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Spatial Optimization of Conservation Practices for Sediment Load Reduction in Ungauged Agricultural Watersheds

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Abstract: Conservation practices (CPs) are used in agricultural watersheds to reduce soil erosion and improve water quality, leading to a sustainable management of natural resources. This is especially important as more pressure is applied on agricultural systems by a growing population and a changing climate. A challenge persists, however, in optimizing the implementation of these practices given their complex, non-linear, and location-dependent response. This study integrates watershed modeling using the Annualized Agricultural Non-Point-Source model and a GIS-based field scale localization and characterization of CPs. The investigated practices are associated with the implementation of riparian buffers, sediment basins, crop rotations, and the conservation reserve program. A total of 33 conservation scenarios were developed to quantify their impact on sediment erosion reduction. This approach was applied in an ungauged watershed as part of the Mississippi River Basin initiative aiming at reducing one of the largest aquatic dead zones in the globe. Simulation results indicate that the targeted approach has a significant impact on the overall watershed-scale sediment load reduction. Among the different evaluated practices, riparian buffers were the most efficient in sediment reduction. Moreover, the study provides a blueprint for similar investigations aiming at building decision-support systems and optimizing the placement of CPs in agricultural watersheds.

Keywords: AnnAGNPS; ungauged watershed; conservation practices; agricultural watershed; soil erosion; sediment load; watershed modeling; GIS; riparian buffer; sediment basin

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1. Introduction

Soil erosion is a global challenge causing the siltation of waterways and dams, the degradation of water quality and the reduction of soil fertility and crop yield among other environmental and socio-economic issues [1–4]. These problems are projected to increase with a changing climate characterized by a higher frequency and intensity of extreme precipitation events [5,6], hence threatening further, the future of food security. Presently, the U.S. agricultural sector loses about $44 billion per year from soil erosion impacts on fertile soil quantity and water quality [7]. In fact, 80% of freshwater bodies in the U.S. are impacted by nonpoint source pollution [8,9], which is primarily caused by soil movement from agricultural fields [10].

Over the last few decades, conservation practices have proven to be an effective measure for preventing or minimizing soil erosion and its negative impacts on crops, water, and soils [11–13]. These practices include, but are not limited to, minimum tillage, permanent soil cover, riparian vegetation buffer, crop rotation, terraces, sedimentation basins, strip cropping, and intercropping [14,15]. The implementation of these practices has shown results in terms of water quality improvement, soil erosion reduction, soil fertility increase, soil moisture retention, long-term yield increase, and food security [16].

However, conservation practices range broadly in effectiveness, since water, nutrients and soil particles are transported along various pathways and controlled by multiple natural and anthropogenic processes [17–23]. One of the main factors impacting conservation practices effectiveness is their spatial placement within the watershed. The non-point source pollution reduction results vary as a function of the upstream area drainage patterns, soil characteristics, topography, vegetation density and land management among other physical factors [23–27]. Hence, the need for investigations to determine the best implementation conditions of these conservation practices while accounting for their complex, nonlinear, and location dependent response. Often, the evaluation of conservation practices at the watershed-scale is conducted by two types of studies.

The first type involves the identification of candidate locations for conservation practices implementation in agricultural watersheds using geographic information system (GIS) analyses [28,29]. These efforts support the development of decision support systems to aid watershed scale conservation plans based on ranking location suitability for specific conservation practices. However, despite the significant contribution of these studies in identifying potential sites for practice implementation, they are not designed to generate temporal sediment yield and load estimates like in the case of comparable watershed models.

The second type involves investigations conducted to evaluate the impact of conservation practices using watershed-scale hydrological models. In this type of study, characterization and simulation of conservation practices is often performed indirectly. Input parameters controlling flow and/or infiltration are adjusted to estimate the impact of the conservation practice within the basic modeling unit (e.g., Hydrological Response Unit (HRU)). For example, in studies based on the Soil and Water Assessment Tool (SWAT) [30], contour farming has been described by adjustments to curve numbers (CNs) [11], conservation tillage has been described by adjustments to CNs and Manning's roughness coefficient (n) [31], and vegetative practices has been simulated by adjusting CN, n, and universal soil loss equation cover management factor (USLE–C) [32]. In addition to an indirect representation of these conservation practices, their location is also under-characterized since the location of HRUs within the sub-catchment is not considered in the calculations [31]. These factors increase the uncertainties in the evaluation of most conservation practices in which efficiency is dependent on location and physical characteristics (e.g., width of the riparian buffer, size of the sediment basin).

In this study, a comprehensive evaluation of conservation practices efficiency was conducted through the integration of both hydrological modeling and GIS-based field scale localization and characterization of these practices in a wide range of scenarios. Four sets of conservation practices are targeted in this study: riparian buffers, sediment basins, crop rotations, and the conservation reserve program. These practices were selected due to their high efficiency in reducing sediment detachment and/or transport at field and/or watershed scales [33–39], in addition to the suitability of the developed integrated methodology in quantifying their location-dependent impact [40–48]. This overarching goal can be further subdivided into the following specific objectives: (1) evaluation of conservation scenarios based on location of conservation practices at field-scale informed by hydrological model results and characterized at raster-grid scale by GIS tools, (2) quantification of type and placement of conservation practices efficiency locally, where they were implemented, and their contribution to the overall watershed's sediment load, and (3) assessment of the tradeoff between gains in sediment load reduction and potential loss in productive area based on a multi-objective function.

2. Materials and Methods

2.1. Study Area

The North Fork Forked Deer River watershed used in this study is in the northern portion of the Lower Mississippi hydrological region in West Tennessee (Figure 1). The total drainage area is 631.31 km^2 flowing into the Forked Deer River. The average annual precipitation in the watershed is 1437 mm, with about 70% occurring during the growing season (March–October), March being the wettest month of the year (i.e., 167 mm on average), and August the driest month (i.e., 84 mm on average). Soils in the watershed include 55 classes as defined by the USDA Web Soil Survey [49], with silt loam being the most dominant soil texture in the watershed.

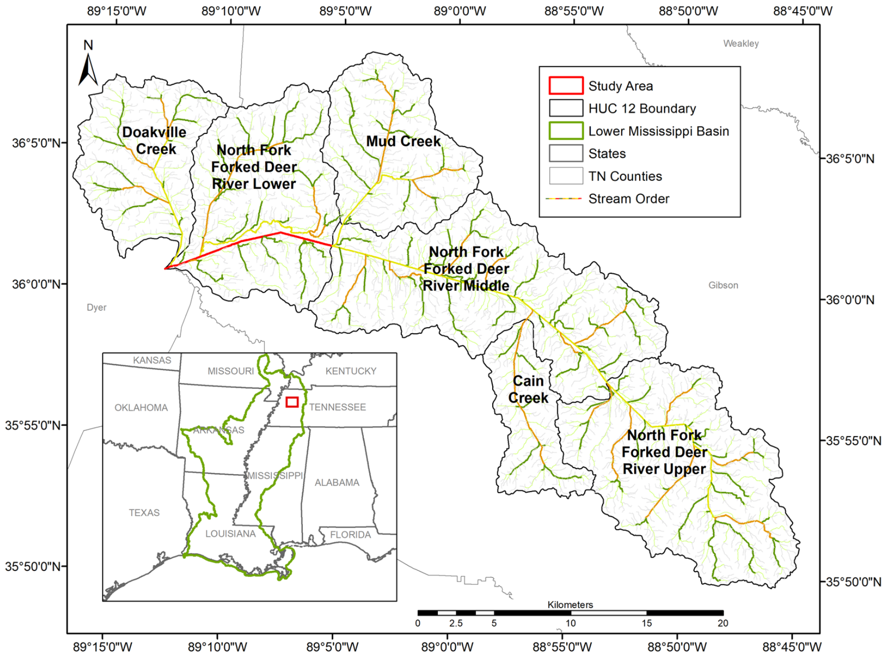

Figure 1. Location of the study area in the lower Mississippi water resource region, including six USGS HUC-12 sub-watersheds.

The watershed consists of six USGS 12-digits hydrologic-unit code (HUC-12), referred to as sub-watersheds by the U.S. Geological Survey (Figure 1). The North Fork Forked Deer River Upper covers a total area of 147.80 km^2 with an average slope of 7%. Predominant land uses include agricultural cropland (38%), forest (36%), pastures (19%), and developed land (7%). Cain Creek is in the southernmost region with a total area of 43.56 km^2 with average slopes of 6.0%. Predominant land uses include agricultural cropland (59%), forest (18%), pastures (10%), and developed land (13%). Mud Creek is in Gibson County. It covers a drainage area of 84.64 km^2 and has an average slope of 4.89%. Predominant land uses within this sub-watershed include agricultural cropland (78%), forest (11%), pastures (4%), and developed land (7%). The North Fork Forked Deer River middle is the largest of the HUC-12 divisions with a total area of 161.13 km^2 and an average slope of 5.6%. Predominant land uses include agricultural cropland (51%), forest (33%), pastures (8%), and developed land (7%). The Doakville Creek is the western-most HUC 12 division and is in Dyer County. It is the second smallest sub-watershed, with a total area of 77.49 km^2. Predominant land uses within this sub-catchment include agricultural cropland (80%), forest (7%), pastures (7%), and developed land (6%). The North Fork Forked Deer River lower covers a drainage area of 115.38 km^2 and has an average slope of 3.84%. Land uses within this sub-watershed include agricultural cropland (73%), forest (19%), pastures (4%), and developed land (4%).

The lack of streamflow observations in most catchments around the world and the nation, especially in small catchments in rural areas has created a setback for hydrological and conservation investigations in these regions [50]. This ungauged watershed represents a study case of this challenge, where conservation practices are needed but cannot be supported by field measured streamflow and sediment data. Methods to minimize the uncertainties introduced by the lack of field gauges are discussed in Section 3.1.

