reforestation upon sediment load and water outflow in the Lower Yazoo River Watershed, Mississippi

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ABSTRACT

Among the world's largest coastal and river basins, the Lower Mississippi River Alluvial Valley (LMRAV) is one of the most disturbed by human activities. This study ascertained the impacts of reforestation on water outflow attenuation (i.e., water flow out of the watershed outlet) and sediment load reduction in the Lower Yazoo River Watershed (LYRW) within the LMRAV using the US-EPA's BASINS-HSPF model. The model was calibrated and validated with available experimental data prior to its application. Two simulation scenarios were then performed: one was chosen to predict the water outflow and sediment load without reforestation and the other was selected to project the potential impacts of reforestation upon water outflow attenuation and sediment load reduction following the conversion of 25, 50, 75, and 100% of the agricultural lands with most lands near or in the batture of the streams. Comparison of the two simulation scenarios (i.e., with and without reforestation) showed that a conversion of agricultural land into forests attenuated water outflow and reduced sediment load. In general, a two-fold increase in forest land area resulted in approximately a two-fold reduction in annual water outflow volume and sediment load mass, which occurred because forests absorb water and reduce surface water runoff and prevent soil erosion. On average, over a 10-year simulation, the specific water outflow attenuation and sediment load reduction were, respectively, 250 m^3/ha/y and 4.02 metric ton/ha/y. Seasonal variations of water outflow attenuation and sediment load reduction occurred with the maximum attenuation/reduction in winter and the minimum attenuation/reduction in summer. Our load duration curve analysis further confirmed that an increase in forest land area reduced the likelihood of a given sediment load out of the watershed outlet. This study suggests that reforestation in or around the batture of streams is a useful practice for water outflow attenuation and sediment load reduction.

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1. Introduction

Sediments in rivers are increasingly recognized as both a carrier and potential source of contaminants in aquatic environments due to their adsorption of toxic chemicals (Ouyang et al., 2002). Additionally, significant changes in river discharge, stage, and morphology as a result of sediment deposition have become an issue of concern due to the broad impacts upon terrestrial and aquatic life as well as river hydrology (e.g., flooding). Transport of sediments in streams occurs in stable and disturbed channel systems. When erosion and sediment transport rates and amounts are so high that biological communities and other designated streams are adversely affected, the surface water systems are considered to be impaired by sediments (Simon and Darby, 2002).

Agricultural, forestry, industrial, and urban activities are the major causes of sediment erosion and deposition in rivers and lakes. This is also true for the Lower Mississippi River Alluvial Valley (LMRAV), which is located within the historic floodplain of the Mississippi River starting at Cairo, Illinois and continuing through Missouri, Kentucky, Arkansas, Tennessee, Mississippi, and Louisiana (King and Keeland, 1999). Among the world's largest coastal and river basins, the LMRAV is one of the most disturbed by human activities such as deforestation, reforestation, dams, levees, and river channel changes (Simon and Darby, 2002; Shaffer and Day, 2007; Keddy et al., 2009). Changes in agricultural and forest practices, clearcutting in bottomland hardwood forests, and conversions from forests to agricultural lands are largely responsible for the increased nutrient and sediment loads in the MRB and its adjacent Gulf of Mexico (GM) watersheds (Zhang and Schilling, 2006; Shields et al., 2008). Goolsby and Battaglin (2001) reported that the concentration of nitrate in the LMRAV has been doubled to an average of 1.45 g N L^{-1} since 1950 and its export to the GM

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has been doubled to about 1,000,000 T y^{-1}. Pennington (2004) estimated that the concentration of phosphorus in the Sunflower River within the MRB ranges from 0.01 to 2.39 mg L^{-1}. Simon and Darby (2002) investigated the effectiveness of grade-control structures in reducing erosion along incised river channels in Hotophia Creek, Mississippi. Land use in this creek is mainly agricultural, with cultivated land (mostly cotton and soybeans) in the valley bottoms and pasture and forest in the uplands. These authors found that the sediment transport rate of a Mississippi stream ranges from 0.01 to 6000 T d^{-1} km^{-2}. Impairment of surface water systems by non-contaminated and contaminated sediments in the LMRAV could pose hazards to fish and benthic communities by reducing dissolved oxygen, disrupting habitat, and degrading water quality. Furthermore, high sediment deposition rates can interrupt river navigation.

Forest cover in the LMRAV has undergone extensive loss during the last century (Stanturf et al., 2000). Deforestation within the LMRAV has resulted in the loss of critical wildlife and fish habitat; increased nutrient, sediment, and herbicide loads; elevated greenhouse gas emissions; and led to changes in regional and local hydrologic cycle. The latter has resulted in floodwater retention reduction and a concomitant loss of flood control (Stanturf et al., 2000). Therefore, restoration of floodplain forests in the LMRAV is essential to surface water quality improvement and flood attenuation. Perhaps the most practical restoration effort is to reforest in the batture along the rivers and streams. Reforestation can reduce the water discharge and sediment load into the rivers and streams and enhance flood attenuation based on watershed characteristics.

During the 1950–1970s, the LMRAV underwent widespread loss of bottomland hardwood forests, primarily as a result of clearing for agriculture, flood control, and floodplain development (MacDonald and Wolfe, 1979; National Research Council, 1982; Wilen and Frayer, 1990). Only less than 1/3 of the original estimated 10 million ha of bottomland hardwoods existed in the LMRAV in 1982 (National Research Council, 1982; Hefner and Brown, 1985). Changes in agricultural and forestry practices, clearcutting in bottomland hardwood forests, and conversions from forests to agricultural lands are largely responsible for the increased sediment loads in surface water systems in the LMRAV (Zhang and Schilling, 2006; Shields et al., 2008).

Forestry management practices have been implemented to improve effects of reforestation on surface water quality in the United States (Parkyn et al., 2005; Mcbroom et al., 2008; Edwards and Williard, 2010; Evans et al., 2013) and around the world (Anbumozhi et al., 2005; Wang et al., 2007). Edwards and Williard (2010) quantified the efficiencies of forestry best management practices (BMPs) for reducing sediment and nutrient losses in the eastern United States. These authors found that the BMP efficacies are 53–94% for sediment, 60–80% for total nitrogen, and 85–86% for phosphorus. Harris (2006) conducted a survey of BMPs voluntarily implemented on forestlands from Big Black, Tombigbee, Tennessee River Basins in Mississippi. This author concluded that through voluntary BMPs, the forestry community has played a part in improving and protecting water quality in the State of Mississippi. Anbumozhi et al. (2005) study the impact of riparian buffer zones on water quality and associated managements in Tokachikawa watershed in Hokkaido, Japan. These authors demonstrated the positive impact of forest buffer zones in reducing the influence of agricultural nutrients and chemicals on surface stream waters. Wang et al. (2007) investigated the impacts of reforestation and soil erosion on the processes of vegetation recovery and vegetation succession under different restoration strategies in south China. These authors found that reforestation with suitable strategies may control erosion and greatly accelerate vegetation succession in the eroded slope land in the subtropical zones.

Despite numerous efforts devoted to investigating the relationships between the ecological and environmental consequences of deforestation and the benefits of reforestation and forestry BMPs in the LMRAV (Harris, 2006), our literature search revealed that studies on the impacts of reforestation and forest management upon sediment load and flood attenuation in the LMRAV are fragmented and poorly documented. With an increased appreciation of the importance of drinking water quality to public health, raw water quality to terrestrial life, and flood attenuation to residential and commercial areas, there is a need to further examine these issues. Since the dynamics of water outflow attenuation and sediment reduction load in a given watershed are complex processes, it is very difficult to quantify them by experimentation alone for different types of land uses patterns, for a variety of soil and hydrological conditions, and for all possible combinations of atmospheric driving forces. Therefore, a need exists to employ the modeling approach for this purpose.

