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Evaluation of the impacts of BMPs and tailwater recovery system on surface and groundwater using satellite imagery and SWAT reservoir function

Xiaojing Ni*, Prem B. Parajuli

130 Creelman St., Mail Box 9632, Dept. of Agricultural and Biological Engineering, Mississippi State University, MS 39762, United States

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ABSTRACT

For an agricultural watershed, best management practice (BMP) is a conservational way to prevent non-point source pollution and soil and water loss. Three BMPs, including tail water recovery pond, conservational tillage, and crop rotation, were evaluated in order to demonstrate the impacts of BMPs on water quality and quantity. Satellite imagery was used to estimate potential tailwater recovery ponds in this study. The Soil and Water Assessment Tool (SWAT) was applied to evaluate BMPs. Results showed that the use of conservational tillage reduced cumulative sediment, total nitrogen (TN), and total phosphorus (TP) yields. In the crop rotation scenario analysis, it was found that sediment and flow were not sensitive to crop rotation management. The corn-soybean rotation scenario had higher TN and lower TP yields than those of the continuous corn scenario. Continuous soybean scenario showed the lowest TN and low TP yields, which may because of the higher nitrogen fertilization demands, greater crop yield, and greater residue of corn than soybean crop. Based on the SWAT model simulation results, the tailwater ponds can reduce sediment yield and improve groundwater storage.

1. Introduction

Watershed management contributes to essential agro-ecosystem services. In the 1950s, studies that focused on flood control in agricultural watersheds became popular (Brakensiek, 1959; Brown and Winsett, 1960). Later, in the 1970s, studies were broadened to nonpoint source pollution (NPS) and erosion control using conservational practices (Summer, 1970; Seay, 1970). According to the Environmental Protection Agency (EPA), agricultural NPS is one of the major sources of pollution that affects the water quality of rivers and streams in the U.S. The best management practice (BMP) concept, used previously by Yoon (1970), was further employed in the 1990s in relation to conservation managements that are both environmentally friendly and agriculturally productive. The Big Sunflower River Watershed (BSRW), investigated in this study, is considered an intensive agricultural watershed with approximately 76% of the area covered by soybean, corn, rice, and cotton crops (USDA/NASS, 2009). Crop production activities, such as tillage and crop rotation, can have potential impacts on surface water quality and quantity within the watershed (Ayers and Westcot, 1985; Shipitalo and Edwards, 1998; Vaché et al., 2002). To improve agricultural watershed management and prevent adverse impacts of agricultural activities on the environment, BMPs were implemented within BSRW over the last few decades.

Groundwater is the main source of water supply in Mississippi (Kenny et al., 2009; Clark et al., 2011; Maupin et al., 2014). Irrigation is the major water application in BSRW (Clark et al., 2011), which makes the groundwater resource directly related to the economy of the state of Mississippi. Tailwater recovery ponds have been constructed as a BMP in BSRW since 2011 to collect irrigation runoff, help reduce groundwater usage, and mitigate groundwater depletion (United States Department of Agriculture, 2011). According to Clark et al. (2011), the cessation of pumping could improve the groundwater level depletion situation within this watershed. Along with other BMPs, the performance evaluation of the tailwater recovery system on improving the groundwater level is necessary. Nakasone and Kuroda (1999) discussed the relationship between the in-pond water quality, and land use and cover of the upland field. They indicated that there was a high correlation between in-pond water quality—such as total suspended sediment (TSS), total nitrogen (TN) and total phosphorus (TP)—and upland agricultural land cover. Their study showed that the downstream water quality from the reservoir depended on the capacity of the pond and in-pond water quality. Thus, it is necessary to evaluate the impact of tailwater recovery ponds on the downstream water quality in BSRW. This is the first study that evaluated tailwater recovery ponds on a watershed scale. In order to create a scenario representing tailwater recovery ponds in the watershed model, satellite imagery data were

* Corresponding author.
E-mail addresses: xn21@msstate.edu (X. Ni), pparajuli@abe.msstate.edu (P.B. Parajuli).

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also used to estimate potential tailwater ponds.

Tillage management is usually used as a seedbed preparation before planting in order to provide a suitable environment for seeds. Two types of tillage managements were considered in this study: conventional and conservational tillage. Conventional tillage, which only leaves a small amount of residue cover after planting, is a traditional tillage management used by farmers in Mississippi (Snipes et al., 2005). Although conventional tillage is usually considered as a method for maximizing crop yield (Triplett et al., 1968; Kapusta, 1979), it is also a potential cause of soil erosion (Montgomery, 2007), which is its drawback. Compared with conventional tillage, conservational tillage management reduces tillage operation in terms of tillage depth, frequency, and amount of residual removal to help prevent soil erosion. Thus, conservational tillage management is usually considered as a soil protection method, and its application in the agricultural field is suggested to improve off-site water quality (EPA, 2017). According to previous studies, tillage management may affect surface water runoff (Shipitalo and Edwards, 1998), TN, TP, and sediments (Tan et al., 2002; Vaché et al., 2002). Hence, it was necessary to evaluate the impact of different types of tillage managements in the locale of this study.