2.2. The AnnAGNPS Model

The USDA Annualized Agricultural Non-Point Source (AnnAGNPS) [40–44] watershed pollution model was designed to evaluate the impact of integrated long-term effects of farming and conservation practices on water quality within ungauged agricultural watersheds. The model contains components to describe processes controlling pollutants sources and sinks, their corresponding movement throughout the watershed, and their interrelated contribution to the watershed total pollutant load. A description of the AnnAGNPS model's components and mathematical formulation has been provided in previous studies [40–44], and only a summary of the AnnAGNPS model's key characteristics relevant to this study is provided.

The watershed is internally represented within AnnAGNPS as cells connected to reaches. Reaches are designated to simulate physical processes resulting from concentrated flow (channels) while cells (often referred to as sub-catchments, fields, or AnnAGNPS cells to distinguish from raster grid cells) are designed to simulate physical processes occurring at upland areas that drain into reaches. Sub-catchments are hierarchically connected to reaches to describe surface and shallow subsurface flow, sediment detachment, transport and deposition processes, and pollutants transport throughout the overland flow areas of the watershed. Upland erosion processes include sheet and rill, tillage-induced ephemeral gullies, and classical and edge-of-field gullies. Reaches and sub-catchments are individually described in terms of topography, weather, soil, and management. Sizes of sub-catchments are often selected based on field sizes to enhance the spatial characterization of practices [45]. Specifically, management input databases are designed to describe farming practices on high temporal resolution (up to daily) to capture unique farming management schedules and their associated operations at the field scale.

2.3. Characterization and Modeling of Riparian Buffers

Riparian buffers are defined as either natural or planted vegetation located at the edge of fields or along reaches. They are designed to reduce the delivery of eroded sediment from fields or sub-catchments (cell-located buffers) into reaches or the delivery of sediments from one reach to another (reach-located buffers). The potential maximum sediment trapping efficiency input for each AnnAGNPS cell containing a riparian buffer was determined using a GIS approach available from the AGNPS Buffer Utility Feature (AGBUF) software package [46]. Using a user-provided GIS layer describing spatially the location of the buffer and the vegetation type, the software analyzes raster grid cells within the sub-catchment to calculate the potential maximum sediment trapping efficiency based on slope, drainage area, and vegetation type [42]. The actual sediment trapped by riparian buffers for each of the five AnnAGNPS sediment particle size classes is determined using relationships involving the potential maximum sediment trapping efficiency from AGBUF and daily surface flow [47]. The advantage of the approach is the scale at which calculations are conducted (3 m raster grid cell) to describe and place the riparian buffer within each sub-catchment (i.e., AnnAGNPS cell).

2.4. Characterization and Modeling of Constructed Sediment Basins

Similar to the riparian buffer component, sediment basins are optimally located within the watershed and physically characterized using GIS-based analyses and the AGNPS Wetland Feature (AGWET) software package [47]. The latter is designed to record information of each sediment basin's surface area, barrier height, presence/absence of vegetation, location in the watershed, and upstream drainage area are calculated using the user-provided GIS layers [48]. The development of the sediment basin input databases for the AnnAGNPS model is generated using AGWET. The AnnAGNPS watershed pollution model is then used to determine the change in energy between inflows and outflows and the respective impact on water quality processes for each sub-catchment. The conservation of mass is applied to both hydrology and pollutant balances. The integration of GIS analyses including the spatial distribution of constructed sediment basins with the sub-catchment, and the description of soil, land use, and topography at raster grid scales enhance the characterization of each sediment basin and its location driven impacts on water and sediment.

2.5. Baseline Conditions

2.5.1. Topography

Topographic information was obtained from LiDAR datasets available in the public data repository of the Tennessee Department of Finance and Administration [51]. Datasets were provided as raster grids with one-meter spatial resolution. Raster grids were mosaiced, reprojected, scaled, resampled to three-meter spatial resolution, and hydrologically enforced. Topographic analyses were performed with the GIS TopAGNPS software package. The TopAGNPS technology is built based on the Topographic Parameterization (TOPAZ) software [52,53]. In addition to standard GIS operations for processing DEM, TopAGNPS has the tools to sub-divide the watershed into reaches and sub-catchments. An iterative approach was applied where datasets generated by the TopAGNPS computer program were compared to high-resolution imagery and auxiliary GIS layers to determine whether manmade obstructions would hinder the flow routing algorithm. The latter could cause structures to work as pseudo-dams resulting in an incorrect surface flow network and/or increase ponding beyond normal levels. A custom computer program has been developed to modify user-selected regions in the DEM to enforce surface flow. Two user-provided parameters control how the watershed is subdivided into sub-catchments and reaches. A critical source area (CSA) value of five hectares and a maximum source channel length (MSCL) value of 250 m were selected, yielding a total of 12,573 sub-catchments and 5047 reaches (Table 1 and Figure 2).

Table 1. Discretization of the watershed into AnnAGNPS cells.

HUC-12 Name	AnnAGNPS Cells (Sub-Catchments)			
	Number	Average Area (ha)	Average Slope (%)	Average Flow Length (m)
North Fork Forked Deer River Upper	2946	5.00	8%	246.45
Cain Creek	904	4.81	8%	245.89
Mud Creek	1682	5.04	6%	255.84
North Fork Forked Deer River Middle	3165	5.10	5%	259.92
Doakville Creek	1565	4.95	6%	243.84
North Fork Forked Deer River Lower	2311	4.99	4%	259.56
Total	12,573			

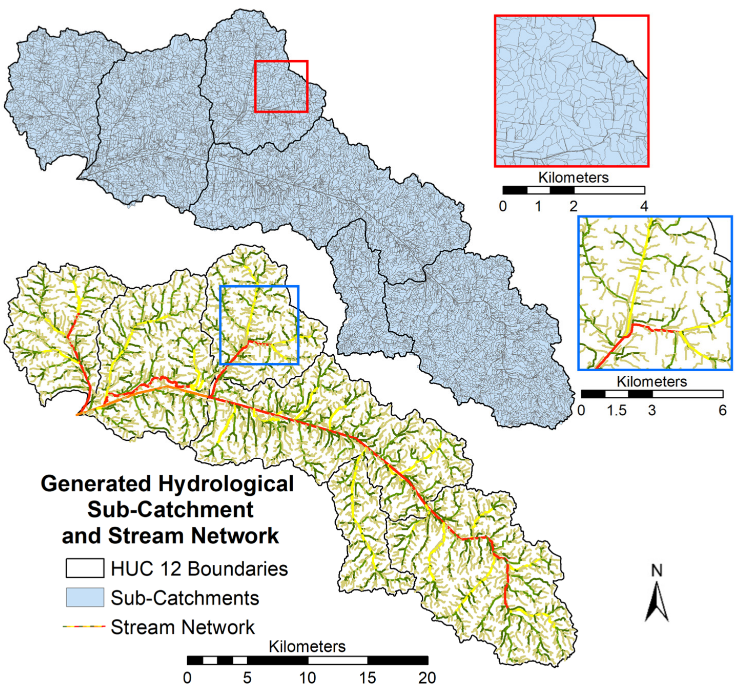

Figure 2. Discretization of the watershed into sub-catchments representing fields (upper map) and reaches representing concentrated flow (lower map).

2.5.2. Climate

Climate datasets at daily temporal scale from 2008 to 2018 were obtained from the U.S. National Oceanic and Atmospheric Administration (NOAA) [54] for Gibson, Dyer, Weakley, Carroll, Crockett, and Madison Counties. These datasets, including daily precipitation and minimum and maximum air temperature information, were pre-processed, quality controlled, and analyzed to identify the weather stations with the greatest temporal data coverage and their location in relation to the watershed. However, most of these stations were located outside of the study area boundaries (Figure 3). Hence, neighboring stations from outside the watershed were used to fill data gaps in the stations located within the study area (referred to as secondary stations). Decision on which station to draw information from was based on spatial zones of influence using Thiessen polygons. The primary station was defined to be in the centroid of the study area (Figure 3) and to be the average of all stations. In the AnnAGNPS watershed model, the primary climate station is only used as a backup to fill a missing data point in the secondary stations. The secondary station records were also filled with data from the nearest neighboring stations (Figure 3) and were evaluated to remove data anomalies. In the AnnAGNPS model, each sub-catchment (i.e., AnnAGNPS cell) is assigned to a secondary climate station.

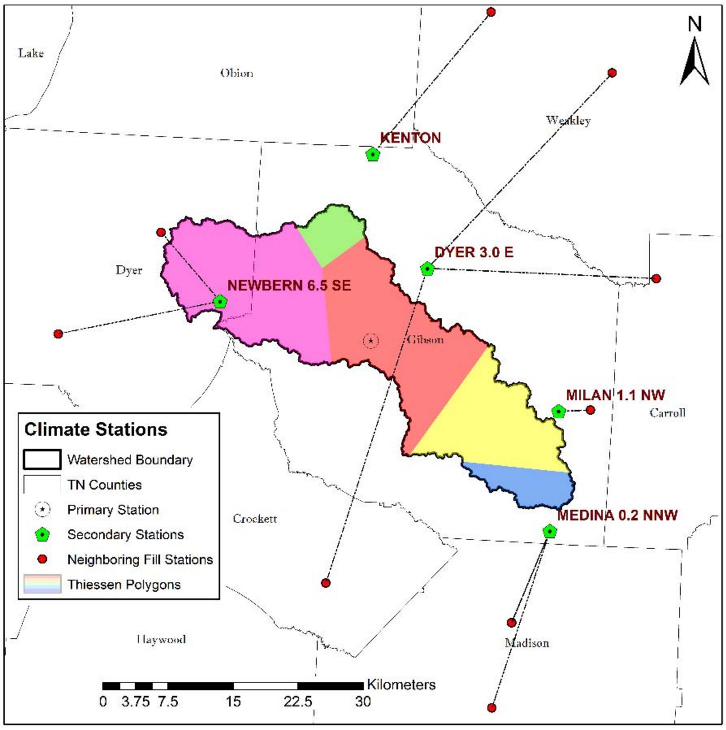

Figure 3. Climate station locations used in the study.

