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Assessing the Effect of Spatial Variation in Soils on Sediment Loads in Yazoo River Watershed

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Abstract: Sediment deposition in river channels from various topographic conditions has been one of the major contributors to water quality impairment through non-point sources. Soil is one of the key components in sediment loadings, during runoff. Yazoo River Watershed (YRW) is the largest watershed in Mississippi. Topography in the watershed has been classified into two types based on land-use and slope conditions: Delta region with a slope ranging from 0% to 3% and Bluff hills with a slope exceeding 10%. YRW spans over 50,000 km^2; the Soil and Water Assessment Tool (SWAT) was used to estimate soil-specific sediment loss in the watershed. Soil predominance was based on spatial coverage; a total of 14 soil types were identified, and the sediment contributed by those soils was quantified. The SWAT model was calibrated and validated for streamflow, sediment, Total Nitrogen (TN), Total Phosphorus (TP), and Crop yield for soybeans. Model performance was evaluated using the Coefficient of determination (R^2), Nash and Sutcliffe Efficiency index (NSE), and Mean Absolute Percentage Error (MAPE). The performance was good for streamflow, ranging between 0.34 and 0.83, and 0.33 and 0.81, for both R^2 and NSE, respectively. Model performance for sediment and nutrient was low-satisfactory as R^2 and NSE ranged between 0.14 and 0.40, and 0.14 and 0.35, respectively. In the case of crop yield, model performance was satisfactory during calibration and good for validation with an R^2 of 0.56 and 0.76 and with a MAPE of 11.21% and 10.79%, respectively. Throughout YRW, soil type Smithdale predicted the highest sediment loads with 115.45 tons/ha/year. Sediment loss in agricultural fields with a soybean crop was also analyzed, where soil type Alligator predicted the highest with 8.37 tons/ha/year. Results from this study demonstrate a novel addition to the scientific community in understanding sediment loads based on soil types, which can help stakeholders in decision-making toward soil conservation and improving the environment.

Keywords: water quality; soils; watershed modeling; hydrology; SWAT

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1. Introduction

Soil loss due to human intervention has been prevalent since pre-historic times [1]. Human-induced activities such as deforestation, fire, agricultural practices, mining, etc., have increased soil erosion with time [2,3]. Global cultivable land has been classified as having moderate to severe soil erosion [4]. The advent of technology and its development helped in finding scientific solutions to this problem. Soil erosion not only poses a threat to the environment but also has implications for the economic aspects of agriculture, silviculture, and other human-dependent activities [5,6]. Sediment loads in surface water have been a key component in water quality impairment [7]. It has adverse effects on aquatic life by increasing the turbidity in the stream channels, channel aggradation, etc. [7,8]. The soil that is eroded is prominently the topsoil, which is the most fertile and where the nutrients are most easily accessible to the majority of crops, resulting in crop yield reduction [9,10]. Waterborne erosion of soil is a vigorous phenomenon with numerous intricacies concerning the intensity of precipitation, slope, soil type, etc., resulting in the loss of cultivable soils [11–13].

Agricultural runoff is one of the major non-point sources (NPS) contributing excessive sediment and nutrient loads to rivers and stream channels [14,15]. Watersheds with dominant agricultural land use produce runoff-carrying topsoil as sediment load, a pollutant source that is deposited into the surface water [16]. Therefore, this study analyzes the sediment loads from the agriculture-dominant and forested regions of the watershed. Numerous programs and studies have indicated that the implementation of Best Management Practices (BMPs) is one of the effective ways to mitigate sediment and nutrient loss from NPS pollutants [17–21].

The Mississippi river basin has the largest drainage area in the United States (US), transporting sediments from the provinces of Canada, passing through 31 states of the US, and draining into the Gulf of Mexico, resulting in eutrophication, sedimentation, depletion in the coral reef, etc. [22–25]. Soil particles are key constituents of sediments, each soil type is different in terms of erodibility, which depends on clay, silt, and sand (CSS) content, including soil biophysical properties, etc. [26,27]. Based on the particle size and presence of organic matter, soil bulk density and porosity vary. YRW has more than 50 different types of soil, with varied CSS signatures, and the watershed drains into the Mississippi river at Vicksburg, MS. Sediment load also depends on peak flow, crop cover, slope length, and the conservation practice that is implemented in the region [28]. Therefore, it is essential to quantify each soil erosion potential variation for implementing appropriate conservation practices.

