EVALUATING THE LEAST COST SELECTION OF AGRICULTURAL MANAGEMENT PRACTICES IN THE FIVE-MILE CREEK AREA OF FORT COBB WATERSHED

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Abstract:

One of the main causes of water quality impairment in the United States is human induced Non-Point Source (NPS) pollution through intensive agriculture. The Fort Cobb Reservoir (FCR) watershed located in southwestern Oklahoma, United States is a rural agricultural catchment with known issues of NPS pollution including suspended solids, siltation, nutrients, and pesticides. The FCR watershed with an area of 813 km^2 includes one major lake fed by four tributaries. Despite efforts and research to improve water quality in the FCR watershed through the implementation of varieties of Best Management Practices (BMPs) for decades, there are still problems of sediment and phosphorous loads in this catchment, which demonstrates the need for research. Since the cost of implementing some BMPs can be expensive, the cost effective selection and location of BMPs can aid in increasing both the efficiency of public funds and the total income of farmers. The major goal of this study was to identify optimal selection and location of livestock-crop-BMPs including crop types, production methods, and agricultural management practices that could further reduce sediment and phosphorous loss from the agricultural fields in Five-Mile Creek (FMC) sub-watershed of FCR watershed at the least-cost to producers and the public in both the dry and irrigated areas with consideration of existing BMPs. For this, a hydrological model of the study area was developed using the Soil and Water Assessment Tool (SWAT). The model was calibrated and validated satisfactorily for streamflow, crop yield, sediment, and phosphorous. The verified model was used to simulate 22 crop-BMP combinations over the 1989–2016 period. A Linear Programming (LP) model was used to determine the crop-BMP choice that would maximize income and minimize public cost while abating sediment and phosphorous under two different scenarios: market solution (maximize revenue with no constraints on sediment and phosphorous production) and tax solution (discourage sediment and phosphorous production through incentive programs).The model was capable of providing precise information for stakeholders to prioritize ecologically sound and economically feasible BMPs that are capable of mitigating human induced impacts at the watershed scale based on soil texture, land slope and dryland and irrigated areas.

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CHAPTER I

INTRODUCTION, PROBLEMS AND OBJECTIVES

Introduction

Soil erosion is one of the serious environmental issues which threatens the agricultural sustainability and productive capacity. Continuous excessive soil erosion causes thinning of soils, removes plant nutrients, changes soil properties, and jeopardizes the sustainability of high levels of crop production. Besides the impact on soil productivity, soil erosion and consequently sediment and nutrient loads have a destructive impact on environmental resources outside the farm fields and are the main sources of pollutants to stream networks and reservoirs worldwide (FAO, 2013). Sediment from soil erosion can cause water body impairment, reduce ecosystem health, threaten drinking water supply, reduce reservoir capacity, increase the cost of drinking water treatment, and reduce the lifespan of reservoirs (Palmieri et al., 2001, Simon and Klimetz, 2008). Sediment may also carry excess nutrients, such as nitrogen and phosphorus (Miller et al., 2014), heavy metals, hydrocarbons, and organics that could threaten human health (Lyman et al., 1987). Although erosion is a natural process, it can be accelerated by human induced activities such as farming and urbanization. According to the United States Environmental Protection Agency (USEPA) (USEPA, 2016), most of the water bodies in the US are impaired by Non-Point Source (NPS) pollution and sediment ranks fifth among all these leading causes of water quality impairments. The federal Clean Water Act (CWA) in the US, adopted in 1972, establishes the basic structure for regulating and governing pollutants discharging into the water bodies of the US and regulating quality standards for surface water. It requires that all states restore their water bodies to be fishable and swimmable. Under the CWA, USEPA has implemented pollution control programs such as 303(d) program. USEPA's 303(d) Program assists states, territories and authorized tribes in submitting lists of impaired waters and developing Total Maximum Daily Load (TMDL), the maximum amount of a pollutant allowed in a waterbody, as the starting point or planning tool for restoring water quality. The 303(d) list comprises those waters that are in the polluted water category, for which beneficial uses like drinking, aquatic habitat, industrial, recreation and use are impaired by pollution. States are required to submit their list for USEPA approval every two years.

The Fort Cobb Reservoir (FCR) watershed located in southwestern Oklahoma, United States is a rural agricultural catchment with known issues of NPS pollution including suspended solids, siltation, nutrients, and pesticides and is listed on Oklahoma 303(d) list. The FCR watershed with an area of 813 km^2 includes one major lake fed by four tributaries; Cobb Creek, Lake Creek, Willow Creek, and Five-Mile Creek. The watershed is largely an agricultural catchment, with crop agriculture and rangeland as the primary land uses. Most parts of the watershed have been terraced for several years and recently several Best Management Practices (BMPs) have been implemented in the watershed (such as no-tillage and cropland to grassland conversion) to improve water quality. However, as a result of remaining sediment loads (ODEQ, 2015), studies are still needed for selection and placement of additional agricultural BMPs to reduce NPS pollution in the watershed. In 2001, the Oklahoma Conservation Commission (OCC) activated a 319 project in the watershed funded by the state and the federal government to target NPS in this watershed and to improve water quality through implementation of BMPs in conjunction with incentive payments (state funds, federal funds, and landowner cost shares) (OCC, 2009). Unfortunately, these programs, while effective, have not completely reduced sediment and nutrient loads to FCR such that it can be delisted as impaired waterbody according to the Oklahoma Department of Environmental Quality (ODEQ) 303d list (ODEQ, 2015).

The purpose of this research was to determine the most cost effective selection and location of these BMPs to reduce sediment loading and define more specific incentive payment programs for producers and landowners to adopt the most cost effective BMPs. To this end, a hydrological model was developed and used with an optimization model to determine the most cost effective set of BMPs that reduce soil erosion on farmlands with consideration of existing conservation practices. The objective function in this study was to find the maximum net benefit over BMP cost and changes in farm income while not exceeding stated sediment and/or phosphorus loads in the FCR watershed from FMC area of the watershed. Linear Programming (LP) was used to optimize the types and locations of the crops and conservation practices for sediment, nutrient and pesticide control at the study area. At the end, the shadow prices from the LP solutions were used to define more specific incentive payment programs for landowners and producers to adopt the most cost effective BMPs.

Problem statement

Issues such as sediment load to streams and reservoirs due to soil erosion in upland areas and streambank erosion have been a major source of agricultural soil degradation and water body impairments for decades and considerable money and time have been spent for protection of agricultural lands and water bodies. According to Kansas State University (2008), freshwater pollution by sediment and nutrients costs individual Americans and government agencies at least $4.3 billion annually. Excessive sediment, in suspension or deposited, can reduce ecosystem health, threatens drinking water supply, reduces reservoir capacity, increases dredging cost, and increases the cost of drinking water treatment. Additionally, continuous soil erosion results in thinning of soil, changes soil properties and removes plant nutrients, and consequently endangers the sustainability of crop yields. According to David et al (1995), soil erosion reduces soil water holding capacity and soil fertility. Thus crop yields on eroded soils are lower than that on protected soils.

According to Garbrecht, et al. (2014), the Southern Great Plains of US has several agricultural issues, such as stressing landscape, increasing uncertainty and risk in agricultural production, and impeding optimal agronomic management of pasture, grazing systems, and crops. According to

Oklahoma State 303 list report, state's list of impaired and threatened water, most of the water bodies in the state of Oklahoma, located in Southern Great Plains, are impaired by sediment and phosphorous (USEPA, 2014). The Upper Washita River basin in southwestern Oklahoma has critical agricultural strategies and sustainability problems. The FCR located in this basin has multiple benefits, such as public water supply, wildlife habitats, and recreation. However the water quality of the FCR and its tributaries has been of concern for more than two decades, with water quality problems first identified in 1981. Four important tributaries which drain the watershed: Five Mile Creek, Willow Creek, Reservoir Creek, and Cobb Cree, are suffering from nutrients, suspended solids, siltation, pesticides, and unknown toxicity (Storm et al., 2003). These NPS pollutants cause taste and odor problems, reduced aquatic animal food, and increased dredging cost in FCR. The FCR watershed is on the Oklahoma 303(d) list due to water quality impairments (suspended solids, siltation, and phosphorous) and it does not meet water quality standards. It made this watershed a primary recipient of government soil and water conservation (SWC) program. Several agencies have made substantial efforts to solve this catchment's problems. In 1981, Oklahoma Department of Agriculture Food and Forestry (ODAFF) recognized water quality issues related to pesticides and nutrients in the FCR watershed. In 2000, FCR was listed as a nutrient limited watershed due to high primary productivity and FCR, Willow Creek, and Lake Creek were listed on the state's 303(d) list as impaired water bodies by turbidity, phosphorus, low dissolved oxygen, and pathogens. In 2001, the OCC activated a 319 project in the watershed to improve water quality through implementation of BMPs including riparian buffer establishment, erosion control, pastureland management, human waste management, and no-till farming (OCC, 2009). Subsequently, in 2005, ODEQ completed a TMDL study for the FCR watershed, recommending a 78% phosphorus load reduction. The OCC expanded earlier research to reduce phosphorus loading, focusing specifically on implementing no-till and reduced tillage farming. In 2009, the OCC suggested $15.0 per acre as incentive payment for no-till system. Through this project sixty landowners installed BMPs, in which 92% of the cost was provided by federal and state and only 8% of the BMP implementation costs was paid by landowners. As a result, NRCS raised the incentive rate for no-till, but switch to no-till required almost completely new equipment, representing a large financial investment and there was not enough funding. In addition, Tong et al. (2016) noted that current incentive system in FCR watershed needs restructuring to provide appropriate and effective attractive incentives to both producers and non-farming/absentee landowners. Despite efforts and research to improve water quality in the FCR watershed, there are still problems of sediment and phosphorous loads in this catchment (ODEQ, 2014) which demonstrates the need for research. Since the cost of implementing some BMPs can be highly variable, the cost effective selection and location of BMPs can aid in increasing both the efficiency of public funds and the total income of farmers. In this regard, there is a question of which conservation practices can minimize the sediment and nutrient loads in the watershed with minimum cost. The answer of this question can show the location and type of crops and agricultural BMPs (e.g. contour farming, conservation tillage, etc.) in each part of the watershed which lead the minimum sediment and nutrient exports with maximum net revenue for producers.

Objectives of the Study

In this study the cost effectiveness of different crops and associated crop production BMPs in reducing sediment and phosphorus loading from upland fields in the study area has been estimated. Hence, the overall objective of this research is to identify the most cost effective and ecologically beneficial placement and selection of crops and BMPs in farmlands to reduce sediment and nutrient loads to the FCR and protect long term water quality and availability. Specific objectives or questions in this research are to determine:

a. Determine which crops and/or crop production methods can reduce sediment and phosphorous loss at least cost to producers.

    1. Determine which crop and/or crop production methods are the most profitable to producers with irrigation while meeting reduced sediment and phosphorous target for the FMC sub-basin.

1-1. Determine how do no-till rotations involving wheat and other crops can affect crop yield and sediment and phosphorous reduction.

2. Determine which crop and/or crop production methods are the most profitable to dryland producers while meeting reduced sediment and phosphorous targets for the FMC sub-basin.
3. Determine which crop-livestock BMPs are the most profitable to producers while meeting reduced sediment and phosphorous target for the FMC sub-basin and ensuring livestock feed supply
4. Determine how many animal units could be supported by different cropping systems.

b. Determine the costs and benefits of maintenance and repair of existing terraces for continued crop production as opposed to converting area to pasture (Bermuda grass).
c. Determine how soil type and land slope affects the economics of BMP and crop choice.
d. Determine how the total and pre-unit cost of sediment and phosphorous abatement increase as sediment and phosphorous losses from crop and pasture land are decreased in FMC sub-basin.
e. Determine how shadow prices for sediment and phosphorous abatement can be used to develop the incentive payments to producers for BMP adoption?

The specific methods to achieve the main goals of this research are; 1) develop a hydrological model and calibrate and validate it for stream flow, sediment, and crop yield 2) generate appropriate BMP scenarios for different crops 3) apply the hydrological model for different scenarios 4) Use LP as an optimization model using General Algebraic Modeling System (GAMS) to provide precise information for stakeholders to prioritize ecologically sound and economically feasible BMPs at least cost.

In previous research on this watershed existing conservation practices in the watershed were not simulated in the hydrological model as a baseline by detail and rotation of no-till wheat with other crops was not addressed. Since most parts of the FCR watershed are being farmed on the contour with terraces for sediment reduction (Zhang et al., 2015) and construction of terraces requires high capital investment, the baseline condition of the watershed will address the presence and condition of existing terraces and contour. Since wheat occupies the largest acreage of any grain crops in this watershed, it is likely that no-till wheat production is one of the best scenarios for sediment reduction. However, continuous no-till wheat production is not really feasible due to the weed and disease cycles associated with wheat production (Edwards et al., 2006). One scenario which will be considered is rotation of no-till wheat with other crops. A row crop rotation, such as canola and winter wheat may be an economically viable scenario to continuous winter wheat, which increases marketability of the winter wheat due to improved consistency and quality of wheat after a row crop rotation (Boyles et al., 2004). This study will consider rotation of no-till wheat with other crops (cotton, canola, and grain sorghum) as additional scenarios.

CHAPTER II

LITERATURE REVIEW AND BACKGROUND

Studies on watershed modeling and NPS pollution control

The main cause of water quality impairment in the Unites States is human induced NPS pollution like agriculture and urbanization (USEPA, 2016). NPS pollutions are forms of diffuse pollution caused by nutrients, sediment, toxic and organic substances originating from particular land use activities such as agricultural activities, which occur over a wide area and carried to reservoirs, lakes and stream channels by surface runoff (Humenik et al., 1987). BMPs are effective and practical scenarios to control and reduce the transport of agricultural NPS to water bodies, but there are concerns regarding the economic efficiency of BMPs in controlling and reducing NPS pollutions. Evaluating different BMPs can ensure the most effective devoting of funding for watershed management and water quality improvement and can prevent the implementation of unnecessary conservation practices in the watershed (USEPA, 2011). Models are valuable tools to simulate the erosion process in watersheds and evaluate the effectiveness of different BMPs and they can be selected by watershed managers for a given set of conditions. Several models have been developed for addressing soil erosion and NPS pollution issue in watersheds and assessing different agricultural BMPs.

The Universal Soil Loss Equation (USLE) is the most widely applied model for estimating soil erosion. USLE was designed by the United States Agricultural Research Service (USDA-ARS). Wischmeier (1978) designed USLE to estimate soil loss from sheet and rill erosion in specific conditions from agricultural fields. The USLE predicts soil loss based on rainfall erosivity results (R), soil erodibility (K), slope length (L), slope (S), cover management factor (C), and support practice parameter (P).

In the late 1970s the Areal Non-Point Source Watershed Environment Response Simulation (ANSWERS) model was developed by Beasley and Huggins (1980) to evaluate the effects of BMPs such as conservation tillage, ponds, grassed waterways, tile drainage on surface runoff and sediment loss from agricultural watersheds. This model used distributed parameters and was an event-oriented, planning model. The overall structure involved a hydrologic model, a sediment detachment/transport model and several routing components necessary to evaluate the movement of water in overland, subsurface and channel flow phases. In a recent development (ANSWERS-2000), a groundwater component was added to the model (Bouraoui et al., 1997) and was validated at the local, field and watershed scales. This model had some weaknesses such as not being well adjusted for large scale catchments or for extremely long simulations. Due to computational requirements and the dependence of nutrient transformations and transport simulation on the empirical statistical equations, the model was time consuming and computationally intensive (Nisrami, 2006).

In November 1980 Chemicals/ Runoff, and Erosion From Agricultural Management Systems (CREAMS) model was developed to evaluate NPS pollution from field-sized areas. CREAMS includes three components: hydrology, erosion/sedimentation, and chemistry and is a field scale model for estimating erosion, runoff, and pollutant movement from agricultural management systems (Foster et al., 1980). CREAMS can be applied with individual storms but can also evaluate long-term effects (over 2-50 year periods). In this model, the impacts of different agricultural conservation practices can be determined by simulation of the potential water, soil, nutrient and pesticide losses in runoff from agricultural lands. This model was modified to CREAMS-WT version, but both versions were limited to small size fields and homogenous areas (Nisrani, 2006).

U.S. Department of Agriculture (USDA) in 1989 developed Agricultural Non-Point Source (AGNPS) pollution model, to solve the problems related to managing NPS pollution in watershed scale (Young et al., 1989). This model is an event-based model and was developed to address the problems related to point source and NPS pollution in surface and groundwater systems and estimates the impacts of different conservation practices in agricultural watershed-scale systems using the Universal Soil Loss Equation (USLE). The application of this model is limited to about 200 km^2 watersheds (Young et al., 1989). A continuous simulation watershed model (AnnAGNPS) was developed and included all the features that were in the AGNPS model plus pesticides, source accounting, settling of sediments due to in-stream impoundments using Modified Universal Soil Loss Equation (MUSLE) (Nisrani, 2006). These models had some limitations in tracking inflow and outflow of water due to lack of a mass balance calculation, sub-surface hydrology, and other weakness points. These problems became more serious by increasing the size of the watershed (Bowen et al., 2004).

Sediment from farmlands and streams threatens sustainability and productive capacity of agriculture. So, it was crucial to develop a model to assess the impact of soil erosion and NPS pollutions on soil fertility, water availability, and crop yield. David et al, (1995) indicated that corn yields on some severely eroded soils decline in many states such as Kentucky, Illinois, Indiana, Michigan, and Georgia. Hagen and Dyke (1980) predicted soil loss would reduce productivity in the US by 8 percent over the next 100 years. In their research they developed a soil/yield loss simulator, in which crop yield was a function of soil characteristics.

Williams et al. (1983) designed the structure of a simple soil and plant P model. By year 1985 it was applied in the Water Resources Conservation Act (RCA) (Williams, 1990). This model included physically and biologically based components for determining plant growth, erosion, and related processes and economic components for evaluating the cost of erosion and for evaluating the best conservation management practices.

Putman et al. (1988) developed the Erosion Productivity Impact Calculator (EPIC) model to estimate the effects of soil erosion on soil productivity and crop yield. EPIC is a continuous simulation model that can be applied to determine the effect of conservation practices on crop yield and soil and water resources. The drainage area considered by this model is generally a field-sized area, up to 100 ha. The major components in EPIC are hydrology, erosion-sedimentation, pesticide fate, nutrient cycling, weather simulation, soil temperature, plant growth, tillage, economics, and plant environment control. Colacicco and Associates (1989) applied EPIC to evaluate the impacts of soil erosion on fertilizer use and crop yields.

The Soil and Water Assessment Tool (SWAT) was developed in 1990 by the USDA Agricultural Research Service (ARS) at the Grassland, Soil and Water Research Laboratory in Temple, Texas (Neitsch et al., 2001). SWAT is a hydrological model to simulate the runoff and soil erosion in large complex watersheds and estimates impacts of different BMPs on crop, water, and sediment yield. The SWAT model is a semi-distributed, comprehensive, river basin scale model and is computationally efficient (Arnold et al., 1995). SWAT is used to assess the impact of different management practices on NPS and water resources in watersheds and requires information provided by the user (digital elevation data (DEM), soil data, land use data, precipitation and other weather data) to simulate runoff and soil erosion. In SWAT, sediment yield is estimated by the Modified Universal Soil Loss Equation. Hydrologic Response Units (HRUs) are portions of a sub-watershed that possess unique land use, slope range, and soil attributes (Neitsch et al., 2004). Engel et al. (1993) applied the SWAT model for the first time; Srinivasan and Arnold (1994) and Arnold et al. (1998) later added a geographic information system (GIS) interface for SWAT. Arnold and Forher (2005) described the expanding global use of SWAT and several releases of the model (96.1, 98.2, 99.2, and 2000 versions) as well. Gassman et al. (2007) described SWAT version 2005, and also reviewed over 250 SWAT-related applications that were done worldwide. They presented the strengths and weaknesses of the model and provided recommended research needs for SWAT. Krysanova and Arnold (2008), Douglas-Mankin et al. (2010), and Tuppad et al. (2011) did further updates on the SWAT model application and development trends, and the latter two articles provide further description of SWAT version 2009, the latest release of the model. SWAT was used to support the USDA Conservation Effects Assessment Project (CEAP), which is conducted to estimate the environmental benefits of conservation practices at both the national and watershed scales (Mausbach and Dedrick, 2004). There are several studies that have used the SWAT model to evaluate the effectiveness of BMPs in soil erosion and NPS pollution reduction and performing TMDL analyses. Biniam (2009) used the SWAT model to identify watershed management scenarios in the Blue Nile Basin of Ethiopia. Biniam illustrated that extreme surface runoff leads to high amount of soil erosion. Zhang et al (2011) conducted a study about agricultural conservation practices to efficiently reduce the sediment load and organophosphate levels in surface runoff. They applied SWAT 2005 to simulate sediment, streamflow and pesticide loads into the Orestimba Creek Watershed in California, US, from 2000 to 2006. They suggested that the SWAT model reasonably evaluated BMP effectiveness at the watershed scale. Dechmi et al (2013) evaluated BMPs under intensive irrigation using the SWAT model. Their research demonstrated that reduced tillage and irrigation management scenarios can result in significant lower total suspended sediment, irrigation return flow, and loss of all phosphorus forms. They concluded that a combination of the BMP scenarios was the best method to reduce total suspended sediments, reduce irrigated return flows, and reduce the loss of all phosphorus forms. Storm et al. (2003) used SWAT to model nutrient and sediment loads from upland areas of FCR watershed. They found that areas of wheat, peanut, and sorghum crops were contributing the largest amounts of sediment and nutrients to the reservoir. Nair et al. (2011) applied SWAT to calibrate corn, soybean, and wheat yields and compared the simulated crop yields to observed yields. They noted that compared to traditional calibration approaches (no crop yield calibration), the approach with crop yield calibration can improve prediction efficiencies, especially for nutrient balances.

Mittelstet et al. (2015a) employed the SWAT model and an empirical relationship to simulate crop yields and salinity levels in North Fork of the River Basin, located in southwestern Oklahoma and the Texas Panhandle. Sarkar et al. (2011), Panagopoulos et al. (2012), and Gikas et al. (2006) utilized the SWAT model to estimate cotton yields. In previous research on the SWAT model for evaluating crop yield drylands from irrigated lands were not separated. Since cotton is one of the main row crops produced in the FCR watershed and most of the irrigated fields in this watershed are covered by cotton, dryland and irrigated crops were separated using center pivot irrigation locations tagged from aerial photography. In this regard, the impact of optimal schedule of irrigation operation can be considered on runoff using this method.

SWAT model calibration

Since SWAT input parameters are process based, they should be within a realistic range using calibration and validation process. Model calibration is the comparison of predicted results to observed data in order to obtain a defined objective function and the modification of parameter values in the model (James and Burges, 1982). For calibration process, it is necessary to determine the most sensitive parameters to be adjusted (Ma et al., 2000). Sensitivity analysis at the watershed level is used to estimate the rate of change in the output of a model with respect to changes in watersheds parameters (Reungsang et al., 2005). There are two types of the sensitivity analysis local and global. Local is based on changing parameters values one at a time, and global, by changing all values at the same time. After determining the value of the most sensitive parameters during the calibration process and reducing the difference between the model prediction and observed data, the final step is validation to demonstrate the sufficiency and accuracy of the model (Refsgaard, 1997). In the calibration and validation process, available observed data are split into two datasets: one for calibration and one for validation. Most of the time data are split by time period, but data can be split spatially. To have good results of calibration and validation and to capture long-term trends, observed data should include wet, average, and dry years (Gan et al., 1997).

Several calibration methods have been developed for calibrating the SWAT model, including manual procedure and automated using calibration tools in the SWAT model. SWAT Calibration and Uncertainty Procedures (SWAT CUP) were developed in 2007 for automatic sensitivity analysis (one-at-a-time, and global), calibration, validation, and uncertainty analysis of the SWAT models (Abbaspour et al., 2007). SWAT-CUP is a freeware program that contains several algorithms for the SWAT model parameters optimization. SWAT-CUP calibration helps the user to obtain a better understanding of the hydrologic process in the model and parameter sensitivity. Using this generic interface, any calibration/uncertainty or sensitivity program can easily be linked to SWAT. There are five different optimization algorithms in SWATCUP: Sequential Uncertainty Fitting version 2 (SUFI-2), Particle Swarm optimization (PSO), Generalized Likelihood Uncertainty Estimation (GLUE), Parametric Solutions (ParaSol), and Markov Chain Monte Carlo (MCMC) vary parameter values to minimize the difference between the observed data and estimated data.

There are a number of previous studies that worked on automated calibration/validation and uncertainty analysis using SWAT-CUP (van Griensven and Meixner, 2006; Faramarzi et al., 2009; Akhavan et al. 2010). Abbaspour et al. (2007) made a multi-objective calibration and validation of the Thur watershed in Switzerland for sediment, stream flow, nitrate, and phosphate in the objective function with uncertainty analysis. Schuol et al. (2008a) calibrated and validated the SWAT model for West Africa and the entire continent of Africa. Yang et al. (2008) compared five different optimization algorithms in SWAT-CUP and calibrated a watershed in China using the MCMC algorithm. Faramarzi et al. (2009) applied the SWAT model as a hydrological model of Iran and calibrated and validated the model with the SUFI2 algorithm. Akhavan et al. (2010) calibrated the SWAT model for the nitrate leaching from the watershed in Iran, and Andersson et al. (2009) used SWAT-CUP to calibrate the SWAT model of the Thukela River basin in South Africa. All of the previous research on SWAT CUP reported the good results of automated calibration/validation and uncertainty analysis using SWAT-CUP. Moriasi et al. (2008) calibrated the SWAT model of FCR watershed for stream flow and suspended sediment based on daily data in 2005 to identify the "hot" spots/cropland in this watershed. They used geomorphic assessment to estimate the channel cover and channel erodibility parameters. In their research, they did not calibrate their model for all wet, dry, and average year but calibrated for one year (daily). Storm et al. (2006) calibrated FCR watershed SWAT model for streamflow at Cobb Creek near Eakley, OK from 1995 to 2001 with monthly data and validated the model from 1980 to 1989. In their research, the calibration of model was done manually for stream flow and phosphorous loads.

Before using SWAT-CUP for automated calibration process, it is necessary to examine the output of the SWAT model to see that is working properly or not. Iterative manual and automated calibration of hydrological model for different parameters like crop yield, stream flow, and sediment over long time periods (including dry, average, and wet years) by adjusting different operation management parameters and their specific schedule is the category for having the accurate calibrated hydrological model and there is limit research concerning all these factors together.

Conservation practices in the FCR watershed

Many studies have been conducted on conservation practices in agricultural fields to efficiently reduce sediment load and organophosphate in reservoirs (Biniam, 2009; Zhang, 2011; Dechmi, 2013; Aaron, 2014; etc.). Conservation practices such as contour and strip farming, terraces, conversion of crop land to Bermuda pasture, reduced till and no-till farming, drop structures, shelter belts, flood retarding structures, etc. have been currently implemented throughout the FCR watershed (Garbrecht and Starks, 2009). However, records detailing types and time of installation of these management practices prior to the 1990s are not readily available in either the state offices of the Natural Resources Conservation Service (NRCS) or the local conservation districts. According to Garbrecht and Starks (2009), 80%-90% of cropland in FCR watershed that needed terraces, has been terraced over the last 50 years. Over the last decade, about 50% of the cropland was in conservation tillage or minimum disturbance tillage. In addition to these management practices, gully reshaping and grad stabilization structures were implemented by conservation funds. Other conservation practices have been implemented without cost sharing assistance. Also, some selected channel bank sections were stabilized and some channels have been fenced to prohibit cattle from eroding banks, small impoundments were constructed, and a number of gravel roads were paved to control cropland erosion in this watershed.

As it was noted, terraces and contour farming were used in most of the cultivated areas in this watershed to protect the land against erosion. Since these conservation practices are effective in controlling soil erosion and sediment, it is important to include them in the baseline hydrological model before model calibration for flow and sediment. Simulation of terraces and contour can be done in different models (Shao et al. 2013). The SWAT model (Arnold et al. 1998; Gassman et al. 2007; Arnold et al. 2012) has successfully simulated these management practices and evaluated the impact of terraces on runoff (Yang et al. 2009 Ouassar et al. 2008). The effects of these practices can be simulated by modifying runoff and erosion parameters such as, slope length, the SCS runoff curve number (CN), and USLE practice factor. These parameters can be adjusted based on the land slope suggested by SWAT documents. There are several studies that simulated existing terraces and contour in their hydrological model. For instance, Bednarz et al. (2003) assumed that half of the cropland in their study watershed was terraced with/without contouring (based on personal communication with agencies and farmers), and the other half was straight-row with no terraces. Yang et al. (2009) assessed the impacts of flow diversion terraces on stream flow and sediment yield at a watershed level using the SWAT model. They assumed more than 50% of cultivated lands in the watershed had been protected by terraces against erosion. They simulated the impacts of terraces on abating water and sediment yields by adjusting P-factor in sub-basin level without considering the placement of them. Ouessar et al. (2009) assessed modeling of water harvesting systems in arid environments. They assumed that crop sites for growing olives are on terraces and they adjusted their SWAT model parameters for terraces on these sites.

SWAT has previously been used in FCR watershed modeling (Storm et al., 2003; Moriasi et al., 2007, 2008; Mittelstet, 2015b). None of the previous research on modeling the existing BMPs, aerial pictures used to distinguish the exact placement of existing terraces and contour and there were assumption about the percentage of watershed area under these practices. Since one of the goals of this research was to identify the placement of conservation practices, it is important to identify the placement of existing conservation practices to prevent reoffering them and assess other scenarios instead. Meanwhile, installing these practices requires high capital investment. Their presence will affect the optimal selection and placement of additional BMPs. Using aerial pictures and GIS located drainage lines can help us to locate broken terraces. Then HRUs can be adjusted in the SWAT model for good quality terraces and contour. In this case, it is possible to find out which of these practices need restoration and then restoration can be simulated to determine the effects of restoration scenario.

One of the other conservation practices that received the most attention in the upper Washita River watersheds was no-till farming. Conversion to no-till practices on at least 50 percent of cultivated area in the FRC watershed was one of the recommendations of the TMDL developed by the ODEQ for the this Watershed (OCC, 2015). Another common conservation practice was conversion of cropland to pasture land. The OCC began a program with emphasis on no-till farming to meet the water quality standards as established by the TMDL. According to OCC (2009) no-till was projected to be one of the most effective conservation practices for controlling both sediment and nutrient loads. No-till farming could help to hold moisture in the soil and protect soil against wind and rain erosion. However, no-till wheat yield has been decreased (Decker et al., 2009; Patrignani et al., 2012). One of the main reasons causing limitation on adaption of continuous no-till winter wheat farming is buildup of weeds and diseases cycles associated with wheat production (Edwards et al., 2006). Several researchers have studied no-till farming and its effect on runoff, NPS pollution and crop yield (Choi et al., 2016; Osei et al., 2012), however there is limited research focusing on rotation of winter wheat with other viable crops to solve the problems related to continuous no-till winter wheat farming and increase marketability of the winter wheat due to improved consistency and quality of wheat after a row crop rotation. Osei et al. (2012) assessed the effects of no-till systems on crop yield in farm-level economics and compared with other tillage systems for wheat production in FCR watershed. They indicated that if winter wheat grain yields are not significantly impacted by tillage systems, no-till would be more profitable than conventional tillage or the current mix of tillage practices in the watershed. In their study they did not address diseases resulted from continuous no-till winter wheat farming and rotation of this crop with other crops was not addressed to solve this issue. The current study will consider rotation of no-till wheat with other viable crops (cotton, canola, and grain sorghum) in the study region as a scenario and will assess its impact on winter wheat yield.