Weather characteristics not available from the historic observations were also generated using AGNPS Generation of weather Elements for Multiple applications (AgGEM) software package [55], including dew point, sky cover, wind speed, and solar radiation. The AgGEM software package generates synthetic data for these four parameters based on long-term statistics derived from records of different regions in the US.

2.5.3. Soil

Soil spatial distribution data was retrieved from the Web Soil Survey (WSS) using the Natural Resources Conservation Service's (NRCS) website [56] for Gibson and Dyer counties. Complementary soil description of physical and chemical properties in tabular format were retrieved from the USDA Soil Data Access website [57]. A custom SQL script was used to query and retrieve soil information needed for the input soil database (e.g., hydrologic soil group, erodibility factor, impervious depth, specific gravity, clay, silt, sand

and rock ratios, and number of soil layers). These datasets were post processed using the National Soil Information System (NASIS) Import to AnnAGNPS (NITA) software package (i.e., a component of the AGNPS modeling system) to ensure the accuracy of the soil characteristics table. Once the data were quality controlled, the soil characteristics data table was joined with the attribute table of the original soil shapefile. Using GIS analysis, each sub-catchment was assigned to a soil type based on spatial majority analysis. A total of 80 unique soil types were used.

2.5.4. Management

Field management within the AnnAGNPS model is represented by a multi-year temporal sequence of operations describing key farming activities and their potential impact on soil cover, surface runoff/infiltration, fertilizer application, irrigation strategy, and soil disturbance by equipment. Each sub-catchment in the watershed is assigned to a management ID. This procedure ensures that farming practices, land cover, and their impact on soil detachment and transportation are characterized in time and space. Land use/land cover information were obtained from the U.S. Department of Agriculture—National Agricultural Statistics Service—CropScape website [58]. Agricultural land use information, referred to as crop data layer (CDL), were downloaded as annual raster grids at 30 m spatial resolution describing crop types and main non-agricultural land covers [59]. In this study, raster grids from 2008 to 2018 were used. Statistical analyses were performed to determine dominant crop types based on datasets for the years 2008, 2013, and 2018. Nine major classes were ascertained from the original land use classes. The nine dominant consistent classes are corn, cotton, winter wheat/soybean, forest, developed, grass/pasture, soybeans, woody wetlands, and water. These classes represent about 99% of the watershed. Crops that were less conventional, such as pumpkins or Christmas trees, were classified under "grass/pasture", given that they represent about 1% of the total watershed area, and their incorporation in the management schedule and operations will significantly increase the processing time and complexity. The original raster grids for all years were re-coded to the nine main land use classes. For each year considered, a majority spatial zonal statistic GIS analysis was used to assign the dominant land use for each sub-catchment (Figure 4).

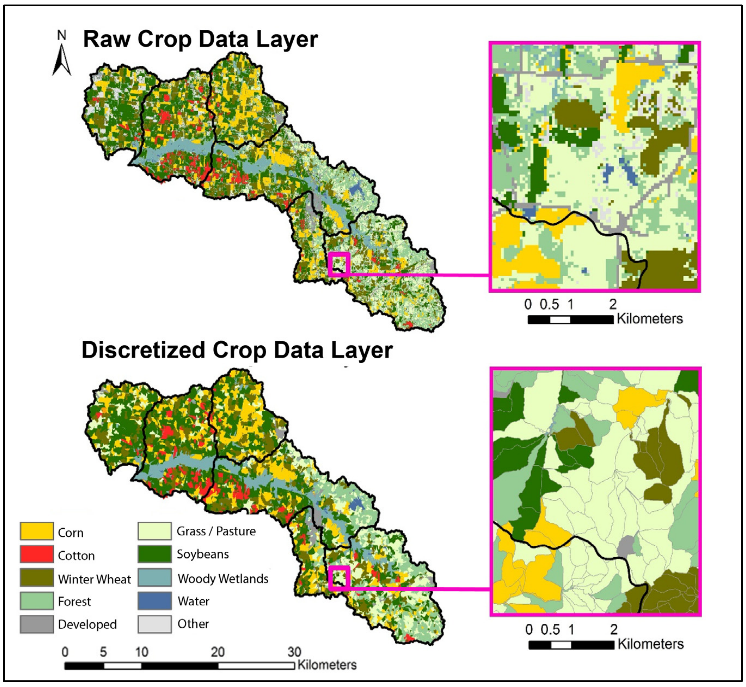

Figure 4. Spatial-temporal characterization of land use. The procedure was applied for all years, but only 2008 is included for illustration purposes.

The input AnnAGNPS farming management database was assembled by integrating three sources of information: (1) spatiotemporal crop type information at sub-watershed scale (from annual discretized CDL datasets), (2) average annual crop type yield information at county scale (from agricultural census downloaded from USDA-NASS [60]), and (3) one-year farming practices (from RUSLE 2 database). The latter represent typical farming operations and schedules for a particular crop type in this region (Table 2). The three datasets were combined using a custom Python script, generating 4135 unique 11-year crop/landuse rotations for the 12,573 sub-catchments in the study area. The output from the custom script are management schedule and operation databases required by the AnnAGNPS model.

Table 2. Example of the annual management schedule for three major crops in the study area.

Crop	Date	Operation
Corn	15 Mar.	Bedder/Lister
	1 Apr.	Disk
	13 Apr.	Fertilizer
	14 Apr.	Disk
	15 Apr.	Sprayer
	16 Apr.	Plant
	9 May	Sprayer
	15 May	Fertilizer
	29 May	Sprayer
	15 Sep.	Harvest
	16 Sep.	Weed Growth
Cotton	17 Apr.	Sprayer
	18 Apr.	Fertilizer
	1 May	Plant
	15 May	Sprayer
	15 June	Fertilizer
	16 June	Sprayer
	15 July	Sprayer
	31 July	Sprayer
	15 Aug.	Sprayer
	29 Aug.	Defoliant
	15 Oct.	Weed Growth
Soybean	20 Mar.	Chisel
	5 May	Fertilizer
	10 May	Disk
	11 May	Plant
	29 May	Sprayer
	20 July	Sprayer
	28 Aug.	Sprayer
	15 Oct.	Harvest
	20 Oct.	Weed Growth

2.6. Conservative Practices Scenarios

2.6.1. Riparian Buffer

A riparian buffer is an area of vegetation designed to slow down and spread surface flow thus promoting infiltration and allowing contaminants and sediment to be deposited. Riparian covers typically include vegetation like grasses, sedges, rushes, and ferns that are tolerant of intermittent flooding or saturated soils. They are established and managed as the dominant vegetation in the transitional zone between upland areas such as agricultural fields and aquatic habitats such as streams [61,62]. The overall sediment trapping efficiency of riparian buffers is impacted by location and buffer physical characteristics (e.g., width, length, vegetation density). In this study we simulate the potential impact of riparian buffers in a wide range of scenarios based on varying their width and location within the watershed.

The use of sediment yield to define potential riparian buffer implementation scenarios, allows to investigate the impact of the conservation practice when is targeted toward hotspot areas only, when is implemented around all streams in the watershed which represents a theoretical maximum reduction, and in-between scenarios. Hence, the first two scenarios involve the implementation of riparian buffers (1) around all streams in the watersheds, and (2) around all streams adjacent to agricultural fields (Figure 5A). In addition, results from the baseline conditions simulation were used to calculate the mean (i.e., 8.94 Mg/ha/year) and the standard deviation (i.e., 5.24 Mg/ha/year) of sediment yield from all agricultural fields in the study area. These values were used in defining a range of location scenarios within the watershed for potential implementation of riparian buffers: (3) around all streams adjacent to agricultural fields that have a sediment yield higher than mean minus standard deviation (referred to as ">medium") (Figure 5B), (4) around all streams adjacent to agricultural fields that have a sediment yield higher than mean plus standard deviation (referred to as ">high") (Figure 5C), and (5) around all streams adjacent to agricultural fields that have a sediment yield higher than mean plus two standard deviations (referred to as ">very high") (Figure 5D).

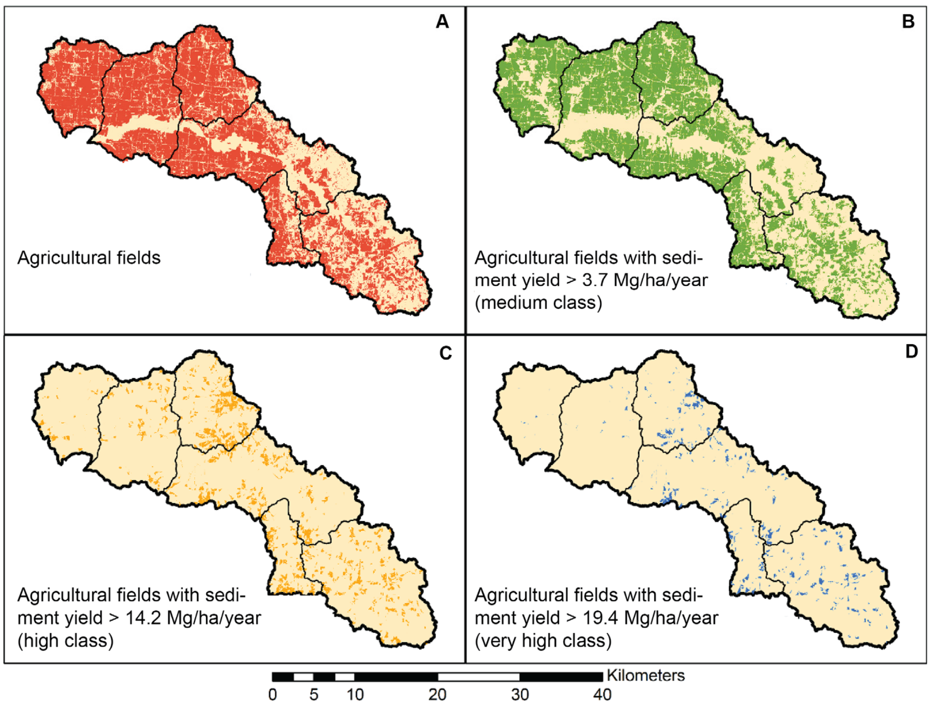

Figure 5. Study area agricultural fields classified by sediment yield ((**A**): All agricultural fields, (**B**): medium class, (**C**): high class, and (**D**): very high class). These four classes are used as scenarios in our final simulations to estimate the contribution of using conservation practices in reducing sediment yield (from least to most restrictive).