Modeling tools had been extremely helpful in estimating outputs for desired fields; they are minimally invasive, robust, and accurate [29]. Numerous models have been developed such as the Revised Universal Soil Loss Equation (RUSLE) [30]; Water Erosion Prediction Project (WEPP) [31]; Annualized Agricultural Non-Point Source (AnnAGNPS) [32]; Soil and Water Assessment Tool (SWAT) [33], etc., to understand sediment and hydrologic processes in watersheds. SWAT has been used globally, for estimating hydrologic and water quality output for various watersheds [34–42]. The SWAT model has been used in this study for the Yazoo River Watershed (YRW), which has a drainage area of more than 50,000 km^2, with a heterogeneous landscape and land-use patterns. Mississippi is one of the largest producers of soybean, about 2.1 million acres are planted and harvested in the USA [43]. Almost half of the total watershed area was occupied by agricultural land, and the major crop during the simulation period was soybean. It is essential to have knowledge about implementing the conservation practices of BMP for optimal utilization of resources and to avoid any economic losses [20,44]. The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) [45] for estimating sediment loads, MUSLE considers peak flow instead of rainfall erosivity in the Universal Soil Loss Equation (USLE) [46]. SWAT uses the MUSLE with the coarse fragment factor (CFRG) to account for the effect of rock percentage while erosion occurs [47]. Recent studies indicate that the application of the MUSLE in watersheds with heterogeneous topography has resulted in accurate sediment load assessments [48–52]. Research on watershed scale sediment load assessment based on soil type and their predominance is very limited and this study introduces sediment loadings based on soil types. Therefore, the objectives of this study were to (i) develop a watershed scale model for YRW; (ii) calibrate and validate the model for hydrologic, water quality, and crop yield parameters; and (iii) quantify the effect of soil spatial variation on sediment loads in YRW.

2. Materials and Methods

2.1. Study Area

YRW has a drainage area of about 50,000 km^2 with nearly 47% agricultural land, 50% forested land, and 3% urban, wetlands, and water. YRW spreads across 30 counties in the state of Mississippi, making it the largest watershed in the state, as shown in Figure 1. The forested area is located toward the northeastern part and the agricultural on the western part of the watershed. The majority of the agricultural land is in the Mississippi Delta, with largely flat slopes. Numerous soil types were found in the watershed but few of them covered the majority of the area. Major soil types found in the region belonged to hydrologic soil groups B, C, and D, listed in Table 1; these soils have moderate to high erosive potential.