The goal of this modeling study was to estimate potential impacts of reforestation upon water outflow (i.e., water flow out of the watershed outlet) attenuation and sediment load reduction in the Lower Yazoo River watershed (LYRW) within the LMRAV. Our specific objectives were to: (1) develop a site-specific BASINS-HSPF model for predicting the water flow and sediment load in the LYRW; (2) calibrate and validate the hydrological and sedimentation components of the model using actual field data; and (3) apply the model to investigate the role of reforestation (i.e., a conversion of agricultural land near or in the batture into forests) on water outflow attenuation and sediment load reduction in the LYRW.

2. Materials and methods

2.1. Study sites

The LYRW is located in the southern part of the Yazoo River Basin (YRB) within the LMRAV with an area of 618 km^2 (Fig. 1). The major reason for selecting this watershed was the availability of certain field-observed data that are necessary for model calibration and validation. The YRB is the largest river basin in Mississippi, USA and has a total drainage area of about 34,600 km^2. This basin is separated into two distinct topographic regions: the Bluff Hills and the Mississippi Alluvial Delta (MDEQ, 2008; Shields et al., 2008). The Bluff Hills region is a hilly upland area where streams originate from the oak-hickory forests and pasture lands which dominate the rural landscape. The Delta Region, on the other hand, is a flat, lowland area of slow moving streams and an extensive system of oxbow lakes. This Delta Region is a highly productive agricultural area and is known for its cotton, corn, soybeans, rice, and catfish (MDEQ, 2008). The LYRW in the YRB primarily consists of 61% forest land and 31% agriculture land (Table 1). The soil types for this watershed range from sand, loam, and clay.

Surface water pollution within the YRB includes excess nutrients, sediments, heavy metals, and herbicides which come from both point and nonpoint sources, and are the result of storm water runoff, discharge from ditches and creeks, groundwater seepage, aquatic weed control, naturally occurring organic inputs, and atmospheric deposition (Nett et al., 2004; Pennington, 2004; Aulenbach et al., 2007; Alexander et al., 2008; Shields et al., 2008). The degradation of water quality due to these contaminants has resulted in altered species composition and decreased overall health of aquatic communities within the YRB. In addition, the high sediment deposition rates in YRB can interrupt river navigation.

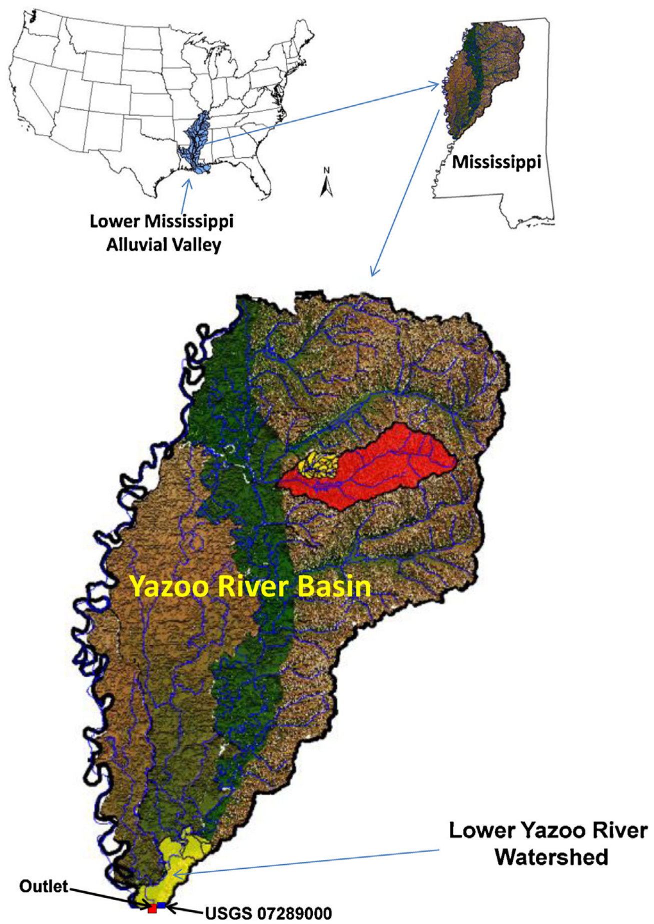

Fig. 1. Location of Yazoo River Basin along with Lower Yazoo River Watershed.

Table 1
Land uses, calibrated input parameter values, and major differences in input values between agricultural land and forest land for the Lower Yazoo River Watershed.

Parameter	Value
Land uses	
Agricultural land (ha)	16,224.67 (31.76%)
Forest land (ha)	31,502.38 (61.66%)
Urban or built-up land (ha)	952.65 (1.86%)
Barren (ha)	151.24 (0.30%)
Wetland (ha)	2257.44 (4.42%)
Total (ha)	51,088.37
Calibrated values	
Hydrology	
LZSN (lower zone nominal storage, m)	6.00
UZSN (upper zone nominal storage, m)	2.00
INFILT (index to the infiltration capacity of the soil)	0.05–0.25
LZETP (lower zone ET parameter)	0.50
IRC (inter-flow recession parameter)	0.30
Sediment	
KRER (coefficient in the soil detachment equation)	0.10
JRER (exponent in the soil detachment equation)	1.50

Major differences in input values between agricultural and forest lands

	Agricultural land	Forest land
FOREST (fraction factor)	0.1	0.5
LZSN	6.0	8.0
INFILT	0.05	0.25
MON-INTERCEP (Monthly water interception)	0.1–0.25 (Varied for each month)	0.2

2.2. Model description

The US-EPA watershed model system BASINS-HSPF was selected for this study. BASINS (*B*etter *A*ssessment *S*cience *I*ntegrating *P*oint and *N*onpoint *S*ources) is a multipurpose environmental analysis system for use by regional, state, and local agencies in performing watershed and water quality based studies. This software makes it possible to quickly assess large amounts of point source and nonpoint source data in a format that is easy to use and understand. The BASINS system integrates an open source geographic information system (GIS) program (MapWindow), national watershed and meteorological data, and state-of-the-art environmental assessment and modeling tools (e.g., HSPF, PLOAD, QUAL2E, and SWAT) into one convenient package (US EPA, 2010).

HSPF (hydrological simulation program—FORTRAN) is a comprehensive model developed by the U.S. Environmental Protection Agency (US-EPA) for simulating many processes related to water quantity and quality in watersheds of almost any size and complexity (Bicknell et al., 2001). HSPF can simulate both the land area of watersheds and the water bodies like streams or lakes. The HSPF model uses information such as daily historic rainfall, temperature and solar radiation data; land surface characteristics such as land use patterns; and land management practices to simulate the processes that occur in a watershed. The result of this simulation is a simulated history of the quantity and quality of runoff from an urban or agricultural watershed which includes the following: the runoff flow rate, sediment load, and nutrient and pesticide concentrations. Thus the simulation results provide a history of water quantity and quality at a watershed outlet. The HSPF simulates three sediment types (sand, silt, and clay) in addition to a single organic chemical and transformation products of that chemical. An elaborate description of the HSPF model can be found in Bicknell et al. (2001).

2.3. Data acquisition

Data collection for the LYRW included watershed descriptions, meteorological conditions, and hydrologic data and several agencies provide these data. Most of the data used in this study such as land use, soil type, topography, precipitation, and discharge are from the National Hydrography Dataset, US Geologic Survey (USGS) National Water Information System, and the 2001 National Land Cover Data. These data can be downloaded directly from the Metadata Section of BASINS.

It should be pointed out that there are currently few observed data available for water discharge and sediment concentrations at the LYRW outlet for model calibration and validation. To overcome this limitation, we have used the observed data collected around the watershed outlet and recalculated the data to represent the average LYRW conditions. For water discharges, 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 suit the watershed average conditions. These multiply stations are very close to the LYRW outlet and within the LYRW.