Economic analysis

Economic evaluation of water pollution involves a combination of biophisycal modeling and economic analysis (Khanna et al., 2003; Lintner and Weersink, 1999). In this regard, economic analysis can have a main role for devising a way to meet the environmental goals at least possible cost. One of the main issues in developing economic measures is to evaluate which conservation practices are cost effective. One measure of an effective conservation practice is whether it can attain a maximum reduction in NPS loads at maximum benefit or minimum cost (Giri et al., 2012). The objective for improving cost-effectiveness is the systematic optimization of real-world efforts (Rabotyagov et al. 2010). Hence, the information on economic influences on the implementation of such practices is critical. The number of possible BMP scenarios within a watershed rises exponentially with the number of fields. The enumerative assessment of all possible combinations of strategies performance in all fields within the watershed is impossible and it becomes neither practical nor economically feasible to select a best combination of BMPs that results maximum pollution reduction for least implementation costs. However, the process can be accomplished through mathematical programming. For example, a watershed with 100 farms and 3 different possible BMPs for each field will require 3^{100} evaluations. In this regard, selection and placement of BMPs in a watershed needs proper optimization method (selection of optimization method is based on the dictated condition of problem) with more efficient manner to result maximum benefit with highest possible pollution reduction rate. Meanwhile, since BMPs are usually implemented under a limited budget, costs associated with inefficient control actions may threaten achievability of designated water quality goals. Therefore, a balance should be considered between the economic and ecological implications of BMP implementation. Recent studies have demonstrated that optimization methods produce good results for optimal allocation of NPS pollution management practices at the watershed scale (Veith, 2003; Arabi, 2006; Jha, 2009; Rabotyagov, 2010). The optimization process will result in maximum net benefit with minimum amount of sediment and nutrient loads by considering the effectiveness and cost of various BMPs and searching for the best solution from all the possible solutions. Therefore, the selection of optimization methods is vital in spatial optimization to ensure that there will be convergence of the objective function. Several optimization methods, such as Monte Carlo simulation (Wu et al., 2006), Tabu search (Qi et al., 2008), scatter search (Zhen, 2006), non-dominated sorted genetic algorithms (Cisneros et al., 2009), and Linear Programing (LP) (Cisneros et al. 2011) have been used to develop a cost-effectiveness strategy. One approach in the present literature review considered the application of evolutionary algorithms like Genetic Algorithm (GA) and other approach considered mathematical optimization methods such as LP. For instance, Srivastava et al. (2002) combined the Annualized Agricultural Non-Point Source model with a GA for implementing the agricultural BMPs in farm lands. Bekele and Nicklow (2005) coupled the SWAT model and a multi-objective evolutionary algorithm to gain the tradeoff between ecosystem service and agricultural production. Maringanti et al. (2009) developed an optimization model for the selection and placement of the BMPs in the L'Anguille River watershed. They argued their method was both economically and ecologically effective at any watershed size. They used a multiobjective genetic algorithm (NSGA II) for optimizing their two objectives. One objective was minimizing net cost and the other one was minimizing the pollutant load from watershed. However, their optimization considered just application of fertilizer, buffer strips, and tillage management. Arabi et al. (2006; 2007) used the same methodology which combined a watershed model (SWAT) with GA for controlling sediment, phosphorus, and nitrogen plans that were multiple and had conflicting objectives. Their optimization used the SWAT model for simulation of sediment and nutrient loads, BMP tool, economic component, and GA for optimization. By this method they were able to select and place BMPs in upland areas and streams. Their solution required only one third the costs for the same level of sediment and nutrient loads in targeting strategies. The upland BMPs which they considered were just field borders and parallel terraces, but they did not consider other conservation practices such as no-till cropping. The stream BMPs considered were grassed waterways and grade stabilization structures. Maringanti et al. (2011) also provided an optimization method to find the placement and type of more feasible BMPs with minimum nitrogen, phosphorus, sediment, and pesticide losses from upland areas of Wildcat Creek watershed, located in northcentral Indiana. The BMPs which they considered in their study were residue management, filter strips, parallel terraces, contour farming, and tillage. For the optimization process, with NSGA II, to reduce computation time, they used a BMP database, which contained the pollution reduction and cost information of different BMPs, as a tool in the watershed model. They illustrated that buffer strips were the most cost efficient BMP compared to the other BMPs. Rabotyagov et al. (2012) integrated a modern and commonly used the SWAT model with multiobjective evolutionary algorithm SPEA. Ahmadi et al. (2013) used the multiobjective genetic algorithm (NSGA II) with mixed discrete-continuous decision variables and the SWAT model to estimate the optimal selection and placement of conservation practices for nitrate and atrazine control from uplands and streams. They considered other BMPs in their study: fertilizer management, grassed waterways and grade stabilization, and tillage and residue management. They demonstrated that by using a mixed variable NSGA II, it was possible to find solutions with higher water quality at lower cost than with binary variable optimization. But, they did not consider the selection of cover crop on the fields and they just considered the selection and location of BMPs.

LP is an optimization technique with a continuous linear objective function and linearly constructed constraints. One of the most common applications of LP is in devoting resources for different activities (Hillier & Lieberman, 1990). These methods have abilities for overcoming the limitation of evolutionary methods or heuristic techniques for solving the problems of Non-Point source pollution management optimization. Most of the problems solved by an evolutionary algorithm like GA require long computation times. Since the structure of watershed management modeling has the complex formation, applying an evolutionary algorithm for optimizing the watershed model becomes computationally complex and time consuming. For example, Muleta and Nicklow (2005) optimized their watershed BMPs using GA in approximately 4.75 days (Sebti et al.

2015). Using a LP allows a global optimum to be reached and local optimums are avoided with little computational time. In this regard, the use of classic optimization techniques like LP and Dynamic Programing (DP) has potential for improving the productivity of stakeholder collaboration (Ancev, et al. 2006). According to Dyke et al. (1985), a LP model plus related models with an associated LP subsystem are more suitable for studying erosion economics. These models prepare a detailed analysis of the land use, water and other resources. Westra and Olson (2001) applied mathematical programing to estimate the most efficient practices for phosphorous abatement in the Minnesota River and finally got 40% reduction. Ancev (2003) used the SWAT model for the Eucha-Spavinaw reservoir watershed in northeastern Oklahoma to simulate the watershed and used the results in a LP model to optimally model phosphorus reduction from chicken litter application. Khanna et al (2003) evaluated the cost effectiveness of the Conservation Reserve Enhancement land retirement program in the Illinois River using AGNPS model and mathematical programming to optimally identify areas for runoff reduction. Whittaker et al. (2003) interfaced SWAT with a data envelope analysis LP model to estimate the most cost effective policies in declining N losses to streams in Columbia Plateau area in the northwest U.S. Their results showed that a 300% tax on N fertilizer was more cost efficient than a mandated 25% reduction in N use. Adams et al. (2005) optimally modeled the location and type of crop and BMPs for pollution abatement in the FCR watershed using SWAT and LP and they could indicate the tradeoffs between producer income, sediment and nutrient load and the spatial allocation of crops in the watershed. Alminagorta et al. (2012) developed a LP to estimate the most cost effective BMPs in Echo Reservoir, Utah for phosphorus reduction. They divided their study watershed into three sub-watersheds (Chalk Creek, Weber River Below and Weber River above Wanship) and for each of them, it was identified nutrient management as the most cost-effective practice. Streambank stabilization and protected grazing land were found to be cost effective BMPs in Chalk Creek, additionally. Sunandar et al. (2014) employed LP in conjunction with the SWAT model to estimate the optimal land cover for decreasing soil erosion in the Asahan Watershed. The optimal land use had been estimated by LP with the objective function of minimizing cost with constraints for erosion. Their optimization showed that erosion can be decreased by reducing dryland farm areas, increasing forest area, and increasing plantation areas. These land use areas change could reduce erosion without decreasing water yield or the economic value of land. Sebti et al. (2015) used LP as an optimization model for the placement and selection of BMP at the watershed level to improve water quality and quantity. Their objective function was to minimize the total cost of conservation practices within the constraints of assuring a surface flow for the whole network during heavy rainfall and limiting the peak flow generated at the watershed outlet at the interceptor capacity for frequent precipitations. Previous research has focused just on some special management practices in upland areas and main streams of watershed to reduce amount of sediment and nutrient loads in channels and lakes.

Again, the purpose of this research was to determine the most cost effective set of BMPs for reducing upland erosion. The methods used developed a watershed simulation model integrated to systems analysis tools such as optimization models to determine optimal set of best management practices and cover crops and their spatial location that reduce soil erosion and meet regulations such as TMDLs with least cost. Eventually by using LP least cost combination of types and locations of upland conservation practices for nutrient and pesticide control and decreasing sediment loads in FCR watershed will be found. The objective function in this case is maximizing the net revenue for farmers while NPS pollution in the watershed is getting minimized simultaneously. To determine the optimal spatial allocation of crops and cropping practices in the watershed, the impacts of the policy changes and various levels of constraints must be examined at both the farm and the watershed level to indicate the changes required to achieve maximum net revenue. In this regard, the next part of literature review is related to incentive programs such that producers and landowners adopt conservation practices that further abate the downstream pollution costs caused by current land management practices.

Incentive programs for conservation practices adaption

There are no effective laws regarding the amount of sediment or nutrients that leaves the producer's land in the US. Thus any reduction in these items may be viewed as a cost by the producers. The producer's cost per unit of sediment (or phosphorous) abatement can be written as $\frac{\Pi_0-\Pi_{bmp}}{q_0-q_{bmp}}$, where Π_0 and Π_{bmp} are respective net revenues without and with the BMP adoption respectively and q_0 and q_{bmp} are respective NPS pollutants leaving the land without and with BMP.

Understanding what benefits from BMPs are preferred and why agricultural producers and landowners decide to adopt conservation practices in the FCR watershed is vital for policy makers, so they can make appropriate policies and incentive programs for both producers and landowners such that both groups implement practices that further abate the downstream pollution costs (externalities) caused by current land management practices. Different conservation programs, such as the Environmental Quality Incentives Program, Conservation Stewardship Program, and others have been developed in the US to provide incentives for further conservation practices adoption on agricultural fields (Cain and Lovejoy, 2004). Until 1985 these incentive programs used natural resource conservation as a reason to support financial funds to agricultural areas through agricultural producers. In the US today, some of the most commonly adopted conservation programs provided by the federal government are the Conservation Reserve Program (CRP), Environmental Quality Incentives Program (EQIP), and Conservation Stewardship Program (CSP) to compensate production losses or expenses for adopting new cropping or tillage systems and other BMPs. The CRP was developed in 1985 and is the first program that considers natural resource conservation seriously (Cain and Lovejoy, 2004). According to the USDA (2015), this program provides annual payments for retiring erosion sensitive lands and installing or maintaining certain crops and plants that abate erosion and increase water quality. EQIP is a program that supports technical and financial assistance to landowners and producers to adopt BMPs through cost sharing (USDA, 2015). CSP supports two payments types to producers enrolled in this program; one is for installing new BMPs, and the other is for adopting crop rotation (USDA, 2015). Some states like Minnesota have applied enhanced conservation programs such as the Conservation Reserve Enhancement Program (CREP) to permanently remove erodible enrolled land from production. Although there is a program entitled CREP in Oklahoma, this program does not permanently remove highly erosive agricultural lands from production (FSA, 2015). Producers in the FCR Watershed have followed the national trend by enrolling in various conservation programs such as CRP, CSP, and EQIP. Despite the positive effects of these programs, agencies such as the OCC, ODEQ, and the Natural Resource Conservation Service (NRCS) listed this region as a focal point for adopting more effective BMPs in order to improve water quality. In addition, the FCR watershed was named a water quality priority watershed by USEPA for 2001-2007 (OCC, 2014). OCC started a 319 project in 2001 funded by the state and the federal government to improve water quality through BMPs implementation such as pasture management, no-till farming, and human waste management in conjunction with incentive payments (state funds, federal funds, and landowner cost shares) (OCC, 2009). These programs were focused on cropland conversion rather than other management practices such as riparian buffers (OCC, 2009). Unfortunately, these programs, while effective, have not completely reduced sediment and nutrient loads to the FCR such that it can be delisted as impaired waterbody according to the ODEQ 303d list (ODEQ, 2015).

The principal approach in the US toward control of NPS pollutions from agricultural fields has been to subsidize adoption of BMPs or provide funds for land retirement and crop rotation, rather than taxing inputs such as nitrogen and fertilizer (Shortle and Horan, 2001). Since all conservation practices may not improve the profitability of enterprise in the farm level and the government is the main source of funding for soil and water conservation (Wang and Berman, 2014), different economic incentives requires to be developed at the local level to incentivize conservation practice adoption (Osmond et al., 2012; Ribaudo, 2015; Carlisle, 2016). Tong et al. (2016) supported Camboni and Napier (1993), Dobbs and Pretty (2004), and Shortle et al. (2012) in the assertion that the current incentive system in FCR watershed needs restructuring to provide appropriate and effective attractive incentives to both producers and nonfarming/absentee landowners. One of the main goals of this study is using different shadow prices from developed LP results to define more specific incentive payment programs for producers and landowners to adopt the most cost effective BMPs for meeting water quality goals.

CHAPTER III

CONTRIBUTION TO SCIENCE

This research developed a hydrologic, agronomic, and economic watershed model that incorporated crop-BMP simulations for making environmental and economic policy decisions. This research improved previous research conducted on the FCR watershed by incorporating GIS based hydrologic and agronomic data into a mathematical Linear Programming model to determine the least social cost for the watershed and construct the new incentive system to provide appropriate and effective incentives to both producers and landowners. The SWAT model was used to simulate crops and management practices and determine crop yield, sediment and phosphorus loading from each hydraulic response unit (HRU). Since SWAT is not an optimization program, a Linear Programming decision model was designed to incorporate the SWAT data to determine the most profitable livestock-crop-management practice in each HRU to meet sediment and phosphorus loss targets at maximum profit for agricultural and livestock producers. This study builds on, improves, and extends previous research by developing different combination of crops and agricultural management practices and techniques for reducing sediment and phosphorus loading at least cost to society to get additional progress needed toward the overall TMDL goal. In this regard, there were contributions to agricultural science, hydrology, and economy.

Since this watershed is a pasture intensive watershed and is a leading source of beef production, optimized number of supported animal unites with their monthly grazing operation to prevent overgrazing and reduce erosion from grazing was evaluated. This can be helpful for a beef producer to plan a year-round grazing system given a specified resource base, which has not been done in previous SWAT based research.

As most parts of the watershed are being farmed on the contour with terraces (Zhang et al., 2015) and construction of terraces requires high capital investment, existing conservation practices were modeled. Aerial pictures were used to distinguish the exact placement of existing terraces and contour and 2-meter LIDAR was used to extract the broken terraces. This process which has not been done in previous researches could improve the accuracy of the SWAT model, especially before the calibration process and could improve the sediment calibration process. One of the other innovative parts of this research is considering rotation of no-till wheat with other possible crops of the region as a highly recommended crop-BMP. Since previously no-till farming was highly recommended in the region of this catchment and since wheat occupies the largest acreage, so no-till wheat was one of the highly recommended crop-BMP (Garbrecht, 2015). But, since continuous no-till wheat production is not really feasible because of weed and disease (Edwards et al., 2006), this research considered the rotation of no-till wheat with other crops to evaluated the impact of rotation on crop yield and how it would affect the most economic choices.

Since the economic evaluation would be different in dryland and irrigated areas, this research separated dryland and irrigated areas to estimate the most cost effective crops and agricultural management practices in dryland and irrigated areas separately. Cotton is one of the main row crops produced in the FCR watershed and most of the irrigated fields are covered by cotton. Hence, center pivot irrigation locations tagged from aerial photography were used to distinguish the irrigated areas.

Since policy making can be helped by science, there was this attempt to make the results of this research more practical. One of the innovative parts of this research was to determine the economically efficient soils and slopes to be targeted for BMP placement to reduce sediment and phosphorous losses. Also, the specific minimum subsidies for adoption of specific conservation practices for adoption on targeted soil textures and slope classes can be determined. This research is a case study and outputs can be generalized to southern Great Plains. For example, the parameters for sediment and streamflow calibration, the targeted soil textures for having the highest rate of sediment and phosphorous loss reduction with maximum benefits and their specific crop-BMPs with the minimum subsidy that producers should paid to adopt them can be can be generalized for watersheds on this region.

CHAPTER IV

EVALUATING EFFECTIVENESS OF AGRICULTURAL CONSERVATION PRACTICES IN THE FIVE-MILE CREEK AREA OF FORT COBB WATERSHED

Abstract

One of the main causes of water quality impairment in the US is human-induced Non-Point Source (NPS) pollution through intensive agriculture. Fort Cobb Reservoir (FCR) watershed located in southwestern Oklahoma is a rural agricultural catchment with known issues of high sedimentation rate. In this study, the Five-Mile Creek (FMC) sub-watershed of FCR was selected to quantify impacts of 22 scenarios of crop/agricultural Best Management Practices (BMPs) on surface runoff, sediment loss and crop yield. For this, a hydrological model of the study area was developed using the Soil and Water Assessment Tool (SWAT) with 43 sub-basins and 15,217 hydrological response units. The model was calibrated (1991–2000) and validated (2001–2010) against the monthly observations of streamflow, sediment grab samples, and crop-yields. The coefficient of determination (R^2), Nash-Sutcliffe efficiency (NS) and percentage bias (PB) were used as gauging statistical matrices. Model parametrization resulted in satisfactory values of R^2 (0.64) and NS (0.61) in the calibration period and an excellent model performance (R^2 = 0.79; NS = 0.62) in the validation period for streamflow. Crop yield was calibrated manually and improved model performance and resulted in slight changes to SWAT default values for harvest index for optimal growing condition (HVSTI), solar radiation use efficiency (BIO_E), Manning's roughness coefficient (OV_N), and maximum leaf area index (BLAI) parameters for main crops in the region.

According to the results, contouring practice reduced surface runoff by more than 18% in both conservation tillage and no-till practices for all crops. Also, contour farming with either conservation tillage or no-till practice reduced sediment loss by almost half. Compared to the conservation tillage practice, no-till system decreased sediment loss by 25.3% and 9.0% for cotton and grain sorghum respectively. Since continuous no-till wheat is not practical because of weeds and diseases, no-till wheat in rotation with other crops increased the sediment rate compared to wheat with conservation tillage. Also, wheat as cover crop for grain sorghum generated lowest runoff followed by its rotation with canola and cotton regardless of contouring. Meanwhile, on dryland, wheat as a double or cover crop reduced soil moisture available for the subsequent crop and sediment loss increased for both cotton and grain sorghum covered with winter wheat. At the end, converting all the crops in the watershed into Bermuda grass would significantly reduce runoff and decrease sediment loss as the most efficient scenario.

Key words: Sediment, streamflow, BMP, SWAT model, crop yield, tillage, rotation, contour

Introduction

Sediment loads have detrimental impacts on environmental resources outside the farm fields and are the main sources of pollution loading to stream networks and reservoirs worldwide (FAO, 2013). Sediment discharge due to farming and urbanization can impair water bodies, reduce reservoir capacity and lifespan, threaten drinking water supply, increase water treatment cost, and reduce the overall ecosystem health (Palmieri et al., 2001, Simon and Klimetz, 2008). Non-Point Source (NPS) pollutions are forms of diffuse pollution caused by nutrients, sediment, toxic and organic substances originating from land use activities such as agricultural activities, which occur over a wide area and carried to reservoirs, lakes and stream channels by surface runoff (Humenik et al., 1987). According to the United States Environmental Protection Agency (USEPA) (USEPA, 2016), over half of the water bodies in the US are NPS pollution impaired, and sediment ranks sixth among all leading causes of water quality impairments.

The majority of states in the US Great Plains region consider agricultural NPS pollution to be a major source of their water quality issue. This is because agriculture constitutes the most intensive and extensive land use activity in this region (Osteen et al., 2012). Several management practices have been adopted to mitigate NPS pollution in this region. For example, the Conservation Technology Information Center (CTIC) by collecting information about adopting a conservation tillage system in Great Plains could replace 10 to 23% of conventional tillage system with conservation tillage system and decrease suspended sediment yields (Bernard et al., 1996). Also, Great Plains Conservation Program (GPCP) provides financial and technical assistance as water quality protection activities in the Great Plains states to ranchers and farmers who adopt total conservation treatment of their entire operation. Along with all effort made to reduce NPS pollution in this region, with increasing population and intensive agriculture and urbanization, there is still this issue in this region as an environmental problem.

The Fort Cobb Reservoir (FCR) watershed located in the Central Great Plains Ecoregion in southwestern Oklahoma, US is a rural agricultural catchment with known issues of NPS pollution, including suspended solids, siltation, nutrients, and pesticides. The FCR watershed with an area of 813 km^2 includes one major lake fed by four tributaries (Cobb Creek, Lake Creek, Willow Creek, and Five-Mile Creek). The watershed is largely an agricultural catchment, with crop agriculture and rangeland as the primary land uses. Although most parts of the watershed have been terraced for several years, continued siltation has resulted in Best Management Practices (BMPs) being implemented in the watershed (such as no-till crop production and conversion of cropland to grassland) to improve water quality. However, as a result of remaining sediment loads (site study), additional selection and placement of additional agricultural BMPs to reduce NPS pollution in the watershed is needed.

Since cotton is one of the main row crops produced in the FCR watershed with 9.1% coverage and most of the irrigated fields in this watershed are covered by cotton (7.1% irrigated cotton coverage), dry and irrigated crops were separated using center pivot irrigation locations tagged from aerial photography. In this regard, the impact of optimal schedule of irrigation operation can be considered on runoff using this method.

Many studies have been conducted on conservation practices in agricultural fields to determine the most efficient methods of reducing sediment loads and organophosphate loads in streams and reservoirs (Biniam, 2009; Zhang, 2011; Dechmi, 2013; Mittelstet, 2015; etc.). Conservation practices such as contour and strip farming, terraces, conversion of crop land to Bermuda pasture, reduced till and no-till farming, drop structures, shelter belts, flood retarding structures, etc. have been currently implemented throughout the FCR watershed (Garbrecht and Starks, 2009). However, records detailing types and time of installation of these management practices prior to the 1990s are not readily available in either the state offices of the Natural Resources Conservation Service (NRCS) or the local conservation districts. According to Garbrecht and Starks (2009), 80%-90% of cropland in FCR watershed that needed terraces, has been terraced over the last 50 years, and over the last decade about 50% of the cropland was in conservation tillage or minimum disturbance tillage. In addition to these management practices, gully reshaping and grade stabilization structures were implemented by conservation funds. Also, some selected channel bank sections were stabilized, some channels have been fenced to prohibit cattle from eroding banks, small impoundments constructed, and a number of gravel roads were paved to control cropland erosion in this watershed.

As noted, terraces and contour farming practices have been used in most of the cultivated areas in this watershed to protect the land against erosion. Since these conservation practices are effective in controlling soil erosion and sediment, it is important to include them in the baseline hydrological model before model calibration for flow and sediment. The SWAT model (Arnold et al. 1998; Gassman et al. 2007; Arnold et al. 2012) has successfully simulated these management practices and evaluated the impact of terraces on runoff (Yang et al. 2009 Ouessar et al. 2008). The effects of these practices can be simulated by modifying runoff and erosion parameters such as, slope length, the SCS runoff curve number (CN), and USLE practice factor. There are several studies that simulated existing terraces and contour farming in their hydrological models. Bednarz et al. (2003) assumed that half of the cropland in their study watershed was terraced with/without contouring (based on personal communication with agencies and farmers), and the other half was straight-row with no terraces. Yang et al. (2009) assessed the impacts of flow diversion terraces on stream flow and sediment yield at a watershed level using the SWAT model. They assumed more than 50% of cultivated lands in the watershed had been protected by terraces against erosion. They simulated the impacts of terraces on abating water and sediment yields by adjusting P-factor in sub-basin level without considering the placement of them. Ouessar et al. (2009) assessed modeling of water harvesting systems in arid environments. They assumed that crop sites for growing olives are on terraces and they adjusted their SWAT model parameters for terraces on these sites.

SWAT has previously been used in FCR watershed modeling (Storm et al., 2003; Moriasi et al., 2007, 2008; Mittelstet, 2015b). However, none of these studies assessed the effectiveness of existing BMPs on surface water quality and they did not model the existing practices. Also, in none of the previous research on modeling the existing BMPs, aerial pictures were used to distinguish the exact placement of existing terraces and contour and there was assumption about the percentage of watershed area under these practices. Since one of the goals of this research was to identify the placement of additional conservation practices, it is important to identify the placement of existing conservation practices to prevent reoffering them and assess other scenarios instead. Meanwhile, installing these practices requires high capital investment. Their presence will affect the optimal selection and placement of additional BMPs. Using aerial pictures and GIS located drainage lines can help us to locate broken terraces. Then HRUs can be adjusted in the SWAT model for good quality terraces and contour.

One of the other conservation practices received the most attention in the upper Washita River watersheds was no-till farming. Conversion to no-till practices on at least 50 percent of cultivated area in the FRC watershed was one of the recommendations of the TMDL developed by the ODEQ for this Watershed (OCC, 2015). The OCC began a program with emphasis on no-till farming to meet the water quality standards as established by the TMDL. According to OCC (2009), no-till was projected to be one of the most effective conservation practices for controlling both sediment and nutrient loads. No-till farming could help to hold moisture in the soil and protect soil against soil and rain erosion. However, continuous no-till wheat production has been shown result in decreased yield (Decker et al., 2009; Patrignani et al., 2012). One of the main reasons causing limitation on adoption of continuous of no-till winter wheat is weeds and diseases cycles associated with wheat production (Edwards et al., 2006).

Several researchers have studied no-till farming and its effect on runoff, NPS pollution and crop yield (Choi et al., 2016; Osei et al., 2012), however there is limited research focusing on rotation of winter wheat with other viable crops to solve the problems related to continuous no-till winter wheat farming and increase marketability of the winter wheat due to improved consistency and quality of wheat after a row crop rotation. Osei et al. (2012) assessed the effects of no-till systems on crop yield in farm-level economics and compared with other tillage systems for wheat production in FCR watershed. They indicated that if winter wheat grain yields are not significantly impacted by tillage systems, no-till would be more profitable than conventional tillage or the current mix of tillage practices in the watershed. In their study, they did not address the issue of diseases resulted from continuous no-till winter wheat farming and rotation of this crop with other crops. The current study will consider rotation and cover cropping of no-till wheat with other viable crops (cotton, canola, and grain sorghum) in the study region as a scenario and will assess its impact on sediment loss and net returns.

The purpose of this study was to determine the effectiveness of different possible BMPs to reduce sediment loading and surface runoff while increase crop yield. To this end, a SWAT hydrological model was developed and calibrated and validated based on streamflow, sediment, and crop yield to determine the effectiveness of BMPs set that reduce soil erosion on farmlands with consideration of existing conservation practices. The adjusted model was then used to simulate crop yields, sediments loads and water runoff with and without management practices.

Methodology

Study area

The Five-Mile Creek sub-watershed (FMC) is located in southwestern Oklahoma within the Fort Cobb Reservoir watershed (Figure 1). FMC has an area of 113.05 km^2. The FMC land use is comprised of 50% cropland, 41% pastureland and 9% others with other activities of cattle and hog operations. The major crops in the study area include winter wheat 30%, cotton (dryland 3.5%, irrigated 12.5%), and grain sorghum (1.5%).

Downstream of the study area is the Fort Cobb Reservoir (FCR), which receives water from four upstream tributaries of Cobb Creek, Lake Creek, Willow Creek, and Five-Mile Creek. The reservoir water quality has been of concern for decades. FCR and other waterbody segments in the region are included in the 303(d) list as being impaired by high levels of sedimentation, phosphorous, nitrogen, bacteria, and ammonia caused primarily by intensive agriculture and pastoral activities (OCC 2009; ODEQ 2014). The 303(d) list comprises those waters that are in the polluted water category, for which beneficial uses like drinking, aquatic habitat, industrial, recreation and use are impaired by pollution. Despite several additional BMPs being implemented, the issues of sedimentation still exist in the study area.

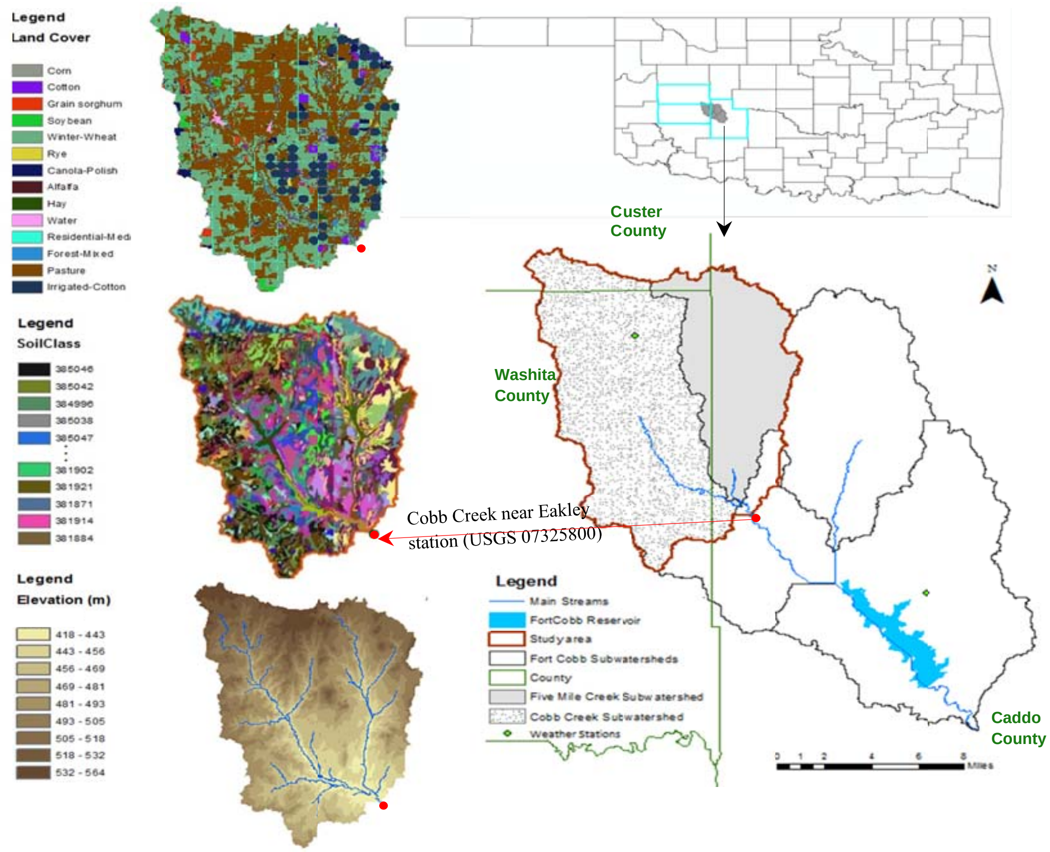

Figure 1. Five-Mile Creek (FMC) watershed located within the Fort Cobb Reservoir watershed (FCR). Land types, slope and soil classes and elevation maps are included.

A hydrological model of Fort Cobb Reservoir (FCR) watershed that includes the target study area of Five-Mile Creek sub-watershed (FMC) was developed using a Soil and Water Assessment Tool (SWAT). The model was calibrated manually and automatically. The verified model was then used to study the impacts of agricultural Best Management Practices (BMPs) on hydrology, sediment, and crop yield of major crops in an agriculture-pasture intensive rural sub-watershed located in southwestern Oklahoma (Figure 1). Details of the methods and steps involved in this study are explained in the sections below.

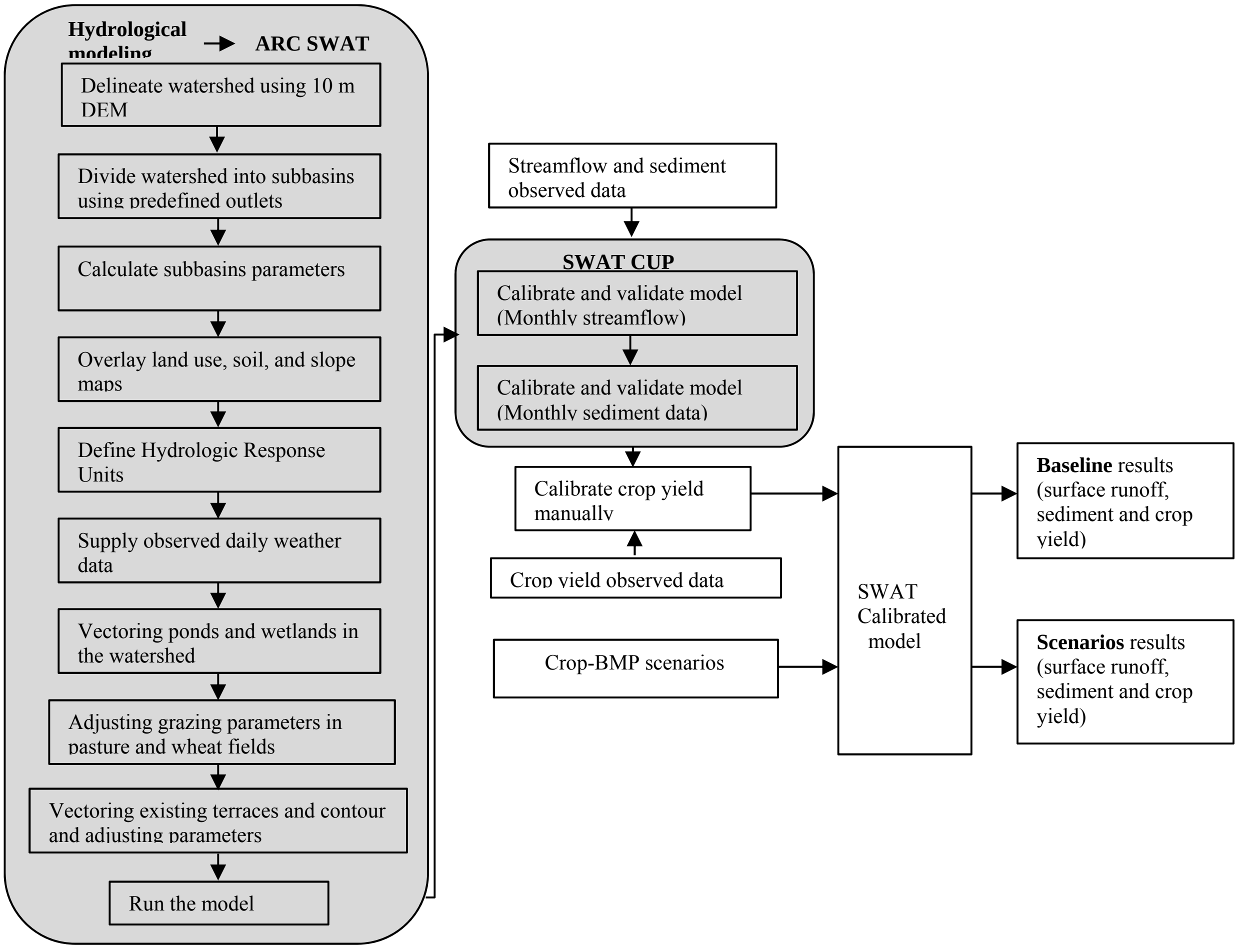

Figure 2. Schematic representation of Best management practices (BMP) implementation in a watershed

Hydrological model

The closest available USGS gage station (Figure 1) received runoff from both the Cobb Creek and FMC sub-watersheds. Therefore, a hydrological model was constructed for the larger area above this station (red basin in Figure 1) containing of the Cobb Creek and FMC and only the FMC portion is used in the later analysis. A hydrological model of the entire red basin that includes Five-Mile Creek sub-watershed was developed using a SWAT. A ten-meter Digital Elevation Model was used for watershed delineation, stream network creation and topographic information. The watershed was divided into spatially related 43 sub-basins with an average area of 8 km^2 (min. 0.2 km^2–max. 28 km^2). Since the study area did not have steep slope areas and was almost flat, the watershed topography was grouped into four slope classes of 0-2%, 2-4%, 4-6%, and >6%. Existing waterbodies including ponds in the watershed were obtained from USDA (2009) and modeled these waterbodies as ponds in each sub-basin (Appendix 1). The SSURGO soil database (USDA, 1995), the finest resolution soil data available, was used to define soil attributes in the watershed (Appendix 2). The land cover uses in the watershed were obtained from the 2014 crop layer map (USDA, 2014). The cultivated land cover types were further separated into irrigated and non-irrigated lands by using the center pivot irrigation locations. These locations are based on the 2014 one-meter resolution aerial images (https://datagateway.nrcs.usda.gov/). It was found that there were 30 pivot circles encompassing 13.67 km^2 (12.1%) of irrigated land dedicated for cotton production in the FMC area. Overlaying these land cover types, soil and slope classes with respective SWAT threshold percentages of 10% for land, 10% for soil and 20% for slope in each sub-basin resulted into 15,217 unique homogeneous units, called Hydrologic Response Units (HRUs) in the watershed. An HRU in SWAT captures watershed diversity by combining similar land, soil and slope areas in each sub-basin. In SWAT, loadings of water, sediments, and crop yield are calculated first at HRU level, summed at each sub-basin and then routed to the watershed outlet.