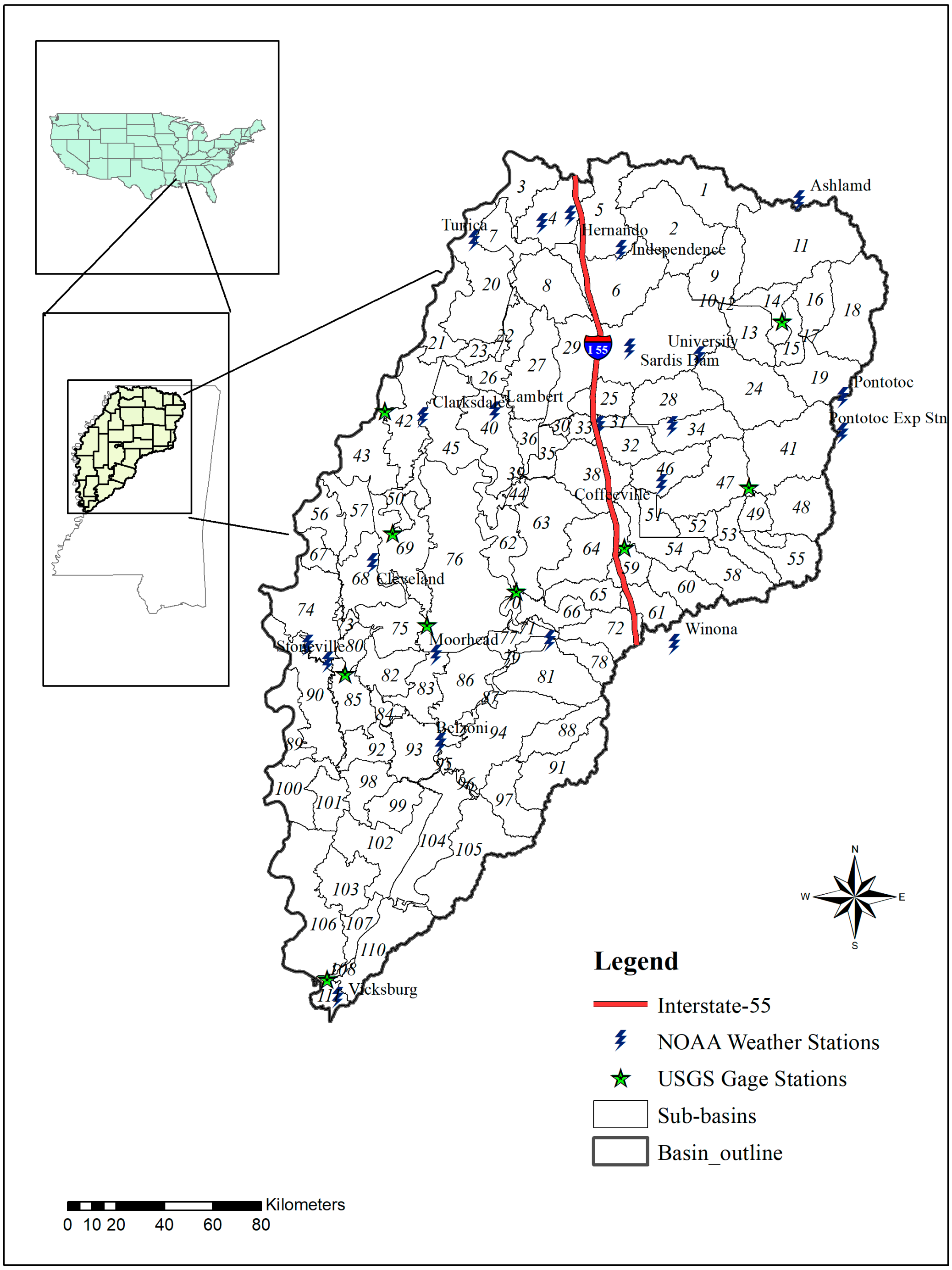

Figure 1. Watershed location showing weather stations and USGS gages.

Table 1. List of predominant soils based on area coverage and clay silt sand percentages.

Sc. No.	Soil Name	No. of HRUs	Hydrologic Soil Group	Area (ha)	Clay-Silt-Sand %	% Watershed Area
1	Alligator	213	D	422,447.36	57-39-4	8.32
2	Arkabutla	83	B, C, D	60,583.066	19-67-14	1.2
3	Collins	77	B, C	146,331.57	12-69-19	2.88
4	Cuthbert	76	C	65,710.24	13-20-67	1.3
5	Dowling	143	D	239,293.23	59-37-4	4.71
6	Dubbs	54	B	64,831.75	13-45-42	1.27
7	Dundee	68	C	169,239.4	17-65-18	3.34
8	Falaya	102	B, C	146,458.34	12-68-20	2.89
9	Forestdale	67	D	148,385.51	28-54-18	2.91
10	Loring	64	C, D	87,445.78	17-78-5	1.73
11	Memphis	176	B	227,375.2	17-77-6	4.48
12	Smithdale	294	B	364,190.11	8-25-66	7.16
13	Sharkey	178	D	451,143.45	62-35-3	8.86
14	Tensas	51	D	11,866.65	33-47-20	1.17
		Total		2,605,301.66		52.22

2.2. Model Description

SWAT is a GIS-based hydrologic and water quality model developed by the United States Department of Agriculture—Agriculture Research Services (USDA-ARS) [33]. It is developed as an extension of ArcGIS [53]. SWAT model was made by combining numerous models [29] such as Groundwater Loading Effect on Agricultural Management Systems (GLEAMS) [54], Erosion Productivity Impact Calculator (EPIC) [55], Simulator for Water in Rural Basins (SWRRB) [56], Chemical, Runoff and Erosion from Agricultural Management Systems (CREAMS) [57], and Routing Outputs to Outlet (ROTO) [58] models. SWAT is capable of estimating streamflow, sediment, and nutrient outputs at daily, monthly, and yearly time steps, and the larger watershed is delineated into smaller sub-basins, which can be further investigated at much smaller Hydrologic Response Units (HRU). This model is beneficial for running simulations for longer periods.