Since there are no observed data available for sediment concentrations, in the LYRW, we have used the data collected within the YRB. Data from the USGS station (#0728875070) in Deer Creek, near Leland, MS as well as the data reported by Rebich (1993) from eight locations within the YRB were used for the sediment component model calibration and validation. Those locations have annual mean total suspended solid concentrations and discharges, whereas the Deer Creek station has short-term total suspended solid and daily discharge data. All of the data were used to obtain the following relationship between total suspended solid and discharge:

$$\mathrm{TSS} = 82.2 + 0.2733\mathrm{Disch} \quad (R^2 = 0.2925, \alpha = 0.05, p < 0.00435) \tag{1}$$

where TSS is the total suspended solid ($\mathrm{mg\,L^{-1}}$) and Disch is the discharge (cft/s). Although the R^2 is low in Eq. (1) due to the highly non-linear and dynamic nature of the YRB, the value of p is much lower than that of α, indicating that the relationship between the TSS and the discharge is acceptable and is assumed to represent the average sediment concentrations for the LYRW. The daily TSS data at the LYRW outlet were then generated with the daily discharge data from the HSPF model using Eq. (1). These "observed-computed" data were used only for model calibration and validation purposes.

The precipitation and air temperature data for the period from January 2000 to December 2010 were obtained from a weather station in Vicksburg, MS near the LYRW. These data were used to represent the entire watershed conditions. The potential evapotranspiration data were computed based on air temperature using the WDMUtil package from the BASINS-HSPF model system.

2.4. Model development

In general, the development of a hydrological model begins with watershed delineation. This process requires the setup of a digital elevation model (DEM) in the ArcInfo grid format, creation of stream networks in shape file, and creation of watershed inlets or outlets using the BASINS watershed delineation tool. Hydrologic models like HSPF require land use and soil data to determine the area and the hydrologic parameters of each land use pattern. This was accomplished by using the land use and soil classification tool in BASINS.

The HSPF model has a modular structure and is a lumped parameter model. Pervious land segments over which an appreciable amount of water infiltrates into the ground are modeled with the PERLND module. Impervious land segments over which infiltration are negligible, such as paved urban surfaces, are simulated with the IMPLND module. Processes occurring in water bodies like streams and lakes are treated with the RCHRES module. These modules have several components dealing with the hydrological processes and processes related to water quality. Detailed information about the structure and functioning of these modules can be found in the elsewhere (Donigian and Crawford, 1976; Donigian et al., 1984; Bicknell et al., 2001; Chen et al., 1998). In this study, the PERLND, IMPLND, and RCHRES modules of the HSPF model were used. The PWATER section of PERLND is a major component of the model that simulates the water budget, including surface flow, inter-flow and ground water behavior, whereas the SEDMNT section of PERLAND is a major component of the model that simulates the sediment transport. In the RCHRES module, section HYDR is utilized to simulate the hydraulic behavior of the stream.

The key steps in modeling a watershed with HSPF are the mathematical representation of the watershed, the preparation of input meteorological and hydrological time series, the estimation of parameters and the calibration and validation process. The time series are fed to the model by utilizing a standalone program called the Watershed Data Management program (WDM) provided in BASINS. Fig. 2 shows the modeled domain for the LYRW used in this study, whereas Table 1 lists the major land use types and areas for the LYRW. These land uses represent the conditions up to year 2001 and were classified according to the Land Use Cover Classification Scheme.

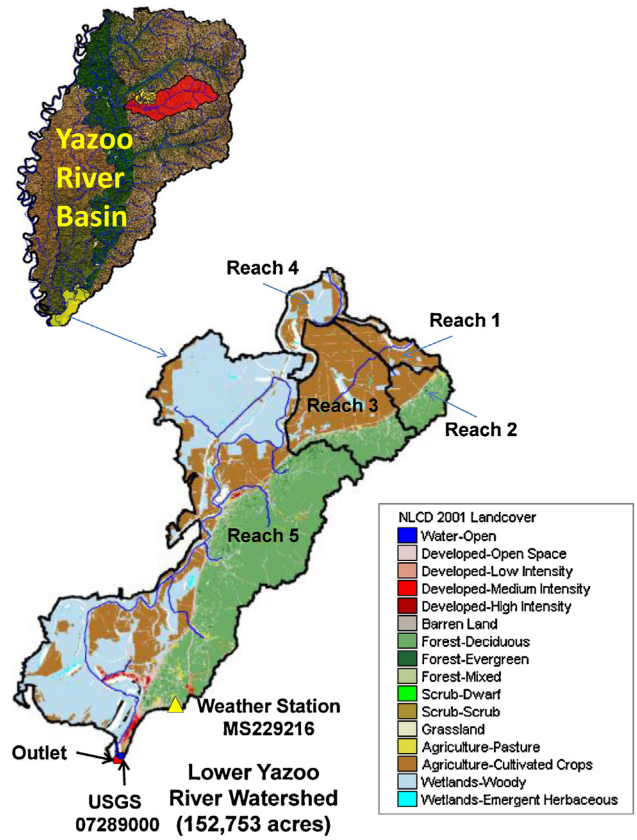

Fig. 2. Land use cover for the Lower Yazoo River Watershed.

2.5. Model calibration and validation

Model calibration is a process of adjusting input parameters within a reasonable range to obtain a match between field observations and model predictions, while a model validation is a process of verifying the calibrated model by comparing field observations and model predictions without adjusting any input parameters. Two steps were used for the model calibration and validation processes in this study, one for the hydrologic component and the other for the sediment component.

2.5.1. Hydrologic component

The calibration period extended from January 1, 2000 to December 31, 2005, whereas the validation period spanned from January 1, 2006 to December 31, 2010. To assure fewer uncertainties in the hydrologic calibration process, we only adjusted the values of the following six hydrologic parameters: LZSN, UZSN, INFILT, LZETP, INTFW, and IRC, which are defined in Table 1. These parameters are most sensitive to the HSPF model predictions (Donigian et al., 1983).

Comparison of the observed and simulated annual volume of water flow is given in Table 2. The difference in error between the observed and simulated volumes was 4.2% over a 5-year simulation period, which was acceptable (Bicknell et al., 2001). The best fit for the LYRW was further estimated graphically with daily discharges (Fig. 3B) and statistically with monthly discharges (Fig. 3C). The daily peak flows from model predictions matched well graphically with those from field observations (Fig. 3B). With the values of R^2 equal to 0.964 in monthly flows (Fig. 3C), we concluded that good agreements were obtained between the model predictions and the field observations.