These HRUs were assigned agricultural BMPs (conservation tillage, no-till, contouring, crop rotation, and conversion to pasture - Bermuda grass) that are most commonly practiced in the study area. Existing contour in the study watershed were identified by using aerial photographs. The broken terraces were recognized using two-meter Lidar drainage lines as indicated in Figure 3. The HRUs with more than 65% contour were classified as being terraced with contour farming. It was found that 8 km^2 of FMC were terraces and contour without breaking, which modeling them resulted into 28% reduction in sediment.

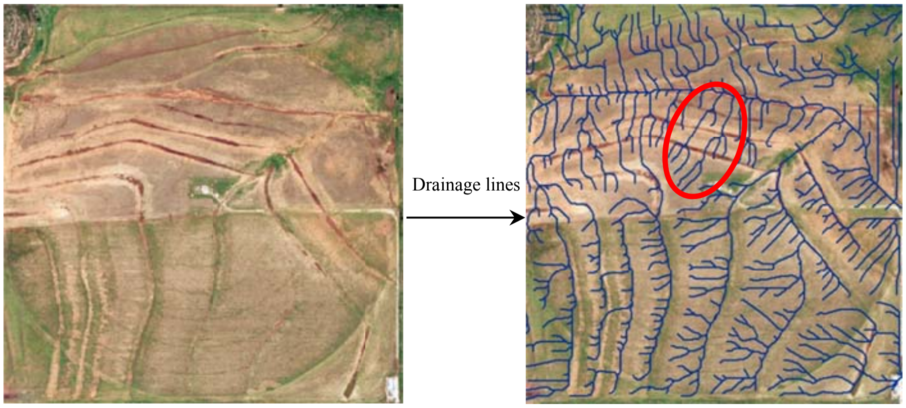

Figure 3. An example of broken terraces in the study area

Information about tillage type and fertilizer application for the selected crops was obtained from relevant literature (Storm et al, 2006; ODEQ, 2006) and consultation with local OSU Cooperative Extension Service and Conservation District personnel (Appendix 3 (a-i)). Additionally, cattle information in these HRUs was incorporated. Based on the NASS data for a 1996–2015 period, cattle stocking rate (0.5 head/ha), consumed biomass (3 kg/ha/day), trampled biomass (0.47 kg/ha/day) and deposited manure (1.5 kg/ha/day) were used as estimated by other sources (USDA-NASS, 2012; Storm et al., 2006).

The current climate pattern (1982-2016) in the watershed was represented by six climate variables: precipitation, minimum temperature, maximum temperature, solar radiation, relative humidity and wind speed. The climate data at daily scale were collected from a combination sources including the USDA Agricultural Research Service (USDA-ARS), the Oklahoma MESONET (McPherson et al., 2007) airport values and the Blackland Research site. In the period of 1982 to 2016, the study area received 2.2 mm/day precipitation with daily average temperature (15.8℃), solar radiation (16.9 MJ/m2), relative humidity (0.6 fractional), and wind speed (4.3 m/s).

Model calibration and validation

First, the model was calibrated manually and then automated iterative calibration was performed using SWAT-CUP tool (Abbaspour et al., 2007) for three important components: streamflow, sediment, and crop yield. Operation management parameters and associated cropping schedules were adjusted manually. Model sensitivity was tested prior to model calibration to determine the most sensitive parameters. Observed data on streamflow, crop yields and sediment loads from 1990 to 2010 were used for model calibration and validation. Three different statistical matrices- coefficient of determination (R^2), Nash-Sutcliffe efficiency (M/NSE for streamflow and Modified NSE for sediment) and percent bias (Pbias) were used to evaluate the model performance.

The coefficient of determination (R^2) is the square of Pearson's product-moment correlation coefficient (Legates and McCabe, 1999). It represents the proportion of total variance in the observed data that can be explained by a linear model and ranges from 0 to 1 with 1 being the perfect fit.

$$R^2 = \frac{\left[\sum_i \left(Q_{m,i} - \bar{Q}_m\right)\left(Q_{s,i} - \bar{Q}_s\right)\right]^2}{\sum_i \left(Q_{m,i} - \bar{Q}_m\right)^2 \sum_i \left(Q_{s,i} - \bar{Q}_s\right)^2} \qquad (1)$$

Where, Q is a variable (e.g. discharge), m and s stand for measured and simulated, i is the i^{th} measured or simulated data.

The Nash-Sutcliffe (NSE) (1970) is used to evaluate the predictive power of hydrological models and it can range from $-\infty$ to 1, with 1 being the perfect fit

$$NSE = 1 - \frac{\sum_i \left(Q_m - Q_s\right)_i^2}{\sum_i \left(Q_{m,i} - \bar{Q}_m\right)^2} \qquad (2)$$

Where, Q is a variable (e.g. discharge), m and s stand for measured and simulated respectively, and the bar stands for average.

The Modified Nash-Sutcliffe efficiency factor (MNSE) is reported to be more sensitive to significant over or under prediction than the square form.

$$MNSE = 1 - \frac{\sum_i \left|Q_m - Q_s\right|_i^p}{\sum_i \left|Q_{m,i} - \bar{Q}_m\right|_i^p} \qquad (3)$$

If p=2 then this is simply NSE as in above. If p=1, the overestimation of a peak is reduced significantly.

Percent bias (Pbias) is the deviation of data being evaluated, expressed as a percentage, measuring the average tendency of simulated data to be larger or smaller than the observations.

$$Pb = 100 * \frac{\sum_i^n (Q_m - Q_s)_i}{\sum_i^n Q_{m,i}} \qquad (4)$$

Streamflow calibration

The model was calibrated for monthly streamflow observed at the USGS gaging station- Cobb Creek near Eakely gage (USGS 07325800) for a ten-year period (1991–2000). Prior to model calibration, the sensitivity of the model to streamflow was tested in SWAT-CUP for 17 parameters. The p-value and t-state indicators were used to identify the most sensitive parameters in the watershed. The smaller the p-value and the larger the absolute value of t-state, the more sensitive the parameter is. The six parameters related to water balance: Curve number (CN), soil evaporation compensation factor (ESCO), groundwater delay (GW_DELAY), deep aquifer percolation fraction (RCHRG_DP), Manning's n value for the main channel (CH_N2), and available water capacity of soil layer (SOL_AWC) were found to be the most sensitive in the watershed (Appendix 4), similar to what other studies found (Moriasi et al., 2008; Storm et al., 2006).

According to Moriasi et al. (2015), model performance can be judged "satisfactory" for flow simulations if daily, monthly, or annual $R^2 > 0.60$, NSE > 0.50, and PBIAS ≤ ±15% for watershed-scale models. The model was calibrated satisfactorily for streamflow with values of R^2 (0.64) and NSE (0.61) and Pbias (5.1%) (Figure 4). The validation of the model with an independent set of monthly observed streamflow at the same gage station for a different ten-year period (2001–2010) indicated a robust model performance with values of R^2 (0.79) and NSE (0.62) and Pbias (-15%) (Figure 5). Calibrated parameters and their final value ranges are listed in Table 1.

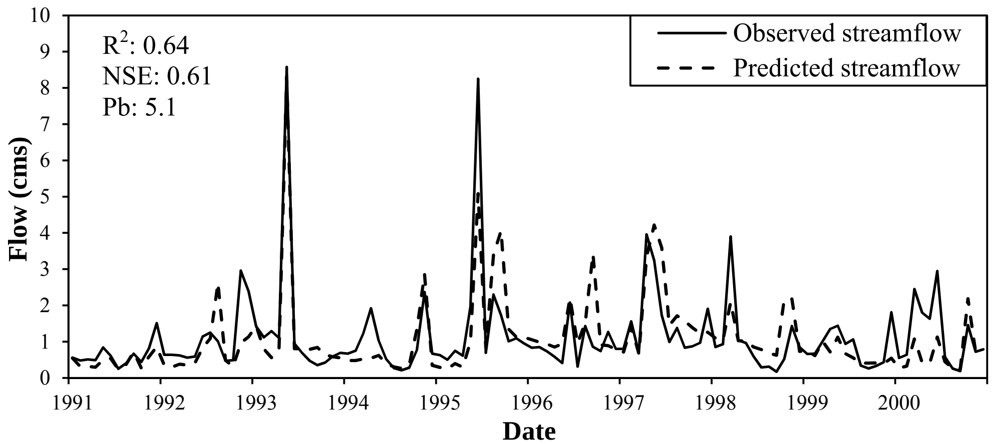

Figure 4. Observed and calibrated SWAT simulated streamflow at Cobb Creek near Eakley, OK (1991-2000)

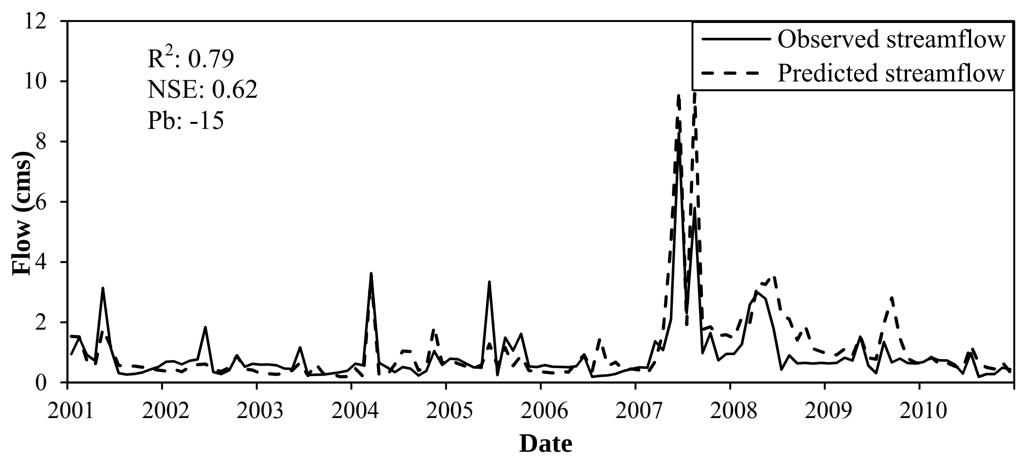

Figure 5. Validation monthly time series (2001–2010) for observed and SWAT predicted streamflow at the Cobb Creek near Eakley, Oklahoma gauging station

Sediment

Suspended sediment was calibrated for ten years (1991–2000) and validated for another ten years (2001–2010) at the watershed outlet. For this grab sample data that were available from 2004 to 2012 (usually 1 to 3 samples per month with a few months missing) was used. This grab sample data provided us an opportunity to estimate sediment loads for the time period that lacked observations using a sediment rating curve method. It is a regression relationship between the observed streamflow and sediment data used popularly to generate sediment information for missing period in many modeling studies (Jothiprakash and Grag, 2009; Salimi et al., 2013; Sarkar et al., 2008; Shabani, 2012; Gray and Simoes, 2008). A strong correlation (R^2=0.9) between the observed grab sample sediment data and runoff in the study watershed (Figure 6) was observed and used this regression relationship to estimate the missing sediment data for the model simulation period.

Despite the use of the filled in grab sample data there were still gaps in measurements and because of the dispersed nature of sediment, the model for monthly sediment loads was calibrated by modifying ten parameters that were related to sediment load (Storm et al., 2006; Moriasi et al., 2008). According to Moriasi et al. (2015), model performance at the watershed scale can be evaluated as "satisfactory" if monthly $R^2 > 0.40$ and MNSE > 0.40 and daily, monthly, or annual PBIAS ≤ ±20% for sediment. The model calibration with values of R^2 (0.30), MNSE (0.35) and Pbias (<20%), (Figure 7) and validation with values of R^2 (0.33), MNSE (0.43) and Pbias (<55%) (Figure 8) was considered acceptable. Calibrated parameters and their final value ranges are listed in Table 1.

It was found that the largest errors in sediment prediction were associated with errors of peak flow estimation. This could be due to the "second storm effect" problem in hydrological models, including SWAT (Abbaspour et al. 2007). The first storm event causes a larger sediment transport and makes remaining surface layers difficult to mobilize. As a result, the second and third storm events regardless of their event sizes, will result in smaller sediment loads. For this study area, the "second storm effect" was not tested since there were no observed sediment data representing flood events (May 1993, June 1995, June 2007) during model calibration-validation period. The simulated sediment data failed to accurately capture these events, resulting uncertainty in sediment calibration. The over-and under-estimation of sediment during flood events was reported in other SWAT based studies (Oeurng et al., 2011).

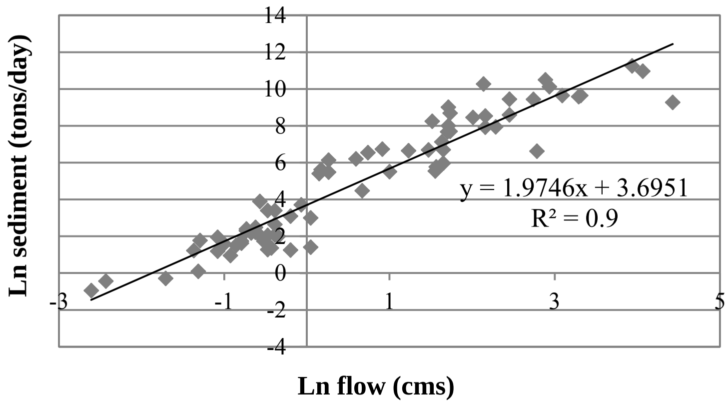

Figure 6. Observed daily discharge and observed daily suspended sediment concentration trend

Table 1. Streamflow and sediment calibration parameter values in study area

Component	Parameter	Parameter value range	Final value
Streamflow	V__GWQMN.gw	0.20_0.60	0.60
	V__GW_REVAP.gw	0.02_0.03	0.02
	V__REVAPMN.gw	0.50_1.50	1.38
	V__RCHRG_DP.gw	0.10_0.50	0.47
	V__GW_DELAY.gw	320_390	376
	R__CN2.mgt	-0.16_-0.13	-0.13
	V__ALPHA_BF.gw	0.80_1.00	0.95
	V__ESCO.hru	0.80_0.90	0.83
	V__EPCO.bsn	0.10_0.60	0.30
	V__CH_K1.sub	0.00_0.40	0.09
	V__SURLAG.bsn	0.50_4.00	3.05
	V__EVRCH.bsn	0.00_0.50	0.34
	V__TRNSRCH.bsn	0.00_0.10	0.10
	V__ALPHA_BNK.rte	0.60_1.00	0.84
	R__SOL_AWC(..).sol	-0.02_0.06	0.04
	V__CH_N2.rte	0.05_0.30	0.18
	V__CH_K2.rte	1.85_2.15	1.98
Sediment	R__USLE_P.mgt	-1.000_0.000	-0.240
	R__SLSUBBSN.hru	0.000_0.230	0.217
	R__USLE_K().sol	-0.500_0.300	-0.247
	V__RSDCO.bsn	0.010_0.100	0.083
	V__BIOMIX.mgt	0.000_0.300	0.297
	V__SPCON.bsn	0.000_1.000	0.009
	V__SPEXP.bsn	1.000_2.000	1.714
	V__CH_ERODMO(..).rte	0.050_0.700	0.355
	V__CH_COV1.rte	0.001_0.800	0.518
	V__CH_COV2.rte	0.001_0.800	0.332

Note: “R” before the parameter name stands for relative change (the parameter is multiplied by 1+value); “V” stands for replacement (the parameter is replaced by a value within the range)

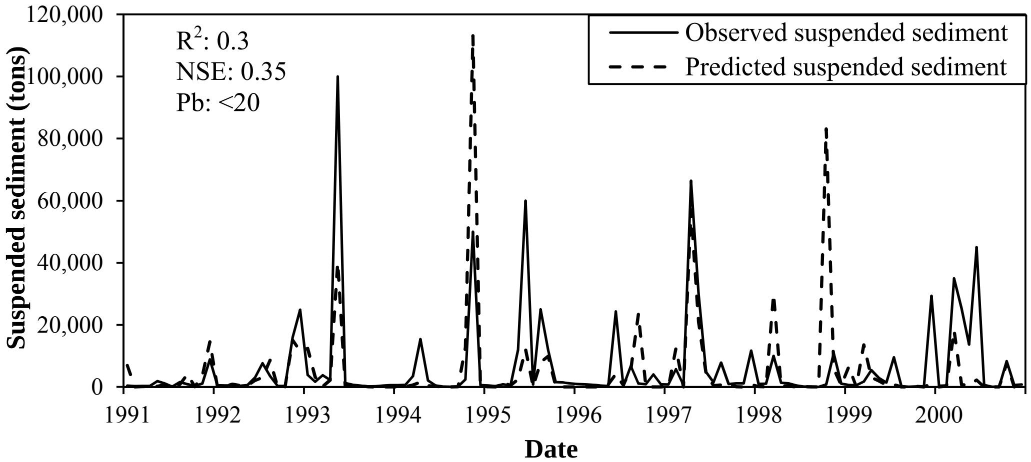

Figure 7. Observed and calibrated SWAT simulated suspended sediment concentration at Cobb Creek near Eakley, OK (1991-2000)

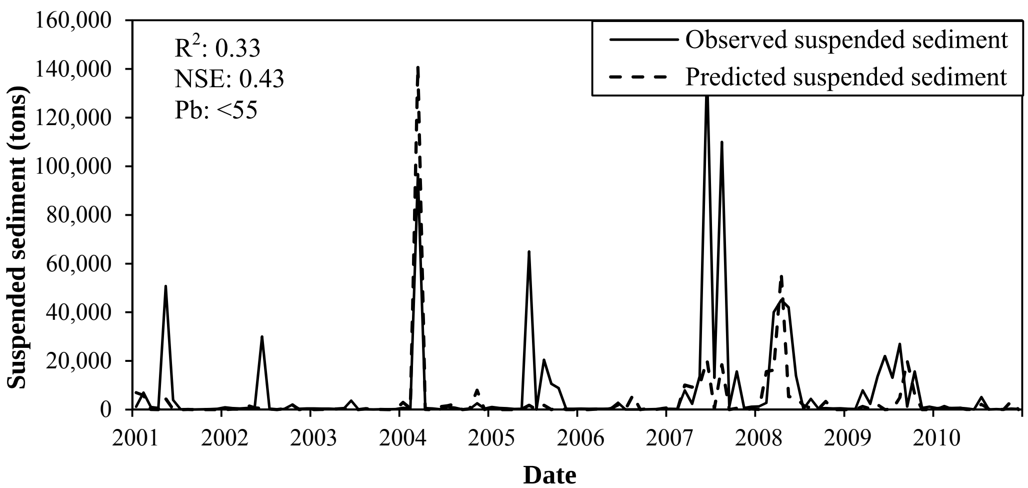

Figure 8. Observed and validated SWAT simulated suspended sediment concentration at Cobb Creek near Eakley, OK (2001-2010)

Crop yield

Crop yield and biomass production affect watershed hydrology through altered erosion and water balance (Hu et al. 2007; Ng et al. 2010a; Andersson et al. 2011; Nair et al. 2011). A combination of the OSU variety trial data from 2001 to 2016 (http://croptrials.okstate.edu/), and the county level NASS data (1986–2005) were used to calibrate yield of crops (winter wheat, grain sorghum, cotton-both dry and irrigated) (USDA-NASS, 1986 to 2005, http://digitalprairie.ok.gov/cdm/ref/collection/stgovpub/id/11177). The variety trial crop yields were collected from sites in seven counties (Apache, El Reno, Homestead, Chickasha, Altus, Tipton, and Thomas) that are located within and nearby the study area. A list of crop yield parameters with their initial and calibrated values is provided in Appendix 5 (a, b). In this study the coefficient of determination (R) was used as an indicator to compare the SWAT simulated yield with the observation. The values of R for cotton, grain sorghum and winter wheat, grain sorghum, and cotton were 0.4, 0.32 and 0.61 respectively which are deemed satisfactory as reported by other studies.

Based on the previous research in this area, the average yields for hay, alfalfa, rye, native pasture, and Bermuda grass yield in the study area were set at 2000, 3000, 3000, 1500, and 6500 kg/ha respectively.

Scenarios of agricultural Best Management Practices

Studies identified sedimentation as one of the water quality issues in the region with the associated ecological and economic impacts (Zhang et al., 2015). As a result, various agricultural BMPs have been implemented in the watershed to abate sediment loading and transport (Becker, 2011). Despite these efforts, there are still soil erosion problem in agricultural fields causing degraded water quality in the region.

Five scenarios that reflect the commonly used agricultural BMPs in the study area and throughout the Great Plains region were developed (Table 2). A combination of land use and these five scenarios resulted into 22 SWAT model simulations. In scenarios 1–4, the study area was simulated for one crop at a time by converting all crops into one (for example, all crops converted to wheat and so on). In scenario 5, all the cropland in the study area was converted to Bermuda grass. Bermuda grass was chosen because producers are having success in cropland conversion in the FCR watershed (result of a meeting with Nolan (2017)).

Table 2. Agricultural Best Management Practices (BMPs) scenarios simulated for, cotton, grain sorghum and winter wheat to evaluate their impacts on hydrology, sediment and crop yield in the study area

Code	BMP Scenario	Description
BL	Baseline	Simulation under the calibrated and validated model with 14 land uses, 8 km^2 FMC under contour farming
S1	Conservation tillage and strip cropping	BMP applied to cotton, grain sorghum, and winter wheat. No changes made to hay and alfalfa. Data obtained from NASS (2014), Storm et al. (2003) and Storm et al. (2006). Total three simulations, one for each crop.
S2	Conservation tillage on contour	Applied contour on scenarios 1; 97 km^2 additional contour as compared to the baseline scenario. Resulted three simulations, one for each crop.
S3	No-till and strip cropping i. No-till wheat in rotation with canola ii. No-till wheat as a cover crop for cotton iii. No-till wheat as a cover crop for grain sorghum	All tillage practices were removed while management practices were kept the same; applied to cotton, grain sorghum and winter wheat. Because of weed and disease problems associated with continuous no-till wheat, wheat was rotated/cover coped with (i) canola, (ii) cotton and (iii) grain sorghum. Total five simulations, one for each crop.
S4	No-till on contour	Applied contour on Scenario 3. Resulted five simulations, one for each crop.
S5	Conversion to pasture	All crops were converted to Bermuda grass pasture. A combination of three grazing start months (May, June and July) and two stocking rates (1,200 and 1,600 kg) were applied. Total of six simulations.

Note: Details of each scenario are provided in Appendix 6

Results

Surface runoff

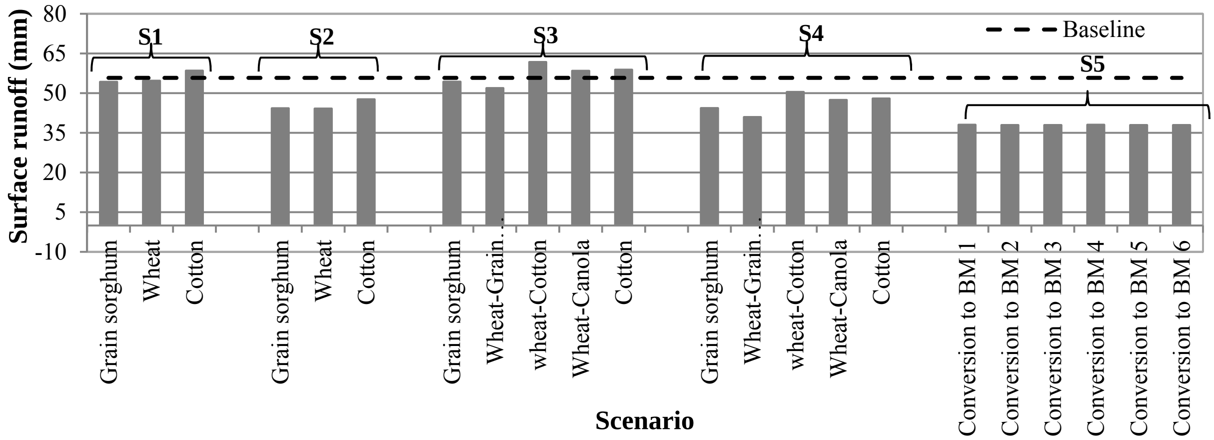

Figure 9. Average surface runoff generated under each agricultural Best Management Practice scenario and the baseline scenario

All five scenarios except for S3 with wheat-cotton and wheat-canola rotations and cotton in S1 and S3 decreased surface runoff compared with the baseline scenario (Figure 9). Under conservation tillage, it was found that surface runoff would reduce by 18.4% for cotton and grain sorghum and by 19.2% for winter wheat when contouring is applied on conservation tillage. Similarly, implementation of contouring on the existing no-till BMP (S4) led to reduction in runoff by 18.4% (cotton and grain sorghum) and 19.4% for wheat compared to the no-till BMP (S3). Between the three major crops in scenarios 1 to 4, grain sorghum was the least runoff generator followed by winter wheat and cotton. The scenario 5 (S5) in which all crops were converted to Bermuda grass generated the least amount of surface runoff as compared to rest of the scenarios. Application of two different grazing operations and stocking rates in S5 resulted virtually the similar runoff generation (37.96 to 38.08 mm) with less than one-third of a percentage point difference between them. Of the 22 combinations of agricultural BMPs simulated in all five scenarios, wheat rotated with cotton under no-till BMP resulted the highest runoff followed by wheat rotated with canola. Also, there is no change in surface runoff by changing the tillage system (conservation to no-till system).

Sediment

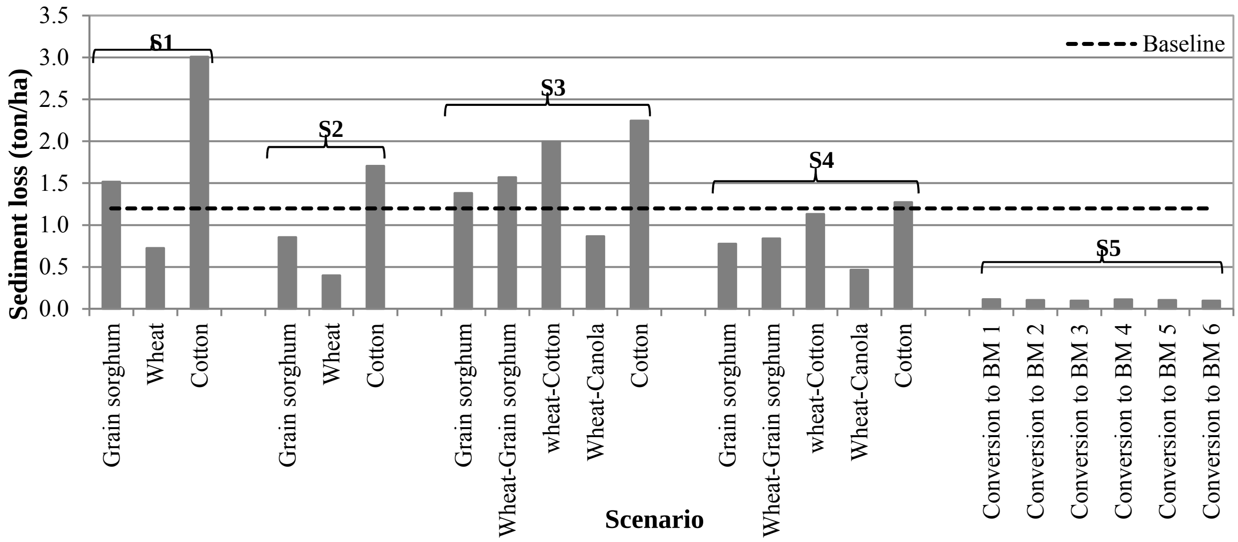

Figure 10. Average annual sediment loss (tons per hectare) under each five agricultural Best Management Practices scenarios compared with the baseline scenario

Simulation results revealed that implementation of contouring practice on conservation tillage (S1 and S2) and on no-till (S3 and S4) would reduce sediment loss nearly by half (Figure 10 and Table 3). Between all 22 combinations of agricultural BMPs, cotton was the lead contributor to sediment loss. For cotton, contour no-till practice generated the least sediment loss (1.27 tons/ha) while the conservation tillage with no contouring contributed to the most sediment loss (3.01 ton/ha). Wheat's contribution to sediment loss was as half as that of grain sorghum and one-fourth of that of cotton (S1–S4). Wheat, under the conservation tillage with contour (S2), was the least contributor of sediment loss (0.4 ton/ha). Rotating wheat with canola was found to be the most effective in controlling sediment loss under no-till system with only 0.87 ton/ha loss as compared to wheat as a cover crop for cotton (2.0 ton/ha) and grain sorghum (1.57 ton/ha). Converting all crops to Bermuda grass pasture with combinations of different grazing time and stocking rate (S5) resulted only 0.10 to 0.12 ton/ha sediment loss. It was found virtually no difference between the combination of grazing timing and stocking rate on the amount of sediment loss.

Table 3. Sediment reduction in percentage as a result of contouring on conservation tillage and no-till practices for cotton, grain sorghum and winter wheat in FMC sub-watershed

Grain sorghum		**Cotton**		**Wheat**			
Conservation tillage	No-till	Conservation tillage	No-till	Conservation tillage	No-till (In cover cropping/rotation with) Grain sorghum	Cotton	Canola
44	44	45	46	43	46	43	43

Four of 11 sub-basins in FMC (#7, 15, 16, 18) had high average sediment rate (1.2–1.5 ton/ha) (Figure 11.a) under the baseline scenario compare to other sub-basins. Almost half of these sub-watersheds have fine sandy loam soil texture and half silty clay loam which are more erosive soils. Also, 20% of crops in this area are cotton (both irrigated and dry), which is one of the reasons for high rate of sediment. The amount and location of these sediment loadings varied between the scenarios. For example, 90% of sediment load was reduced under Bermuda grass scenario (S5), while it was increased by 76% with cotton under no-till and 135% with cotton under conservation tillage. Figure 11 illustrates the change of sediment rate in different subbasins of watershed when all cropland in the watershed is converted to each BMP. As shown above in Figure 10, the least erosion occurs with Bermuda grass (Figure 11, panel b) and the greatest amount of erosion occurs with cotton (Figure 11, panels e, f, g, and h).