The simulated riparian buffer has widths of 10 m, 30 m and 60 m. We selected these buffer widths, given that the EPA defines narrow buffer width as 1–15 m and wide buffer width as broader than 50 m. State and federal guidelines range from seven to 200 m [63,64]. Multiple studies investigated and reported an efficient and cost-effective buffer at widths ranging between 10 and 30 m [65–67]. In addition to these two typical widths (10 and 30 m), we simulated a wide buffer (i.e., 60 m) to quantify the impact of doubling the riparian width from the typical previously investigated scenarios, while still being within the applicable limits [68]. The channel network was buffered by the three buffer widths and the resulting polygon layers were intersected with sub-catchments that meet the sediment yield condition of the respective simulated class.

The combination of these different conditions (i.e., sediment yield class, all or just agricultural areas, buffer width) yielded a total of 15 scenarios (Figure 6a). In addition, a sixteenth scenario was created to represent existing riparian buffer conditions. The existing riparian vegetation (mainly trees) was delineated using a custom script, consisting of a pretrained machine learning canopy detection model based on LiDAR point cloud data [69].

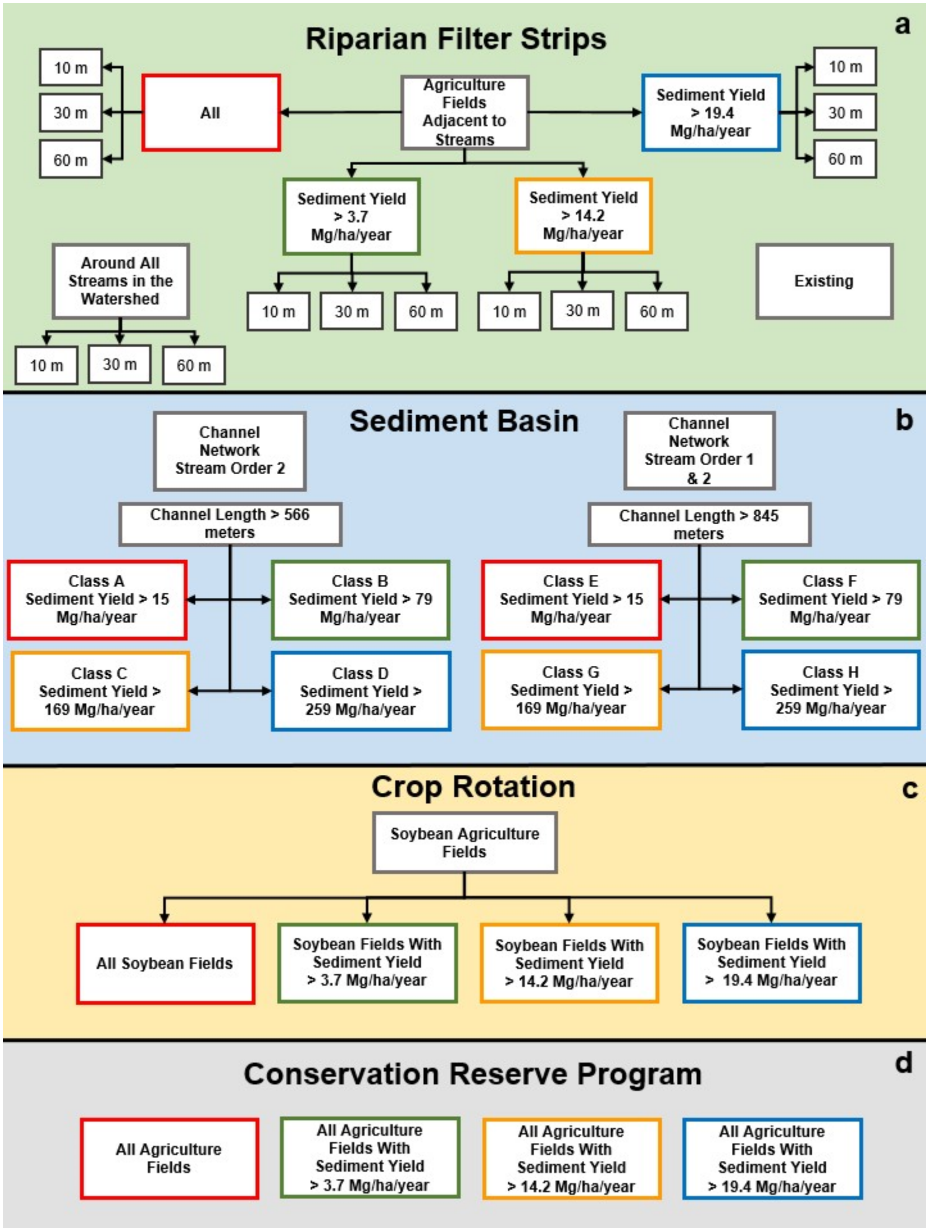

Figure 6. Flowchart summarizing all simulated conservation practice scenarios and their differences (**a**–**d**).

These 16 riparian buffer GIS layers were further processed at a 3 m spatial resolution using the AGBUF GIS tool (Section 2.3) to evaluate all flow paths through the riparian layer and allowing the determination of a potential sediment trapping efficiency for each sub-catchment. The outcomes of this analysis are used as input databases describing physical properties of riparian zones for each sub-catchment for 16 separate AnnAGNPS simulations.

2.6.2. Sediment Basin

Sediment basins are built to capture runoff, changing the energy of surface flow, and, therefore, allowing the settlement of sediment and other suspended solids [70]. The existing sediment basins were digitally delineated by researching and examining all the water bodies in the watershed using publicly available high resolution remotely sensed imagery, available via Google Earth and ESRI base-maps. As a result, 57 water bodies were identified as sediment basins (Figure 7). These polygons were described using the AGWET tool (Section 2.4) by performing GIS analysis at 3 m spatial resolution to determine area, barrier height, average water depth, and other properties [48,71]. AGWET was used in an iterative mode to delineate the extent of the existing sediment basins and determine the appropriate weir height for each one of them that matches their observed surface area in high resolution satellite imagery. The goal of this process is to find a relationship between sediment basin weir height and upstream area specific to this watershed. This relationship is used to partially determine the morphological characteristics of the proposed new sediment basins in the watershed.

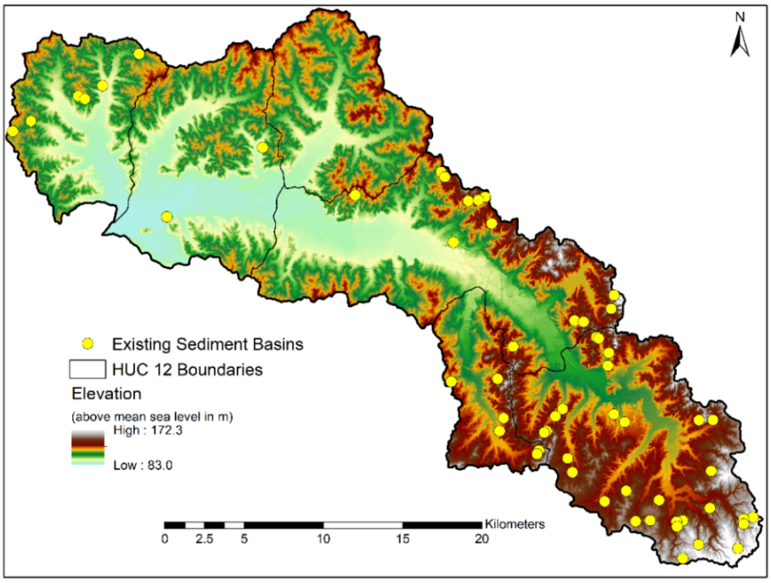

Figure 7. Distribution of existing sediment basins in the study area.

The potential new sediment basin locations were selected based on three criteria: (1) channel stream order to ensure intermittence of flow (i.e., stream order 1 or 2), (2) channel stream length above a statistical threshold (i.e., mean length) to eliminate noisy minuscule channels, and (3) sub-catchment sediment yield categorized into four classes based on its statistical distribution in the targeted sub-catchments as well as on sediment yield in the delineated existing sediment basins, to ensure replication of similar conditions and expansion of impact.

Results from the baseline conditions simulation were used to calculate the mean sediment yield for the AnnAGNPS cells in which the 57 existing sediment basins are located (i.e., 15 Mg/year/ha), and the mean and the standard deviation of all the targeted AnnAGNPS cells by criteria 1 and 2 (i.e., mean: 79 Mg/year/ha and standard deviation: 90 Mg/year/ha). These values were then used in defining a range of location scenarios within the watershed. The considered sediment yield classes are: (1) above mean sediment yield for existing sediment basins (i.e., 15 Mg/year/ha), (2) above mean sediment yield of the considered sub-catchments (i.e., 79 Mg/year/ha), (3) above (mean + standard deviation) sediment yield of the considered sub-catchments (i.e., 169 Mg/year/ha), and (4) above (mean + 2 × standard deviations) sediment yield of the considered sub-catchments (i.e., 259 Mg/year/ha). The use of a statistical distribution to generate simulation classes allow testing the impact of sediment basins based on a spectrum of scenarios ranging from most to least conservative in terms of number of basins, location, and sediment yield, providing multiple options of targeted implementation for stakeholders.