2.3. Model Data Inputs

SWAT is a data-driven model, some of the primary inputs for the model are Digital Elevation Models (DEM) [59] with 30 m × 30 m resolution; Soil data layers from the Soil Survey Geographic (SSURGO) database [60]; Cropland Data Layer from USDA—National Agriculture Statistical Service [61]; Weather data mainly precipitation and temperature from National Oceanic and Atmospheric Administration [62]; Crop management inputs such as scheduling planting date, fertilizer inputs, irrigation, pesticide inputs, and harvest dates for Soybean Crop were obtained from Mississippi Agricultural and Forestry Extension Service [63]; Organic manure inputs were given as per ASABE manure Standards [64] and Forest Management inputs were obtained Mississippi Forestry Commission Handbook [65].

2.4. Calibration and Validation

SWAT model for YRW calibrated and validated for streamflow, sediment, TN, and TP. Streamflow had been calibrated from 2005 to 2008 and validated from 2009 to 2012. Observed daily flow in m^3/s was obtained from the United States Geological Survey [66]. SWAT—Calibration Uncertainty Program (SWAT-CUP) is an auto-calibration tool, which uses Sequential Uncertainty Fitting—2 (Sufi—2) algorithm for adjusting multiple parameters [67]. Sediment, TN, and TP were calibrated from 2014 to 2016 for the Big Sunflower—USGS gage station at Merigold, MS, and validated for the same period Bogue Phalia—USGS gage station at Leland, MS. Observed Sediment, TN, and TP data were obtained from the field-collected samples at bi-weekly intervals from 2014 to 2016. Manual calibration method was adopted to calibrate sediment and nutrient outputs. Statistical indices such as Coefficient of determination (R^2) [68], Nash and Sutcliffe Efficiency index (NSE) [69], and Mean Absolute Percentage Error (MAPE) [70] were used to determine the model performance during calibration and validation of streamflow, sediment, and nutrient loads and crop yield. Sensitive parameters for Hydrologic and water quality parameters were listed in the study conducted by Venishetty and Parajuli, in 2022 [71]. Calibration of crop yield was performed to account for the errors possible in estimating runoff, soil erosion, and water balance due to uncalibrated crop growth/yield [72,73]. Sensitive parameters in calibrating crop yield were obtained from different studies [74–77] Table 2.

Table 2. Sensitive parameters adjusted during calibration and validation of crop yield.

Crop Yield Parameters	Definition	Fitted Value
BIO_E ((kg/ha)/(MJ/m^2))	Biomass Energy ratio	25
HVSTI ((kg/ha)/(kg/ha))	Harvest Index	0.34
BLAI (m^2/m^2)	Maximum Potential Leaf area index	6
WSYF ((kg/ha)/(kg/ha))	Lower limit corresponding to harvest index	0.01
DLAI (Heat units/heat units)	Fraction of the plant growing season when leaf area begins to decline	0.6

2.5. Sediment Load Estimation

Modified Universal Soil Loss Equation (MUSLE) [45] is used in sediment load estimation by SWAT and was developed as an improvement to USLE. Sediment calculations were performed based on runoff factor where the energy required for soil particle separation and transportation was included. Delivery ratios in rainfall erosivity factor (R) of USLE consider just the energy required for soil particle separation. Therefore, the results from USLE resulted inaccurate while estimating sediment load by water quality models. The following Equation (1) is used while calculating sediment load with MUSLE [47]:

$$Y = 11.8\left(Q * q_p\right)^{0.56} * K * LS * C * P * CFRG \quad (1)$$

$$CFRG = e^{(-0.053 \, * \, rock \, \%)} \quad (2)$$

where Y is Storm specific sediment yield in metric tons (MT); Q is runoff volume of the respective storm event, measured in m^3; q_p is peak runoff rate, measured in m^3/s; K is soil erodibility factor, K values are assigned based on soil and topographic conditions by the model, using the equations listed in the SWAT—Input/output Documentation [74]. The SWAT model assigned default K values based on HRU characteristics were used in this study. LS is the slope length and slope gradient factor; C is the crop management factor; P is the conservation practice factor; and 11.8 and 0.56 are unit conversion factors to MT. The $CFRG$ is the coarse fragment factor.