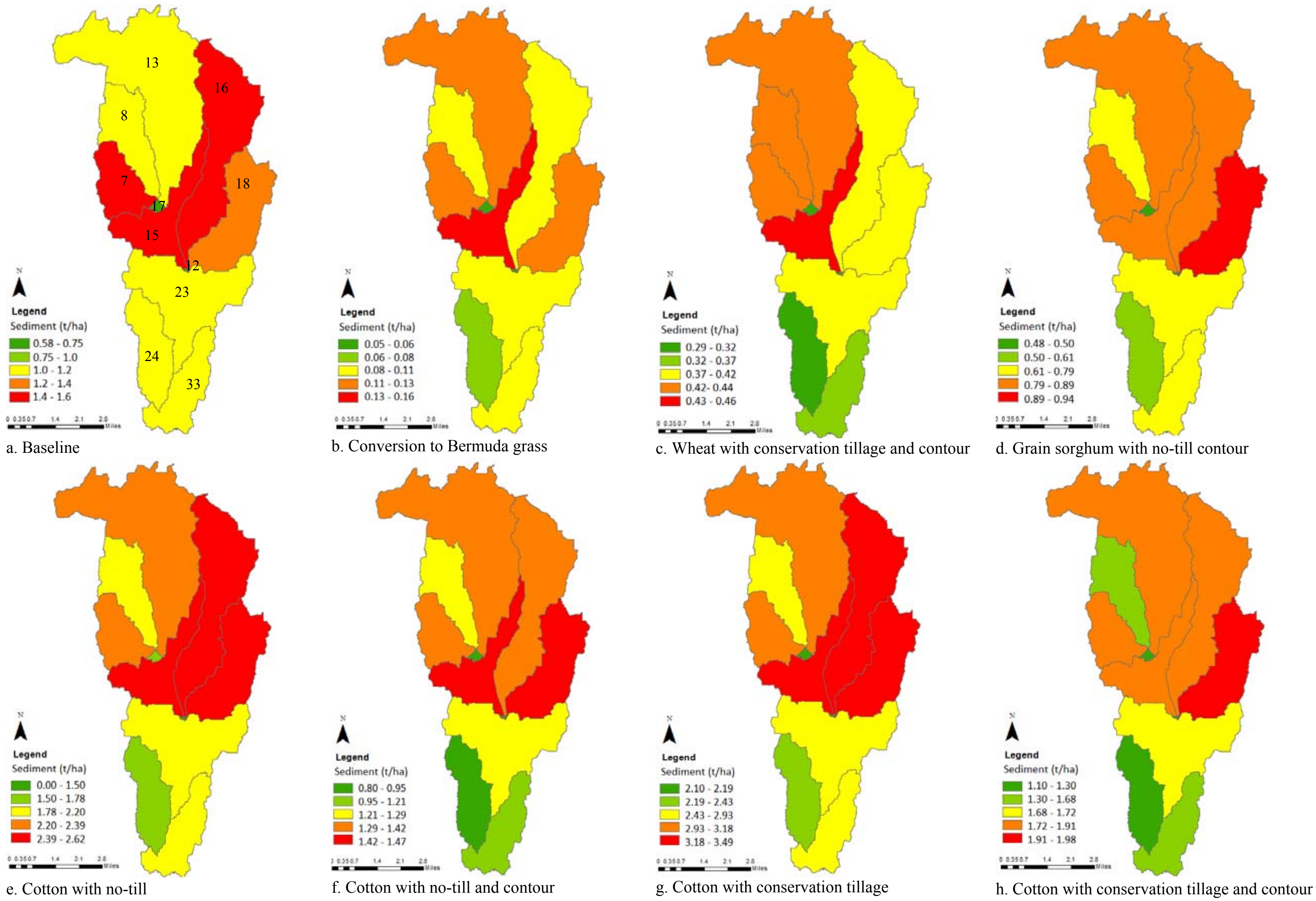

Figure 11. SWAT simulated sediment loadings (tons/ha) in Five-Mile Creek sub-watershed under baseline, best and worst scenarios at sub-basin level **Error! Reference source not found.**

Crop yield

It was found that there was no significant effect of contouring and tillage systems on simulated yields for cotton, grain sorghum and winter wheat. Under the no-till practice, grain sorghum yield covered with wheat increased by 18.5% (S3 and S4). It was found that covering/rotated with winter wheat resulted into reduced yield for both cotton and grain sorghum regardless of contouring (S3 and S4). When covering/rotated with winter wheat, cotton yield decreased by 52% with or without contouring while grain sorghum yield decreased by 28.4% (no contour) and by 14.8% with contour (S3 and S4). The reason is that this region is water limited region and by rotating crops with wheat in no-till system, there will be wheat residues on the fields once the crop (cotton or grain sorghum) is being planted, hence the moisture of the soil will not be enough for the second crop (cotton or grain sorghum) and it will reduce their yield. This reduction in cotton yield is more than grain sorghum yield when they are being rotated/covered with wheat. In the hypothetical scenario of converting all crops into Bermuda grass pasture (S5), it was found that there was virtually no effect of stocking rate on grazing start month on yield (Figure 12).

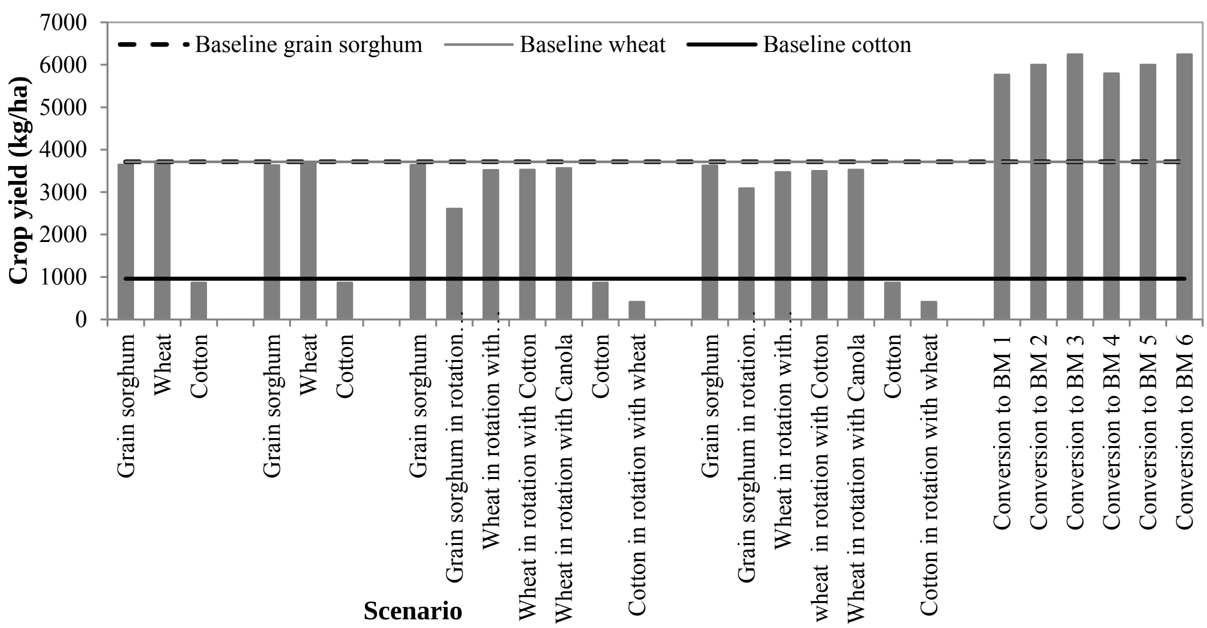

Figure 12. Crop yields under different agricultural Best Management Practices scenarios

Discussion

As of 2005, approximately 89% of the FCR watershed lands were devoted to the agricultural production of row crops like wheat, grain sorghum, cotton, peanuts, and pasture (Becker, 2011). In order to reduce erosion in FCR watershed, a series of BMPs has been implemented (OCC, 2014). The federal government currently offers conservation programs to install new tillage or cropping systems (USDA, Farm Service Agency [FSA], 2016). Some farmers have removed the more erosive parts of their land from crop production and planted Bermuda grass (USDA-FSA, 2015). Most farms have received financial and technical assistance and installed terraces where needed. According to Zhang et al. (2015), the average sedimentation rates in the FCR were three to five times higher during the 1957 to 1963-time period than during the 1964 to 2011 period and it is because of the implementation of numerous conservation measures in the watershed, including check dams, terraces, changing cropping patterns, and progressive adoption of no-till and conservation tillage systems. However, as of 2013, measures have not reduced sediment loads in the FCR watershed to target levels (ODEQ, 2014). This research is evaluating the effectiveness of additional crop/agricultural BMPs in this region on water quality and quantity and crop yield in the FMC area of FCR watershed.

The Fort Cobb Reservoir (FCR) watershed is a typical example of agriculture-pasture intensive watershed in the US Great Plains that can be used as a test bed for simulating the impacts of agricultural activities in combination with various BMPs on water quality and quantity. The FCR watershed contains a multi-purpose lake that has been beneficially used for water supply, recreational tourism and aesthetics (OCC, 2009 - p4).

Effect of contouring on runoff, sediment loss and crop-yield: Contour farming and terracing are recommended conservation practices in the western gently sloping part of Oklahoma (Nelson, 1937). Contour farming across the slopes and following contour lines reduces the formation of gullies and rill in heavy runoff period and consequently, reduces erosion. Terracing is used to prevent rainfall runoff causing soil erosion by cutting wide steps around the slopes of hills. These two are one of the most technically efficient BMPs in this region, and therefore, used as one of the strategies in this research. In this study area, it is estimated that 90 percent of the land where terraces are practical has been terraced to reduce the erosion (Garbrecht, et al., 2009). Contour with either conservation tillage or no-till farming prevented sediment loss by almost half. It was also found that contouring practice reduced surface runoff by more than 18% in both conservation tillage and no-till practices for all crops.

Effect of tillage on runoff, sediment loss and crop-yield: Garbrecht et al. (2008) stated that over the last decades, 50% of cropland was under the minimum tillage or conservation tillage system cropping or no-till in the FCR watershed. It was found that conservation tillage and no-till practices on cotton and grain sorghum have virtually no effect on surface runoff and crop-yield. Compared to the conservation tillage practice, no-till decreased sediment loss by 25.3% and 9.0% for cotton and grain sorghum respectively.

Effect of crop rotation/cover cropping on runoff, sediment loss and crop-yield: It was found that surface runoff decreased for sorghum (-4.6% vs. -8.1% with contour) and increased for cotton (+5% regardless of contouring) when these crops were rotated with winter wheat. The effect of wheat as cover crop for grain sorghum generated lowest runoff followed by its rotation with canola and cotton regardless of contouring. Sediment loss increased for sorghum (13.7% vs. 8.0% with contour) and it decreased for cotton (11.0% regardless of contouring) when these crops were rotated with winter wheat. The sediment loss was the highest for cotton followed by grain sorghum and canola when rotated with winter wheat regardless of contouring. The reason of increasing sediment loss once there was rotation or cover cropping is that this region is water limited region and rotation with wheat will take the moisture of soil once planting and having wheat on the ground. Yields of both cotton and grain sorghum decreased once winter wheat was used as a cover crop for cotton and grain sorghum,. Cotton yields decreased by 52.2% regardless of contouring (51% dry land cotton and 62% irrigated lands cotton). Grain sorghum yields decreased by 28.4% vs. 14.8% under contour farming. Winter wheat yield remained virtually the same when rotated with canola and used as a cover crop for grain sorghum and cotton regardless of contouring. Osei (2016) applied three conservation practices in the

FCR watershed to find the optimal distribution of conservation practices and indicated that no-till winter wheat production in central Oklahoma results in a small cost reduction while maintaining yields and is the win-win option. But since continuous no-till wheat is not possible because of weeds and other disease, it is not the good scenarios for adoption.

Effect of converting crops into pasture on runoff, sediment loss and crop-yield: Garbrecht et al. (2008) stated that substantial reduction in sediment yield in FCR watershed in the second half of the 20th century was related to conversion of cropland to pasture land. They stated that from 1940-1948, about 72% of the FCR watershed was in agricultural production and only 25% was in pasture, and there were no conservation practices before 1950. At the beginning of 21th century (2004-2007), only about 52% of watershed was in agricultural production and 36% was in pasture or grass lands. It was found that converting all the crops in the watershed into Bermuda grass would significantly reduce runoff by 6.8 to 38.5%, and decrease sediment loss by 72.5 to 96.3%. However, it was found virtually no effect of two different stocking rates (1,200 and 1,600) on three grazing timings on surface runoff and sediment loss. Osei (2016) in the research on FCR watershed indicated that although conversion to pasture entails a significant cost to farmers, it leads substantial and consistent reductions in all environmental indicators (runoff volumes and sediment and nutrient losses), which is same as this study's results.

Success of the BMP installation in the FCR watershed is of interest to many groups because erosion and transport of sediment and associated nutrients are common problems in other agricultural watersheds (Becker, 2011). Moreover, state and federal funding has supported the implementation of conservation practices in the watershed (Steiner and others, 2008). Boyer et al. (2017) stated that farming experience, gender and attitudes towards soil and water conservation increases the total number of practices adopted. According to Tong et al. (2017), negative externalities are the main challenges for adoption of conservation practices in the FCR watershed, and this point indicates the need for new extension educational efforts, economic incentives from government, and research efforts to reduce to negative externalities. These negative effects of sediment and other NPS pollutions are not paid for by the producers and landowners. Instead, downstream users (e.g. recreationists and municipal systems) face the costs. The principal approach for adoption of conservation practices for reduction of NPS pollution from agricultural fields in USA is subsidizing adoption of conservation practices instead of taxing inputs like sediment and phosphorous. So, there should be motivations from government for landowners and producers to implement conservation practices. In this regard, apart from the environmental impact of different agricultural BMPs, there should be economic consideration of these management practices for selecting the most cost efficient BMPs since funding agencies are better appreciating the link between farm economics and producer adoption of the conservation practices.

Conclusions

Response of surface runoff, sediment loss and crop-yield was investigated under five different agricultural BMPs in an agriculture-pasture intensive watershed located in southwestern Oklahoma. SWAT model was applied to develop the hydrological model and to quantify the pre- and post-BMP implementation characteristics in the FMC sub-watershed. First, the model was satisfactory calibrated and validated for streamflow, sediment, and crop yields with consideration of existing BMPs in the watershed. Then some 22 different crop-BMP scenarios were simulated in each of the crop HRUs in the watershed. Through the evaluation of agricultural BMPs in the watershed, efforts can be made to implement the more successful BMPs in the catchment or in other similar catchments.

According to the results, contour tillage practices reduced surface runoff by more than 18% in both conservation tillage and no-till practices for all crops. Also, contour farming with either conservation tillage or no-till practice reduced sediment loss by almost half. Compared to the conservation tillage practice, no-till system decreased sediment loss by 25.3% and 9.0% for cotton and grain sorghum respectively. Since continuous no-till wheat is not practical because of weeds and other diseases, no-till wheat was simulated in rotation/cover cropped with other crops. On dryland, wheat as a double or cover crop reduced soil moisture available for the subsequent crop. As a result, there was an increase in the sediment rate compared to wheat with conservation tillage. Also, the effect of wheat as a cover crop for grain sorghum generated lowest runoff followed by its rotation with canola and cotton regardless of contouring. Surface runoff decreased for grain sorghum rotated with wheat, but increased for cotton rotated with winter wheat. Meanwhile, sediment loss increased for both cotton and grain sorghum rotated with winter wheat and the reason was that this region is water limited region and rotation or cover cropping with wheat will take the moisture of soil once planting and having wheat on the ground. At the end, converting all the crops in the watershed into Bermuda grass would significantly reduce runoff by 6.8 to 38.5%, and decrease sediment loss by 72.5 to 96.3%.

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Appendix

Appendix 1. Reservoir and Ponds Information in the SWAT model

Sub-basin	principle surface area (ha) PND_PSA	principle volume (10^4 m3) PND_PVOL	emergency spillway surface area (ha) PND_ESA	emergency spillway volume (10^4 m3) PND_EVOL	drainage area (ha)	sub-basin area (ha)	drainage area/ sub-basin area PND_FR
1	1.52	3.05	2.29	4.57	45.7	1214.17	0.04
2	2.65	5.31	3.98	7.96	79.6	694.81	0.11
3	1.09	2.18	1.64	3.27	32.7	2112.78	0.02
4	-	-	-	-	-	-	-
5	4.84	9.69	7.27	14.53	145.3	570.03	0.25
6	20	40.30	30	62.45	724.5	784.94	0.92
7	2.06	4.11	3.08	6.17	61.7	625.04	0.10
8	1.93	3.86	2.90	5.79	57.9	817.80	0.07
9	6.29	12.59	9.44	18.88	37.74	37.74	1.00
10	0.84	1.67	1.26	2.51	25.1	697.89	0.04
11	12.62	25.24	18.93	37.86	57.45	57.45	1.00
12	0.04	0.07	0.06	0.11	1.1	23.70	0.05
13	20	41.71	30	62.56	925.6	2822.14	0.33
14	7.54	15.09	11.31	22.63	226.3	571.50	0.40
15	7.94	15.89	11.92	23.83	238.3	882.17	0.27
16	4.37	8.73	6.55	13.10	131.0	1823.63	0.07
17	-	-	-	-	-	-	-
18	5.37	10.73	8.05	16.10	161.0	1185.20	0.14
19	20	40.48	30	62.73	727.3	1139.11	0.64
20	20	40.68	30	62.02	730.2	2560.27	0.29
21		-	-	-	-	-	-
22	11.80	23.60	17.70	35.40	354.0	1574.00	0.22
23	5.96	11.92	8.94	17.88	178.8	1596.47	0.11
24	1.42	2.84	2.13	4.25	42.5	773.11	0.06
25	8.95	17.89	13.42	26.84	268.4	1665.47	0.16
26	3.77	7.53	5.65	11.30	113.0	1415.00	0.08
27	1.85	3.69	2.77	5.54	55.4	560.79	0.10
28	0.04	0.07	0.05	0.11	1.1	53.39	0.02
29	3.18	6.36	4.77	9.54	95.4	952.56	0.10
30	3.26	6.51	4.89	9.77	97.7	888.28	0.11
31	0.26	0.52	0.39	0.79	7.9	218.01	0.04
32	0.15	0.30	0.23	0.45	4.5	64.24	0.07
33	7.42	14.85	11.14	22.27	222.7	753.34	0.30
34	6.19	12.39	9.29	18.58	185.8	1328.45	0.14
35	-	-	-	-	-	-	-
36	2.48	4.96	3.72	7.44	74.4	919.52	0.08
37	-	-	-	-	-	-	-
38	-	-	-	-	-	-	-
39	1.51	3.02	2.27	4.53	45.3	904.65	0.05
40	0.07	0.14	0.11	0.21	2.1	217.57	0.01
41	1.83	3.66	2.74	5.49	54.9	655.48	0.08
42	0.09	0.18	0.13	0.27	2.7	198.45	0.01
43	2.42	4.83	3.62	7.25	72.5	748.99	0.10

Appendix 2. Soil characteristics for each soil ID (SSURGO database)

MUID	SEQN	SNAM	S5ID	Texture
381869	508001	Acme	OK015	SICL-BR
381870	508004	Grant	OK015	L-L-SIL-L-BR
381871	508011	Binger	OK015	FSL-SCL-BR
381872	508018	Binger	OK015	FSL-SCL-BR
381873	508023	Binger	OK015	FSL-SCL-BR
381874	508024	Binger	OK015	FSL-SCL-BR
381875	508025	Binger	OK015	FSL-SCL-BR
381876	508027	Cyril	OK015	FSL-L
381879	508036	Darnell	OK015	FSL-FSL-BR
381881	508040	Dougherty	OK015	LFS-LFS-SCL-FSL-LFS
381882	508045	Dougherty	OK015	LFS-LFS-SCL-FSL-LFS
381883	508052	Eufaula	OK015	FS-FS-FS
381884	508058	Eufaula	OK015	LFS-FS-FS
381887	508073	Gracemont	OK015	FSL-FSL-L
381888	508077	Grant	OK015	L-L-SIL-L-BR
381889	508078	Grant	OK015	L-L-SIL-L-BR
381890	508079	Grant	OK015	L-L-SIL-L-BR
381891	508080	Grant	OK015	L-L-SIL-L-BR
381894	508088	Konawa	OK015	LFS-SCL-LFS
381895	508093	Konawa	OK015	LFS-SCL-LFS
381897	508095	Ironmound	OK015	FSL-L-BR
381898	508097	Ironmound	OK015	FSL-L-BR
381901	508107	Minco	OK015	VFSL-SIL-SIL
381902	508110	Minco	OK015	VFSL-SIL-SIL
381903	508111	Minco	OK015	SIL-SIL-SIL
381904	508112	Noble	OK015	FSL-FSL
381905	508118	Noble	OK015	FSL-FSL
381908	508130	Pond Creek	OK015	FSL-SICL-L
381909	508136	Pond Creek	OK015	FSL-SICL-L
381910	508142	Pond Creek	OK015	SIL-SICL-L
381911	508148	Pond Creek	OK015	SIL-SICL-L
381912	508154	Pond Creek	OK015	SIL-SICL-L
381913	508155	Port	OK015	SIL-SIL-L
381914	508162	Port	OK015	SIL-SIL-L
381915	508168	Pulaski	OK015	FSL-FSL-SR LFS L
381916	508174	Ironmound	OK015	L-L-BR
381918	508181	Minco	OK015	SIL-SIL-SIL
381920	508192	Darnell	OK015	FSL-FSL-BR
381921	508194	Lovedale	OK015	FSL-SCL-SL-S
381922	508200	Lovedale	OK015	FSL-SCL-SL-S

381928	508213	Water	OK015	water
381929	508214	Woodward	OK015	SIL-SIL-BR
382310	507114	Carey	OK039	SIL-SICL-L-BR
382316	507133	Cornick	OK039	SIL-BR-BR
382325	507160	Grant	OK039	L-L-L-L-BR
382326	507161	Hardeman	OK039	FSL-FSL
382327	507162	Lucien	OK039	VFSL-VFSL-BR
382328	507164	Minco	OK039	VFSL-VFSL-VFSL
382332	507173	Pond Creek	OK039	FSL-SIL-SICL-SIL
382333	507179	Pond Creek	OK039	SIL-SIL-SICL-SIL
382334	507185	Pond Creek	OK039	SIL-SIL-SICL-SIL
382339	1170380	Quinlan	OK039	SIL-SIL-BR
382341	507217	Lovedale	OK039	FSL-FSL-SCL-FSL
382342	507218	St. Paul	OK039	SIL-SICL-SICL-SICL-SIL
382343	507224	St. Paul	OK039	SIL-SICL-SICL-SICL-SIL
382344	507225	St. Paul	OK039	SIL-SICL-SICL-SICL-SIL
382345	507227	Water	OK039	water
382348	507230	Woodward	OK039	SIL-SIL-BR
382349	507231	Woodward	OK039	SIL-SIL-BR
382350	507238	Woodward	OK039	SIL-SIL-BR
382351	507241	Quinlan	OK039	SIL-SIL-BR
384993	508521	Clairemont	OK149	SIL-SIL
384994	508527	Cordell	OK149	SICL-SICL-GRV-SICL-BR
384995	508528	Cordell	OK149	SICL-SICL-GRV-SICL-BR
384996	508530	Cornick	OK149	SIL-BR-BR
384997	508532	Devol	OK149	LFS-FSL-LFS
384998	508538	Devol	OK149	LFS-FSL-LFS
385003	508496	Altus	OK149	FSL-FSL-SCL-SCL
385004	508565	Dill	OK149	FSL-FSL-BR
385005	508567	Dill	OK149	FSL-FSL-BR
385007	508575	Dougherty	OK149	LFS-LFS-SCL-FSL-LFS
385011	508590	Hardeman	OK149	FSL-FSL
385012	508596	Hardeman	OK149	FSL-FSL
385013	508597	Hardeman	OK149	FSL-FSL
385018	508601	Pond Creek	OK149	FSL-SICL-SIL
385019	508607	Pond Creek	OK149	FSL-SICL-SIL
385020	508613	Port	OK149	SIL-SICL-SIL
385021	508619	Eda	OK149	LFS-LFS-LFS
385023	508622	Quinlan	OK149	L-L-BR
385024	508624	Quinlan	OK149	L-L-BR
385026	508626	Quinlan	OK149	L-L-BR
385027	508628	Quinlan	OK149	FSL-L-BR
385028	508630	Reinach	OK149	SIL-SIL

385030	508637	Lovedale	OK149	FSL-SCL-FSL-FSL
385031	508643	Lovedale	OK149	FSL-SCL-FSL-FSL
385032	508644	St. Paul	OK149	SIL-SICL-SICL-SICL-SIL
385033	508650	St. Paul	OK149	SIL-SICL-SICL-SIL
385034	508656	St. Paul	OK149	SIL-SICL-SICL-SIL
385036	508511	Binger	OK149	FSL-SCL-BR
385037	508660	Woodward	OK149	SIL-SIL-BR
385038	508661	Woodward	OK149	SIL-SIL-BR
385039	508662	Woodward	OK149	SIL-SIL-BR
385040	508663	Woodward	OK149	SIL-SIL-BR
385041	508673	Woodward	OK149	L-SIL-BR
385042	508675	Woodward	OK149	L-SIL-BR
385044	508512	Binger	OK149	FSL-SCL-BR
385045	508513	Carey	OK149	SIL-CL-L-BR
385046	508514	Carey	OK149	SIL-CL-L-BR
385047	508515	Clairemont	OK149	SIL-SIL
385048	508682	Water	OK149	water

Appendix 3 (a). Conventional (reduced) tillage for dryland crops and pasture

Crop	Date	Operation
Cotton	1.1	Tillage operation (Disk Plow Ge23ft)
	3.15	Tillage operation (Disk Plow Ge23ft)
	5.15	Tillage operation (Springtooth Harrow Ge15ft)
	6.1	Tillage operation (Finishing Harrow Lt15ft) Pesticide Operation (Pendimehalin, 0.25 kg)
	6.10	Fertilizer application (Elemental Nitrogen, 50 kg)
	6.11	Plant
	7.1	Tillage operation (Row Cultivator Ge15ft)
	11.15	Harvest and kill
Pasture	1.1	Plant
	3.1	Auto fertilization
	5.1	Grazing operation (Beef-Fresh Manure, GRZ_DAYS*: 180, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Winter wheat	3.15	Fertilizer application (Elemental Nitrogen, 80 kg)
	6.1	Harvest and kill
	7.1	Tillage operation (Chisel Plow Gt15ft)
	8.1	Tillage operation (Offset Dis/heavduty Ge19ft)
	9.20	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg)
	9.22	Tillage operation (Disk Plow Ge23ft)
	9.24	Tillage operation (Springtooth Harrow Lt15ft)
	9.25	Plant
	12.1	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Grain sorghum	5.1	Plant
	5.27	Fertilizer application (Elemental Nitrogen, 150 kg)
	5.28	Tillage operation (Springtooth Harrow Ge15ft, Disk Plow Ge23ft, Mecoprop Amine, 125), Pesticide Operation (Mecoprop Amine, 125 kg)
	10.18	Tillage operation (Disk Plow Ge23ft)
	10.20	Tillage operation (Springtooth Harrow Ge15ft)
	10.30	Harvest and kill
Alfalfa	4.1	Harvest only
	5.15	Harvest only
	7.1	Harvest only
	8.29	Fertilizer application (Elemental Nitrogen, 50 kg), (Elemental Phosphorous, 20)
	9.7	Plant
	10.15	Harvest only
Hay	4.1	Harvest only
	7.1	Harvest only
	8.29	Auto fertilization
	9.7	Plant
	10.15	Harvest only
Rye	6.10	Harvest only
	8.10	Fertilizer application (Elemental Nitrogen, 80 kg), (Elemental Phosphorous, 35)
	9.20	Plant
	9.15	Grazing operation (GRZ_DAYS*: 150, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)

*AUTO_NSTRS: Nitrogen stress factor of cover/plant triggers fertilization. This factor ranges from 0.0 to 1.0 where 0.0 indicates there is no growth of the plant due to nitrogen stress and 1.0 indicates there4 is no reduction of plant growth due to nitrogen stress.
*GRZ_DAYS: Number of consecutive days grazing takes place in the HRU
*BIO_EAT: dry weight of biomass consumed daily ((kg/ha)/day)
* BIO_TRMP: dry weight of biomass trampled daily ((kg/ha)/day)
*MANURE_KG: dry weight of manure deposited daily ((kg/ha)/day)

Appendix 3 (b). Conventional (reduced) tillage for irrigated crops and pasture

Crop	Date	Operation
Cotton	1.1	Tillage operation (Disk Plow Ge23ft)
	3.15	Tillage operation (Disk Plow Ge23ft)
	5.15	Tillage operation (Springtooth Harrow Ge15ft)
	6.1	Tillage operation (Finishing Harrow Lt15ft) Pesticide Operation (Pendimehalin, 0.25 kg) Irrigation operation (IRR_AMT*, 33 mm)
	6.10	Fertilizer application (Elemental Nitrogen, 50 kg)
	6.11	Plant
	7.1	Tillage operation (Row Cultivator Ge15ft) Irrigation operation (IRR_AMT, 33 mm)
	7.8 till 9.15 (One irrigation per week)	Irrigation operation (IRR_AMT, 33 mm)
	11.15	Harvest and kill
Pasture (Bermuda)	1.1	Plant
	3.1	Auto fertilization
	4.1	Auto irrigation
	5.1	Grazing operation (Beef-Fresh Manure, GRZ_DAYS*: 180, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Winter wheat	3.15	Fertilizer application (Elemental Nitrogen, 80 kg)
	4.3	Auto irrigation
	6.1	Harvest and kill
	7.1	Tillage operation (Offset Dis/heavduty Ge19ft)
	8.1	Tillage operation (Chisel Plow Gt15ft)
	9.20	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg) Auto irrigation
	9.22	Tillage operation (Disk Plow Ge23ft)
	9.24	Tillage operation (Springtooth Harrow Lt15ft)
	9.25	Plant
	11.3	Auto irrigation
	12.1	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Grain sorghum	5.1	Plant
	5.27	Fertilizer application (Elemental Nitrogen, 150 kg)
	5.28	Tillage operation (Springtooth Harrow Ge15ft, Disk Plow Ge23ft, Mecoprop Amine, 125)
	6.1	Auto irrigation initial
	10.18	Tillage operation (Disk Plow Ge23ft)
	10.20	Tillage operation (Springtooth Harrow Ge15ft)
	10.30	Harvest and kill

*IRR_AMT: Depth of irrigation water applied on HRU (mm)

Appendix 3 (c). No-till irrigated cotton with winter wheat as cover crop

Crop	Date	Operation
	03.15	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 30 kg)
	04.03	Auto Irrigation
Winter wheat	06.1	kill
	06.2	Pesticide Operation (Pendimehalin, 0.25 kg)
	06.03	Irrigation operation (IRR_AMT, 33 mm)
	06.10	Fertilizer application (Elemental Nitrogen, 150 kg)
Cotton	06.11	Plant
	07.1 till 09.15 one irrigation in per week	Irrigation operation (IRR_AMT, 33 mm)
Cotton	11.1	Harvest and kill
	11.2	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg)
	11.2	Auto Irrigation
Winter wheat	11.3	Plant
	12.01	Auto Irrigation
Winter wheat	12.20	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)

Appendix 3 (d). Rotation of winter wheat with canola in dryland with no-till system

Crop	Year	Date	Operation
Winter wheat	Year 1	01.01	Plant wheat
		06.01	Harvest and kill
		09.20	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg)
		09.25	Plant wheat
		12.01	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Winter canola	Year 2	03.01	Fertilizer application (Elemental Nitrogen, 80 kg)
		06.01	Harvest and kill
		09.20	Fertilizer application (Elemental Nitrogen, 38 kg) (Elemental Phosphorus, 15 kg)
		09.25	Plant winter canola
Winter wheat	Year 3	04.01	Fertilizer application (Elemental Nitrogen, 76 kg) (Elemental Phosphorus, 30 kg)
		06.10	Harvest and kill
		09.01	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg)
		09.25	Plant wheat
		12.01	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Winter canola	Year 3	03.01	Fertilizer application (Elemental Nitrogen, 80 kg)
		06.01	Harvest and kill
		09.20	Fertilizer application (Elemental Nitrogen, 38 kg) (Elemental Phosphorus, 15 kg)
		09.25	Plant winter canola

Appendix 3 (e). Rotation of winter wheat with irrigated canola with no-till system

Crop	Year	Date	Operation
Winter wheat	Year 1	01.01	Plant wheat
		04.01	Auto irrigation
		06.01	Harvest and kill
		08.25	Auto irrigation
		09.20	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg)
		09.25	Plant wheat
		11.11	Auto irrigation
		12.01	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Winter canola	Year 2	03.01	Fertilizer application (Elemental Nitrogen, 80 kg)
		04.03	Auto irrigation
		06.01	Harvest and kill
		09.20	Fertilizer application (Elemental Nitrogen, 38 kg) (Elemental Phosphorus, 15 kg)
		09.25	Plant winter canola
Winter wheat	Year 3	04.01	Fertilizer application (Elemental Nitrogen, 76 kg) (Elemental Phosphorus, 30 kg)
		06.10	Harvest and kill
		08.25	Auto irrigation
		09.01	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg)
		09.25	Plant wheat
		11.03	Auto irrigation
		12.01	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Winter canola	Year 3	03.01	Fertilizer application (Elemental Nitrogen, 80 kg)
		04.03	Auto irrigation
		06.01	Harvest and kill
		09.20	Fertilizer application (Elemental Nitrogen, 38 kg) (Elemental Phosphorus, 15 kg)
		09.25	Plant winter canola