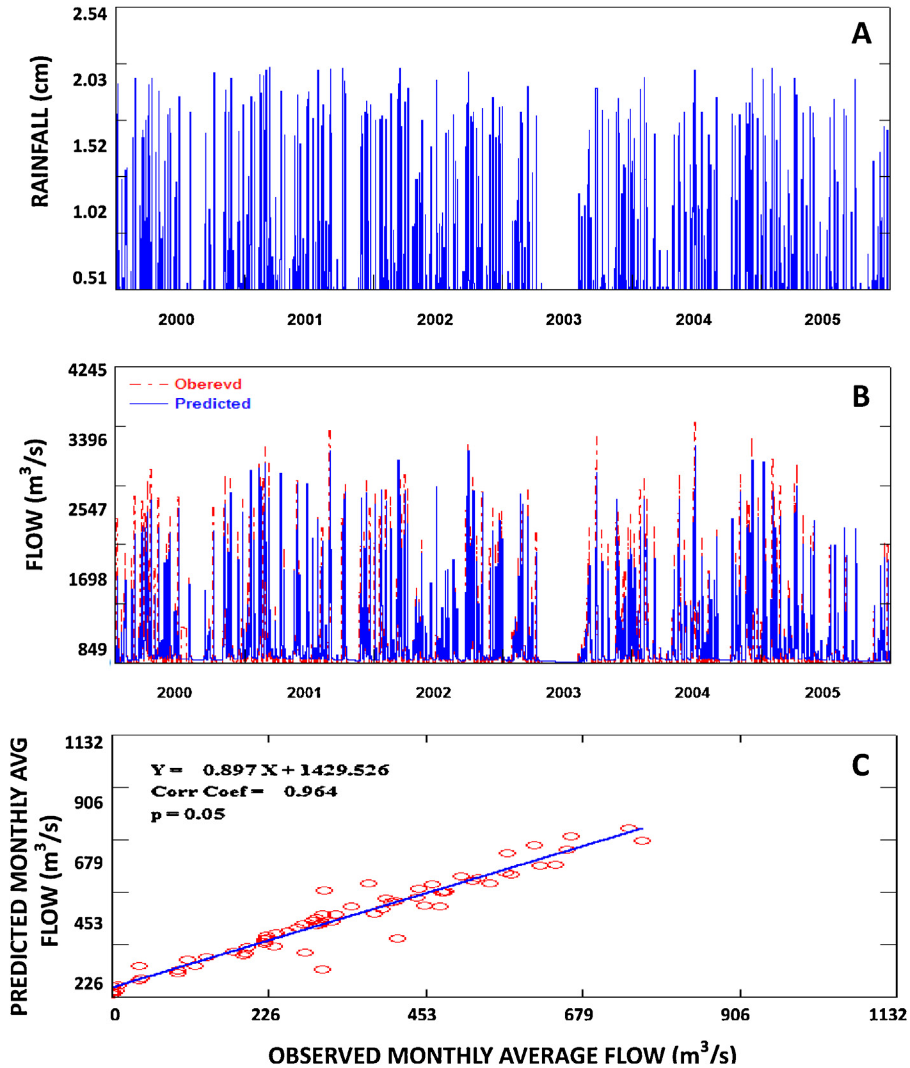

Fig. 3. Daily rainfall event (A), daily flow calibration (B), and monthly flow calibration (C) for the Lower Yazoo River Watershed.

Validation of the calibrated hydrology model was given in Fig. 4. This figure compared water discharges between field observations and model predictions over a time period from January 1, 2006 to December 31, 2010. With a good match graphically in daily peak flows (Fig. 4A) as well as with an $R^2 = 0.978$ (Fig. 4B) in monthly flows, we concluded that a very good agreement was obtained between the model predictions and the field observations.

2.5.2. Sediment component

Fig. 5 shows the sediment calibration for the LYRW, which was accomplished by adjusting KRER and JRER parameters (Table 1) to match the predicted total suspended solids (TSS) with the field measurements. The calibration period was from January 1, 2000 to December 31, 2005. The daily peak sediment concentrations from model predictions matched well graphically with those from field observations (Fig. 5A). With the values of R^2 equal to 0.903 in monthly sediment concentrations (Fig. 5B), we concluded that a good agreement was obtained between the model predictions and the field observations.

Validation of the calibrated sediment model for LYRW was given in Fig. 6. This figure compared sediment concentrations between field observations and model predictions over a time period from January 1, 2006 to December 31, 2010. With a very good match graphically in daily sediment concentration peaks (Fig. 6A) as well as with an $R^2 = 0.942$ (Fig. 6B) in monthly sediment concentrations, we concluded that a good agreement was obtained between the model predictions and the field observations.

Table 2
Simulated and observed annual water outflow volumes from the Lower Yazoo River Watershed outlet during model calibration.

	Prediction (m^3)	Observation (m^3)	Difference (%)
Year			
2000	9.93E+09	1.07E+10	−7.54
2001	1.26E+10	1.18E+10	6.43
2002	1.22E+10	1.19E+10	2.59
2003	6.99E+09	7.10E+09	−1.62
2004	1.21E+10	1.16E+10	4.39
2005	8.64E+09	7.98E+09	8.32
Overall	5.25E+10	5.04E+10	4.22

3. Results and discussion

To obtain a better understanding of the role of reforestation upon water outflow (i.e., water flow out of watershed outlet) and sediment load, two simulation scenarios were performed in this study. The first scenario (or the base scenario) was chosen to predict

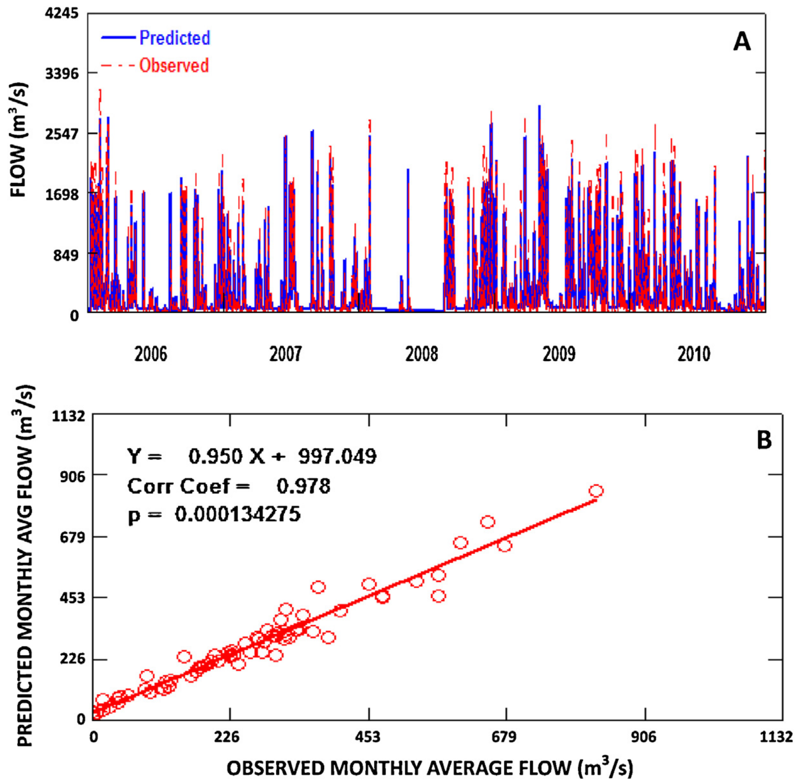

Fig. 4. Daily flow validation (A) and monthly flow validation (B) for the Lower Yazoo River Watershed.