The combination of the aforementioned three criteria (i.e., sediment yield, stream order and channel length) led to eight total scenarios (Figure 8) including 233 sediment basins for class A, 147 sediment basins for class B, 67 sediment basins for class C, 21 sediment basins for class D, 527 sediment basins for class E, 297 sediment basins for class F, 126 sediment basins for class G, and 54 sediment basins for class H. A sediment basin scenario generation flowchart is summarized in Figure 6b.

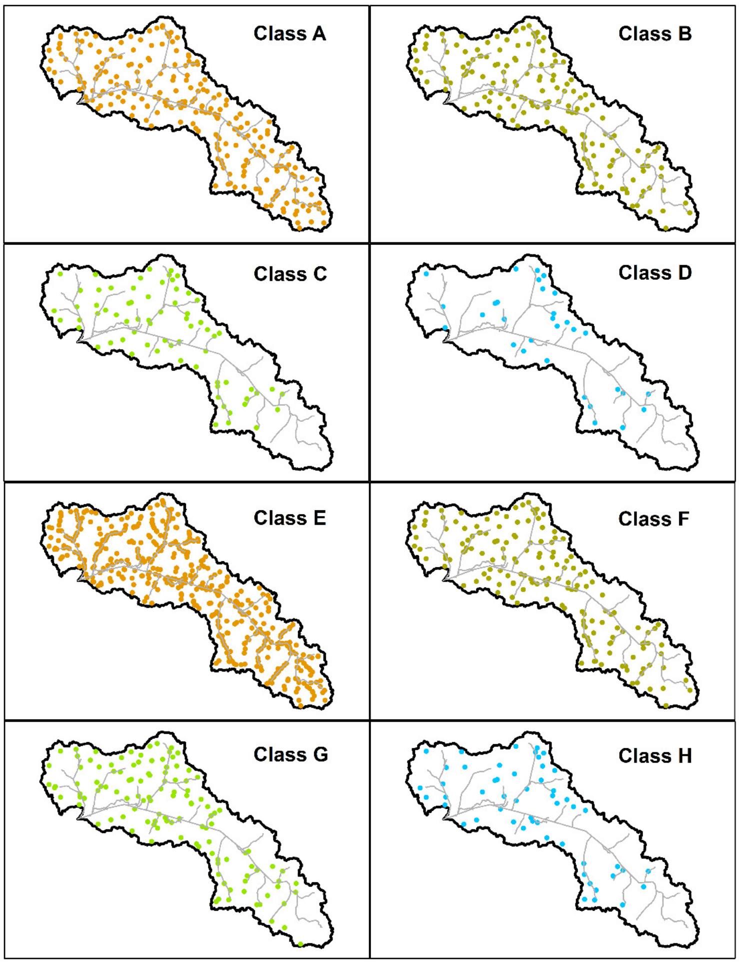

Figure 8. Proposed sediment basin locations corresponding to 8 scenarios (i.e., (**A**–**H**) described in Section 2.6.2).

Each proposed sediment basin location was analyzed using AgWET. The weir height and surface area of each sediment basin were determined based on the local topography and the average characteristics of the existing delineated sediment basins. These characteristics alongside the location of the basins were inputted into AnnAGNPS to simulate sediment basin impact on sediment reduction in the watershed.

2.6.3. Crop Rotation

Conservation crop rotation was applied as a seasonal sequence of crops grown in the same field yielding a multi-crop rotation cycle. The crops in the rotation should include a high residue producing crop such as wheat or corn along with a low residue producing crop such as soybeans or vegetables. Conservation crop rotation has many benefits which includes reducing sheet, rill, and wind erosion, increasing soil health and organic matter content, and improving soil moisture efficiency [72–75].

The only major crop in our study area that allows rotation is soybeans, so we simulated the soybeans/winter wheat rotations in four location scenarios: (1) all soybean agricultural fields amounting to 7340 AnnAGNPS cells (Figure 5A), (2) soybean agricultural fields that have a sediment yield higher than mean—standard deviation (referred to as ”>medium”) amounting to 5689 AnnAGNPS cells (Figure 5B), (3) soybean agricultural fields that have a sediment yield higher than mean + standard deviation (referred to as ”>high”) amounting to a total of 1166 AnnAGNPS cells (Figure 5C), and (4) soybean agricultural fields that have a sediment yield higher than mean + 2 × standard deviation (referred to as ”>very high”) amounting to a total of 424 AnnAGNPS cells (Figure 5D). The used mean (i.e., 5.25 Mg/ha/year) and standard deviation (i.e., 8.94 Mg/ha/year) values represent the statistical distribution of sediment yield baseline conditions of all agricultural fields in the study area as highlighted in Section 2.6.1.

The simulation of the crop rotation scenarios was conducted by adjusting the management schedule from Soybean to Soybean/Winter Wheat (Table 3) for each AnnAGNPS cell under the respective four crop rotation scenarios. These four scenarios are summarized in Figure 6c.

Table 3. Comparison of annual management schedule for soybean and soybean + winter wheat rotation.

Crop	Date	Operation
Soybean (with no rotation)	20 Mar.	Chisel
	5 May	Fertilizer
	10 May	Disk
	11 May	Plant
	29 May	Sprayer
	20 July	Sprayer
	28 Aug.	Sprayer
	15 Oct.	Harvest
	20 Oct.	Weed Growth
Winter Wheat + Soybean Rotation	30 Oct.	Sprayer
	31 Oct.	Fertilizer
	1 Nov.	Rill or Air Seeder
	15 Nov.	Sprayer
	15 Feb.	Fertilizer
	15 Mar.	Sprayer
	10 May	Disk
	15 May	Sprayer
	10 June	Harvest
	11 June	Sprayer
	13 June	Plant
	27 June	Sprayer
	20 July	Sprayer
	28 Aug.	Sprayer
	15 Oct.	Harvest
	20 Oct.	Weed Growth

2.6.4. Conservation Reserve Program

The Conservation Reserve Program (CRP) is a voluntary program implemented by the USDA Farm Service Agency (FSA) in coordination with agricultural landowners, to remove environmentally fragile land from agricultural production and improve water quality, wildlife habitat, and prevent soil erosion. During the period of the program, the land is not farmed or ranched but planted with native plant species that improve the long-term environmental health and quality of the land. The contract between farmers and FSA lasts between ten to fifteen years with annual rental payments and cost share assistance provided by FSA [76–78].

The simulation period for this study is 11 years (January 2008–December 2018), which fits the typical duration range of CRP. The selected scenarios for this conservation practice are: (1) all agricultural fields (Figure 5A), (2) all agricultural fields that have a sediment yield higher than mean minus standard deviation (referred to as ">medium") (Figure 5B), (3) all agricultural fields that have a sediment yield higher than mean + standard deviation (referred to as ">high") (Figure 5C), and (4) all agricultural fields that have a sediment yield higher than mean + 2 × standard deviation (referred to as ">very High") (Figure 5D). The used mean (i.e., 5.25 Mg/ha/year) and standard deviation (i.e., 8.94 Mg/ha/year) values represent the statistical distribution of sediment yield baseline conditions of all agricultural fields in the study area as highlighted in Section 2.6.1.

We implemented CRP in our simulations by changing the crop type and schedule to grass for the selected cells under each considered scenario. The grass rotation simulates the conditions of land being returned to native plant species with no farming activities. The four CRP scenarios are summarized in Figure 6d.

2.6.5. Optimization and Comparison of Conservation Practice Scenarios

A multi-dimension scoring function was employed to compare all the considered conservation scenarios. This cost function was designed to account for the relative reduction in annual average sediment yield per unit area while, at the same time, consider the potential reduction in productive agricultural land. This analysis was performed for all individual sub-catchments affected by the conservation practice. Both sediment yield per unit area and the area of land converted from agricultural production to conservation were normalized to values between 0 and 1 and the totals from all sub-catchments were calculated. The score for each alternative scenario i was calculated as follows:

$$Score_i = \frac{(T_{S_i} \times W_S) + (T_{L_i} \times W_L)}{(W_s \times W_L)} \quad (1)$$

where T_{S_i} is the total scaled sediment yield per unit area for scenario i, T_{L_i} is the total area converted into a conservation practice, and W_S and W_L are the weighting factors for sediment load and spatial footprint, respectively.

3. Results

3.1. Baseline Conditions

Evaluation of simulation results were performed spatially (Figure 9) and temporally (Figure 10) using two output parameters: sediment yield and sediment load, respectively. Sediment yield is reported as annual average per unit area for each sub-catchment in Mega grams per hectare per year and it represents eroded sediment by inter-rill and rill processes leaving the field into streams. The annual average sediment yield per unit area is intended to describe non-point sources spatially and to serve as a reference to quantify the effect of conservation practices locally (field scale at different parts of the watershed). Sediment load is reported as the annual average at the watershed outlet in Mega grams and is intended to demonstrate how the overall watershed responds to natural drivers (e.g., climate/weather), anthropogenic drivers (e.g., farming management), and to quantify the combined effect of conservation practices on the system. Both parameters are described by key particle sizes: sand, silt, and clay.