Appendix 3 (f). Cover cropping of winter wheat with grain sorghum in dryland with no-till system

Crop	Year	Date	Operation
Winter wheat	Year 1	01.01	Plant wheat
		06.01	Harvest and kill
		10.01	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg)
		10.01	Plant wheat
		12.01	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
	Year 2	03.15	Fertilizer application (Elemental Nitrogen, 80 kg)
		06.01	Harvest and kill

Grain Sorghum, Winter wheat	Year 3	05.01	Fertilizer application (Elemental Nitrogen, 150 kg)
		05.01	Plant grain sorghum
		09.30	Harvest and kill
		10.01	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg) Plant wheat
		12.01	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
	Year 4	03.15	Fertilizer application (Elemental Nitrogen, 80 kg)
		06.01	Harvest and kill

Appendix 3 (g). Cover cropping of winter wheat with irrigated grain sorghum with no-till system

Crop	Year	Date	Operation
Winter wheat	Year 1	01.01	Plant wheat
		06.01	Harvest and kill
		10.01	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg)
		10.01	Plant wheat
		12.01	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
	Year 2	03.15	Fertilizer application (Elemental Nitrogen, 80 kg)
		04.01	Auto irrigation
		06.01	Harvest and kill
Grain Sorghum, Winter wheat	Year 3	05.01	Fertilizer application (Elemental Nitrogen, 150 kg)
		05.01	Plant grain sorghum
		06.01	Auto irrigation
		09.30	Harvest and kill
		10.01	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg) Plant wheat
		12.01	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
	Year 4	03.15	Fertilizer application (Elemental Nitrogen, 80 kg)
		04.01	Auto irrigation
		06.01	Harvest and kill

Appendix 3 (h). Cover cropping of winter wheat with cotton in dryland with no-till system

Crop	Year	Date	Operation
Winter wheat	1	09.20	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg)
		09.25	Plant
		12.01	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Cotton	2	03.15	Fertilizer application (Elemental Nitrogen, 80 kg)
		06.01	Harvest and kill wheat
		06.02	Pesticide Operation (Pendimehalin, 0.25 kg)
		06.10	Fertilizer application (Elemental Nitrogen, 50 kg)

		06.11	Plant
		11.04	Harvest and kill cotton

Appendix 3 (i). Cover cropping of winter wheat with irrigated cotton with no-till system

Crop	**Year**	**Date**	**Operation**
Winter wheat	1	09.20	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg) Auto Irrigation
		09.25	Plant
		11.03	Auto Irrigation
		12.01	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Cotton	2	03.15	Fertilizer application (Elemental Nitrogen, 80 kg)
		04.3	Auto Irrigation
		06.01	Harvest and kill wheat
		06.02	Pesticide Operation (Pendimehalin, 0.25 kg) Irrigation operation (IRR_AMT, 33 mm)
		06.10	Fertilizer application (Elemental Nitrogen, 50 kg)
		06.11	Plant
		07.1 till 09.15 one irrigation in per week	Irrigation operation (IRR_AMT, 33 mm)
		11.04	Harvest and kill cotton

Appendix 4. Global sensitivity analysis results of SWAT-CUP for streamflow

Parameter	Description	t-stat	p-value
6:R__CN2.mgt	SCS Curve number adjustment for soil moisture condition II	72.99	0.00
8:V__ESCO.hru	Soil evaporation compensation factor	-55.38	0.00
5:V__GW_DELAY.gw	Groundwater delay [Days]	51.67	0.00
4:V__RCHRG_DP.gw	Deep aquifer percolation fraction	17.20	0.00
16:V__CH_N2.rte	Manning's n value for the main channel	-12.20	0.00
15:R__SOL_AWC(..).sol	Available water capacity of soil layer (mm H2O/mm soil)	9.43	0.00
14:V__ALPHA_BNK.rte	base flow alpha factor for bank	3.32	0.00
10:V__CH_K1.sub	Effective hydraulic conductivity in tributary channel alluvium ((mmhr-1))	-2.88	0.00
13:V__TRNSRCH.bsn	Fraction of transmission losses partitioned to deep aquifer	2.51	0.01
7:V__ALPHA_BF.gw	Baseflow Alpha Factor [Days]	2.09	0.04
3:V__REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur [mm]	-1.06	0.29
12:V__EVRCH.bsn	reach evaporation adjustment factor	-0.96	0.34
17:V__CH_K2.rte	Main channel conductivity	-0.83	0.41
9:V__EPCO.bsn	Plant uptake compensation factor	0.75	0.46
11:V__SURLAG.bsn	Surface runoff lag coefficient	-0.63	0.53
1:V__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0.60	0.55
2:V__GW_REVAP.gw	Groundwater "revap" coefficient	0.14	0.89

Appendix 5 (a). Cotton yield calibration parameters

Parameter	Parameter definition	Default value	Calibrated value
BIO_E [(kg/ha)/(MJ/m^2)]	Radiation use efficiency or biomass energy ratio	15	14
USLE_C	Minimum value of USLE C factor for water erosion	0.2	0.1
HVSTI [(kg/ha)/(kg/ha)]	Harvest index for optimal growing season	0.4	0.3
OV_N	Manning's "n" value for overland flow	0.14	0.12
BLAI (m^2/m^2)	Maximum potential leaf area index	4	3
FRGRW1(fraction)	Fraction of plant growing season to the first point on the optimal leaf area development curve	0.15	0.14
FRGRW2 (fraction)	Fraction of plant growing season to the second point on the optimal leaf area development curve	0.5	0.3
LAIMX1 (fraction)	Fraction maximum leaf area index to the first point on the optimal leaf area development curve	0.01	0.005
CNYLD (kg N/kg seed)	Normal fraction of nitrogen in yield	0.015	0.018
CPYLD (kg P/kg seed)	Normal fraction of Phosphorus in yield	0.0025	0.0027

Appendix 5 (b). Wheat, pasture, and grain sorghum yield calibration parameters

Parameter	Winter wheat		Pasture		Grain sorghum	
	Default value	Calibrated value	Default value	Calibrated value	Default value	Calibrated value
BIO_E [(kg/ha)/(MJ/m^2)]	30	29	35	28	33.5	37
USLE_C	0.03	0.02	0.003	0.003	0.2	0.2
HVSTI [(kg/ha)/(kg/ha)]	0.4	0.3	0.8	0.8	0.45	0.3
OV_N	0.14	0.12	0.3	0.25	0.14	0.12
BLAI (m^2/m^2)	4	3	4	2.5	3	4.5
FRGRW1(fraction)	0.05	0.03	0.05	0.03	0.15	0.15
FRGRW2 (fraction)	0.45	0.35	0.49	0.35	0.5	0.5
LAIMX1 (fraction)	0.05	0.03	0.05	0.03	0.05	0.05
CNYLD (kg N/kg seed)	0.025	0.02	0.0234	0.0134	0.0199	0.02
CPYLD (kg P/kg seed)	0.0022	0.0018	0.0033	0.0022	0.0044	0.0032

Appendix 6. Definition of modeling of crop rotation in SWAT

In rotation calculation, half of each HRU area was considered as one of the rotation crops and it was assumed that each year both crops would be planted in half of the field and the average of the sediment and surface runoff for those two scenarios was used in that year.

CHAPTER V

EVALUATING THE LEAST COST SELECTION AND PLACEMENT OF CROPS AND AGRICULTURAL MANAGEMENT PRACTICES IN THE FIVE-MILE CREEK AREA OF FORT COBB WATERSHED

Abstract

The Fort Cobb Reservoir (FCR) watershed located in the Upper Washita River basin in southwestern Oklahoma provides multiple benefits, such as public water supply, wildlife habitats and recreation. However, the FCR watershed presents critical agricultural challenges and sustainability problems primarily related to sediment and phosphorous loads. Despite efforts and research to improve water quality in the FCR watershed through the implementation of varieties of Best Management Practices (BMPs) for decades, there are still problems of sediment and phosphorous loads in this catchment, which demonstrates the need for research. Since the cost of implementing some BMPs can be expensive, the cost effective selection and location of BMPs can aid in increasing both the efficiency of public funds and the total income of farmers. The major goal of this study is to identify optimal selection and location of crop-BMPs including crop types, production methods, and agricultural management practices that could further reduce sediment and phosphorous loss from the agricultural fields in Five-Mile Creek (FMC) sub-watershed of FCR watershed at the least-cost to producers and the public in both the dry and irrigated areas. For this, a hydrological model of the study area was developed using the Soil and Water Assessment Tool.

The model was calibrated and validated satisfactorily for streamflow, crop yield, sediment, and phosphorous. The verified model was used to simulate 22 crop-BMP combinations over the 1989–2016 period. A Linear Programming (LP) model was used to determine the crop-BMP choice that would maximize income and minimize public cost while abating sediment and phosphorous under two different scenarios: market solution (maximize revenue with no constraints on sediment and phosphorous production) and tax solution (discourage sediment and phosphorous production through incentive programs). Results indicated that the tax solution would outperform both baseline and market solution scenarios in terms of average reduction of sediment and phosphorous in the study area. With the tax solution, average $1.2 million/year compensation to producers to adopt crop-BMPs would result in 28% sediment (4,507 tons) and 27% phosphorous (17 tons) reduction annually over the baseline scenario. Compared to the market solution, the tax solution scenario would result in reduction of sediment and phosphorous by 15% and 2% respectively. The optimized land crop-BMP in tax solution scenario included an increase in wheat area by 60% and 21% compared to the baseline and market solution respectively, and decrease in the cotton area by 88% and 80% compared to the baseline and market solution respectively. Fine sandy loam soil was the targeted soil in changing tillage system of wheat and silty clay soil was the targeted soil for conversion of cotton and grain sorghum to wheat.

Key words: Sediment, phosphorous, best management practices, SWAT, Linear Programming

Introduction

The main cause of water quality impairment in the Unites States is human-induced Non-Point Source (NPS) pollution from sources like agriculture and urbanization. NPS pollution is a form of diffuse pollution caused by nutrients, sediment, toxic, and organic substances mainly originating from agricultural activities, which occur over a wide area and carried to reservoirs, lakes and stream channels by surface runoff (Humenik et al., 1987). Best Management Practices (BMPs) are effective and practical scenarios to control and reduce the transport of agricultural NPS to water bodies, yet there are concerns regarding the economic efficiency of BMPs in controlling and reducing NPS pollutions. Evaluating different BMPs can ensure the most cost effective use of funding for watershed management and this allows for greatest reduction of pollutants within a limited budget. In this regard, modeling is a necessary step in watershed management to assess the impact of different conservation practices on NPS pollutions. Since BMPs are usually implemented under a limited budget, costs associated with inefficient BMP choice and location may threaten achievability of water quality goals. Therefore, a balance should be considered between the economic and ecological implications of BMP implementation. The principal approach for adoption of conservation practices for reduction of NPS pollution from agricultural fields in USA is to subsidize the adoption of conservation practices instead of taxing or directly limiting pollutants like sediment and phosphorous. In this regard, apart from the environmental impact of different agricultural BMPs, there should be an economic consideration of BMP costs, both the actual BMP cost and producers income changes from their adoption. One measure of an effective conservation practice is whether it can attain a maximum reduction in NPS loads at minimum per unit cost (Giri et al., 2012). The objective for improving cost-effectiveness is the systematic optimization of real-world efforts (Rabotyagov et al. 2010). Hence, the information on economic influences on the implementation of such practices is critical.

The number of possible BMP scenarios within a watershed rises exponentially with the number of fields. Without computer optimization the assessment of all possible combinations of strategies performance in all fields within the watershed is impossible. It becomes neither practical nor economically feasible to select a best combination of BMPs that results maximum pollution reduction at a minimum cost. Selection and placement of BMPs in a watershed needs a proper optimization method (selection of an optimization method is based on the dictated condition of the problem) with more efficient manner to result maximum benefit with highest possible pollution reduction rate. Recent studies have demonstrated that optimization methods produce good results for optimal allocation of NPS pollution management practices at the watershed scale (Veith, 2003; Arabi, 2006; Jha, 2009; Rabotyagov, 2010). Linear Programing (LP) is an optimization technique than can devote resources for different activities (Hillier & Lieberman, 1990). According to Dyke et al. (1985), an LP model or related models with an associated LP subsystem are more suitable for studying erosion economics.

The Fort Cobb Reservoir (FCR) watershed is located in the Central Great Plains Ecoregion in southwestern Oklahoma. FCR is a rural agricultural catchment with known issues of NPS pollution, including suspended solids, siltation, nutrients, and pesticides (OCC, 2014). Conservation practices such as contour and strip farming, terraces, conversion of crop land to Bermuda pasture, reduced till and no-till farming, drop structures, shelter belts, and flood retarding structures have been implemented throughout the FCR watershed (Garbrecht and Starks, 2009). According to Osei (2016), substantial cost savings can be achieved if conservation practice distributions can be optimized. The Soil and Water Assessment Tool (SWAT) developed in 1990 by the USDA Agricultural Research Service (USDA-ARS) at the Grassland, Soil and Water Research Laboratory in Temple, Texas (Neitsch et al., 2001), has previously been used in FCR watershed modeling (Storm et al., 2003; Moriasi et al., 2007, 2008; Mittelstet, 2015b) to estimate the impact of different BMPs on crop, water, and NPS pollution loading and solve the problem. Garbrecht and Starks (2009) stated that 80%-90% of cropland in FCR watershed that needed terraces has been terraced over the last 50 years, and over the last decade about 50% of the cropland was in conservation tillage or minimum disturbance tillage. However, none of these studies assessed the cost effectiveness of existing BMPs on surface water quality. One of the goals of this research is to identify the placement of additional conservation practices. Therefore, it is important to identify the presence and location of existing conservation practices. Installing these practices requires high capital investment, and their presence and location affect the optimal selection and placement of additional BMPs.

One of the other conservation practices that has recently received the most attention in the upper Washita River watersheds was no-till farming. Conversion to no-till practices on at least 50 percent of the cultivated area in the FRC watershed was one of the recommendations of the TMDL developed by the ODEQ for this Watershed (OCC, 2015). The OCC began a program with emphasis on no-till farming to meet the water quality standards as established by the TMDL. According to OCC (2009) no-till was projected to be one of the most effective conservation practices for controlling both sediment and nutrient loads. No-till farming could help to hold moisture in the soil and protect soil against soil and rain erosion. However continuous no-till wheat production has been shown result in decreased yields (Decker et al., 2009; Patrignani et al., 2012). The main reasons limiting continuous no-till winter wheat are weeds and disease cycles associated with wheat production (Edwards et al., 2006). Several researchers have studied no-till farming and its effect on runoff, NPS pollution and crop yield (Choi et al., 2016; Osei et al., 2012), however, there is limited research focusing on the use of winter wheat as a cover crop with other viable crops. Osei et al. (2012) assessed the effects of no-till systems on crop yield in farm-level economics and compared with other tillage systems for wheat production in FCR watershed. They indicated that if winter wheat grain yields are not significantly impacted by tillage systems, no-till would be more profitable than conventional tillage on the current mix of tillage practices in the watershed. Their study did not address diseases resulted from continuous no-till winter wheat. This study considers the use of no-till wheat as a cover crop with other viable crops (cotton, canola, and grain sorghum) in the study region as a scenario and assesses the economic results.

In this study, a watershed simulation model (SWAT) of the FMC watershed was developed with consideration of existing BMPs such as terraces in the region. Then the SWAT model results were analyzed using the optimization models (LP) to determine the optimal set of BMPs and cover crops and their spatial locations that maximize profit to farmers and minimize public costs while realizing the environmental benefits of reduced sediment and phosphorous loads. Four important questions are addressed in this study: 1) how do no-till rotations involving wheat and other crops can affect crop yield, and sediment and phosphorous loads, 2) which crop and/or crop production methods are the most profitable to dryland producers while meeting reduced sediment and phosphorous targets for the FMC sub-basin, 3) how does the total and pre-unit cost of sediment and phosphorous abatement increase as sediment and phosphorous losses from crop and pasture land are decreased in FMC sub-basin, 4) how do soil type and land slope affect the economics of BMPs and crop choice.

Study watershed

The Fort Cobb Reservoir (FCR) watershed, located in southwestern Oklahoma, US, in the Upper Washita sub-basin with an area of 813 km^2, is an agricultural watershed. Land in the FCR watershed is comprised of highly erosive, fine sandy loam soils, which even under natural conditions contribute to erosion, sediment loading, stream bank and channel instability (OCC, 2009). The water quality of the Fort Cobb reservoir in southwestern Oklahoma and its tributaries has been of concern for more than two decades, with water quality problems first identified in 1981. The FCR and other waterbody segments in the FCR watershed are impaired by different causes (OCC 2009). Many of crop fields such as former peanut fields have been converted to wheat or to pastureland which improves soil stability and reduces erosion. However, continued sedimentation in the FCR, despite previous conservation practices, demonstrates the need to expand adoption of privately and publically funded BMPs. Recently, additional BMPs such as no-till crop production methods and conversion of cropland to grassland have been introduced to improve water quality.

In this study, a SWAT model was constructed and combined with Linear Programing to evaluate the most ecological feasible and cost effective BMPs in just the Five-Mile Creek (FMC) area of FCR watershed. However, the only available USGS gage station (Figure 1) receives runoff from both the Cobb Creek and FMC sub-watersheds. Therefore, the SWAT model was constructed, calibrated, and validated for the larger area above this station (red basin in Figure 1) containing both Cobb Creek and FMC. Only the FMC portion was used in the later analysis. The FMC (grey basin in the Figure 1) has an area of 113.05 km^2. Land use in the FMC sub-watershed constitutes of 50% cropland, 41% pastureland and 9% in other uses such as roads, trees, and residential buildings, cattle, and hog operations. The major crops in the study area are winter wheat 30%, cotton (dryland 3.5%, irrigated 12%), and grain sorghum and canola 4%.

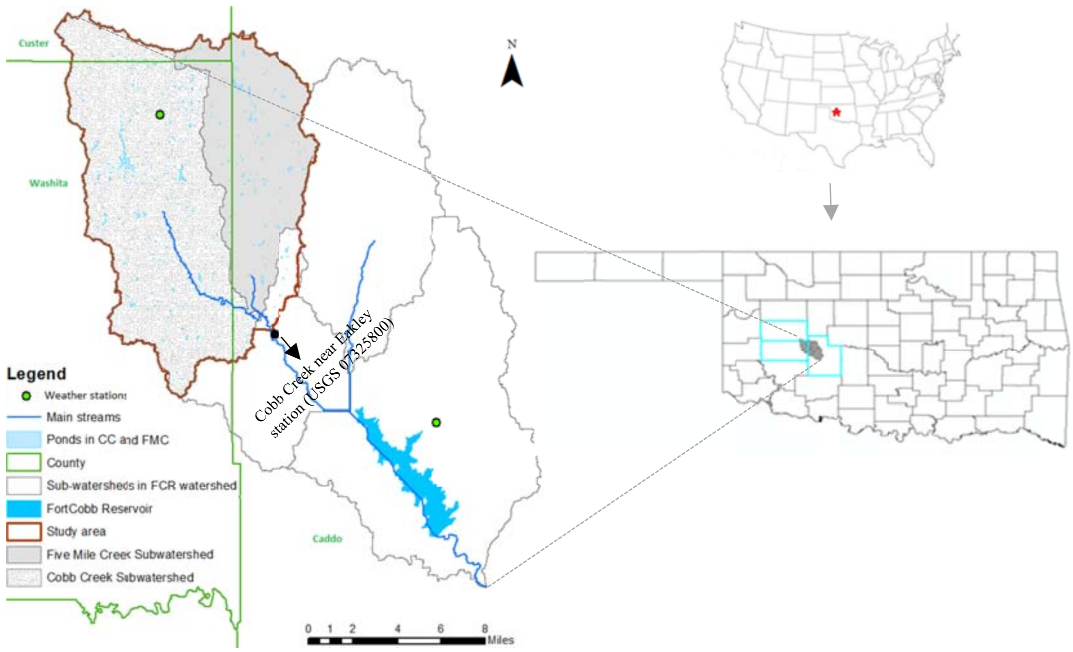


Figure 1. FCR watershed and FMC and Cobb Creek areas

Methodology

Figure 2 describes the methodology followed during the hydrological modeling and optimization for placement and selection of crops and agricultural BMPs in the watershed.

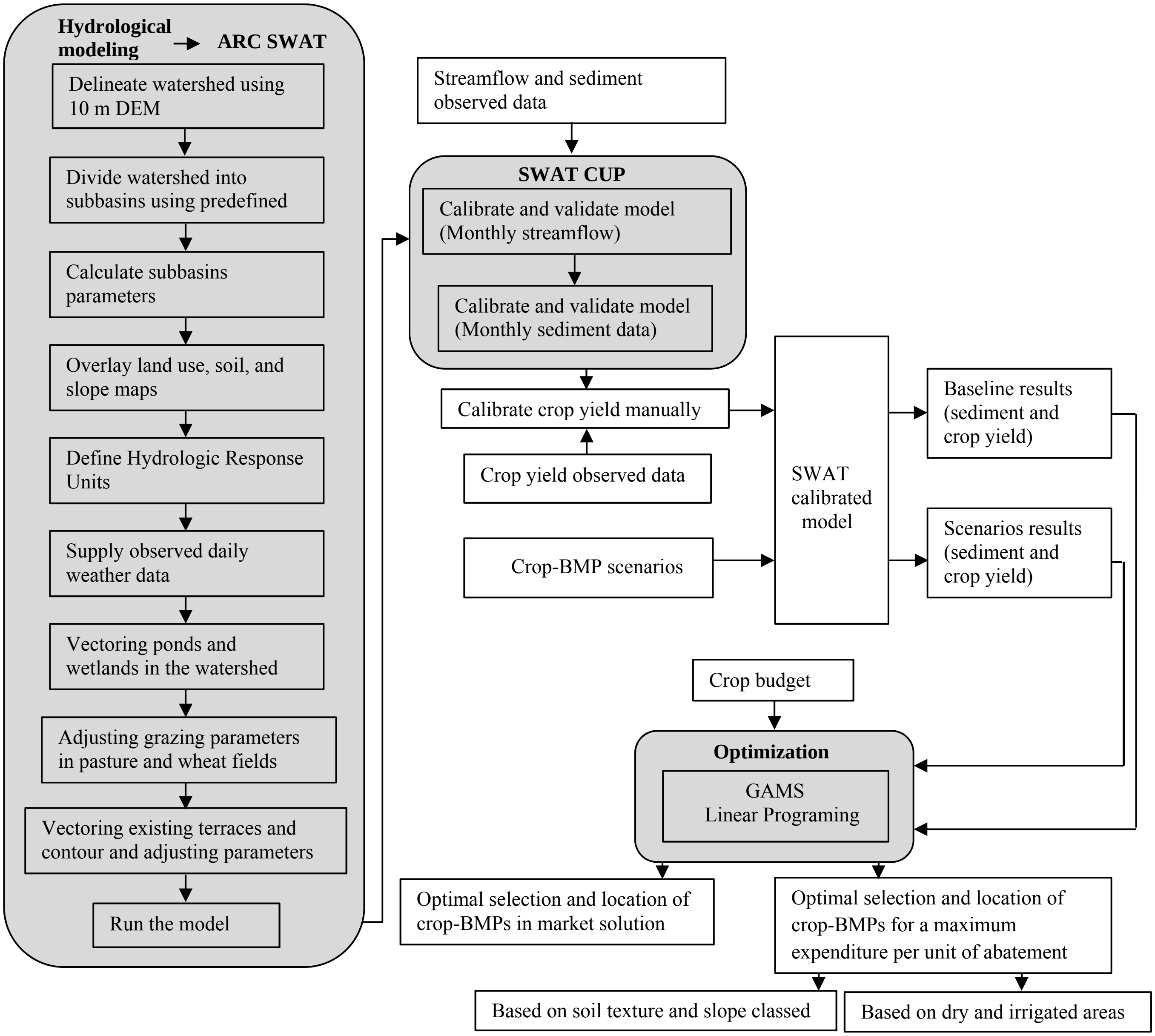


Figure 2. Schematic representation of optimal control model

SWAT model development

The SWAT model was employed as a hydrological tool to simulate the Cobb Creek and FMC sub-watersheds and estimate surface runoff, sediment and nutrient loads, and crop yields. The watershed and stream network were delineated using a 10-m Digital Elevation Map (DEM) and divided into 43 subbasins by identifying outlets in the study area. The USGS gage station (#07325800) in Cobb Creek near Eakely was defined as a final output of the watershed. Elevation data were collected from the USDA Geospatial Data Gateway (http://datagateway.nrcs.usda.gov). The SSURGO soil data (USDA, 1995), collected by the National Cooperative Soil Survey with the higher spatial resolution compared to STATSGO data were used. Four slope classes (0-2%, 2-4%, 4-6%, and >6%) were delineated. The USDA, National Agricultural Statistics Service (NASS) crop layer for 2014 was used for baseline land use. The watershed was divided into 15,217 smaller homogeneous units (Hydrologic Response Units- HRUs) by the SWAT model. Since cotton is one of the main row crops produced in the FCR watershed and most of the irrigated fields in this watershed are covered by cotton, dryland and irrigated crops were separated using center pivot irrigation locations tagged from aerial photography. The impacts of irrigation operations on runoff are available using this method. Historical climate data were collected from two weather stations (Figure 1). Observed precipitation, minimum and maximum daily temperature data from USDA Agricultural Research Service (USDA-ARS) were applied to create files for daily data in 1982 to 2010. Precipitation, minimum and maximum daily temperatures data for 2011 to 2016 were taken from the Oklahoma MESONET data (McPherson et al., 2007) added to the USDA-ARS data. The data for wind speed, relative humidity, and solar radiation were from a mix of sources (Oklahoma MESONET, airport values, and Blackland Research site).

Since 41% of this watershed is pasture and it is an agricultural watershed, grazing and stocking rate have a significant impact on erosion rate and nutrient loads. County level NASS cattle estimates for the period 1996-2015 were applied with land cover data to determine the stocking rate on pastures within the watershed. Based on NASS data and previous research (Storm et al., 2006) on the FCR watershed, a stocking rate of 0.5 head/ha was used. The daily biomass consumption values (BIO_EAT) of 3 ((kg/ha)/day), dry weight of biomass trampled daily (BIO_TRMP) 0.47 ((kg/ha)/day), and dry weight of manure deposited daily (MANURE_KG) 1.5 ((kg/ha)/day) estimated by Storm et al. (2006) were also used.

Other components added to the hydrological model were wetlands and ponds. Since ponds affect the hydrology and NPS pollutions by impounding water, sediment, and nutrients, modeling these wetlands has a significant impact on hydrological modeling and water resources analyzing. The area and location of large ponds and reservoirs (Appendix 1) were taken from the U.S. Army Corps of Engineers National Inventory of Dams (NID) (USDA, 2009) and USGS 7.5-minute quad maps and then vectored in ArcGIS (Figure 1). According to these sources, there are 320 small ponds, lake, and artificial wetlands and reservoirs in this study area with an average area of 0.7 ha each. They covered 120.4 ha of the watershed area.

Terraces and contour farming were used in most of the cultivated areas in this watershed to protect the land against erosion. Since these conservation practices are effective in controlling soil erosion and sediment, they were included in the baseline hydrological model before model calibration for flow and sediment. All existing terraces and contour in the study watershed were identified using aerial photographs. The availability of these georeferenced photos allows determination of the exact placement of existing terraces and contour not available in previous studies. There were several places where terraces and contour have been broken and appeared to make the erosion problem worse. The broken terraces were recognized using 2-meter Lidar drainage lines and were modeled as un-terraced fields. HRUs where more than 65% of them were terraced and/or contour farming were classified as being terraced with contour farming. The effects of terraces and contour were simulated by modifying runoff and erosion parameters such as, slope length, the SCS runoff curve number (CN), and USLE practice factor. These parameters were adjusted as suggested by SWAT documents (Table 1).

Table 1. USLE-P value for contour farming, strip cropping and terracing

Land Slope %	USLE-P Contour farming	Strip cropping	Terracing
1 to 2	0.6	0.3	0.12
3 to 5	0.5	0.25	0.1
6 to 8	0.5	0.25	0.1
9 to 12	0.6	0.3	0.12
13 to 16	0.7	0.35	0.14
17 to 20	0.8	0.40	0.16
21 to 25	0.9	0.45	0.18

Source: SWAT 2012 User's guide (Winchell et al., 2013)

Information about tillage type and fertilizer application for the selected crops was obtained from relevant literature (Storm et al, 2006; ODEQ, 2006) and consultation with local OSU Cooperative Extension Service and Conservation District personnel (Appendix 2).

SWAT model calibration

The SWAT model for Cobb Creek and FMC sub-watersheds was calibrated first manually and then automatically using SWAT-CUP (Abbaspour et al., 2007) for monthly streamflow and sediment concentration. It was also calibrated manually for yield of the main crops in the watershed. The USGS gage station- Cobb Creek near Eakely (USGS 07325800) was used as a source of observed flow and sediment data for the ten-year (1991–2000) for calibration period and also for the ten-year validation period (2001–2010). Among the seventeen selected parameters for surface runoff calibration (Table 2), the SCS Curve number (CN), Soil evaporation compensation factor (ESCO), Groundwater delay (GW_DELAY), Deep aquifer percolation fraction (RCHRG_DP), Manning's n value for the main channel (CH_N2), and available water capacity of soil layer (SOL_AWC) were the most sensitive parameters. Table 2 shows the adjusted data for these parameters in the model. The coefficient of determination (R^2) was used as an objective function in order to evaluate different interpolation methods. Two other metrics, the (Nash-Sutcliffe efficiency- NSE for streamflow and Modified NSE for sediment were used. Percent bias (Pb) was also used to evaluate the model performance. The results of streamflow calibration and validation are shown in Figures 3 and 4. The model provided satisfying estimation and reasonable predictions for the calibration (the R^2 was 0.64, the NSE was 0.61, and the Pb was 5.1) and validation period R^2 was 0.79, the NSE was 0.62, and the Pb was -15.

Suspended sediment was calibrated for ten years, (1991–2000) and validated for another ten years, (2001–2010) at the watershed outlet. The grab sample data that were available from 2004 to 2012 (usually 1 to 3 samples per month with a few months missing) were used along with stream flow date to estimate sediment loads for days when daily stream flow measurements were available. A double log regression between the observed streamflow and measured sediment data was estimated. Suspended sediment transport rating curves has been used to generate sediment information for missing periods in many studies (Walling, 1977; Walling and Webb, 1988; Asselman, 1999; Horowitz, 2003, Jothiprakash and Grag, 2009; Salimi et al., 2013; Sarkar et al., 2008; Shabani, 2012; Gray and Simoes, 2008). There was a strong correlation (R^2=0.9) between the observed grab sample sediment data and runoff in the study watershed (Figure 5). Therefore this regression relationship (Ln (sediment) = 1.97 × Ln (runoff) + 3.69) was used to estimate the missing daily sediment data for the model simulation period. Ten parameters were selected for sediment calibration. The USLE equation support practice factor (USLE_P), the average slope length (SLSUBBSN), and the USLE equation soil erodibility factor (USLE_K) were the most sensitive parameters. Table 2 shows the adjusted data for these parameters. The results of sediment calibration and validation are shown in Figures 5 and 6. According to Moriasi et al. (2015), model performance at the watershed scale can be evaluated as "satisfactory" if monthly $R^2 > 0.40$ and NSE > 0.45 and daily, monthly, or annual PB ≤ ±20% for sediment. In our case, the model provided reasonable predictions for the calibration (R^2 was 0.30 and MNSE was 0.35 and Pb was <20) and the validation period (R^2 was 0.33 and MNSE was 0.43 and Pb was <53). Since there were some gaps in observed sediment data, the SWAT model was not able to be adequately calibrated for sediment concentration. Other reasons could be dispersed nature of the sediment data and poor accuracy of the measured data. However, the largest error in sediment prediction was associated with errors of peak flow estimation. As Abbaspour et al. (2007), stated in his research, the “second storm effect” can also be a reason for inaccurate sediment predictions. It means that after a storm, there is less sediment to be transferred, and the remaining surface layer is much more difficult to mobilize. Therefore, a similar size storm, or even a bigger size second or third storm could actually result in smaller sediment loads. However, the model does not simulate this effect but produced a good simulation of sediment load for the first storm, while for the second and the third storms it overestimated the load. Therefore, adjustment of the parameters is actually compensating for the lack of precision in the measurement or errors in the conceptual model. Despite these reasons, it was found the results quite useful, given that only grab samples were used to measure the sediment load.