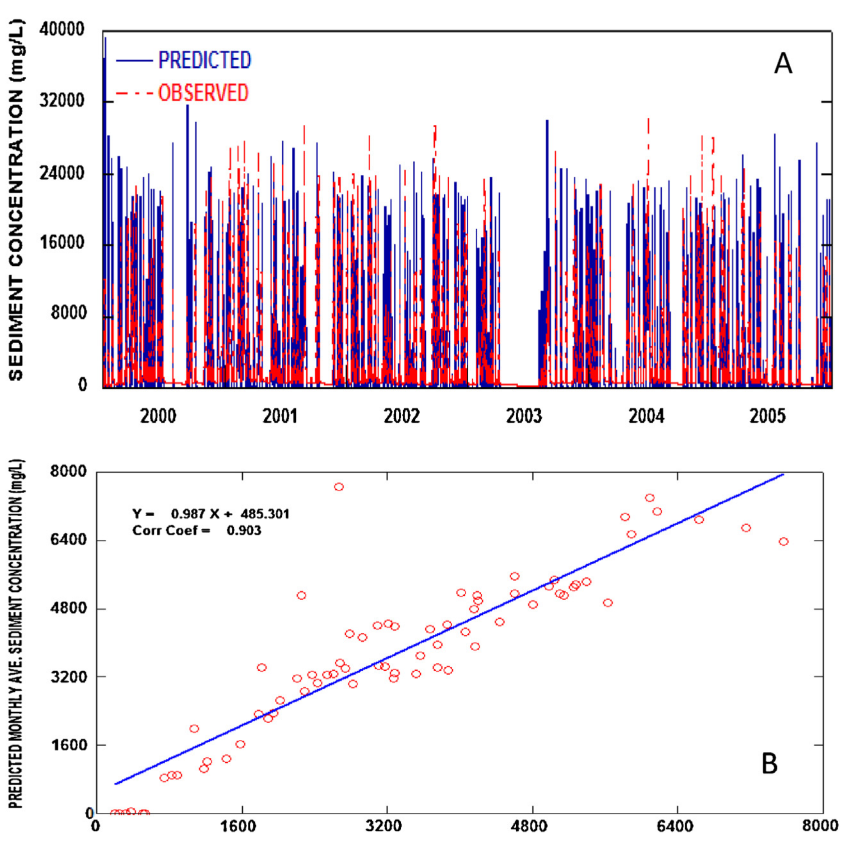

Fig. 5. Daily sediment concentration calibration (A) and monthly sediment calibration (B) for the Lower Yazoo River Watershed.

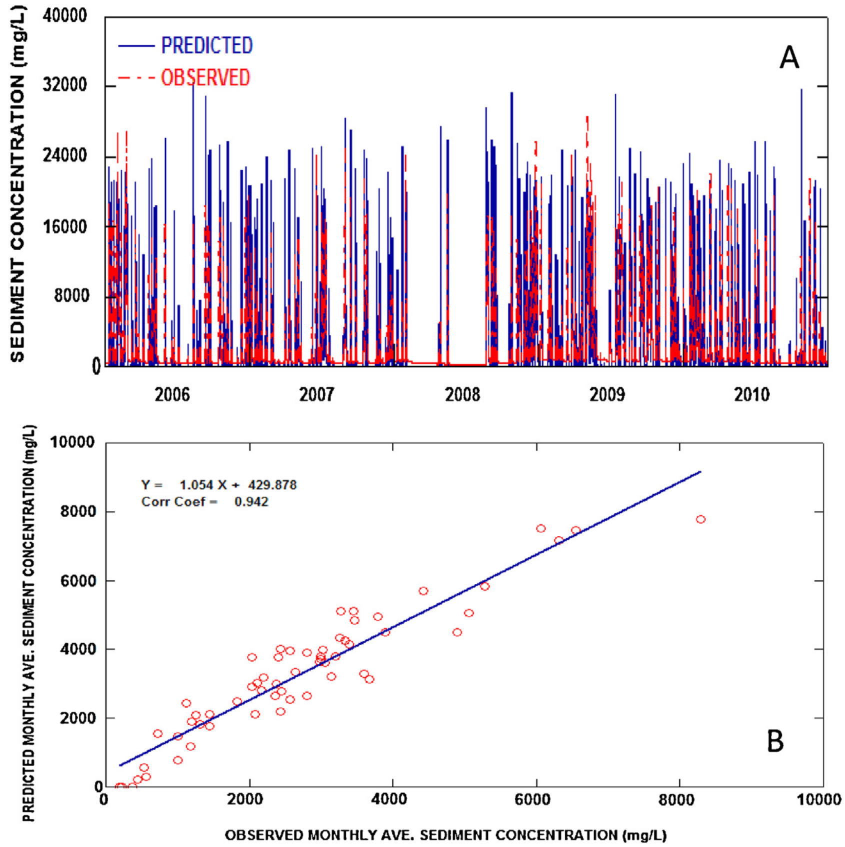

Fig. 6. Daily sediment validation (A) and monthly sediment validation (B) for the Lower Yazoo River Watershed.

the water outflow and sediment load without reforestation (i.e., 0% land use conversion). In this scenario, all of the simulation conditions and input parameter values were the same as those used in model validations. The second scenario was selected to project the potential impacts of reforestation upon water outflow attenuation and sediment load reduction by converting 25, 50, 75, and 100% of the agricultural lands into the forests. These land use conversions occurred in or near the batture of the streams (Fig. 2). Table 4 lists the area of agricultural land reduction and forest land increase in the LYRW for each percent conversion. In this second scenario, all of the simulation conditions and input parameter values were the same as those used in the first scenario except for the land use conversions. Therefore, comparison of the simulation results from the two scenarios (i.e., with and without reforestations) allowed us to evaluate the potential impacts of reforestation upon the daily, seasonal, and annual water discharge and sediment transport as well as the water outflow attenuation and sediment load reduction. The simulation period was 10 years starting at the first day of 2000 and terminating at the end of 2010 for each scenario, and the agricultural land conversion only occurred in Reach 5 (Fig. 2). It should be pointed out here that HSPF model includes the following five land uses: urban or built-up, agricultural, forest, wetland/water, and barren land. Each land use has a forest fraction value as input in HSPF. For example, the forest fraction is 0.1 for urban or built-up land, 0 for barren land, 0.1 for agricultural land, and 0.7 for forest land. A conversion of one land use to another will change the forest fraction in HSPF model. Additionally, the input parameter values for sediment wash off, soil moisture content, soil temperature, etc. are all different for different land uses. The forest fraction and many other parameters are used to calculate evapotranspiration and surface water runoff, and sediment erosion. Table 1 lists the major differences in input parameters values between the agricultural land and the forest land. An elaborate description of these calculations and differences can be found in HSPF user's manual (Bicknell et al., 2001).

3.1. Daily and annual variations

Daily variations of rainfall events, water discharge, and sediment concentration, which occurred from 2000 to 2010 without reforestation (base scenario) at the LYRW, are shown in Fig. 7. The rainfall event was obtained from nearby weather station and further computed to represent the average watershed conditions, whereas the water discharge and sediment concentration were attained from the model simulations. Two dry periods (infrequent rainfall periods) were observed, one in 2003 and the other in 2008. Comparison of the results in Fig. 7 shows that effects of rainfall event on water discharge and sediment concentration were minimal for the two dry periods (i.e., 2003 and 2008), but were profound for the rest of the years. Results suggested that the rainfall event is a driving force for the daily variations of water discharge and sediment concentration. However, one observation is worth mentioning here with respect to the peaks of rainfall rate, water discharge, and sediment concentration. That is, a highest rainfall rate at a given time may not correspond well to the highest water discharge and sediment concentration. For example, the highest rainfall rate was found in early 2001 (Fig. 7A), while the highest water discharge was observed in the middle of 2004 (Fig. 7B) and the highest sediment concentration was detected in the middle of 2006 (Fig. 7C). It is apparent that other watershed characteristics such as topography, land use cover, soil types, and seasonal soil moisture regime also play important roles in daily variations of water discharge and sediment concentration.