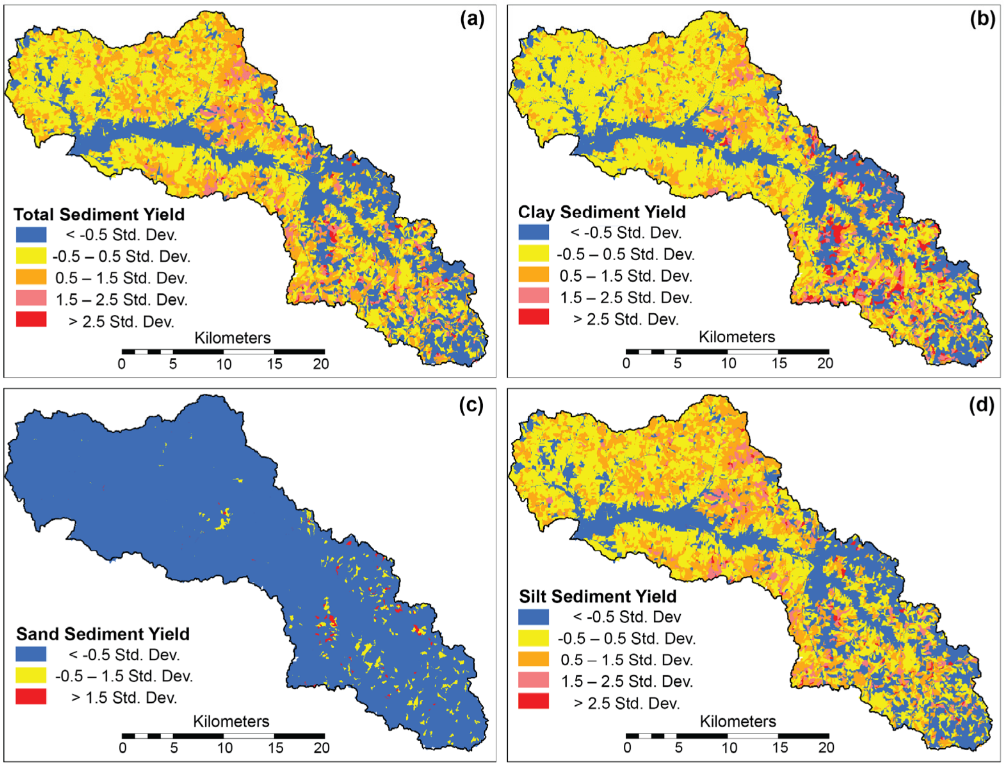

Figure 9. Spatial distribution of sediment yield for different particles sizes: (**a**) clay, (**b**) sand, (**c**) silt, and (**d**) total sediment, estimated using the AnnAGNPS model to describe existing conditions (baseline condition simulation). Graph depicts standardized approach in which values are expressed as deviations from the mean value of all 12,573 sub-catchments.

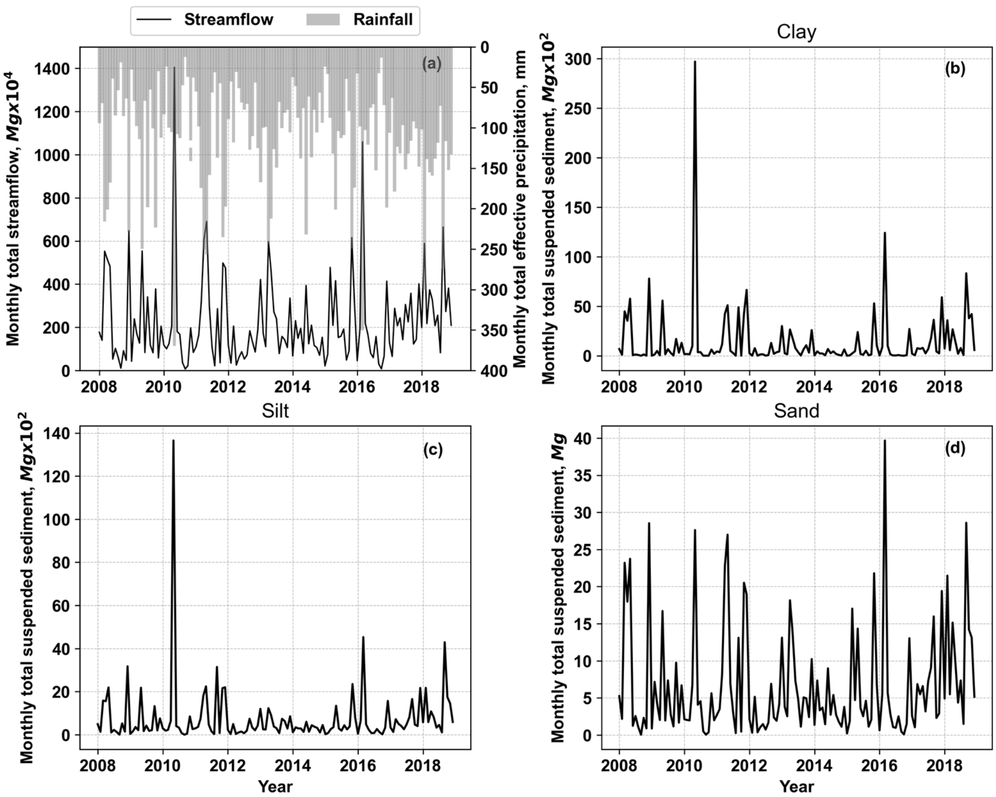

Figure 10. Streamflow (**a**) and suspended sediment load for silt (**b**), clay (**c**), and sand (**d**) sizes at the watershed outlet as simulated by the AnnAGNPS model representing existing conditions.

The lack of streamflow observations in most catchments around the world and the nation, especially in small catchments in rural areas has created a setback for hydrological and conservation investigations in these regions [67]. In this study, the uncertainties caused by the lack of observed data (streamflow and sediment gauges) were minimized by the following. First, the AnnAGNPS watershed pollution model was selected due to its suitable application to agricultural ungauged watersheds based on the detailed spatiotemporal information needed to characterize natural and anthropogenic processes in this type of watersheds [79–85]. Second, relative measurements were used instead of absolute to evaluate conservation scenarios. This was achieved by comparing average sediment load at the outlet of the watershed for each scenario (33 different AnnAGNPS simulations describing conservation practices) to baseline conditions. Absolute sediment load/yield was not used as the basis for any recommendation. Third, comparisons of annual average streamflow with the publicly available web-based Generalized Watershed Loading Function Enhanced (GWLF-E) model [86] indicate that the two estimates are in agreement (i.e., 42.22 cm/year and 42.27 cm/year for AnnAGNPS and GWLF-E, respectively).

Sediment yield was reported as annual average per unit area for each sub-catchment. Results were classified for each particle size per its statistical distribution to facilitate visualization and allow a spatial identification of hot spot sub-catchments in terms of sediment yield (Figure 9). The generated maps were used as the basis for the development of alternative conservation scenarios to target problematic sub-catchments and reduce their sediment yield.

Results from the baseline simulation indicates an overall low sand particle yield relatively to both silt and clay. Sediment yield of both silt and clay are high especially in Mud Creek, North Fork Forked Deer River Lower and Doakville Creek in comparison to Cain Creek and North Fork Forked Deer River Upper (Figure 9). Simulation results demonstrate the combined effect of complex processes driving sediment sources and sinks as well as the spatiotemporal variation of land cover, climate, soil, and farming practices, with agricultural fields driving most of the sediment detachment and transport in the study area.

Temporal evaluation of monthly streamflow at the outlet (Figure 10a) highlights a major rainfall event in 1–2 May 2010, responsible for significant floods in the region. Streamflow peaks correlate with peaks of suspended silt (Figure 10b) and clay (Figure 10c). Sand load peaks does not correlate with streamflow peaks, with the former peaking in 2016 (Figure 10d). It is important to note that estimates of sediment load of sand size particles are two orders of magnitude smaller than silt and clay.

3.2. Conservation Practices Scenarios

In addition to the baseline condition simulation, 33 AnnAGNPS simulations (i.e., 16 for riparian buffer, 9 for sediment basin, 4 for crop rotation and 4 for CRP), with a computer run time of up to 50 h per simulation, were performed to explore the impact of these conservation practices on sediment reduction in a wide range of conditions.

Tables 4–7 summarize the simulation results for the four sets of the investigated conservation practices. Each table includes scenario characteristics, relative reduction of sediment load at the outlet of the watershed from the baseline conditions, as well as the area of land used to implement the practice. The implementation decision is a tradeoff, between maximizing soil erosion reduction and minimizing the economic burden on farmers represented by the area of land that is taken out of production.

Table 4. Riparian buffer scenarios results.

Simulation ID	Location Description	Riparian Buffer Width	Sediment Load (Mg/Year)	Sediment Reduction (%)	Spatial Footprint (Ha)
1	All Streams	10 m	71,312.7	65%	506.6
2	All Streams	30 m	44,970.2	78%	1458.3
3	All Streams	60 m	39,745.7	81%	2728.2
4	All streams adjacent to agricultural fields.	10 m	113,389.3	45%	338.0
5	All streams adjacent to agricultural fields.	30 m	99,602.6	52%	1018.9
6	All streams adjacent to agricultural fields.	60 m	96,321.7	53%	2043.8
7	All streams adjacent to agricultural fields with a sediment yield higher than 3.7 Mg/ha/year	10 m	118,246.5	43%	228.6
8	All streams adjacent to agricultural fields with a sediment yield higher than 3.7 Mg/ha/year	30 m	105,205.8	49%	893.9
9	All streams adjacent to agricultural fields with a sediment yield higher than 3.7 Mg/ha/year	60 m	101,905.8	51%	1823.0
10	All streams adjacent to agricultural fields with a sediment yield higher than 14.2 Mg/ha/year	10 m	178,229.7	13%	60.9
11	All streams adjacent to agricultural fields with a sediment yield higher than 14.2 Mg/ha/year	30 m	175,074.4	15%	175.0
12	All streams adjacent to agricultural fields with a sediment yield higher than 14.2 Mg/ha/year	60 m	174,124.0	15%	357.9
13	All streams adjacent to agricultural fields with a sediment yield higher than 19.4 Mg/ha/year	10 m	195,271.1	5%	19.1
14	All streams adjacent to agricultural fields with a sediment yield higher than 19.4 Mg/ha/year	30 m	194,101.3	6%	52.7
15	All streams adjacent to agricultural fields with a sediment yield higher than 19.4 Mg/ha/year	60 m	193,756.4	6%	106.5
16	Existing riparian buffer	Variable	178,956.2	13%	4683.8
Baseline Conditions	No buffer is integrated into the model	0 m	205,880.2	0%	0

Table 5. Sediment basin scenarios results.