2.6. Soil Classification

Soil Classification was performed by using the soil input file from the SSURGO database that was extracted from the soil layer [60]. Soil profile for all the HRUs was identified including the CSS percentages. Major soil types in the watershed had been isolated based on the area covered by the soils and the number of HRUs present in each soil. Each soil type was matched based on the unique identification number in each subbasin obtained from the HRU report generated by the model. A minimum of 50 HRUs was set as the threshold during the analysis. The majority of these soils were classified under hydrologic soil groups B, C, and D, which were moderate to severe erodible soils, as mentioned in Table 1.

3. Results and Discussion

3.1. Calibration and Validation

Model calibration and validation were performed monthly for streamflow, from 2005 to 2008, and from 2009 to 2012, respectively, at seven USGS gage stations in the watershed. Overall model performance was good, with R^2 ranging from 0.34 to 0.83 and NSE from 0.33 to 0.81 during calibration, and R^2 0.65 to 0.78 and NSE from 0.57 to 0.75 during validation, as shown in Table 3. The calibration and validation trends are shown in Figure 2 for the USGS gage station in Skuna River at Bruce, MS (Station number. 7283000).

Table 3. Streamflow calibration and validation from 7 gage stations in the watershed.

Sc. No	Gage Station	USGS Gage Station Number	Calibration		Validation	
			R^2	NSE	R^2	NSE
1	Skuna River, Bruce, MS	7283000	0.83	0.81	0.71	0.7
2	Big Sunflower, Sunflower, MS	7288500	0.75	0.71	0.66	0.59
3	Little Tallahatchie, Etta, MS	7268000	0.63	0.60	0.77	0.68
4	Big Sunflower, Merigold, MS	7288280	0.66	0.65	0.72	0.61
5	Bouge Phalia, Leland, MS	7288650	0.81	0.81	0.73	0.75
6	Tallahatchie River, Money, MS	7281600	0.55	0.4	0.65	0.57
7	Steel Bayou, Vicksburg, MS	7288955	0.34	0.33	0.78	0.72