Table 2. Streamflow and sediment calibration parameter values in study area

Component	Parameter	Parameter value range	Final value
Streamflow	V__GWQMN.gw	0.20_0.60	0.60
	V__GW_REVAP.gw	0.02_0.03	0.02
	V__REVAPMN.gw	0.50_1.50	1.38
	V__RCHRG_DP.gw	0.10_0.50	0.47
	V__GW_DELAY.gw	320_390	376
	R__CN2.mgt	-0.16_-0.13	-0.13
	V__ALPHA_BF.gw	0.80_1.00	0.95
	V__ESCO.hru	0.80_0.90	0.83
	V__EPCO.bsn	0.10_0.60	0.30
	V__CH_K1.sub	0.00_0.40	0.09
	V__SURLAG.bsn	0.50_4.00	3.05
	V__EVRCH.bsn	0.00_0.50	0.34
	V__TRNSRCH.bsn	0.00_0.10	0.10
	V__ALPHA_BNK.rte	0.60_1.00	0.84
	R__SOL_AWC(..).sol	-0.02_0.06	0.04
	V__CH_N2.rte	0.05_0.30	0.18
	V__CH_K2.rte	1.85_2.15	1.98
Sediment	R__USLE_P.mgt	-1.000_0.000	-0.240
	R__SLSUBBSN.hru	0.000_0.230	0.217
	R__USLE_K().sol	-0.500_0.300	-0.247
	V__RSDCO.bsn	0.010_0.100	0.083
	V__BIOMIX.mgt	0.000_0.300	0.297
	V__SPCON.bsn	0.000_1.000	0.009
	V__SPEXP.bsn	1.000_2.000	1.714
	V__CH_ERODMO(..).rte	0.050_0.700	0.355
	V__CH_COV1.rte	0.001_0.800	0.518
	V__CH_COV2.rte	0.001_0.800	0.332

Note: "R" before the parameter name stands for relative change (the parameter is multiplied by 1+value). While "V" stands for replacement (the parameter is replaced by a random value within the range)

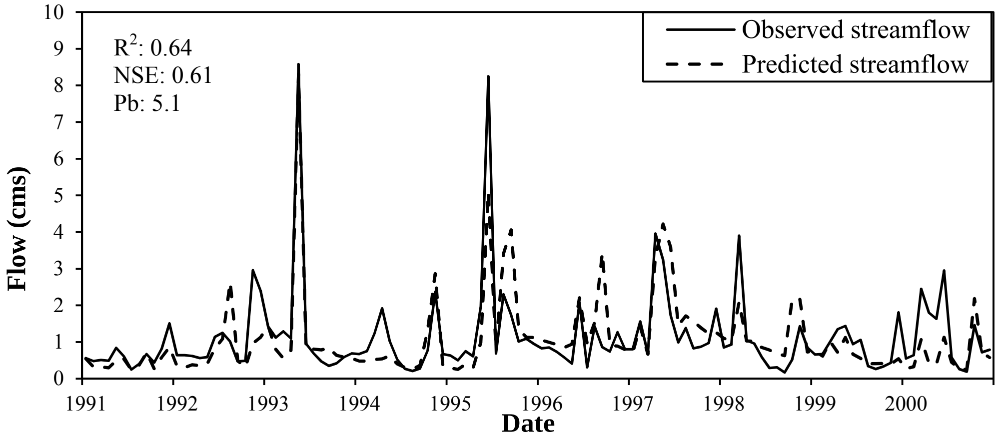


Figure 3. Observed and calibrated SWAT simulated streamflow at Cobb Creek near Eakley, OK (1991-2000)

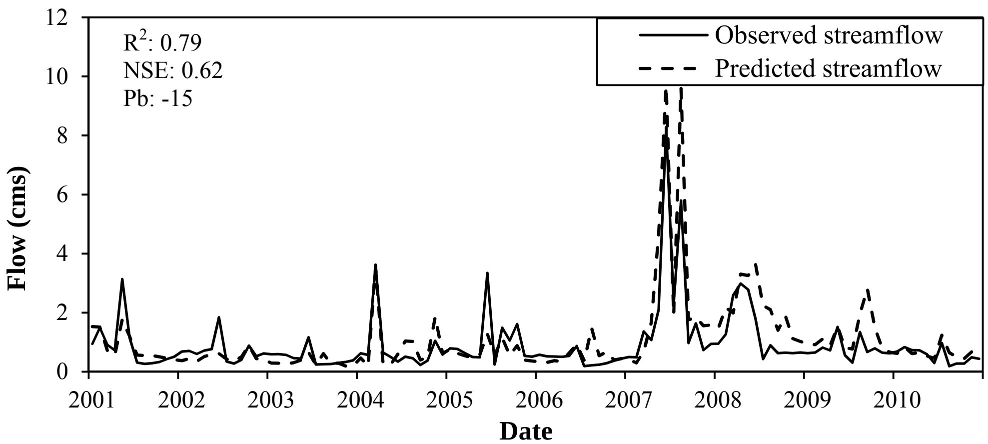


Figure 4. Validation time series for observed and SWAT predicted flow at the Cobb Creek near Eakley, OK (2001 to 2010)

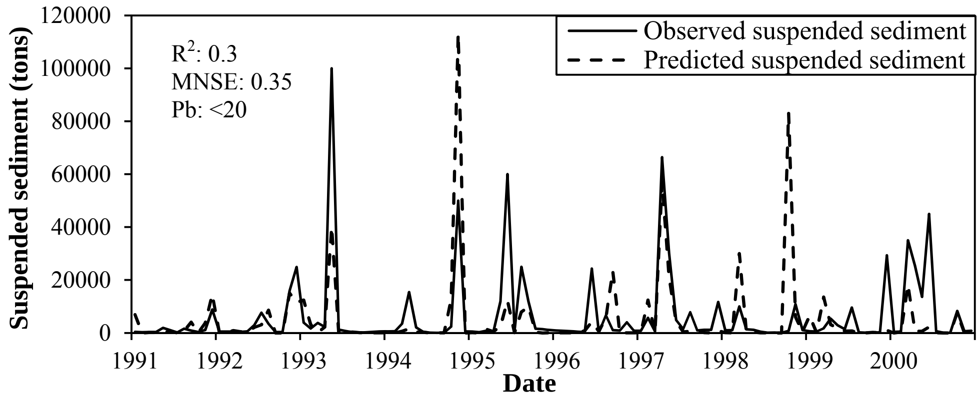


Figure 5. Observed and calibrated SWAT simulated suspended sediment concentration at Cobb Creek near Eakley, OK (1991-2000)

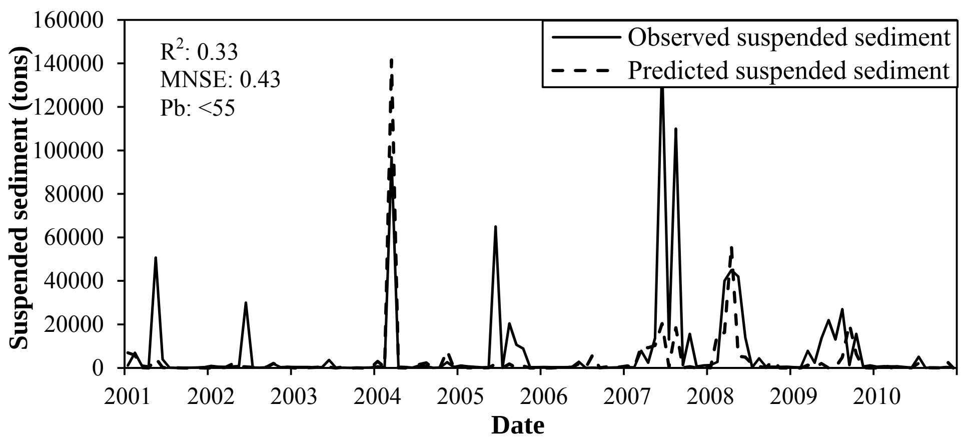


Figure 6. Observed and validated SWAT simulated suspended sediment concentration at Cobb Creek near Eakley, OK (2001-2010)

Based on grab sample data for phosphorous in Cobb Creek near Eakley gage station that was available from 2004 to 2012, stream daily phosphorous load was estimated using the regression relationship between the stream runoff and phosphorous (Figure 7). Since measured data for phosphorus at the gauging station were very sparse, therefore grab phosphorous data could not be used for model calibration. But model outputs for phosphorus concentration was compared with the estimated data from measurements in the watershed to make sure that the calibrated outputs were within the range of the values measured in the watershed (Figure 8). In our case, the model provided reasonable predictions for the phosphorous outputs (R2 was 0.46).

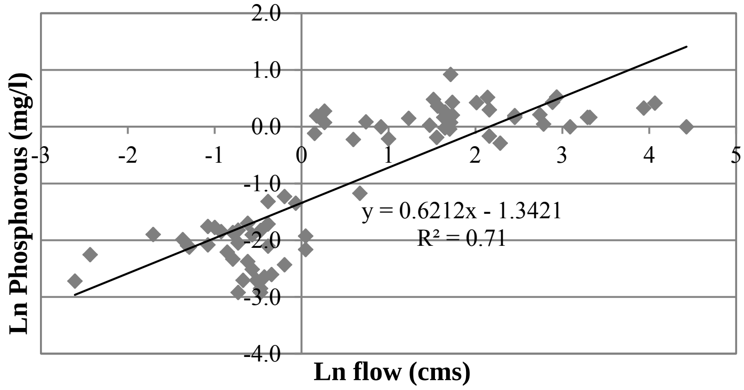


Figure 7. Observed daily discharge and observed daily phosphorous concentration trend at the Cobb Creek near Eakley, OK

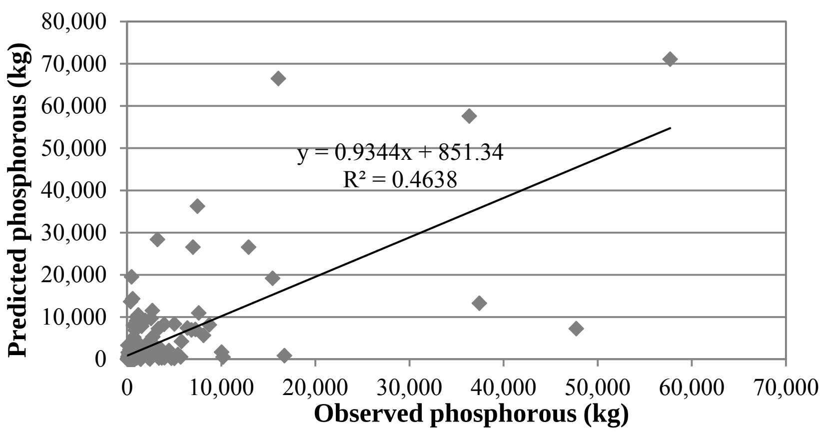


Figure 8. Observed total phosphorus concentrations vs SWAT model with modified sediment and runoff parameters) predictions

For crop yield calibration a combination of the OSU variety trial data from 2001 to 2016 (http://croptrials.okstate.edu/), and the county level NASS data (from 1986 to 2005) were used to calibrate yield of three different crops (winter wheat, grain sorghum, cotton- both dry and irrigated) in the study watershed (USDA-NASS, 1986 to 2005, http://digitalprairie.ok.gov/cdm/ref/collection/stgovpub/id/11177). Variety trial yield are taken to represent the maximum possible yield with current varieties. Input information on fertilizer and pesticides used is often available. The variety trial crop yields were collected from seven sites within and nearby the study area (Apache, El Reno, Homestead, Chickasha, Altus, Tipton, and Thomas). A list of crop yield parameters with their initial and calibrated values is provided in Appendix 3 and 4. Pb was used as an indicator to compare the SWAT simulated yield with the observation. The values of Pb for winter wheat, grain sorghum, dryland cotton and irrigated cotton were -6.0%, -27.3%, -9.0% and +0.9% respectively.

Management practices and scenarios

In this study, a total of 22 different combinations of crop-BMPs were considered by combining three major crops grown in the study area (winter wheat, cotton and grain sorghum) with five different management practices. Winter wheat (including rotations with other crops), cotton (dry and irrigated) and grain sorghum were combined with four different management practices: conservation tillage, conservation tillage under contour farming, no-tillage, and no-tillage under contour farming to produce 16 combinations of crop BMPs. The rest of the six crop-BMPs were resulted by converting crop lands to pasture land (Bermuda grass) using two different stocking rates and three different grazing schedules (Table 3).

Table 3. Crop-BMP Scenarios

<table>
<tr><th rowspan="2">Code</th><th rowspan="2">Management practice</th><th rowspan="2">Explanation</th><th colspan="6">Abbreviation for different crops in different BMPs</th></tr>
<tr><td colspan="3">Winter wheat</td><td colspan="2">Grain sorghum</td><td>Cotton</td></tr>
<tr><td>S1</td><td>Conservation tillage</td><td>The conservation tillage system was considered for all crops except hay and alfalfa</td><td colspan="3">WhCv</td><td colspan="2">GRSG</td><td>CtCV</td></tr>
<tr><td>S2</td><td>Conservation tillage in combination with contour farming</td><td>The contour conservation tillage was used following the operations-crop calendars for all crops except hay and alfalfa</td><td colspan="3">WhCC</td><td colspan="2">GSCC</td><td>CtCC</td></tr>
<tr><td rowspan="3">S3</td><td rowspan="3">No-Till farming plus strip cropping</td><td rowspan="3">No-till was simulated in regular crop calendars for all crops except hay and alfalfa*:
- Cotton no-till was simulated in irrigated areas with wheat as a cover crop
- Wheat no-till was simulated in rotations/cover cropping with canola, cotton, and grain sorghum</td><td colspan="3">Cover crop for grain sorghum: WGNS</td><td colspan="2" rowspan="3">GSNS</td><td rowspan="3">CtNS
(notill irrigate cotton covered with wheat: CNWc)</td></tr>
<tr><td colspan="3">Cover crop for cotton: WCNS</td></tr>
<tr><td colspan="3">In rotation with Canola: WKNS</td></tr>
<tr><td rowspan="3">S4</td><td rowspan="3">No-Till farming on the contour</td><td rowspan="3">It is the combination of two management practices (no-till and contour farming).</td><td colspan="3">Cover crop for grain sorghum: WGNC</td><td colspan="2" rowspan="3">GSNC</td><td rowspan="3">CtNC</td></tr>
<tr><td colspan="3">Cover crop for cotton: WCNC</td></tr>
<tr><td colspan="3">In rotation with Canola: WKNC</td></tr>
<tr><td rowspan="2">S5</td><td rowspan="2">Conversion of crop lands to pasture (Bermuda grass)</td><td rowspan="2">replaces all crop land uses (except hay and alfalfa) into Bermuda grass pasture**</td><td colspan="3">BIO_MIN 1200 kg</td><td colspan="3">BIO_MIN 1600 kg</td></tr>
<tr><td>Grazing starts in May BERM1-1</td><td>Grazing starts in Jun BERM2-1</td><td>Grazing starts in July BERM3-1</td><td>Grazing starts in May BERM1-2</td><td>Grazing starts in Jun BERM2-2</td><td>Grazing starts in July BERM3-2</td></tr>
</table>

*Note: Continuous no-till wheat was not considered feasible because of weed and disease problems and was used as a cover crop for cotton and grain sorghum, and in rotation with canola.

**According to the result of a meeting with Nolan (2017), Caddo and Grady counties agent, producers are having success in cropland conversion to Bermuda grass in the FCR watershed. For this scenario different stocking rate by changing BIO_MIN and grazing time has been considered.

Optimization model development

Optimization methods in previous studies (Veith, 2003; Arabi, 2006; Jha, 2009; Rabotyagov, 2010) have given satisfactory results for optimal allocation of NPS pollution management practices at the watershed scale. In SWAT model, the runoff from each HRU is assumed to go directly to the reach. Thus, each HRU can be modeled as independent of all other HRUs. This allows construction of an LP model continuous (non-integer) with nonnegative constraints and convex objective function in terms of the land-use variables (BMPs and crops). A convex cost function can be expressed as a piecewise linear function. A global optimum solution to even a relatively large LP (with 43,283 rows and 340 columns) can be found in a short time (less than 1 minute). Hence, in this study an LP model was used as an optimization method using General Algebraic Modeling System (GAMS) to find the most cost effective selection and location of BMPs on fields of the FMC sub-watershed. LP allows the selection of one of some 22 BMPs for each of some 5,750 HRUs in a way that provides maximum producer income while minimizing the public cost of reducing sediment and or phosphorous runoff. Hence, the objective function has two parts; producers' income and public charge. Producer's income is calculated using crop yield, each crop's price and costs of production and public charge is from limit on total sediment and/or phosphorous loss.

Since "watershed planning process is inherently a multi-objective problem" with conflicting objectives (Ahmadi et al., 2013), LP approaches multi-objective problems by parametrization. In this research, the objective function is maximizing net revenue per hectare based on crop produced subject to a limit on total sediment and/or phosphorous from the watershed by changing agricultural conservation practices.

The optimization model is stated mathematically as below:

$$Maximize\ revenue = \left[\sum_{s=1}^{S}\sum_{h=1}^{H}\sum_{i=1}^{I}\sum_{k=1}^{K}\left((P_i . Y_{shik}) - C_{shik}\right) \times X_{ik}\right] - SED_{tot} \times Schg - Ph_{tot} \times Pchg \quad (1)$$

Subject to:

$$\sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{h=1}^{H}\sum_{i=1}^{I} SED_{shik} \times X_{ik} = SED_{tot} \quad (2)$$

$$\sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{h=1}^{H}\sum_{i=1}^{I} Ph_{shik} \times X_{ik} = Ph_{tot} \quad (3)$$

$$\textstyle\sum_{i=1}^{I}\sum_{k=1}^{K} X_{ik} \leq Ta_{sh}, \qquad \text{for all s and h} \quad (4)$$

$$X_{ik} \geq 0 \quad (5)$$

Where:

S: Sub-basin, h: HRU, i: crop, K: BMP

P_i: Price of pasture and $Crop_i$

Y_{shik}: Yield of pasture and $Crop_i$ with BMP_k on one hectare in HRU_h in $subbasin_s$

C_{shik}: Total Cost to produce pasture and $Crop_i$ with BMP_k on one hectare in HRU_h in $subbasin_s$

X_{ik}: The number of hectares of pasture and $Crop_i$ with BMP_k

Ta_{sh}: Total hectares in HRU_h

SED_{shik}: Sediment runoff from HRU_h under pasture and $Crop_i$ with BMP_k in $subbasin_s$

Ph_{shik}: Phosphorus runoff from HRU_h under pasture and $Crop_i$ with BMP_k in $subbasin_s$

SED_{tot}: Total amount of sediment leaving HURs in the watershed

Schg: Charge or tax on each ton of sediment leaving fields in the watershed

Ph_{tot}: Total amount of phosphorous leaving HRUs in the watershed

Pchg: Charge on each kg of phosphorus leaving fields in the watershed

The principal approach in the US toward control of NPS pollutions from agricultural fields has been to subsidize adoption of BMPs or provide funds for land retirement and crop rotation, rather than taxing inputs such as nitrogen and fertilizer (Shortle and Horan, 2001).

Each crop-BMP combination was simulated separately in a SWAT run. The mean crop yield, sediment, and phosphorous loadings from each HRU were collected for use in the LP model. The LP model constructed with 43,283 rows and 385 columns and was solved using GAMS. In the LP model, two scenarios for optimization have been considered: (1) market solution scenario: it's objective is to identify a crop-BMP that produces the maximum net revenue without consideration of sediment and phosphorous constrains (public charge), and (2) tax solution scenario: it's objective is to identify a crop-BMP that produces the maximum net revenue determining the amount of sediment and phosphorus that can be abated for a specified charge per unit. The tax solution scenario determines the amounts of sediment and phosphorous that could be abated by incentivizing producers to adopt a crop-BMP that would minimize sediment and phosphorous loadings. It is implemented in the LP model as a charge on sediment and phosphorous loss from the field considering $100 /ton of sediment and $300/ton of phosphorous as tax. Indeed, these taxes in the LP model yield the minimum subsidy which government should pay farmers to change their crops and adopt relative BMP as incentives.

Crop price and management cost

Average crop prices (2010–2016), were obtained from the Oklahoma Agricultural Statistics (https://www.nass.usda.gov/Statistics_by_State/Oklahoma) as shown in Table 4.

Table 4. Average crop prices in the study area

Crop	Alfalfa	Bermuda	Canola	Corn	Cotton	Grain Sorghum	Hay	Rye	Soybean	Winter Wheat
Price ($/unit ton)	203.7	88.7	461.7	216.2	1525.6	201.7	88.7	88.7	424.8	248.7

Management costs are the expenses incurred from crop planting to harvesting for farmers. In this study, the management costs included expenses in seed, fertilizer, custom harvest, pesticide, harvest aids, crop insurance, annual operating capital, machinery labor, machinery fuel, and irrigation. The management cost for the study area was calculated using the Machsel program and the Oklahoma State University's enterprise budget software (Kletke and Sestak, 1991). The average costs ($/hectare) for each management practice (conservation tillage, conservation tillage under contour farming, ,no-tillage, and no-tillage under contour farming) in Oklahoma were obtained from the

Oklahoma enterprise budget software and the OSU study on no-till wheat production (Doye et al., 2004) as shown in Table 5 and 6.

Table 5. Management cost ($/hectare) for three major crops in the study area

Crop	Conservation tillage		Conservationtillage+Contour		No-till		No-till +Contour	
	Dry	Irrigated	Dry	Irrigated	Dry	Irrigated	Dry	Irrigated
Cotton	754.0	1,612.0	798.1	1,721.0	769.7	1,612.5	779.4	1,690.3
Grain Sorghum	308.5	422.2	327.4	441.8	383.2	401.9	399.8	418.6
Winter Wheat	355.2	365.3	372.7	383.9	341.8	352.8	354.0	335.2

Table 6. Management cost ($/hectare) for rotation of wheat and canola in the study area

Rotation straight row		Rotation contour farming	
Dry		**Irrigated**	
Wheat	Canola	Wheat	Canola
350.1	388.3	367.3	407.5

Results and discussions

In this study, an LP model was designed to determine optimal crop-BMPs that would maximize net revenue for farmers, minimize public cost (government subsidy), and reduce sediment and phosphorous loadings.

Net revenue is calculated as a difference between the selling price of a given crop (mulitiple by crop yield) and the associated management cost of that crop. Figure 9 illustrates the net revenue of each crop-BMP in the study area. It was found that wheat (in S1 and S2), cotton (in S1-S4), and wheat in rotation with canola (in S3 and S4) are economically beneficial crops to farmers. Figure 10 shows the net revenue per hectare with the average sediment loss leaving the field for each crop-BMP combination for all slope classes and soil types. Here, HRUs with each baseline crop has been replaced with cotton, wheat, and grain sorghum in different BMP scenarios (Table 3) to see how each BMP affects the sediment loss and net revenue for that specific crop.

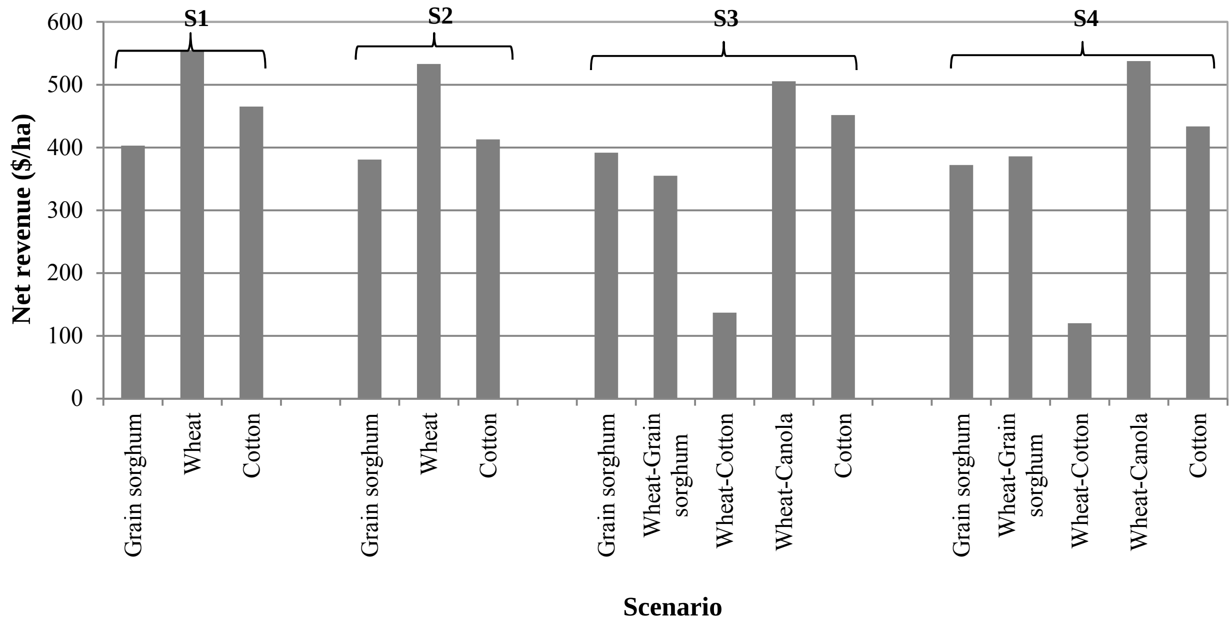


Figure 9. Average annual net revenue per hectare for each crop-BMP combination in the FMC sub-watershed

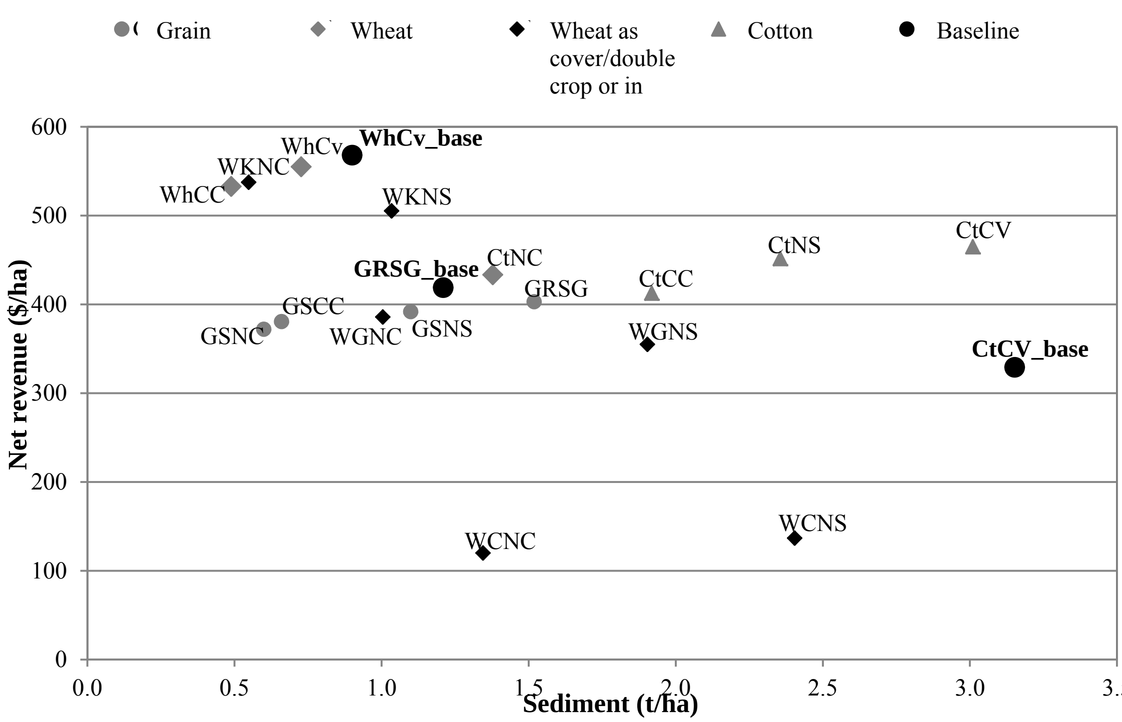


Figure 10. Net return and sediment loss per hectare by crop-BMPs in the Five-Mile Creek watershed

It was found that wheat (conventional tillage under both contour and non-contour farming) and wheat canola rotations (no till and no till under contour farming) generated the highest revenue and the lowest sediment loadings (top left of Figure 10). A wheat-grain sorghum rotation has similar amounts of erosion but less income per hectare. The cotton single crop and cotton rotations had similar levels of income as the wheat-grain sorghum rotations but higher amounts of erosion. The BMP using wheat as cover crop (especially with cotton), did not allow for the replenishment of soil moisture, had less biomass, lower yields, and slightly higher erosion than continuous cotton although all these planting are in no-till systems.

Since there should be a balance between economic and environmental aspects of each crop-BMP, the LP model selected a crop-BMP in each HRU, so that the income of all farmers in the watershed maximized in two different scenarios; 1) market solution (without considering public costs of sediment and phosphorous abatements) and 2) tax solution (considering \$100 /ton of sediment and \$300 /ton of phosphorous as tax). In this regard, results of baseline (2014 USDA land use and their specific conservation practices) were shown and then were compared with two mentioned scenarios.

Baseline scenario

In the baseline scenario, pasture (41% of the area), wheat with conventional reduced tillage (30% of the area), and all cotton (15.6% of the area divided into irrigated cotton 12% and dryland cotton 3.5% of the area) were the most dominant land uses. The SWAT simulated crop yields were used with the crop price and management cost information to estimate net revenue (producer's income) for each crop type. The average annual net-revenue for the study area was \$3,026,795 with 16,513 tons of sediment and 69 tons of phosphorous generated. Table 7 shows the land characteristics (soil texture and slope percent) for cotton (dry and irrigated), grain sorghum, pasture, and winter wheat under the baseline scenario.

Table 7. Distribution of cotton, grain sorghum, pasture and winter wheat in the study area on different soil texture and slope classes in the baseline scenario

*Soil texture	Slope (%)	Hectares of Land use				
		Irrigated cotton	Dryland cotton	Grain sorghum	Native pasture	Winter wheat
CL	Total	-	2.6	0.1	198.5	9.5
	0-2	-	2.1	0.1	148.8	8.7
	2-4	-	0.4	-	29.0	0.6
	4-6	-	0.1	-	8.8	0.1
	>6	-		-	11.8	0.0
FS	Total	262.0	32.5	17.7	443.6	313.7
	0-2	97.9	9.1	4.4	93.5	73.3
	2-4	95.3	11.8	5.1	109.5	100.2
	4-6	40.8	5.4	3.7	91.4	67.7
	>6	28.0	6.3	4.4	149.2	72.6
FSL	Total	404.1	90.0	**34.3**	**2620.1**	1068.7
	0-2	185.0	25.8	5.8	331.6	361.2
	2-4	112.4	30.3	8.5	484.1	283.0
	4-6	53.8	20.7	8.7	590.7	196.4
	>6	52.9	13.2	11.4	1213.7	228.2
LFS	Total	56.9	12.3	1.2	61.3	45.4
	0-2	28.4	4.1	0.6	13.9	13.1
	2-4	16.7	5.8	0.3	15.0	16.2
	4-6	7.3	2.1	0.1	11.0	8.6
	>6	4.5	0.3	0.2	21.4	7.5
SICL	Total	**471.4**	**163.9**	22.9	270.8	**1095.6**
	0-2	371.0	118.9	13.5	130.9	789.5
	2-4	80.3	34.5	6.2	80.5	236.5
	4-6	14.7	7.9	2.3	36.5	50.3
	>6	5.3	2.5	0.9	23.0	19.3
SIL	Total	154.5	93.0	15.0	752.5	762.1
	0-2	61.4	38.1	3.2	81.5	266.7
	2-4	49.8	30.2	3.9	167.0	248.0
	4-6	23.7	17.0	4.0	201.5	145.3
	>6	19.5	7.7	3.9	302.5	102.2
VFSL	Total	18.3	4.1	1.0	256.9	91.9
	0-2	4.4	1.9	0.2	16.7	9.3
	2-4	5.9	1.2	0.4	41.1	24.2

	4-6	3.4	0.8	0.2	59.3	27.0
	>6	4.6	0.2	0.2	139.8	31.5
Total		1367.1	398.5	92.8	4619.8	3387.7

*Note: CL is clay loam, FS and FSL are fine sandy loam, LFS is loamy fine sand, SICL is silty clay loam, SIL is silt, and VFSL is very fine sandy load.

The most dominant soil texture for the cotton and wheat was silty clay loam (SICL) (Table 7). Some 75% of the cotton and 72% of the wheat areas on these soils were planted on lands with 0–2 percent slope. The second most common soil texture for cotton and wheat was fine sandy load (FSL). For grain sorghum the most dominant soil texture was FSL, which some 33% of grain sorghum areas on these soils was planted on lands with more than six percent slope. Pasture was mostly on soil with FSL texture and almost half of pasture on these soils was planted on lands with more than six percent slope. According to the slope classification in the baseline scenario, 52% of the cotton (irrigated and dryland) was planted on land with 0–2% slope and only 8% of the cotton was planted on land with more than six percent slope. Thirty percent of grain sorghums were planted on lands with 0–2% slope, but most of the pasture was located on land with more than six percent slope. More than half of the wheat was planted on land with 0–2% slope, 26% was grown on land with 2–4% slopes, and only 20% was grown on land with more than four percent slope.

Market solution (without a charge for sediment and phosphorous loads)

This solution estimates changes in crops and BMPs that have incentives for adoption because of changes in market prices. Table 8 shows the crop-BMPs compared between the market and baseline scenarios.