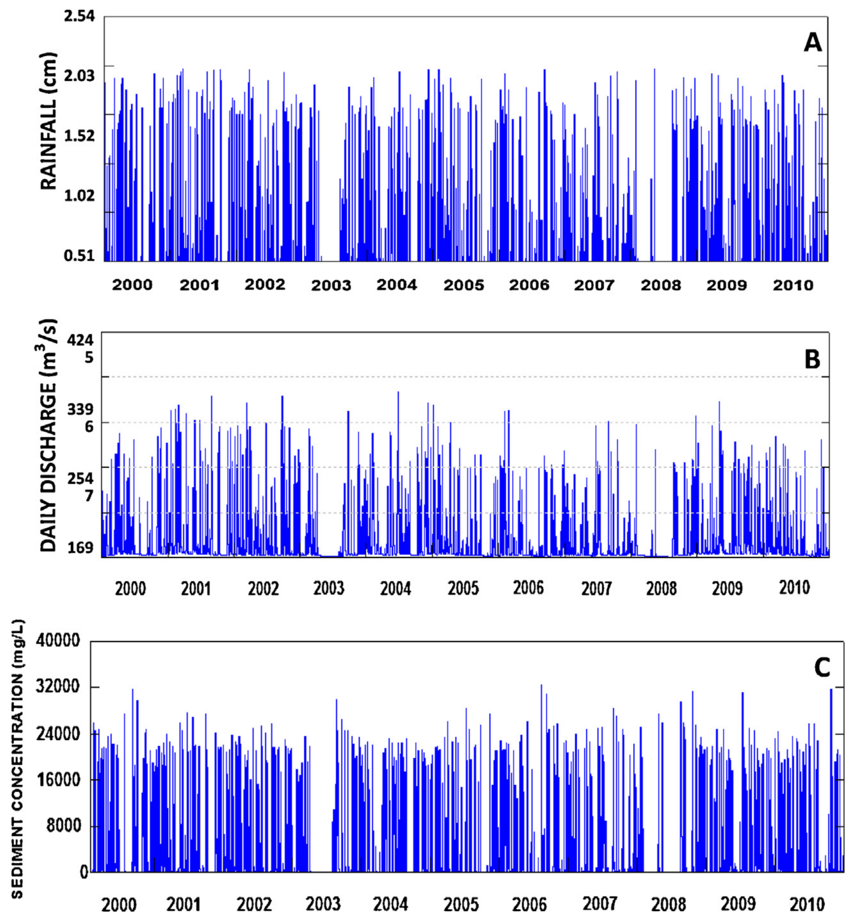

Fig. 7. Daily rainfall (A) as well as predicted water flow (B) and sediment concentration (C).

Annual average water outflow and sediment load through the LYRW outlet, for the base scenario over a simulation period from 2000 to 2010, are shown in Fig. 8. This figure illustrates that the pattern of the annual average sediment load was similar to that of the annual average water outflow, i.e., as the water outflow increased, more sediments were transported out of the watershed outlet. A plot of the annual average sediment load against the annual average water outflow for a 10-year simulation period yielded the following linear regression equation:

$$\text{Sediment load} = 0.9178 \times \text{water outflow} \tag{2}$$

With an $R^2 = 0.9602$, Eq. (2) could be used to approximate the annual sediment load for the LYRW given the annual water outflow or vice versa. Eq. (2) further revealed that the ratio of the average annual water outflow to the average annual sediment load was 0.9178. In other words, every 1.0 acre-ft (or 1233.5 m^3) water outflow could bring about 0.9178 (metric) ton of sediments out of the watershed outlet.

3.2. Reforestation vs. water outflow attenuation

Table 3 compares the seasonal and annual volumes of water outflow from the LYRW outlets among five different levels of land use conversion (i.e., 0, 25, 50, 75, and 100% conversions of agricultural lands into forests) and the corresponding percentage changes of water outflow volume. In general, a conversion of agricultural land into forests decreased the seasonal volume of water outflow from the watershed outlet. For example, a 50% reduction of agricultural land (or a 4249-ha increase in forest land (Table 4)) attenuated the volume of water outflow by 0.53% in winter, 0.35% in spring, 0.11% in summer, and 0.44% in fall (Table 3); while a 75% reduction of agricultural land (or a 6378-ha increase in forest land (Table 4)) reduced the volume of water outflow by 0.76% in winter, 0.45% in spring, 0.14% in summer, and 0.55% in fall (Table 3). Results demonstrated that an increase in forests near or in the batture of the streams attenuated water outflow. This occurred because forests absorb water and reduce the surface water runoff. Table 3 also reveals that the maximum water outflow attenuation occurred in winter, while the minimum water outflow attenuation happened in summer. This took place because of the wetter winters and drier summers in these watersheds, and because vegetation takes up water, and forest canopies intercept rainfall, in the summer but not in the winter.

Analogous to the case of average seasonal water outflow, the average annual water outflow attenuation with reforestation was also observed (Table 3). For instance, a 25% reduction of agricultural land or a 2125-ha increase in forest land (Table 4) reduced the volume of annual water outflow by 0.11% (Table 3), whereas a 50% reduction of agricultural land or a 4249-ha increase in forest land (Table 4) decreased the volume of annual water outflow by 0.26% (Table 3). In other words, a two-fold increase in forest land would result in an approximately two-fold decrease in volume of annual water outflow. Results further confirmed that reforestation in or near the batture of the streams is a useful practice for water outflow attenuation.

It should be kept in mind that in this study, only the agricultural lands in Reach 5 (which are near the streams) rather than the entire agricultural land in LYRW were converted to forests.

Table 3
Comparison of water outflow and sediment load reduction among five percentages of land use conversion from agricultural and forest land at Lower Yazoo River Watershed (LYRW).

Time	0% conversion from agricultural to forest land		25% conversion from agricultural to forest land		50% conversion from agricultural to forest land		75% conversion from agricultural to forest land		100% conversion from agricultural to forest land	
	Volume (m^3)	Change (%)	Volume (m^3)	Change (%)	Volume (m^3)	Change (%)	Volume (m^3)	Change (%)	Volume (m^3)	Change (%)
	Water outflow from LYRW outlet (Reach 5)									
Winter	1.133E+08	0	1.130E+08	−0.25	1.127E+08	−0.52	1.124E+08	−0.76	1.121E+08	−1.03
Spring	8.903E+07	0	8.905E+07	0.01	8.872E+07	−0.35	8.863E+07	−0.45	8.864E+07	−0.44
Summer	8.107E+07	0	8.103E+07	−0.06	8.098E+07	−0.11	8.096E+07	−0.14	8.091E+07	−0.21
Fall	1.077E+08	0	1.075E+08	−0.20	1.072E+08	−0.44	1.071E+08	−0.55	1.070E+08	−0.66
Annual	3.909E+08	0	3.905E+08	−0.11	3.899E+08	−0.26	3.891E+08	−0.46	3.887E+08	−0.57
	Sediment load from LYRW outlet (Reach 5)									
	Load (ton)	Change (%)	Load (ton)	Change (%)	Load (ton)	Change (%)	Load (ton)	Change (%)	Load (ton)	Change (%)
Winter	8.398E+04	0	8.136E+04	−3.12	7.891E+04	−6.04	7.637E+04	−9.06	7.385E+04	−12.07
Spring	6.474E+04	0	6.279E+04	−3.02	6.092E+04	−5.91	5.902E+04	−8.83	5.702E+04	−11.92
Summer	6.021E+04	0	5.848E+04	−2.87	5.676E+04	−5.72	5.495E+04	−8.73	5.321E+04	−11.63
Fall	8.089E+04	0	7.840E+04	−3.08	7.610E+04	−5.92	7.369E+04	−8.90	7.128E+04	−11.88
Annual	2.898E+05	0	2.814E+05	−2.92	2.727E+05	−5.90	2.641E+05	−8.88	2.555E+05	−11.86

The areas converted were small as compared to the entire LYRW. Therefore, it is not wise to use the percentages (relative values) to compare with other watersheds on how well the water outflow attenuation and sediment load reduction were after reforestation. For a better comparison, the concepts of specific water outflow attenuation and specific sediment load reduction were introduced in this study. A specific water outflow attenuation is defined here as the volume of water outflow attenuation per hectare increase in forest land per year. This value was obtained by dividing the volume of annual water outflow with the total area of forest land increment. For example, a specific water outflow attenuation of 211.2 m^3/ha/y means that for every hectare increase in forest land, the water outflow from its watershed outlet is reduced by 211.2 m^3 per year. Table 4 lists the forest land increment and the specific water outflow attenuation among the five different percentage levels of land use conversion. This table shows that a reduction in agricultural land associated an increase in forests, in general, enhanced the specific water outflow attenuation. For example, the specific water outflow attenuation was 211.2 m^3/ha/y with a 25% reduction of agricultural land, but was 281.5 m^3/ha/y with a 75% reduction of agricultural land. The former was about 1.3 times less than the latter. This occurred because the reduction in agricultural land associated with the increase in forests near or in the batture of the streams greatly reduced the surface water runoff and increased water outflow attenuation.