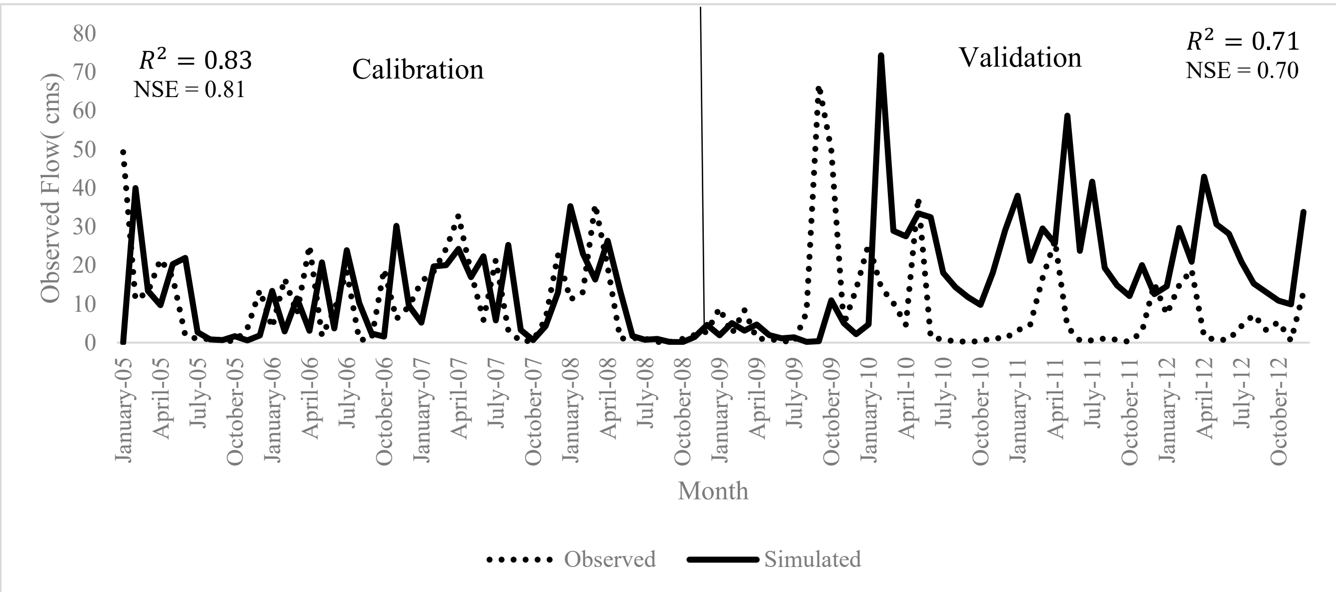

Figure 2. Streamflow calibration and validation trend at Skuna River gage (7283000), Bruce, MS, USA.

Model performance for sediment and nutrient calibration was found to be poor and satisfactory, respectively, but within the acceptable range from previous studies [19,38,78,79]; this was due to extreme weather conditions while field sampling for the calibration and validation period in the region [80], and the availability of observed data was limited, from 2014 to 2016 for two stations. Calibration was performed for the USGS gage station at Merigold, MS; R^2 and NSE for sediment were 0.18 and 0.18; TN: 0.07 and 0.12; and TP: 0.34 and 0.20, respectively. Validation for water quality parameters was performed at the USGS gage station at Leland, MS; R^2 and NSE for sediment: 0.15 and 0.14; TN: 0.09 and 0.14; and TP: 0.40 and 0.35, respectively.

In the case of soybean crop yield, model performance was good and verified with previous literature [75,76,81]. For agricultural watersheds, the impact of crop yield is high in estimating runoff, for accurate water and nutrient balance. Therefore, calibration of the model for crop yield parameters was essential for water quality processes [72,73,82,83]. The average annual observed soybean yield was collected from USDA—NASS. Model performance for soybean yield is shown in Table 4.

Table 4. Model performance for Soybean yield.

Soybean Yield			
Process	**County**	**R^2**	**MAPE**
Calibration	Sunflower	0.56	11.21
Validation	Leflore	0.76	10.79

3.2. Sediment Load Assessment

3.2.1. Watershed Scale

Average annual sediment loss from all the sub-basins in the watershed based on soil coverage was estimated; our results indicated that the highest amount of sediment load was estimated from the area with Smithdale soils, with CSS% 8-25-66 covered, which was 115.45 tons/ha/year, then followed by Loring with CSS% 17-77-6, Arkabutla with CSS% 19-67-14, and Memphis with CSS% 17-77-6, which were 55.67, 48.17, and 44.78 tons/ha/year, respectively. The least sediment load was estimated for Dubbs, CSS% 13-45-42, which was about 0.22 tons/ha/year. The sediment load for 14 predominant soils was quantified and mentioned in Table 5, in the order of highest to lowest. Figure 3 shows the comparison of sediment load concerning soil type. The soils in Mississippi were formed during the last glacial period about 11,700 years ago and through the Holocene. The alluvial deposits in the Mississippi valley were formed by the Holocene Mississippi River floodplain deposits. With time, clay, sand, and silt from the Mississippi River bed spread across the Delta and the Bluff hill region of Mississippi [84]. The soil types simulated by the model matched the characteristics mentioned in the soil survey reports of the Natural Resources Conservation Service (NRCS) [60]. Although some of the soil types had moderate erodibility, they resulted in high sediment yield due to heterogeneity in slope length, gradient, and crop cover. These soils were in the hilly region with slopes starting from 3% and exceeding more than 10%. With the increase in slope, slope length decreased, starting from about 91.51 m and going as low as 24.12 m, respectively, resulting in higher runoff and sediment load. Smithdale soils are largely located in the region with higher slopes, sand being one of the major components of these soils, and there is less water-holding capacity. The steep slope and lower water holding capacity resulted in increased erosion and higher sediment loads. Although Loring soils have a similar topography, the percentage of their clay content is higher, which has a better water-holding capacity than sand, as clay particles stick to the ground allowing them to create some resistance [85–87].

Table 5. Sediment load of predominant soils throughout the watershed.