Table 8. Crop-BMP (hectare) in market solution and baseline scenarios

Land use	Rye	Canola	Soybean	Grain sorghum		Wheat		Cotton	
				GRSG	GSNS	WhCv	WGNC	CtCV	Irrigated Cotton
Market solution	2.8	2.9	1.5	2.7	160.0	4,472.6	1.0	1,070.0	0.5
Baseline	71.3	373.6	43.6	92.8		3,387.7		398.5	1,367.1

In the market solution scenario, wheat (40%), and cotton (10%) were the dominant crops in the study area. Since the native pasture area modified by the model, the area of pasture remains constant except for possible conversion of cropland to Bermuda grass pasture. It was found that with average 2010–2016 market prices, the optimal crop choice, from among the conventional crops and added BMPs would increase the net revenue (producer's income) in the watershed by 26% ($805,200) over the baseline solution. This scenario also reduced total sediment and phosphorous loads at the watershed outlet by 12% and 26% respectively as compared to the baseline (Table 13). Changes in relative input prices increased returns from no-till methods relative to conventional tillage methods. Table 9 shows the new optimal crop-BMPs and the associated crops that were converted to these new crop-BMPs.

Table 9. New crop-BMP scenarios in market solution

New crop-BMP	CtCv				GSNS	WhCv				
Area (ha)	927.5				41.1	1895.3				
Converted crop	wheat	Canola	Grain sorghum	Rye and soybean	Irrigate cotton	Irrigated cotton	Canola	Dryland cotton	Grain sorghum	Rye and soybean
Area (ha)	810	82.3	22.3	12.9	41.1	1186.1	288.4	255.9	67.2	97.7

In the market scenario, cotton with conservation tillage on straight rows (CtCv) was optimal on 8.2% of the area, grain sorghum with non-contour no-till (GSNS) was optimal on 1.5% of the area, while wheat with non-contour conservation-till (WhCv) was optimal on 16.8% of the area. These crop-BMPs were suggested to be implemented as additional strategies to reduce 12% of sediment and 26% phosphorous loadings from agricultural lands and maximize income. 100% of GSNS crop-BMP was from conversion of irrigated cotton and most of the WhCv crop-BMP was from conversion of irrigated cotton. Most of CtCv crop-BMP was from conversion of wheat, which was because of this fact that cotton in dryland is an economic choice if there would be no limit for sediment and phosphorous. In these new conservation strategies, it was found that 38.3% of cotton (CtCV) should be planted on the flat areas (0–2% slope), 31% on lands with 2–4% slope, 17.4% on lands with 4–6% slope, and only 13.4% on lands with more than 6% slope. For grain sorghum (GSNS), it was found that it should be planted mostly on flat area as well (78% on 0_2% slope and 22% on 2–4% slope). For wheat (WhCv) the result were similar, 90% on land with 0–4% slope and 10% on land with more than 4% slope.

Comparison of market solution with baseline

In the market solution scenario, the optimal area of rye, canola and soybean decreased by 96%, 99%, and 96% respectively as compared to the baseline scenario. Grain sorghum increased by76%, of which 98% was no-till. Wheat area increased by 32%, all planted with non-contour conservation tillage. The overall cotton (irrigated and dryland) area declined by 39%. However, the areas of dryland cotton with conservation tillage increased by 169% while the irrigated cotton area decreased by 99%. Some 20.5 hectares of irrigated cotton, 1.5% of the total irrigated cotton area, was converted to Bermuda grass. An additional 11.7% of the irrigated cotton was converted to grain sorghum under a no-till non-contour system. However, 86.7% of irrigated cotton was converted to wheat under a conservation tillage system, which was the main reason of sediment reduction.

Tax solution scenario

The objective of this scenario is to determine the most cost efficient crop-BMPs and their spatial locations in the watershed for additional sediment and phosphorous abatement. Table 10 provides a comparison between the tax solution, market solution, and baseline scenarios in terms of crop-BMP distribution.

Table 10. Crop-BMP distribution (ha) under tax solution, market solution, and baseline scenarios

Land use	Rye	Canola	Soybean	Grain sorghum	Wheat			Cotton		
				GRSG	WhCv	WGNC	WhCC	CtCV	Irrigated Cotton	CtNc
Tax solution	2.8	2.9	1.5	2.7	4791.7	1.0	633.9	87.3	0.5	125.6
Baseline	71.3	373.6	43.6	92.8	3387.7	-	-	398.5	1367.1	-

In the tax scenario, wheat (48%) was the dominant crop with cotton remaining at only 2%. In the tax solution scenario, the net revenue of selected crops and BMPs in the watershed with considering constraints for sediment and phosphorous load was $2,611,627 which was14% and 32% less than the baseline and market solution, respectively (Table 13). The reason for this decrease is considering tax for minimizing sediment and phosphorous. Indeed, the net revenue is producer's uncompensated income which subsidy will make it compensated income. Sediment loadings were reduced by 27% (4,507 tons) and the phosphorous loadings were reduced by 28% (17 tons) as compared to the baseline scenario. The respective sediment and phosphorus loadings were 17% and 2% lower than that in the market solution scenario (Table 13). This shows that $1.2 million compensation to producers to adopt BMPs would result in 28% sediment (4,507 tons) and 27% phosphorous (17 tons) reduction over the baseline. Table 11 shows the new crop-BMPs in tax solution scenario as converted from the baseline crops and the associated crops that were converted.

Table 11. Optimal crop-BMPs in tax solution scenario

New crop-BMP	CtCV					CtNc			
Area (ha)	77.7					125.6			
Converted crop	Wheat	Canola			Other*	Wheat	Canola	Dryland cotton	Other*
Area (ha)	67.1	6.3			4.2	100.8	11.0	8.0	5.8
New crop-BMP	WhCC					WhCv			
Area (ha)	633.8					2062.0			
Converted crop	Wheat	Canola	Cotton Irrigated	Cotton Dry	Other*	Cotton Irrigated	Cotton Dry	Canola	Other*
Area (ha)	489.5	35.0	43.6	22.3	43.4	1238.4	358.5	318.3	146.7

*Note: other means Rye and grain sorghum

In tax solution scenario, cotton with conservation tillage (CtCV) (0.7%), cotton with no-tillage on contour rows (CtNc) (1.1%), wheat with conservation tillage on contour rows (WhCC) (5.6%), and wheat with conservation tillage on straight rows (WhCv) (18.2%) were the selected crop-BMPs to abate the sediment and phosphorous loadings from the agricultural lands in the study area. Most of the CtNc and WhCC were from conversion of wheat and most of the WhCv was from conversion of irrigated cotton. Table 12 shows the subsidy distribution in different new significant crop-BMPs based on the soil texture and slope. Results show that for implementing the new crop-BMPs to have 27 and 28% sediment and phosphorous reduction respectively, the highest rate of subsidy should be devoted to the areas with fine sandy loam soil texture (especially on lands with more than four percent slope). The second targeted soil was silty clay loam soil.

Table 12. Subsidy distribution in different new crop-BMPs based on the soil texture and slope

*Soil texture	Slope	New crop-BMP				
		Bermuda grass	CtCV	CtNc	WhCC	WhCv
CL	Total				16.1	164.2
	0-2					89.3
	2-4					64.3
	4-6					10.5
	>6				16.1	
FS	Total	83.2	496.4	2,850.5	4,829.5	9,227.2
	0-2		493.3			225.7
	2-4		3.0	1,412.1		873.4
	4-6			1,319.2	475.7	4,630.7
	>6	83.2		119.2	4,353.8	3,497.3
FSL	Total	1,846.8	238.6		58,708.9	21,868.2
	0-2	3.9	238.6			2,587.3
	2-4	32.0				6,361.0
	4-6	139.7			2,678.8	10,897.0
	>6	1,671.2			56,030.1	2,022.8
LFS	Total	8.2	411.6		3,782.0	3,690.8
	0-2		411.6			223.3
	2-4					346.3
	4-6	0.3			229.2	3,038.8
	>6	7.9			3,552.9	82.4
SICL	Total		382.0	140.3	4,903.8	17,787.6
	0-2		382.0	38.4		7,503.5
	2-4			102.0		6,067.9
	4-6				27.2	3,314.3
	>6				4,876.6	902.0
SIL	Total				18,122.6	12,254.0
	0-2					1,032.6
	2-4					4,131.1
	4-6				3,858.8	6,200.5
	>6				14,263.9	889.9
VFSL	Total	216.8			17,376.7	3,378.8
	0-2					298.2
	2-4				8.0	972.0
	4-6				4,830.6	203.4
	>6	216.8			12,538.0	1,905.1

*Note: CL is clay loam, FS and FSL are fine sandy loam, LFS is loamy fine sand, SICL is silty clay loam, SIL is silt, and VFSL is very fine sandy load.

Comparison between baseline and tax solution scenarios

Table 13 shows the conversion of main crops (irrigated cotton, dryland cotton, grain sorghum, and wheat) to different crop-BMPs in seven different soil texture and four slope classes. The purpose of this part is identifying the targeted soils for each crop-BMP conversion. The results of tax solution scenario indicated that the area of canola, rye and soybean decreased by 99%, 96% and 96% respectively from the baseline scenario. The wheat area increased by 60% from the baseline of which, 11% were planted on contour. Eighty-six percent of conversion of wheat to CtCV was on lands with

FS soil texture, of which 100% were on less than two percent slope. Ninety-four percent of conversion of wheat to CtNc happened on soil with FS texture, of which 83% of them were on lands with 2–4% slope. Half of wheat with conservation tillage non-contour conversion to wheat with conservation tillage contour was on FSL soil texture which 90% of them were on lands with more than six percent slope. The cotton area decreased by 87.9% from the baseline; dry cotton with conservation tillage decreased by 46.5% and irrigated cotton decreased by 99%. Fifty-nine percent of cotton was planned on contour with no-till. 6.2% of total irrigated cotton (84.7 ha) was converted to Bermuda grass with 1,200 kilograms of stocking rate which would be grazed out in 6 months starting July. Almost 3% of irrigated cotton was converted to wheat with conservation tillage system and contour cropping. Ninety-one percent of irrigated cotton was converted to wheat with conservation tillage system and straight cropping. Ninety-six percent of dryland conversion to CtNc is on lands with FS soil texture, of which 92% were on lands with 0–2% slope. 50% of dryland cotton conversion to WhCC was on lands with FSL soil texture, 100% of which were on lands with more than six percent slope. 45% of dryland cotton conversion to WhCv was on lands with SICL soil texture, of which 73% of them were on lands with less than two percent slope. In irrigated cotton conversion to Bermuda grass, 60% happened on FSL soil texture, of which 66% were on lands with more than six percent slope. 50% of irrigated cotton conversion to WhCC occurred on SIL soil texture, of which 100% were on lands with greater than six percent slope. 40% of irrigated cotton conversion to WhCv occurred on SICL soil texture, of which 80% were on lands with less than two percent slope.

According to the results of this part, fine sandy loam soil was the targeted soil in changing tillage system of wheat from conventional tillage to conservation tillage, and these changes would be more effective in sediment and phosphorous abatement once they were combined with contour farming on steep slope areas. In conversion of conventional tillage wheat to cotton, sandy loam soils were more targeted and once they were on steep slope areas, it would be done with contour farming. The targeted soils for conversion of grain sorghum and cotton to wheat were silty clay loams with less than two percent slope and once the land slope was more than six percent, it would be combined with contour farming.

Table 13. Conversion of baseline crops to different crop-BMPs based on soil texture and land slope in tax solution scenario

*Soil texture	Slope (%)	Conversion of baseline irrigated cotton to			Conversion of baseline dryland cotton to			Conversion of baseline grain sorghum to					Conversion of baseline minimum till wheat to			
		BM31	WhCC	WhCv	CtNc	WhCC	WhCv	CtCV	CtNc	WGNC	WhCC	WhCv	CtCV	CtNc	WGNC	WhCC
CL	Total						2.5					0.1				
	0-2						2.1					0.1				
	2-4						0.4									
	4-6															
	>6															
FS	Total	25.0		237.0	7.7	5.9	12.0	3.5	4.4		3.8	5.9	**57.7**	**94.8**		72.5
	0-2			97.9			2.4	3.5				0.9	57.7			
	2-4			95.3	7.1		4.6	0.1	3.7			1.3		79.1		
	4-6			40.8	0.6		4.7		0.4			3.3		15.7		
	>6	25.0		3.0		5.9	0.3		0.2		3.8	0.4				72.5
FSL	Total	48.7	14.0	341.1		10.9	77.2				10.9	21.9	9.0			**241.3**
	0-2	0.3		184.7			24.9					5.5	9.0			
	2-4	5.8		106.5			30.0					8.1				
	4-6	10.4		43.3			20.3					8.3				30.4
	>6	32.1	14.0	6.7		10.9	2.0				10.9					**210.9**
LFS	Total	7.4	0.6	49.0		0.3	12.0				0.2	0.9	0.5			5.9
	0-2			28.4			4.1					0.6	0.5			
	2-4			16.7			5.8					0.3				
	4-6	3.4		3.9			2.1					0.1				
	>6	3.9	0.6			0.3					0.2					5.9
SICL	Total		5.1	**466.2**	0.3	1.3	**162.0**				0.2	**22.3**		6.0		18.2
	0-2			**371.0**	0.3		**118.6**					**13.4**		5.2		
	2-4			80.3			34.4					6.1		0.8		
	4-6			14.7			7.8					2.2				
	>6		**5.1**	0.2		**1.3**	1.2				**0.2**	0.6				18.2
SIL	Total		19.5	134.9		3.5	89.2				3.3	11.3				93.4
	0-2			61.4			38.0					3.1				
	2-4			49.8			30.2					3.7				
	4-6			23.7			17.0					3.9				4.1
	>6		19.5			3.5	4.0				3.3	0.5				89.4
VFSL	Total	3.7	4.4	10.2		0.3	3.8				0.3	0.7				58.2
	0-2			4.4			1.9					0.2				
	2-4			5.9			1.2					0.4				
	4-6		3.4			0.2	0.6				0.1	0.1				26.7
	>6	3.7	1.0			0.1	0.1				0.2					31.5

*Note: CL is clay loam, FS and FSL are fine sandy loam, LFS is loamy fine sand, SICL is silty clay loam, SIL is silt, and VFSL is very fine sandy load.

Comparison between the baseline, market solution and tax solution scenarios

Table 14 shows the economic and environmental tradeoffs between the scenarios. It was found that the market solution scenario would generate the highest revenue for farmers, producing sediment and phosphorous loads intermediate between the baseline and tax solution (uncompensated) scenarios. The tax solution scenario would produce the lowest sediment and phosphorous loadings. Compared to the baseline scenario, $1.21 million compensations to the farmers would reduce the sediment and phosphorous loadings by at least 27% and increase the uncompensated income for farmers by 26%. Figure 11 illustrates the comparison between three different scenarios' land use in the study area. Table 15 shows the significant crop-BMPs in each scenario.

Table 14. Differences in net revenue, sediment, and phosphorous between the scenarios

Scenarios	Net revenue (uncompensated income) ($)	Tax cost (producer's compensation subsidy) ($)	Producer's income (compensated income) ($)	Sediment (ton)	Phosphorous (ton)
Baseline	3,026,795	_	_	16,512.8	62.6
Market solution	3,831,996	_	_	14,546.8	46.3
Tax solution	2,611,628	1,214,134	3,825,762	12,005.4	45.

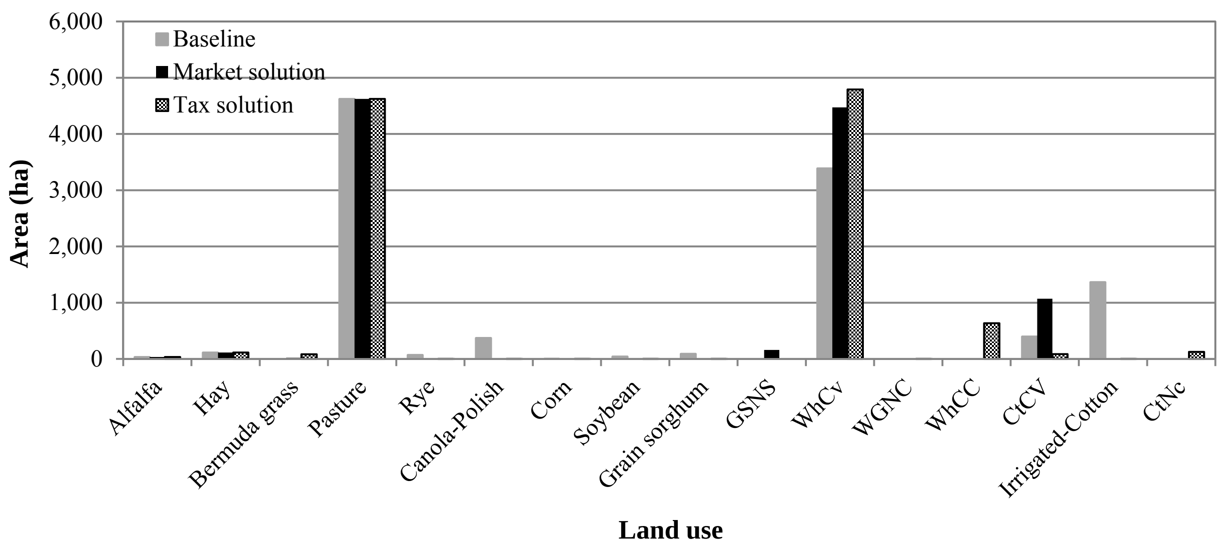


Figure 11. Land use variation in different scenarios

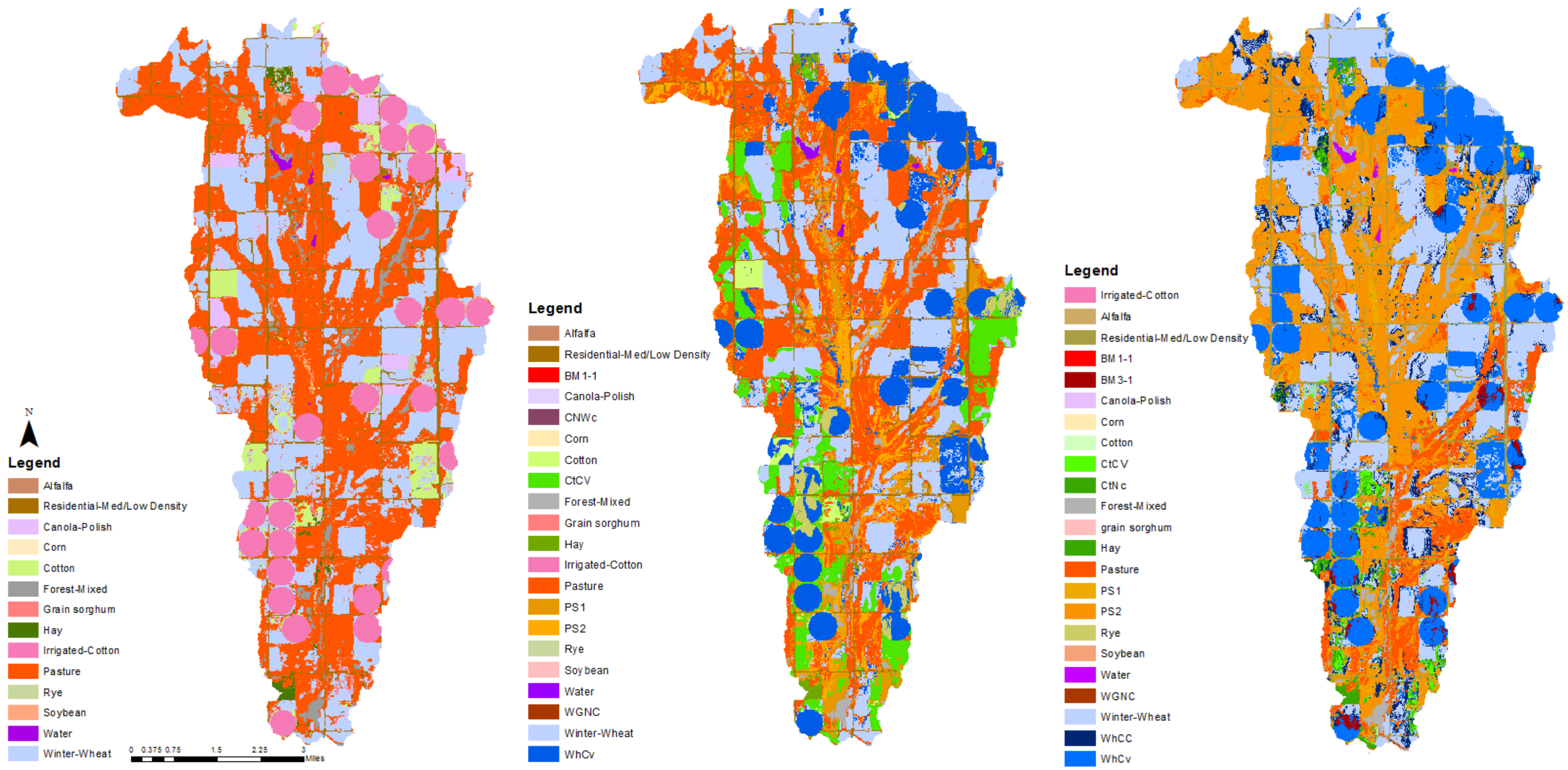
Table 15. The significant crop-BMPs in each scenario

Scenario	BMPs/Crop	Comment
Baseline	Native pasture, grain sorghum, irrigated and dryland cotton, and wheat with conventional reduced tillage	
Market solution	Native pasture, Bermuda grass, grain sorghum with non-contour no-till, dryland cotton with conventional tillage, cotton with non-contour conservation tillage, wheat with conventional reduced tillage, wheat with non-contour conservation tillage	Only wheat, grain sorghum and cotton were considered
Tax solution	Native pasture, Bermuda grass, cotton with non-contour and contour conservation tillage, and wheat with conventional reduced tillage, wheat with non-contour and contour conservation tillage	Only wheat, grain sorghum and cotton were considered

The results show that continuous minimum till wheat remains the dominant crop in the FMC area (until problem of weeds and diseases with continuous no-till wheat can be solved). Simulations with winter wheat as a cover crop or double crop in rotation with cotton or grain sorghum gave lower economic returns and some increase in erosion.

Wheat was found to be the most beneficial crop both economically and environmentally. Osei (2016) applied three conservation practices in the FCR watershed to find the optimal distribution of conservation practices and indicated that no-till winter wheat production in central Oklahoma would be a win-win option. But, since continuous no-till wheat is prone to issues of weeds and other diseases, it is not a good scenario for adoption (Edwards et al., 2006). Authors further indicated that although conversion to pasture entailed a significant cost to farmers, it resulted in substantial and consistent reductions in all environmental indicators such as runoff volumes and sediment and nutrient loadings, which is consistent with the results of this research.

Figure 12 shows the crop-BMP distribution of land uses under three scenarios targeted at abating sediment and phosphorous loads in the study area. Figure 12-b illustrates optimal crop-BMP for 12% sediment and 26% phosphorous abatement (market solution) and Figure 12-c shows optimal crop-BMPs for an additional 27% sediment and 28% phosphorous reduction (tax solution).



a) Baseline land use b) Market solution c) Tax solution

Figure 12. Spatial allocation of FMC crop-BMP in different sediment and phosphorous abatement scenarios

Summary and conclusions

Twenty-two crop-BMP combinations were simulated in 5,750 HRUs in the study area. The tillage methods (conservation tillage with contour and non-contour and no-till with contour and non-contour) were simulated with cotton, grain sorghum, and wheat. Wheat was also considered as a cover or double crop with cotton and grain sorghum. No-till wheat-canola rotations were also considered in contour and non-contour farming systems. The conversion of cropland to Bermuda grass with different grazing times and stocking rates was also considered. Average crop yield, sediment, and phosphorous loads from each HRU were recorded. The LP model was designed to estimate net revenue generated with different crop-BMPs in the study area for two different scenarios: market solution and tax solution

The market solution scenario represented maximum net revenue without constraints on sediment and phosphorous loadings. Here, the objective was to maximize net revenue or producer's income. The tax solution scenario was obtained with charges on sediment and phosphorus production. Here, the objective was to maximize net revenue subject to determining the amount of sediment and phosphorus leaving the field that could be abated for $100 and $300 per ton respectively. These charges serve as subsidy (compensated income) to farmers. The charges assist in determining the type and location of crop-BMPs in the watershed to reduce sediment and phosphorus loadings for an amount less than or equal to the charge. The charge gives the same result as a payment to the producer to prevent a unit of phosphorus or sediment loss from their field. Using the income maximization approach, crop-BMPs were compared for reduction in sediment and phosphorous loadings across all HRUs in different scenarios.

By maximizing net revenue without constraints on sediment and phosphorous reduction (market scenario), there was 26% increase in income, 12% increase in sediment abatement, and 26% increase in phosphorous abatement. In market scenario, most of the new strategies for replacement of row crops with new conservation practices are wheat and cotton with non-contour conservation tillage and grain sorghum with non-contour no-till. In cotton with non-contour conservation tillage, the conversion was from wheat with conventional tillage system. For wheat with conservation tillage, the most of the conversion was from irrigated cotton. In grain sorghum with non-contour no-till, all of the conversion was from irrigated cotton. It means that cotton is a profitable crop economically on dryland but irrigated cotton was less profitable than other crops in this study area. The conversion of 39 percent of the cotton area to wheat and other crops was accompanied by a decrease in sediment and phosphorus loss. This was especially true on the irrigated area.

The tax solution scenario was to determine how much additional sediment and phosphorus could be reduced at a cost of \$100 per ton of sediment and \$300 per ton of phosphorus. The producer's income (compensated income) in this solution was increased by 26.4% leading to a reduction of sediment (27%) and phosphorous (28%) as compared to the baseline scenario. The net revenue without considering the compensated income would be 13.7% less than that of the baseline scenario. This shows that 1.2 million dollars compensation to producers to adopt crop-BMPs would result in 28% sediment (4,507 tons) and 27% phosphorous (17 tons) reduction over the baseline. This would also result in additional 15% and 2% respectively in sediment and phosphorous reduction over the market solution. The increase in abatement required replacement of 2,697 hectares of row crops with wheat; most of the change was on lands with silty clay loam (especially on lands with less than two percent slope) and fine sandy loam (especially on lands with more than six percent slope). The solution contained fewer cotton areas which were targeted for sediment and phosphorous abatement, but the new suggested cotton were from conversion of wheat with reduced tillage to cotton with contour no-till (mostly on lands with fine sandy soil texture with less than four percent slope). Soils with fine sandy loam texture were the targeted soils in changing tillage system of wheat from conventional tillage to conservation tillage, and these changes was more effective on sediment and phosphorous reduction once they were combined with contour farming on steep slope areas. In conversion of conventional tillage wheat to cotton, sandy loam soils were more targeted and once they were on steep slope areas, it would be done with contour farming. The targeted soils for conversion of grain sorghum and cotton to wheat were silty clay loams with less than two percent slope and once the land slope was more than six percent, it would be combined with contour farming. Meanwhile , results showed that for implementing the new crop-BMPs to have 27% and 28% sediment and phosphorous reduction respectively, the highest rate of subsidy should be devoted to the areas with fine sandy loam soil texture (especially on lands with more than four percent slope). The second targeted soil was silty clay loam soil.

For each crop, loss in net revenue per ton of reduced sediment load increases with the total amount of sediment abated since the model selects less productive and highly erodible lands first and gradually moves to more productive and less erodible lands as the constraint level is increased. This is desirable since the objective is to obtain the highest possible load reduction per dollar lost as a result of replacing a more profitable land cover type by less profitable ones.

According to the result of LP, if sediment and phosphorous constrains were considered, this conversion to wheat with non-contour conservation tillage would be more profitable. Once there was no constrains on sediment and phosphorous load and the goal is just maximizing producer's income, wheat was the first best crop and then no-till grain sorghum was the second best crop for irrigated areas. But with considering constrains for NPS loads, wheat with non-contour conservation tillage would be preferred in irrigated lands.

Dryland cotton and grain sorghum were the most profitable crops for farmers. However, they had higher NPS pollution than wheat. Wheat under conservation tillage was both economically and environmentally beneficial crop in both dry and agricultural fields. The percentage of the area devoted to wheat increased when charges were placed on field losses of sediment and phosphorus. The rotation or double crop of wheat with other crops (cotton, canola, and grain sorghum) with no-tillage system (with both contour and non-contour farming) was not the most economic and environmental strategy with the abatement level used in this study.

Limitation of this study

In no-till farming there is a problem of crop resistance to the diseases from using herbicides and pesticides. One of the limitations of this study is that in the modeling part using SWAT, this resistance was not considered in crop yield calculation. The changes in relative crop prices or proven yields and crop insurance rates will also affect producers' ability to change crops.