Plot of the annual average water outflow volume against the forest land increment is given in Fig. 9A. With an $R^2 = 0.9912$, we concluded that a highly linear correlation existed between the annual average water outflow volume and the forest land increment. In other words, an increase in forest land area decreased the annual average water outflow. Under the assumption that other conditions remained the same except for reforestation, as used in this study, we have demonstrated that the percentage increase in forest land is proportional to the percentage decrease in total volume of water outflow through the watershed outlet.

3.3. *Reforestation vs. sediment load reduction*

Seasonal variations of sediment load reduction from the LYRW outlets among the five different land use conversion rates (i.e., 0, 25, 50, 75, and 100% conversions of agricultural lands into forests) are given in Table 3. A decrease in agricultural land associated with an increase in forest land increased the seasonal sediment load reduction. For example, a 25% reduction of agricultural land decreased the sediment load through the watershed outlet by 3.12% in winter, 3.02% in spring, 2.87% in summer, and 3.08% in fall; while a 50% reduction of agricultural land reduced the sediment load through the watershed outlet by 6.04% in winter, 5.91% in spring, 5.72% in summer, and 5.92% in fall. Results showed that an increase in forest land near or in the batture of the streams reduced the seasonal sediment load, which occurred because the increase in forest land attenuated the surface water runoff and soil erosion thereby reducing the sediment load in the streams. Additionally, the maximum sediment load reduction occurred in winter, while the minimum sediment load reduction took place in summer. This was so because of the wetter winter and drier summer for the LYRW and because of the effect of vegetation taking up water and the forest canopy intercepting water during the growing season.

Similar to the case of seasonal sediment load reduction, the annual sediment load reduction with reforestation was observed among the five different percentages of land use conversion (Table 3). A 25% reduction in agricultural land reduced the annual sediment load by 2.9%, whereas a 50% reduction in agricultural land decreased the annual sediment load by 5.9%. A two-fold percentage increase in agricultural land conversion resulted in about a two-fold

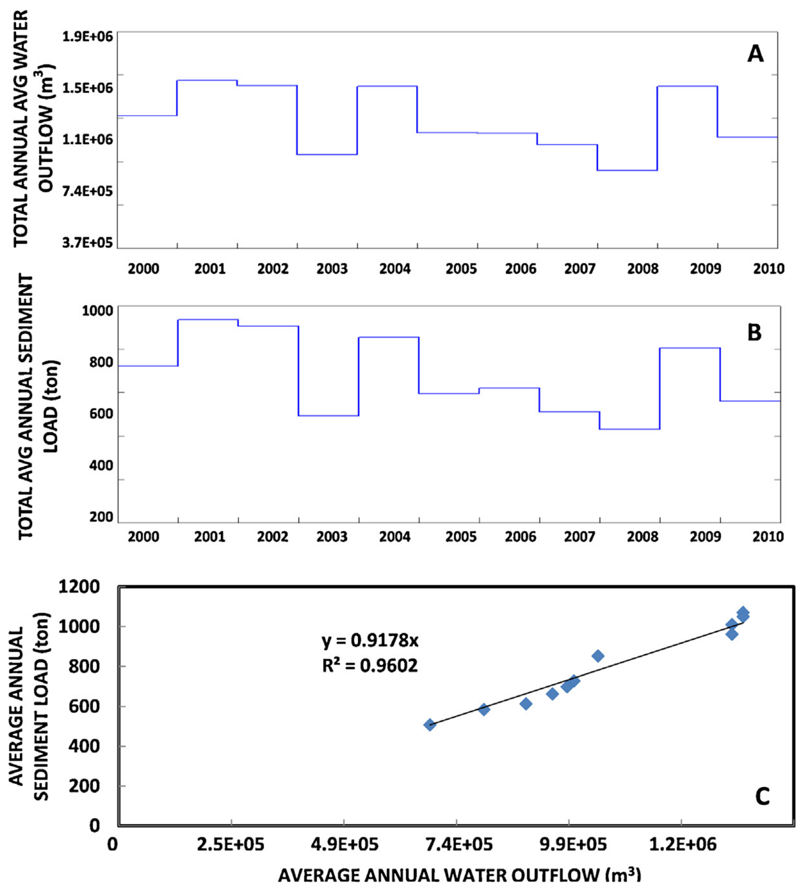

Fig. 8. Annual average water outflow (A), sediment load (B), and their relationship (C) from the base simulation scenario for the Lower Yazoo River Watershed.

sediment load reduction. Results further confirmed that reforestation in or near the batture of the streams had a discernible effect in reducing sediment load.

A specific sediment load reduction is defined here as the mass of sediment load reduction per hectare increment in forest land per year. This value was calculated by dividing the mass of annual sediment load by the total area of forest land increment per year. For example, a specific sediment load reduction of 3.98 ton/ha/y means that for every ha increase in forest land, the sediment load from its watershed outlet is reduced by 3.98 ton/y. Table 4 lists the forest land increment and the specific sediment load reduction among the five different percentages of land use conversion for the LYRW. In general, a reduction in agricultural land associated with an increase in forest land enhanced the specific sediment load reduction. For example, the specific sediment load reduction was 3.98 ton/ha/y with a 25% reduction of agricultural land, but was 4.02 ton/ha/y with a 50% reduction of agricultural land. These load reductions occurred because of the decrease in agricultural land and concomitant increase in forest land near the batture of the streams that greatly reduced the surface water runoff and soil erosion thereby enhancing the sediment load reduction.

Relationship between the annual sediment load reduction and the forest land increment for the LYRW is given in Fig. 9B. With an $R^2 = 1.0$, we concluded that an excellent linear correlation existed between the annual sediment load reduction and the forest land increment. Under the assumption that other conditions remained the same except for reforestation, as used in this study, the percentage increase in forest land is proportional to the percentage decrease in sediment load reduction through the watershed outlet.

A load duration curve represents a relationship between any given value of sediment load and the percentage of time that this value is equaled or exceeded. Historically, very little effort has been devoted to applying load duration curves to sediment load reduction analysis (Ouyang et al., 2013). Fig. 10 shows the annual average sediment load duration curve for the LYRW. This load duration

Table 4
Forest land increment, specific water outflow attenuation, and specific sediment load reduction among five different percentages of land use conversion from agricultural land into forest land at the Lower Yazoo River Watershed.