Rank	Soil Name	Sediment Load (Tons/ha/Year)
1	Smithdale	115.45
2	Loring	55.67
3	Arkabutla	48.17
4	Memphis	44.78
5	Collins	33.92

Table 5. *Cont.*

Rank	Soil Name	Sediment Load (Tons/ha/Year)
6	Cuthbert	17.61
7	Alligator	8.37
8	Sharkey	7.28
9	Dowling	1.87
10	Falaya	1.46
11	Forestdale	0.86
12	Dundee	0.67
13	Tensas	0.28
14	Dubbs	0.22

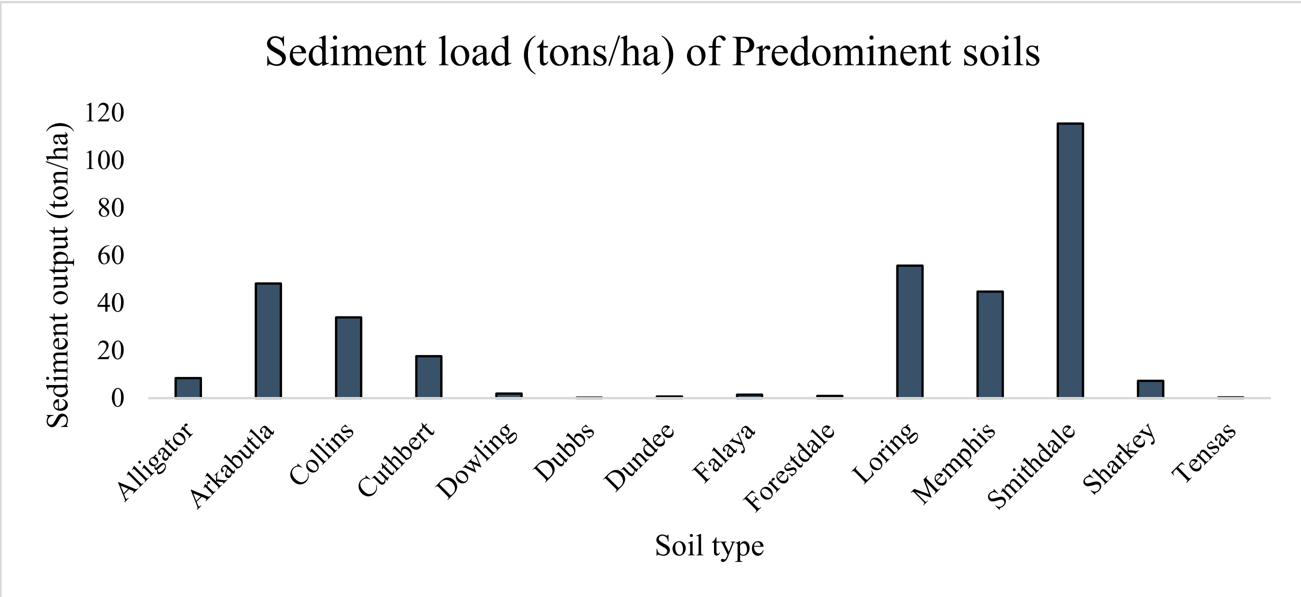

Figure 3. Sediment load comparison among soil types.

3.2.2. Agriculture Dominant Region

The soybean crop was chosen as a major crop in the agriculture prevalent region since the area planted was more than 55% soybean, with the rest being corn, cotton, and wetlands. This region was classified as delta with a constant slope, with a slope that was 1–3% and a slope length of 121.90 m, including constant cropping practices with minimal runoff. The highest sediment load was estimated for Alligator soils with CSS% 57-39-4 as about 8.37 tons/ha/year, followed by Sharkey with CSS 62-35-3, and Memphis with CSS 17-77-6, which were 6.55 and 4.70 tons/ha/year, respectively. The least sediment load was estimated for the Dubbs soil type, CSS% 13-45-42, which was about 0.22 tons/ha/year. A total of 9 out of 14 were found in this region and are listed in Table 6, with a comparative analysis between soil types shown in Figure 4. With the advent of increased sediment load due to topsoil loss, a moderate correlation was observed between crop yield and sediment load; the correlation was verified and followed previous studies [12,88,89] since the model predictions for sediments and crop yield are based on different variables. The sediment loads are estimated considering flow, slope, topography, etc., whereas crop yield is estimated based on seed variety, irrigation, precipitation amount, temperature, etc. Although model predictions indicate a decrease in yield over the simulation period, the advancement of technology and the adoption of different varieties of soybean accounted for the yield losses [63].