Crop rotation is a common agricultural practice that allows growing different crops in the same area through different seasons or years. The main purpose of crop rotation is to adjust the nutrient ratio of the soil. Previous studies, which focused on how crop rotation affected soil quality and productivity (Karlen et al., 2006; Klocke et al., 1999; Power et al., 2000), showed that different crop rotation plans affected the amount of nitrogen leaching through the subsurface soil profile. Nutrients on the surface or in the shallow soil profile could move with water and enter the water body (Novotny, 1999). The impact of crop rotation on surface water is mainly on water quality (Vaché et al., 2002), because of different amounts of fertilizer demands of rotated crops. Corn and soybean are among the most commonly used rotation plants in Mississippi. Four crop rotation scenarios were evaluated in this study: baseline, continuous corn, continuous soybean, and corn-soybean rotation. Because both tillage and crop rotation management are agricultural activities applied to the field during the crop growing season, these two managements are usually cross evaluated (Power et al., 2000; Parajuli et al., 2013).

The evaluation of the impacts of agricultural management on the downstream water quality and quantity on a watershed scale requires the use of modeling tools that consider both watershed hydrological and agricultural activity factors. The Soil and Water Assessment Tool (SWAT) is a process-based watershed-modeling tool that considers the physical characteristics of the watershed including surface elevation, soil type, land use, and factors affecting water routing within the watershed (Arnold et al., 1993; Neitsch et al., 2011). Moreover, it contains modules that simulate agricultural activities such as irrigation, fertilization, and tillage. The SWAT was widely used in previous studies that focused on agricultural watershed management and BMP evaluation. Arabi et al. (2008) systematically discussed the representation of conservational management, including crop rotation, using SWAT. Lee et al. (2010) described and simulated four BMP scenarios, including controlling the amount of crop fertilization, conversion of bare soil to grassland, application of riparian buffer system, and installation of vegetative filter strips. Their study utilized stream discharge, sediment, TN, and TP as indicators to evaluate the impacts of BMPs on water quality. Specific to tailwater recovery pond simulation, the reservoir function in the SWAT model was used to simulate potential tailwater recovery ponds grouped by sub-basins, which is the main novelty of this study.

The main objectives of this study are as follows: (i) estimate potential tailwater recovery ponds using satellite imagery data; (ii) evaluate BMP impacts, including conservational tillage and tailwater recovery systems; (iii) quantify the impacts of crop rotation change on the downstream water quality.

2. Material and method

2.1. SWAT model

In this study, the Big Sunflower River Watershed was divided into 22 sub-basins based on surface elevation. The sub-basins were further divided into hydrologic response units (HRUs) based on soil type, land use, and slope length. To define HRUs, this study used a 5% threshold value for soil type, 3% for land use, and 5% for slope lengths. The input data included the following: digital elevation model (USGS, 1999); soil type from the Soil Survey Geographic database (USDA, 2005); land use and cover data from the United States Geological Survey (USGS) Land Cover Institute (USDA/NASS, 2009); climate information, including precipitation, temperature, solar radiation, wind speed, and relative humidity from the Climate Forecast System Reanalysis database (NCDC, 2015). Crop management schedules, including the date, amount of irrigation, and fertilization were summarized from the Mississippi Agricultural and Forest Experiment Station (MAFES) annual report (MAFES, 2000–2014MAFES, -, 2014MAFES, 2000–2014). The source of irrigation was the groundwater from each sub-basin. The total irrigation depth from the tailwater recovery pond was set as 8.89 cm. Other croplands were set as auto-irrigated based on the default requirements for crop water in the SWAT model. The tillage management setting was based on the study of Parajuli et al. (2013).

For the SWAT hydrologic model calibration, the auto-calibration program, SWAT-Cup SUFI2, was used to determine the final fitted values of parameters that resulted in the high coefficient of determination (R^2) and Nash–Sutcliffe model efficiency coefficient (NSE). This was accomplished by comparing the simulated monthly stream flow rate with that of the USGS gage station data. Manual calibration was applied based on the Soil Conservation Service (SCS) curve number method (NRCS, 1986) after the auto-calibration. Table 1 summarizes the calibrated parameters and fitted values for the hydrologic model. There were three USGS gage stations, including Merigold, Sunflower, and Leland (Fig. 1), which were employed for model calibration in previous studies of BSRW (Jayakody et al., 2014; Parajuli et al., 2016). In order to take advantage of the long-term stream flow data, the USGS gage station of Big Sunflower River near Merigold and its corresponding sub-basins (Fig. 1) were calibrated from 1998 to 2015. The calibrated parameters were later applied to the model with the boundary of sub-basins corresponding to the USGS gage station of Bogue Phalia near Leland for validation (Fig. 1). The model simulation was scaled up to the entire BSRW using all three USGS gage stations for revalidation

Table 1
Monthly stream flow calibration parameters.

	Parameter Name	Description (Arnold et al., 2013)	Fitted Value
1	ESCO	Soil evaporation compensation coefficient	0.660
2	ALPHA_BF	Base flow recession constant (d)	0.690
3	GW_DELAY	Delay of time for aquifer recharge (d)	40.700
4	CH_N2	Manning's coefficient for the main channel	0.157
5	SOL_AWC	Available water capacity (mm/mm)	0.108
6	RCHRG_DP	Aquifer percolation coefficient	0.090
7	GW_REVAP	Groundwater revap coefficient	0.146
8	GWQMN	Threshold water level in shallow aquifer for base flow (mm)	501
9	EPCO	Plant uptake compensation factor	0.660
10	SURLAG	Surface runoff lag coefficient (d)	3.800
11	REVAPMN	Threshold water level in shallow aquifer for revap (mm)	40.900
12	CN2	SCS curve number	68–93; varies by land use and soil type