Percentage conversion of agricultural land to forest land (%)	Forest land (ha)	Increase in forest land (ha)	Average annual water outflow (m^3)	Specific water outflow attenuation (m^3/ha/y)	Average annual sediment load (ton)	Specific sediment load reduction (ton/ha/y)
0	33,040	0	3.91E+08	0	289,818	0
25	35,165	2125	3.90E+08	211.120	281,364	3.979
50	37,289	4249	3.90E+08	237.510	272,727	4.022
75	39,414	6374	3.89E+08	281.494	264,091	4.036
100	41,538	8498	3.89E+08	263.900	255,455	4.044

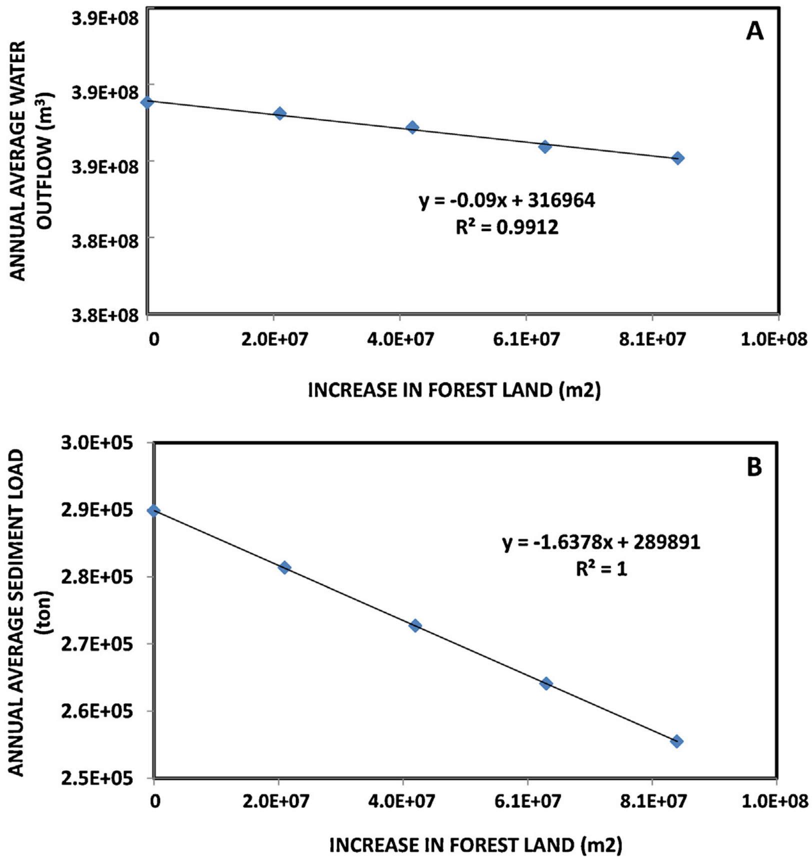

Fig. 9. Relationships of annual average water outflow (A) and sediment load (B) to forest land increment for the Yazoo River Watershed.

curve could provide a good tool for determining appropriate sediment load targets. For example, if the sediment load criterion is arbitrarily set at 640 ton/y for the LYRW, the likelihood that the sediment load will exceed this value is 73% with 0% agricultural land conversion, 70% with 25% agricultural land conversion, 63% with 50% agricultural land conversion, 55% with 75% agricultural land conversion, and 50% with 100% agricultural land conversion (Fig. 10). In other words, a decrease in agricultural land associated

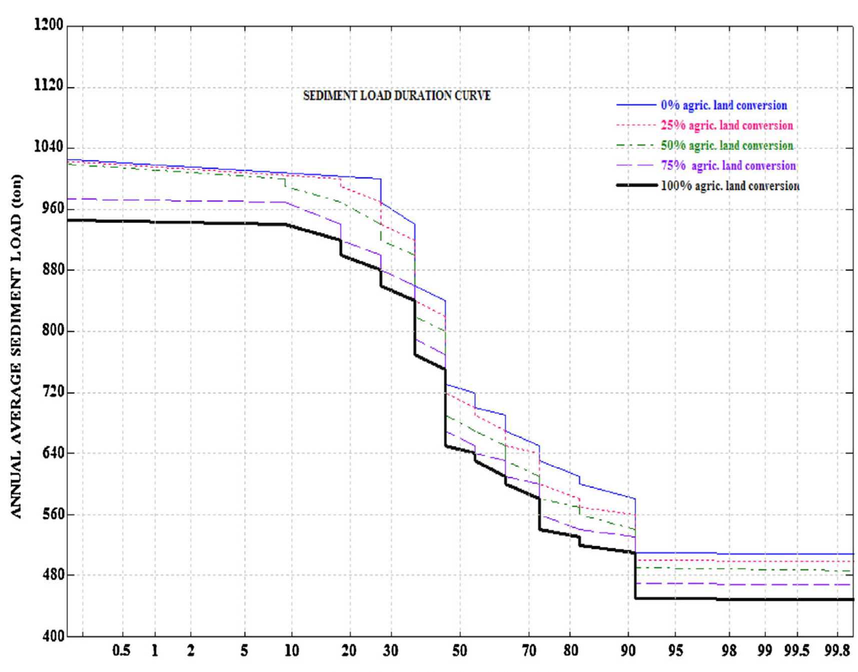

Fig. 10. Annual sediment load duration curves for the Lower Yazoo River Watershed.

with an increase in forest land reduced the likelihood of sediment load through the watershed outlet.

4. Summary

Comparison of the simulation results from the two scenarios (i.e., with and without reforestation) showed that a conversion of agricultural land into forests around or in the batture of the streams greatly attenuated water outflow and reduced sediment load, which occurred because forests absorb water and reduce surface water runoff and prevent soil erosion. In general, the larger the conversion area was, the better the water outflow attenuation and sediment load reduction that resulted, although specific outcomes were site-dependent. Overall, a two-fold increase in forest land area would result in approximately a two-fold reduction in the annual volume of water outflow as well as an annual reduction in the mass of the sediment load into the stream.

A specific water outflow attenuation is defined here as the volume of water outflow attenuation per acre increase in forest per year. On average, over a 10-year simulation, the specific water outflow attenuation was 250 m^3/ha/y for the LYRW. That is, per each hectare increase in forests, the water outflow through the LYRW outlet was reduced by 250 m^3 per year. Results demonstrated that reforestation in or around the batture of the streams had profound impacts and is a useful practice for water outflow attenuation. Similarly, a specific sediment load reduction is defined here as the mass of sediment load reduction per acre increase in forest per year. On average, over a 10-year simulation, the specific sediment load reduction was 4.02 ton/ha/y for the LYRW. That is, per each hectare increase in forests, the sediment load through the watershed outlet was reduced by4.02 ton/y. Results showed that reforestation in or around the batture of the streams had discernible impacts on sediment load reduction.

Seasonal variations of water outflow attenuation and sediment load reduction were also observed, with the maximum attenuation and reduction occurring in winter and the minimum attenuation and reduction occurring in summer. These occurred because of the wetter winters and drier summers in these watersheds, and because vegetation takes up water, and forest canopies intercept rainfall, in the summer but not in the winter.

A highly significant negative linear correlation existed between the annual average water outflow volume (or the annual average sediment load) and the forest land increment. In other words, an increase in forests decreased the annual average water outflow and sediment load.

A load duration curve depicts the relationship between any given value of sediment load and the percentage of time that this value is equaled or exceeded. Historically, very little effort has been devoted to applying load duration curves to sediment load reduction analysis. Our application of the load duration analysis technique showed that a decrease in agricultural land area associated with an increase in forest land area reduced the likelihood of a sediment load moving through the watershed outlet.

Under the assumption that other conditions remained the same except for reforestation, we demonstrated that the percentage increase in forest land is proportional to the percentage decrease in total volume of water outflow, and to the total reduction of the mass of sediment load, through watershed outlets. Therefore, reforestation is a practical way to attenuate water outflow and reduce sediment load in streams.

Improvements to the model can be made by collecting and adding more extensive hydrological and water quality data. Currently, long-term water quality data collection in the LMRAV is insufficient to facilitate needed modeling to address specific management and research questions. Water quality data for nitrogen, phosphorus, sediments, and pesticides are necessary for a comprehensive characterization of surface water contamination in the LMRAV. Therefore, we recommend the initiation of a surface water quality monitoring program for this purpose.

Finally, a successful reforestation program requires an understanding of site variations within floodplains and the importance of matching the establishment and growth requirements and relative flood tolerances of tree species to site characteristics. Soil physical and chemical conditions, including aeration, nutrient availability, and moisture availability during the growing season also must be considered in matching species to site. Further study is therefore warranted to address these issues. This information, in conjunction with added computer modeling, would provide a more comprehensive answer to the question of how reforestation impacts water quality and quantity in the LMRAV.

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