Table 6. Major soils with major agricultural land use.

Rank	Soil Name	Sediment Yield (Ton/ha/Year)
1	Alligator	8.37
2	Sharkey	6.55
3	Memphis	4.71
4	Dowling	1.63
5	Forestdale	0.86
6	Collins	0.73
7	Dundee	0.56
8	Falaya	0.33
8	Tensas	0.28
9	Dubbs	0.22

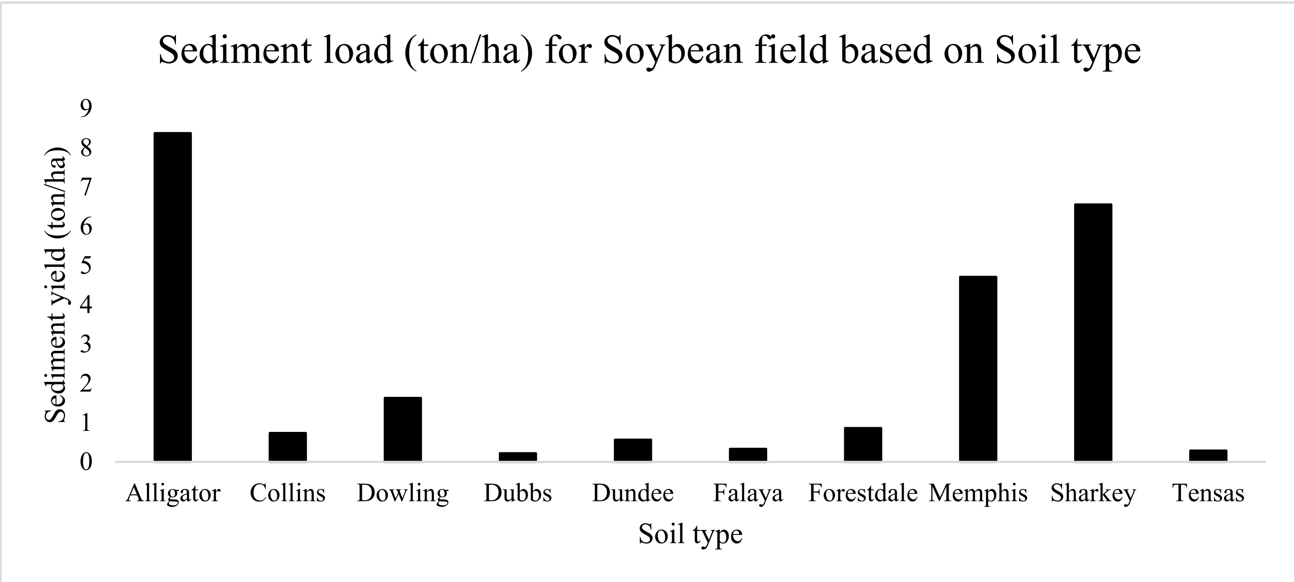

Figure 4. Comparative analysis among major soils in the agriculture dominant region.

4. Conclusions

Results from this study indicate that there is a significant difference in sediment loads with respect to spatial variability for different soil types and land-use conditions. Overall, sediment load results from the analysis show that Smithdale soils contributed the highest amount, and the least sediment load was for Dubbs soils, for heterogeneous slope gradient, slope length, and the crop management factor over the landscape. Although the slope gradient, slope length, and crop management were kept constant with nominal flow conditions, it was observed that the soil types found in the agricultural land use of the YRW, mainly Alligator, Sharkey, and Memphis, were highly erodible. The correlation between the sediment load and crop yield was moderate; to minimize the loss in crop yield, new technologies have been adopted by farmers including the seeding of high-yielding varieties. Numerous studies have discussed that the loss of topsoil in sediments has a significant impact on crop yield since most of the plant-available minerals and nutrients are present in the top few inches of the soil layer [9,90,91]. Therefore, it is evident that variability in soil type resulted in variable sediment loads. The results from this research study will provide a novel input toward soil conservation and soil-sediment dynamics. The soil-specific analysis that was presented in this paper could assist stakeholders from diverse backgrounds working on ecological sustainability including sediment control, water quality, and environmental science research, in selecting appropriate crop management and conservation practices based on the severity of erosion and sediment loading.

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