Simulation ID	Scenario Classification (Figure 6b)	Sediment Load (Mg/Year)	Sediment Reduction (%)	Spatial Footprint (Ha)
17	Class A	10,699.1	95%	214.3
18	Class B	70,137.00	66%	200.7
19	Class C	184,607.9	10%	91.2
20	Class D	199,254.0	3%	39.9
21	Class E	164,705.5	20%	252.1
22	Class F	179,666.4	13%	276.4
23	Class G	179,073.7	13%	172.2
24	Class H	198,661.2	4%	79.6
25	Existing Sediment Basins	204,992.0	0%	82.8
Baseline conditions		205,880.2	0%	0

Table 6. Crop rotation scenarios results.

Simulation ID	Description	Sediment Load (Mg/year)	Sediment Reduction (%)	Spatial Footprint (Ha)
26	Crop rotation is applied to all soybean fields in the watershed	182,278.4	11%	0 *
27	Crop rotation is applied to all soybean fields in the watershed with a sediment yield higher than 3.7 Mg/ha/year	193,476.4	11%	0 *
28	Crop rotation is applied to all soybean fields in the watershed with a sediment yield higher than 14.2 Mg/ha/year	182,969.3	6%	0 *
29	Crop rotation is applied to all soybean fields in the watershed with a sediment yield higher than 19.4 Mg/ha/year	197,905.3	4%	0 *
Baseline Conditions	No additional crop rotation is integrated into the model	205,880.2	0%	0 *

* No land is taken out of production during crop rotation, since winter wheat is planted in the winter when the land is not being used to grow other crops.

Table 7. CRP scenarios results.

Simulation ID	Description	Sediment Load (Mg/Year)	Sediment Reduction (%)	Spatial Footprint (Ha)
30	CRP is applied to all agricultural fields in the watershed	38,598.1	81%	7146.9
31	CRP is applied to all agricultural fields in the watershed with a sediment yield higher than 3.7 Mg/ha/year	44,460.2	78%	6792.5
32	CRP is applied to all agricultural fields in the watershed with a sediment yield higher than 14.2 Mg/ha/year	154,930.8	25%	1519.3
33	CRP is applied to all agricultural fields in the watershed with a sediment yield higher than 19.4 Mg/ha/year	186,290.7	10%	388.5
Baseline Conditions	No CRP is simulated in the model	205,880.2	0%	0

Riparian buffers work by slowing surface flow and promoting infiltration and fine sediment deposition. Our simulations results indicate that sediment reduction of this practice when compared to the baseline condition range between 6% and 81% based on location and buffer width (Table 4). Even though implementation of riparian buffers around every stream in the watershed is not feasible, the value of 81% represents a theoretical maximum potential reduction by this practice. The simulations also indicate that existing riparian buffers provide a reduction of 13% as opposed to a maximum potential of 81%, demonstrating that the watershed is under-served in terms of riparian buffers.

In addition, simulation results indicate that an increase of riparian buffer width from 30 m to 60 m leads to a sediment load reduction at the outlet of the watershed of only 1%, 2%, 0%, and 0% in scenarios 6, 9, 12 and 15, respectively (Table 4). These results highlight a non linear relationship between the buffer width and sediment trapping efficiency, indicating that the expansion of the overall length of the riparian buffer is more effective than increasing the width beyond a certain optimal value [46,87,88].

Sediment basin simulation results indicate a wide range in sediment load reduction from 4% to 95% (Table 5). The overall reduction is a function of not only the number of sediment basins but also their placement throughout the watershed. It can be observed that a similar reduction in sediment load for scenarios 22 and 23 represent a different spatial footprint (i.e., 276.4 and 172.2 hectares, respectively). Additionally, alternative scenarios 17 and 18 that focus on stream order 2 seem significantly more efficient than scenarios 21 and 22. Based on these findings, it is suggested to prioritize the size of the upstream area when deciding where to place sediment basins in the candidate locations in the watershed.

Simulation results indicate that crop rotation between soybean and winter wheat would reduce sediment load at the outlet of the watershed by 4% in case of selecting the top (i.e., mean plus two standard deviations) fields in terms of sediment production and by about 11% in case of implementation in all soybean fields (Table 6), which represent about 27% of the total area of the watershed. This represents a relatively small sediment load reduction, but is a cost-effective alternative since the production areas are not reduced. The only major crop rotation identified in the study area was soybean with winter wheat. A more widespread application of crop rotation could further decrease the sediment yield in the watershed.

Sediment reduction using CRP ranges between 10% and 81% for the study area based on how many fields were removed from production (Table 7). While CRP is one of the most effective tools to address nutrient loss, sediment erosion and wildlife habitat reduction, CRP is one of the costliest practices for the landowners by taking their land completely out of production; hence financial incentives are often provided by the U.S. federal government for this purpose [76,77,89,90].

4. Discussion

An effective implementation of conservation practices designed to promote water quality and minimize soil erosion depends on a comprehensive understanding of watershed processes, farming practices and sediment and agrochemical sources and sinks [48]. This study is an integrated approach using both GIS spatial analysis and watershed modeling to provide stakeholders with a blueprint for targeted conservation plans especially in ungauged watersheds. This investigation allowed us to make four major observations.

4.1. Prioritization of Conservation Practice Location

The definition for the optimal spatial distribution of the proposed conservation practices and their temporal impact on sediment and nutrient detachment, transport, deposition, and trapping is important [28,48]. The description of these spatiotemporal relationships requires the incorporation of specialized technology into watershed modeling, that allows a careful selection of the location and type of practice to optimize implementation [47,48,91,92].

An example corroborating the importance of conservation location is from riparian buffer simulations. Despite an overall positive correlation between the size of the buffer and the amount of sediment reduction, Figure 11 shows that scenarios 4 and 12 use an almost equal buffer surface area (i.e., 338 and 357.9 ha, respectively) but lead to a large difference in sediment load reduction (i.e., 45% and 15%, respectively). Similarly, scenarios 7 and 11 are based on a similar surface area (i.e., 228.6 and 175 ha, respectively) but also lead to a large difference in sediment yield reduction (i.e., 43% and 15%, respectively).

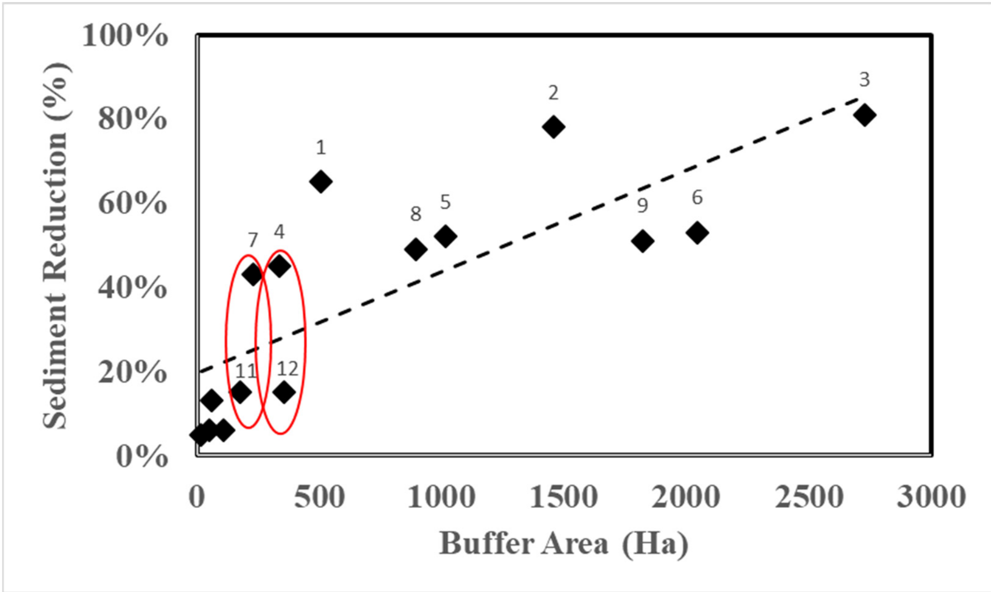

Figure 11. Relative sediment reduction (%) from baseline conditions for riparian buffers in function of their surface area. The numbers refer to scenario ID from Table 4. The two red circles highlight two examples in which a similar riparian buffer area size leads to a large difference in sediment reduction.

A second example is from sediment basin simulations. It was found that proposed scenarios 17 and 18 (i.e., classes A and B of sediment basin) that focus on stream order 2 are significantly more efficient than scenarios 21 and 22 (i.e., classes E and F for sediment basin). In fact, scenario 17 was simulated using optimally located 147 basins, leading to a reduction of 66% in sediment load whereas scenario 22, including more sediment basins (i.e., 297) leads to a reduction of only 13%. Hence, it is suggested to prioritize the size of the upstream area when placing sediment basins in the watershed, while respecting NRCS guidelines.

The selection of where to place the conservation practice within the watershed is important to optimize the available resources and maximize the conservation practices impact on non-point source pollutants.

4.2. Optimization and Comparison of Conservation Practice Scenarios

Three optimization evaluations were performed by varying the weights of both considered parameters: (a) sediment reduction and spatial footprint have equal weight (Figure 12a), (b) a weight of 5 to 1 prioritizing reduction in sediment yield (Figure 12b) and (c) a weight of 5 to 1 prioritizing reduction in spatial footprint (Figure 12c).

When comparing all alternative scenarios using the cost function, riparian buffer seems to be the most efficient. Varying weights can generate different outcomes and this approach can be used by stakeholders to tailor outputs to fit their priorities. Scenarios 1, 2, 3, and 7, representing variations in riparian buffers, were identified as the most efficient conservation practice under all weighting conditions. Conversely, scenarios 21 and 17, representing sediment basins, were scored as least efficient, especially when weights were adjusted to prioritize sediment reduction. Scenarios 30 and 31, which both represent CRP practices, were scored as least efficient when a larger weight was placed on converting land from production to support conservation efforts.

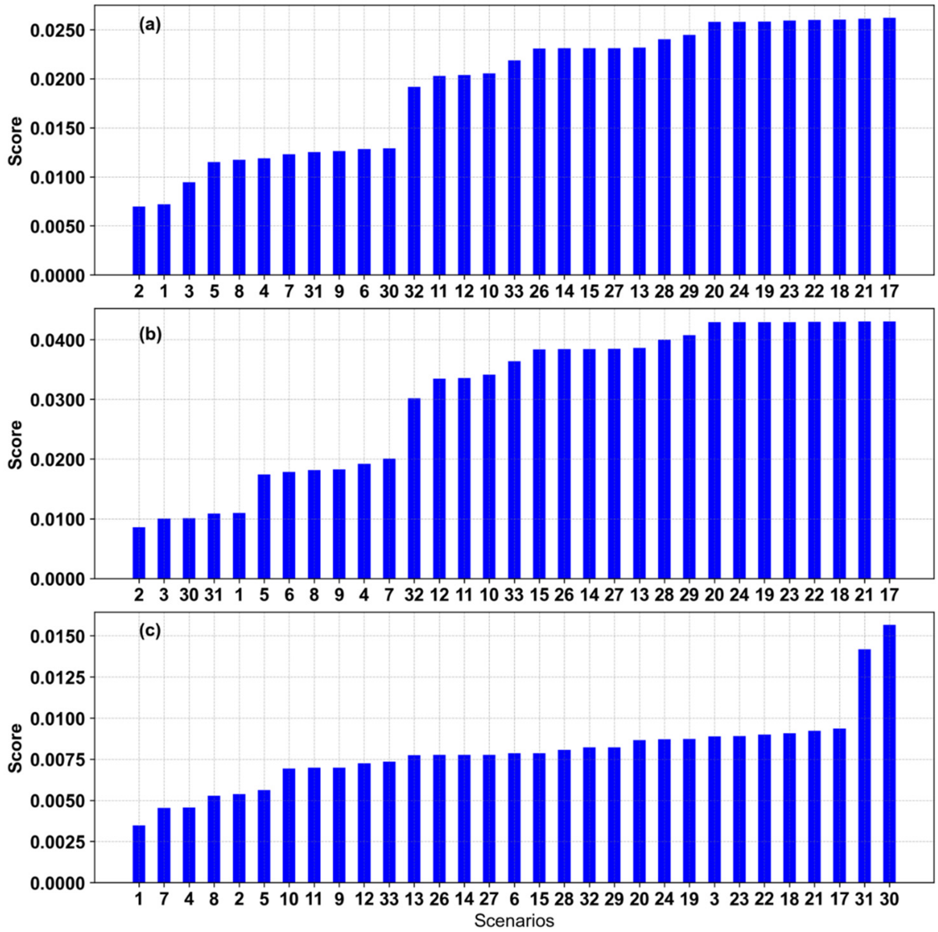

Figure 12. Scoring results comparing alternative conservation scenarios based on sediment yield per unit area and total land converted from agricultural production to a conservation practice. Three evaluations were performed: (**a**) equal weight for sediment yield and spatial footprint, (**b**) prioritize reduction in sediment yield by a factor of 5 to 1, and (**c**) prioritize reduction in spatial footprint by a factor of 5 to 1.

4.3. Building Decision Support Tools Based on Study Results: A Riparian Buffer Example

Simulation results indicate riparian buffers to be the most effective conservation practice for sediment reduction in this watershed, hence they were selected to demonstrate the utility of building decision support tools for stakeholders when implementing practices on the ground designed for optimal reduction of non-point source pollution. Representing simulation results as ranked ratio of accumulated sediment yield per unit of area and accumulated contributing area (Figure 13) illustrates a simple, but effective way, to evaluate individual conservation practices and/or contrast multiple conservation alternatives. For example, based on the AnnAGNPS simulation representing baseline conditions, 40% of the watershed total area has shown to produce 75% of sediment leaving fields into streams. A conservation strategy designed to reduce sediment yield by 25%, could be implemented by targeting specifically those sub-catchments. Alternatively, it is possible to evaluate a wide range of alternative scenarios based on their potential overall reduction. The alternative conservation scenario considering implementing 60 m constructed riparian buffers at sub-catchments classified as “very high” sediment producing locations reduces the overall sediment yield by 7% when compared with baseline conditions. Instead, an alternative scenario considering 10 m constructed riparian buffers implemented in sub-catchments identified as “high” lead to an overall reduction of 27% when compared with baseline conditions. A cluster of alternative scenarios implementing riparian buffers at all agricultural fields and at “medium” classified sub-catchments produce similar reductions

(38–48%) when compared to the baseline scenario. This indicates potential flexibility in selecting where in the watershed and what buffer width to install to obtain similar overall reductions. This decision support tool can assist in the design of conservation practices unique to each watershed.

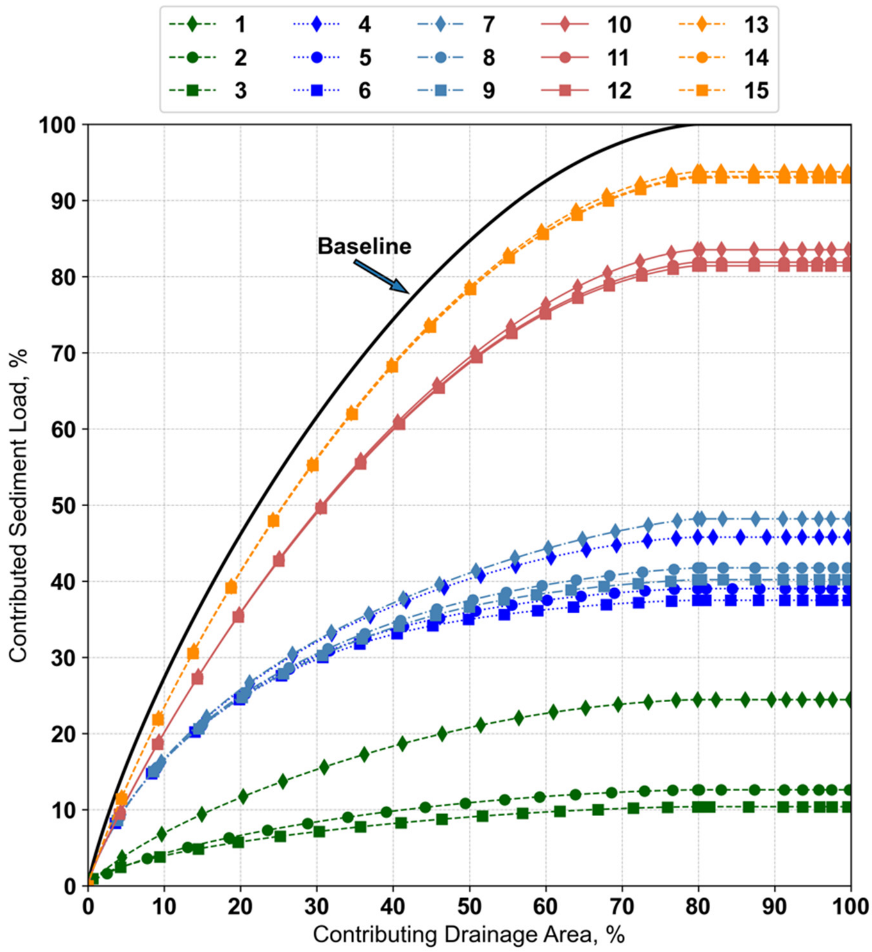

Figure 13. Ranked ratio analysis between accumulated sub-catchment annual average sediment yield per unit area and their corresponding accumulated drainage area.

4.4. Methodology Uncertainties

It is important to recognize that, conservation efforts are often implemented at the watershed scale as a combination of practices varying in type, location, and stakeholder in charge of implementation. In this study, each type of conservation practice was considered separately; this approach was chosen to quantitatively evaluate the effectiveness of individual practices and to provide a platform to compare them. Furthermore, there is an infinite number of possibilities when considering all potential combinations of types of conservation practice, their controlling parameters (width, area, vegetation type, etc.), and, more importantly, their location at the watershed. Additionally, in this investigation, the main quantified sources of sediment are from inter-rill and rill processes, and therefore, channel processes (streambank and streambed erosion) were outside the scope of the study and were kept constant between simulations.

5. Conclusions

Development of conservation plans designed to improve water quality in agricultural watersheds, and in downstream waterways, depends on a detailed spatiotemporal understanding of natural and anthropogenic controlling variables and processes. This constitutes a challenge for conservation stakeholders while managing limited resources, minimizing agricultural production loss, and maximizing sediment load reduction. Watershed modeling technology can support the spatial optimization of conservation practices even at ungauged watersheds.

The integration of GIS-based analyses with hydrological modeling at watershed scales provides additional capabilities to quantify the effect of conservation practices to sediment loads by spatially characterizing different types of conservation practices and scenarios and their relative impact on sediment reduction.

The proposed methodology was applied to the North Fork Forked Deer River watershed in west Tennessee as part of the Mississippi River Basin Initiative (MRBI). This watershed was identified as impaired due to high loads of suspended sediment from agricultural sources [93]. Despite the non-availability of continuous runoff and sediment monitoring stations, a detailed characterization of anthropogenic and natural drivers was performed to obtain a relative evaluation of sediment reduction between baseline conditions and potential conservation scenarios. This could serve as a pilot study toward the improvement of non-point source pollution from agricultural activities in ungauged watersheds across the nation and in the Mississippi basin specifically, given that it is responsible for one of the largest aquatic dead zones in the world.

Future directions of this investigation could involve the inclusion of more variables in the scoring function, such as costs of implementation, costs of maintenance, and potential loss of income from a reduced production area. Additionally, the integration of this methodology with machine learning algorithms could aid in the task of selecting and simulating a combination of different types of practices, controlling parameters, and their location in the watershed. This technology could lead to the development of a hybrid customized solutions for impaired watersheds.

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