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Appendix

Appendix 1. Reservoir and Ponds Information in the SWAT model

Sub-basin	principle surface area (ha) PND_PSA	principle volume (10^4 m^3) PND_PVOL	emergency spillway surface area (ha) PND_ESA	emergency spillway volume (10^4 m^3) PND_EVOL	drainage area (ha)	sub-basin area (ha)	drainage area/ sub-basin area PND_FR
1	1.52	3.05	2.29	4.57	45.7	1214.17	0.04
2	2.65	5.31	3.98	7.96	79.6	694.81	0.11
3	1.09	2.18	1.64	3.27	32.7	2112.78	0.02
4	-	-	-	-	-	-	-
5	4.84	9.69	7.27	14.53	145.3	570.03	0.25
6	20	40.30	30	62.45	724.5	784.94	0.92
7	2.06	4.11	3.08	6.17	61.7	625.04	0.10
8	1.93	3.86	2.90	5.79	57.9	817.80	0.07
9	6.29	12.59	9.44	18.88	37.74	37.74	1.00
10	0.84	1.67	1.26	2.51	25.1	697.89	0.04
11	12.62	25.24	18.93	37.86	57.45	57.45	1.00
12	0.04	0.07	0.06	0.11	1.1	23.70	0.05
13	20	41.71	30	62.56	925.6	2822.14	0.33
14	7.54	15.09	11.31	22.63	226.3	571.50	0.40
15	7.94	15.89	11.92	23.83	238.3	882.17	0.27
16	4.37	8.73	6.55	13.10	131.0	1823.63	0.07
17	-	-	-	-	-	-	-
18	5.37	10.73	8.05	16.10	161.0	1185.20	0.14
19	20	40.48	30	62.73	727.3	1139.11	0.64
20	20	40.68	30	62.02	730.2	2560.27	0.29
21		-	-	-	-	-	-
22	11.80	23.60	17.70	35.40	354.0	1574.00	0.22
23	5.96	11.92	8.94	17.88	178.8	1596.47	0.11
24	1.42	2.84	2.13	4.25	42.5	773.11	0.06
25	8.95	17.89	13.42	26.84	268.4	1665.47	0.16
26	3.77	7.53	5.65	11.30	113.0	1415.00	0.08
27	1.85	3.69	2.77	5.54	55.4	560.79	0.10
28	0.04	0.07	0.05	0.11	1.1	53.39	0.02
29	3.18	6.36	4.77	9.54	95.4	952.56	0.10
30	3.26	6.51	4.89	9.77	97.7	888.28	0.11
31	0.26	0.52	0.39	0.79	7.9	218.01	0.04
32	0.15	0.30	0.23	0.45	4.5	64.24	0.07
33	7.42	14.85	11.14	22.27	222.7	753.34	0.30
34	6.19	12.39	9.29	18.58	185.8	1328.45	0.14
35	-	-	-	-	-	-	-
36	2.48	4.96	3.72	7.44	74.4	919.52	0.08
37	-	-	-	-	-	-	-
38	-	-	-	-	-	-	-
39	1.51	3.02	2.27	4.53	45.3	904.65	0.05
40	0.07	0.14	0.11	0.21	2.1	217.57	0.01
41	1.83	3.66	2.74	5.49	54.9	655.48	0.08
42	0.09	0.18	0.13	0.27	2.7	198.45	0.01
43	2.42	4.83	3.62	7.25	72.5	748.99	0.10

Appendix 2. Conventional (reduced) tillage for dryland crops and pasture

Crop	Date	Operation
Cotton	1.1	Tillage operation (Disk Plow Ge23ft)
	3.15	Tillage operation (Disk Plow Ge23ft)
	5.15	Tillage operation (Springtooth Harrow Ge15ft)
	6.1	Tillage operation (Finishing Harrow Lt15ft) Pesticide Operation (Pendimehalin, 0.25 kg)
	6.10	Fertilizer application (Elemental Nitrogen, 50 kg)
	6.11	Plant
	7.1	Tillage operation (Row Cultivator Ge15ft)
	11.15	Harvest and kill
Pasture	1.1	Plant
	3.1	Auto fertilization
	5.1	Grazing operation (Beef-Fresh Manure, GRZ_DAYS*: 180, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Winter wheat	3.15	Fertilizer application (Elemental Nitrogen, 80 kg)
	6.1	Harvest and kill
	7.1	Tillage operation (Chisel Plow Gt15ft)
	8.1	Tillage operation (Offset Dis/heavduty Ge19ft)
	9.20	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg)
	9.22	Tillage operation (Disk Plow Ge23ft)
	9.24	Tillage operation (Springtooth Harrow Lt15ft)
	9.25	Plant
	12.1	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Grain sorghum	5.1	Plant
	5.27	Fertilizer application (Elemental Nitrogen, 150 kg)
	5.28	Tillage operation (Springtooth Harrow Ge15ft, Disk Plow Ge23ft, Mecoprop Amine, 125), Pesticide Operation (Mecoprop Amine, 125 kg)
	10.18	Tillage operation (Disk Plow Ge23ft)
	10.20	Tillage operation (Springtooth Harrow Ge15ft)
	10.30	Harvest and kill
Alfalfa	4.1	Harvest only
	5.15	Harvest only
	7.1	Harvest only
	8.29	Fertilizer application (Elemental Nitrogen, 50 kg), (Elemental Phosphorous, 20)
	9.7	Plant
	10.15	Harvest only
Hay	4.1	Harvest only
	7.1	Harvest only
	8.29	Auto fertilization
	9.7	Plant
	10.15	Harvest only
Rye	6.10	Harvest only
	8.10	Fertilizer application (Elemental Nitrogen, 80 kg), (Elemental Phosphorous, 35)
	9.20	Plant
	9.15	Grazing operation (GRZ_DAYS*: 150, BIO_EAT*: 3,

		BIO_TRMP*: 0.47, MANURE_KG*: 1.5)

*AUTO_NSTRS: Nitrogen stress factor of cover/plant triggers fertilization. This factor ranges from 0.0 to 1.0 where 0.0 indicates there is no growth of the plant due to nitrogen stress and 1.0 indicates there4 is no reduction of plant growth due to nitrogen stress.
*GRZ_DAYS: Number of consecutive days grazing takes place in the HRU
*BIO_EAT: dry weight of biomass consumed daily ((kg/ha)/day)
* BIO_TRMP: dry weight of biomass trampled daily ((kg/ha)/day)
*MANURE_KG: dry weight of manure deposited daily ((kg/ha)/day)

Appendix 3. Cotton yield calibration parameters

Parameter	Parameter definition	Default value	Calibrated value
BIO_E [(kg/ha)/(MJ/m^2)]	Radiation use efficiency or biomass energy ratio	15	14
USLE_C	Minimum value of USLE C factor for water erosion	0.2	0.1
HVSTI [(kg/ha)/(kg/ha)]	Harvest index for optimal growing season	0.4	0.3
OV_N	Manning's "n" value for overland flow	0.14	0.12
BLAI (m^2/m^2)	Maximum potential leaf area index	4	3
FRGRW1(fraction)	Fraction of plant growing season to the first point on the optimal leaf area development curve	0.15	0.14
FRGRW2 (fraction)	Fraction of plant growing season to the second point on the optimal leaf area development curve	0.5	0.3
LAIMX1 (fraction)	Fraction maximum leaf area index to the first point on the optimal leaf area development curve	0.01	0.005
CNYLD (kg N/kg seed)	Normal fraction of nitrogen in yield	0.015	0.018
CPYLD (kg P/kg seed)	Normal fraction of Phosphorus in yield	0.0025	0.0027

Appendix 4. Wheat, pasture, and grain sorghum yield calibration parameters

Parameter	Winter wheat		Pasture		Grain sorghum	
	Default value	Calibrated value	Default value	Calibrated value	Default value	Calibrated value
BIO_E [(kg/ha)/(MJ/m^2)]	30	29	35	28	33.5	37
USLE_C	0.03	0.02	0.003	0.003	0.2	0.2
HVSTI [(kg/ha)/(kg/ha)]	0.4	0.3	0.8	0.8	0.45	0.3
OV_N	0.14	0.12	0.3	0.25	0.14	0.12
BLAI (m^2/m^2)	4	3	4	2.5	3	4.5
FRGRW1(fraction)	0.05	0.03	0.05	0.03	0.15	0.15
FRGRW2 (fraction)	0.45	0.35	0.49	0.35	0.5	0.5
LAIMX1 (fraction)	0.05	0.03	0.05	0.03	0.05	0.05
CNYLD (kg N/kg seed)	0.025	0.02	0.0234	0.0134	0.0199	0.02
CPYLD (kg P/kg seed)	0.0022	0.0018	0.0033	0.0022	0.0044	0.0032

CHAPTER VI

OPTIMIZED LANDUSE, CONSERVATION PRACTICES, AND GRAZING OPERATION IN AN AGRICULTURAL, PASTURE INTENSIVE WATERSHED, OK, USA

Abstract

Non-Point source (NPS) pollution from agriculture is a major environmental problem in the US. Adoption of Best Management Practices (BMPs) is one of the strategies to control NPS pollutions and improve water quality. The main objective of this study is to identify the most cost efficient livestock-crop-BMPs and grazing operations in the Five-Mile Creek watershed in southwestern Oklahoma to reduce sediment and phosphorous loads from agricultural fields. The Soil and Water Assessment Tool (SWAT) was used to model the watershed and generate crop yield, and sediment and phosphorous loads from 22 different crop-BMPs. A Linear Programming (LP) model was designed to evaluate the effectiveness of these crop-BMPs targeted at reducing the loads of sediment and phosphorus at the least cost possible. The LP model was used to determine the optimal crop-BMP in each field that would give maximum net farm income subject to different pollutant charges. The results indicated soil textures and slope classes where less erosive crops and/or no-till practices could replace conventional crops with the least amount of social cost (farm income reduction and/or public subsidy). It was noted that changes in relative input prices could reduce sediment and phosphorous loads by 11% (1,796 tons) and 6.5% (4.1 tons) respectively and increase producer’s income by 29% ($870,482) over the 2014 baseline. An additional 2,873 and 3,140 and 3,215 tons of field sediment loss could be prevented with charges of $100, $200, and $300 per ton of sediment respectively. The results show that continuous minimum till wheat remains the dominant crop in the study area until problems with continuous no-till wheat can be solved. Increased contour farming (wheat and cotton), increased no-till farming (cotton) and decreased no-till farming (wheat) would increase sediment abatement. Winter wheat as a cover crop or in rotation with cotton or grain sorghum would generate lower economic returns and some increase in sediment loads. The rotation of no-till wheat with canola especially with contour farming was economically viable while reducing sediment. Fine sandy loam soils are the targeted soils for changing tillage system of wheat to conservation or no-till and once the contour are the most effective solution, these changes should be implemented more on steep slope areas. The targeted soils for conversion of cotton to wheat are fine sandy and silty clay loam, which silty clay loam is the targeted soil once we want to plant wheat in rotation with canola and fine sandy loam is the targeted soil for conversion of cotton to wheat with conservation tillage.

Keywords: Non-Point source, best management practices, livestock operation, SWAT, linear programming, cost effectiveness, soil texture, slope

Introduction

Non-Point Source (NPS) pollutants are forms of diffuse pollution caused by nutrients, sediment, toxic and organic substances originating from particular land use activities such as agricultural activities. These occur over a wide area and carried to reservoirs, lakes and stream channels by surface runoff (Humenik et al., 1987). According to the United States Environmental Protection Agency (USEPA) (2016), almost half of the water bodies in the US are impaired by NPS pollution and sediment ranks fifth among the causes of water quality impairments. Agricultural activities that cause NPS pollution most usually occur from the lack of a proper management and conservation plan. Impacts can be generated from agricultural practices like plowing too often or at the wrong time, improper application of fertilizer, poorly located or managed animal feeding operations and manure, and overgrazing (USEPA, 2017). In rural catchments, the major sources of nutrients may include runoff from agricultural fields applied with fertilizer and manure, runoff from grazing fields with animal wastes associated with the erosion of sediments, and runoff from concentrated animal operations (Howry et al., 2008). Best Management Practices (BMPs) are effective and practical scenarios to control and reduce the transport of agricultural NPS pollutants to water bodies. Livestock management and grazing are also essential components in NPS pollution control in pasture intensive watersheds. In agricultural catchments with NPS pollution, preventing overgrazing with ensuring a livestock food supply is critical both environmentally and economically. Evaluating different crop-livestock/BMPs can help ensure the most effective allocation of funding for watershed management and water quality improvement. The cost effective selection and location of crop-livestock/BMPs can aid in increasing both the efficiency of public funds and the total income of farmers and producers.

The Upper Washita River basin in southwestern of Oklahoma, US contains critical pollution and sustainability problems. The Fort Cobb Reservoir (FCR) watershed located in this basin is largely an agricultural catchment, an area with high rates of wheat and cattle production (mainly cow-calf and stocker operations). Cattle and stocker production use both cropland pasture, planted pasture and range lands in this watershed (Starks et al., 2014). The primary land uses of this watershed are crop agriculture and rangeland. Wheat is the major crop and is heavily grazed by stocker cattle in the winter months (Osei, 2016). Sustainable cattle and stocker production require an ensured twelve month food supply which is especially critical during the winter months. On the other hand, since sediment and phosphorus lost from grazed pastures and cropland pasture, such as wheat pasture, all contribute to NPS, at the watershed level. There should be a balance between crop-animal production, and sediment and phosphorous reduction.

Most of this watershed has been terraced for several years. However, additional BMPs (such as no-tillage and cropland to grassland conversion) have been implemented in the watershed to improve water quality. The water quality still does not meet the water quality standards as given in the Clean

Water Act. In spite of the already implemented BMPs, studies are still needed for selection and placement of additional cost-efficient crop/agricultural BMPs and grazing systems to reduce sediment and phosphorous load in the watershed.

There are several studies that have investigated the least-cost mix, location, and magnitude of grazing management practices to reduce phosphorus loading in different watersheds (Ancev, 2003, Machooka, 2007, Marumo, 2007). Also, there are several studies on FCR watershed to improve water quality and control NPS pollution, without considering grazing operations and rotation of crops (Storm et al., 2003, 2006; Moriasi et al., 2007, 2008; Osei et al., 2012; Mittelstet, 2015). However, none of these studies have directly assessed the cost-effectiveness of adding additional BMPs to the existing BMPs. Since one of the goals of this research is to identify the placement of conservation practices, it is important to identify the placement of existing conservation practices to prevent reoffering them and assess other scenarios instead. Meanwhile, installing these practices requires high capital investment. Their presence will affect the optimal selection and placement of additional BMPs. This study builds to improve and extend previous studies on this watershed by developing different agricultural management practices and land uses for reducing sediment and phosphorus loading from Five Mile Creek area of FCR watershed at least cost to the society with consideration of existing conservation practices in the study area.

The no-till wheat cropping system was a highly recommended crop-BMP in this catchment (Osei et al., 2012). No-till farming leaves a ground cover that can hold moisture in the soil and protect soil against soil and rain erosion. However no-till wheat production has been shown to result in decreased yield over time (Decker et al., 2009; Patrignani et al., 2012). Some of the reasons causing the limitation of continuous of no-till winter wheat farming are weed and disease cycles associated with wheat production (Edwards et al., 2006). Several researchers have studied no-till farming and its effect on runoff, NPS pollution and crop yield (Choi et al., 2016; Osei et al., 2012), however there is limited research on rotation and double cropping of winter wheat with other viable crops to solve the problems related to continuous no-till winter wheat farming. Osei et al. (2012) assessed the effects of no-till systems on crop yield in farm-level economics and compared with other tillage systems for wheat production in FCR watershed. They indicated that if winter wheat grain yields are not significantly impacted by tillage systems, no-till would be more profitable than conventional reduced tillage or the current mix of tillage practices in the watershed. In their study they did not address diseases resulted from continuous no-till winter wheat farming and rotation of this crop with other crops was not addressed to solve this issue. In this study, the result of several possible crop-livestock/BMPs has been evaluated using the Soil and Water Assessment Tool (SWAT).

There are no effective laws regarding the amount of sediment or nutrients that leave the producer's land in the US. Thus any reduction in these items may be viewed as a cost by the producers. The principal approach in the US toward control of NPS pollutions from agricultural fields has been to subsidize adoption of BMPs or provide funds for land retirement and crop rotation, rather than taxing inputs such as nitrogen and fertilizer (Shortle and Horan, 2001). Since all conservation practices may not improve the profitability of enterprises at the farm level, the government is the main source of funding for soil and water conservation (Wang and Berman, 2014). Different economic incentives are required at the local level to incentivize conservation practice adoption (Osmond et al., 2012; Ribaudo, 2015; Carlisle, 2016). Tong et al. (2016), Camboni and Napier (1993), Dobbs and Pretty (2004), and Shortle et al. (2012) agree in the assertion that the current incentive system in FCR watershed needs restructuring to provide appropriate, effective and attractive incentives to both producers and non-farming/absentee landowners. The end goal of this research is to define more specific incentive payment programs for producers and landowners to adopt the most cost effective BMPs. To this end, the shadow prices from the LP solutions will be used to define more specific incentive payment programs for landowners and producers to adopt the most cost effective BMPs.

The main goal of this study is to identify crop-livestock BMPs that would be the most profitable to cattle and agricultural producers while reducing cost to the society because of sediment and phosphorous abatements. For this, different combinations of crops, livestock, and agricultural management practices including grazing schedule were simulated in a hydrological model (SWAT). The simulation results then were analyzed to get the optimal land use, optimal conservation practices, and optimal number of cattle supported in this region with appropriate grazing schedule using the LP model. One of the specific objectives of this study is to estimate impact of different soil types and slope classes on economics of crop-BMP choices, crop rotation, and grazing operation management.

Methods and data

Study area

The Fort Cobb Reservoir (FCR) watershed located in southwestern Oklahoma, US, in the Upper Washita sub-basin with an area of 813 km2, is an agricultural watershed. Land in the FCR watershed is comprised of highly erosive, fine sandy loam soils, which even under natural conditions contribute to erosion, sediment loading, stream bank and channel instability (OCC, 2009). The water quality of the Fort Cobb reservoir in southwestern Oklahoma and its tributaries (Cobb Creek, Lake Creek, Willow Creek, and Five-Mile Creek) has been of concern for more than two decades, with water quality problems first identified in 1981. Recently, several BMPs have been implemented in the watershed (such as no-till crop production methods and conversion of cropland to grassland) to improve water quality. The continued sedimentation in the FCR, despite previous conservation practices, demonstrates the need to expand adoption of both privately and publically funded BMPs. In this study, a SWAT model has been constructed and combined with Linear Programing to evaluate the most ecological feasible and cost effective crop-livestock BMPs in just Five Mile Creek (FMC) (grey basin) area of FCR watershed. However the only available USGS gage station (Figure 1) receives runoff from both the Cobb Creek and FMC sub-watersheds. Therefore, the SWAT model was constructed for the larger area above this station (red basin in Figure 1) containing of the Cobb Creek and FMC and only the FMC portion is used in the later analysis. FMC has an area of 113.05 km2 and is composed of predominately cropland (50%), pastureland (44%), and others (6%) (NASS-USDA, 2014). Historically, peanuts and cotton were major crops but in recent years many of these fields have been transitioned to winter wheat farming and pastureland. In 2014, 30% of the watershed was in winter wheat, 15.6% of the area was in cotton (irrigated 12.1%, dry 3.5%), and 1.5% of the watershed area was in grain sorghum.

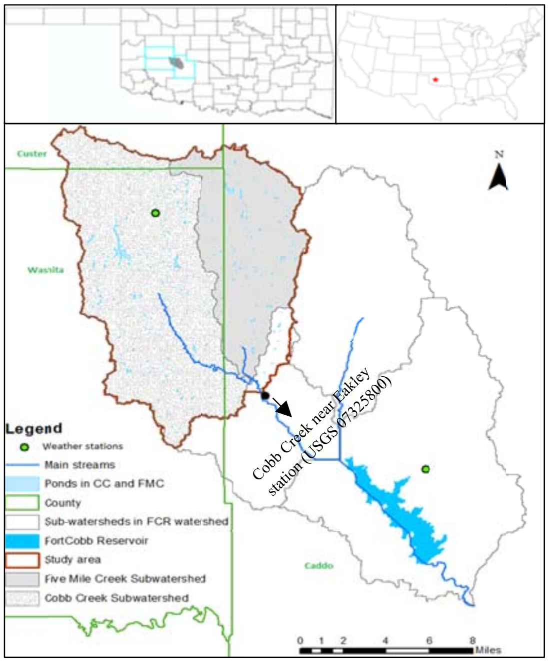


Figure 1. Five-Mile Creek (FMC) watershed located within the Fort Cobb Reservoir watershed (FCR)

Figure 2 describes area studies through the hydrological modeling and optimization for placement and selection of crops and agricultural BMPs and cattle grazing in the watershed.

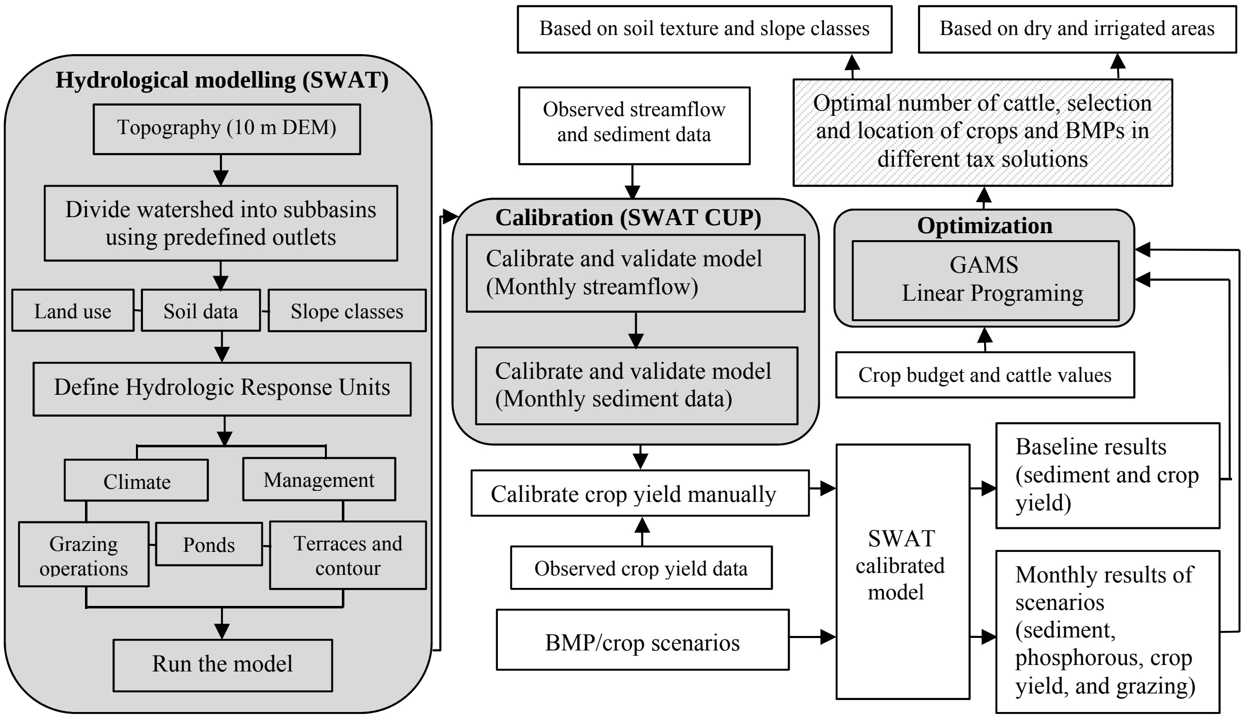


Figure 2. Schematic representation of optimal control model

Hydrological model

The Soil and Water Assessment Tool (SWAT) (Arnold, 1995) was used to model the western portion of the FCR watershed (see Figure 1) in western Oklahoma. The model was calibrated and verified both manually and automatically for monthly streamflow, sediment, and annual yield of winter wheat, cotton, grain sorghum, and pasture. A 10-m USGS Digital Elevation Model (DEM) was used to delineate the watershed boundary. The gage station (USGS 07325800) was used as the watershed outlet. Then the delineated watershed was divided into 43 sub-basins with an average sub-basin area of 8 km^2 (min. 0.2 km^2−max. 28 km^2). The Soil Survey Geographic Database- SSURGO soil data, the US Department of Agriculture crop layer and the USGS elevation-slope information were overlaid to produce 15,217 polygons which constitute unique combinations of soil, land use and slope. These are called hydrologic response units (HRUs). In SWAT, an HRU is the finest scale of measurement, and therefore routings of water, nutrients, and sediments are calculated at HRU level and aggregated to the sub-basin and finally to the watershed level. Therefore, a large number of HRUs, at the expense of computational efficiency, were generated to understand the detailed effects of different conservation practices in a crop-pasture intensive watershed in rural Oklahoma. Two weather stations (C349422 and C341504) from the United States Department of Agriculture (USDA) Agricultural Research Service (ARS) (https://datagateway.nrcs.usda.gov/) were used to characterize current climate and drive model simulations. Major water body (lakes, ponds and wetlands) data were collected from the U.S. Army Corps of Engineers National Inventory of Dams (NID) (USDA, 2009). Also USGS 7.5-minute quad maps were used. There were a total of 320 waterbodies in the study area with an average area of 0.055 km^2 draining 62.9 km^2 of the study area. The characteristics associated with these waterbodies were calculated following Mittelstet et al. (2015). The average depth of the ponds was assumed to be two meters given that these waterbodies are shallow and mostly used for livestock. The drainage area of each waterbody was assumed to be 30 times of the surface area of the waterbody as suggested by Whitis (2002). Information related to fertilizer use and management practices (Appendix 1) for the selected crops were incorporated as observed in the study area between 1982–2015 while developing the model prior to model calibration (Storm et al, 2006). Garbrecht and Starks (2009) stated that 80%-90% of cropland in FCR watershed that needed terraces has been terraced over the last 50 years. Aerial pictures were used to distinguish the exact placement of existing terraces and contour. There were several places where terraces and contour have been broken and appeared to make the erosion problem worse. The broken terraces were recognized using 2-meter Lidar drainage lines and treated as being un-terraced in the model. HRUs where more than 65% of the area was terraced and contour farmed were classified as being terraced with contour farming. The effects of terraces and contour were simulated by modifying runoff and erosion parameters for slope length, the SCS runoff curve number (CN), and USLE practice factor. These parameters can be adjusted based on the land slope suggested by SWAT documents (Table 1).

Table 1. USLE-P value used for contour farming, strip cropping and terracing

Land Slope %	USLE-P		
	Contour farming	**Strip cropping**	**Terracing**
1 to 2	0.6	0.3	0.12
3 to 5	0.5	0.25	0.1
6 to 8	0.5	0.25	0.1
9 to 12	0.6	0.3	0.12
13 to 16	0.7	0.35	0.14
17 to 20	0.8	0.40	0.16
21 to 25	0.9	0.45	0.18

Source: SWAT 2012 User's guide (Winchell et al., 2013)

Hydrological model calibration and validation

The SWAT model was calibrated and validated for streamflow, sediment, and crop yield. First, the SWAT Calibration and Uncertainty Procedures (SWAT-CUP) (Abbaspour, 2011) was employed to automate model sensitivity, parameterization and validation using the observed streamflow data. Seventeen parameters related to streamflow were used to carry out model parametrization (Table 2). To calibrate the model, a 10-year (1991–2000) monthly streamflow observations dataset, recorded at the USGS gauge station (USGS 07325800) was used. The model performance was determined using three statistical measures: coefficient of determination (R^2), Nash-Sutcliffe efficiency (ENS), and percentage bias (PB). The values of R^2 (0.64), ENS (0.61), and PB (5%) in the calibration period (Figure 3) were deemed to be satisfactory as suggested by other SWAT-based studies (Moriasi et al., 2015). The model was validated by comparing the USGS observations with SWAT simulated streamflow data for a different time period (2001–2010) and found reasonable model performance (R^2 = 0.79; ENS = 0.62; PB = -15%) as shown in Figure 4.

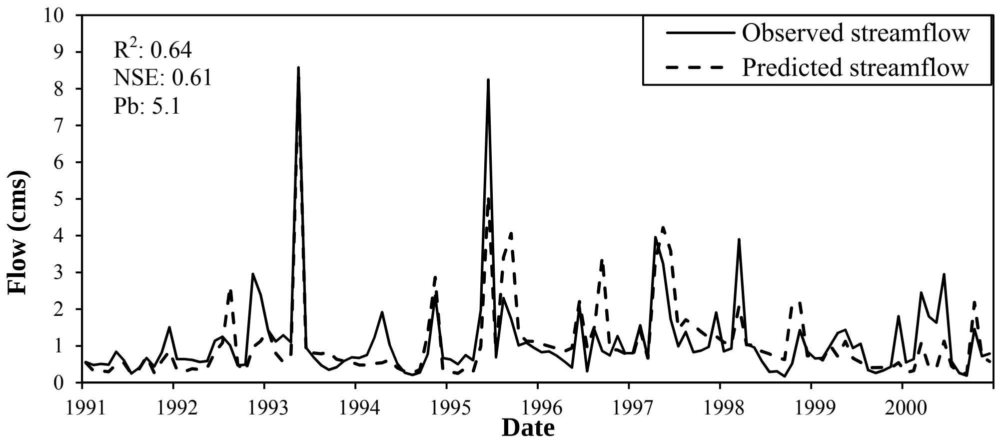


Figure 3. Observed and calibrated SWAT simulated streamflow at Cobb Creek near Eakley, OK (1991-2000)

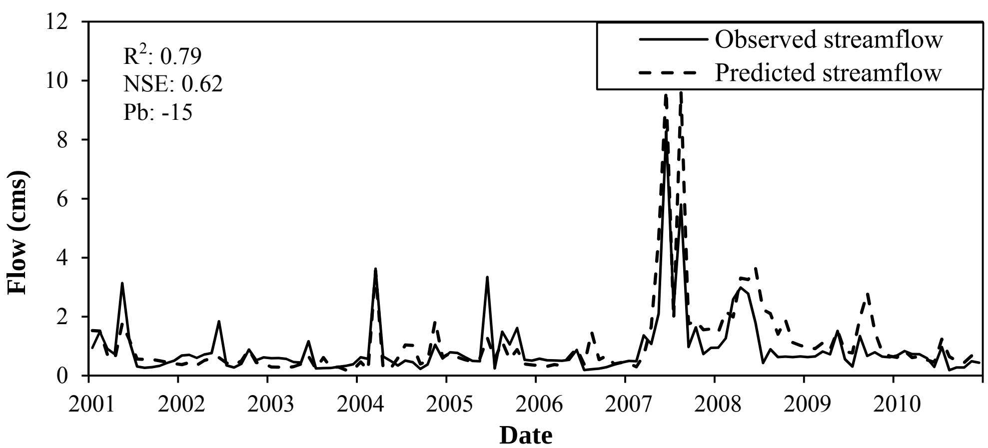


Figure 4. Validation time series for observed and SWAT predicted flow at the Cobb Creek near Eakley, OK (2001 to 2010)

Suspended sediment was calibrated for ten years, (1991–2000) and validated for another ten years, (2001–2010) at the watershed outlet. The grab sample data that were available from 2004 to 2012 (usually 1 to 3 samples per month with a few months missing) were used along with stream flow date to estimate sediment loads for days when when daily stream flow measurements were available. A double log regression between the observed streamflow and measured sediment data was estimated. This method has been used to generate sediment information for missing periods in many studies (Jothiprakash and Grag, 2009; Salimi et al., 2013; Sarkar et al., 2008; Shabani, 2012; Gray and Simoes, 2008). There was a strong correlation (R^2=0.9) between the observed grab sample sediment data and runoff in the study watershed (Figure 5). Therefore this regression relationship was used to estimate the missing daily sediment data for the model simulation period.

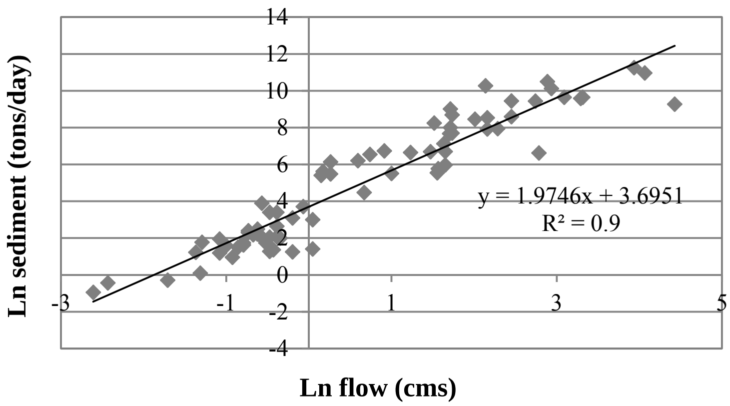


Figure 5. Observed daily discharge and observed daily suspended sediment concentration trend at the Cobb Creek near Eakley, OK

Table 2. Streamflow and sediment calibration parameter values in study area

Component	Parameter	Parameter value range	Final value
Streamflow	V__GWQMN.gw	0.20_0.60	0.60
	V__GW_REVAP.gw	0.02_0.03	0.02
	V__REVAPMN.gw	0.50_1.50	1.38
	V__RCHRG_DP.gw	0.10_0.50	0.47
	V__GW_DELAY.gw	320_390	376
	R__CN2.mgt	-0.16_-0.13	-0.13
	V__ALPHA_BF.gw	0.80_1.00	0.95
	V__ESCO.hru	0.80_0.90	0.83
	V__EPCO.bsn	0.10_0.60	0.30
	V__CH_K1.sub	0.00_0.40	0.09
	V__SURLAG.bsn	0.50_4.00	3.05
	V__EVRCH.bsn	0.00_0.50	0.34
	V__TRNSRCH.bsn	0.00_0.10	0.10
	V__ALPHA_BNK.rte	0.60_1.00	0.84
	R__SOL_AWC(..).sol	-0.02_0.06	0.04
	V__CH_N2.rte	0.05_0.30	0.18
	V__CH_K2.rte	1.85_2.15	1.98
Sediment	R__USLE_P.mgt	-1.000_0.000	-0.240
	R__SLSUBBSN.hru	0.000_0.230	0.217

R__USLE_K().sol	-0.500_0.300	-0.247
V__RSDCO.bsn	0.010_0.100	0.083
V__BIOMIX.mgt	0.000_0.300	0.297
V__SPCON.bsn	0.000_1.000	0.009
V__SPEXP.bsn	1.000_2.000	1.714
V__CH_ERODMO(..).rte	0.050_0.700	0.355
V__CH_COV1.rte	0.001_0.800	0.518
V__CH_COV2.rte	0.001_0.800	0.332

Note: "R" before the parameter name stands for relative change (the parameter is multiplied by 1+value); "V" stands for replacement (the parameter is replaced by a value within the range)

Despite the use of only grab sample sediment data filled in by daily regression estimates of sediment loads based on the daily flow, the model was successfully calibrated for monthly sediment loads by modifying ten parameters that were related to sediment transport (Storm et al., 2006; Moriasi et al., 2008) (Table 2). The model calibration with values of R^2 (0.30), MNSE (0.35) and Pbias (20%), (Figure 6) and validation with values of R^2 (0.33), MNSE (0.43) and Pbias (53%) (Figure 7) was considered acceptable. It was found that the largest error in sediment prediction was associated with errors of peak flow estimation. It could be due to the "second storm effect" prone to hydrological models including SWAT (Abbaspour et al. 2007). The first storm event causes a larger sediment transport and makes remaining surface layers difficult to mobilize. As a result, the second and third storm events, regardless of their event sizes, result in smaller sediment loads. For this study area, the "second storm effect" was not tested since there were no observed sediment data representing flood events (May 1993, June 1995, June 2007) during model calibration-validation period. The simulated sediment data failed to accurately capture these events, resulting uncertainty in sediment calibration. The over-and under-estimation of sediment during flood events was reported in other SWAT based studies (Oeurng et al., 2011).

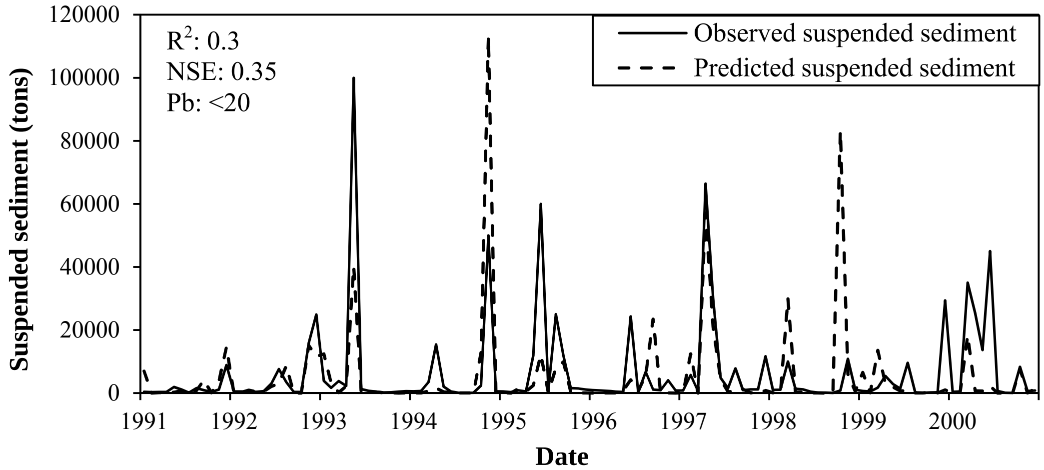


Figure 6. Observed and calibrated SWAT simulated suspended sediment concentration at Cobb Creek near Eakley, OK (1991-2000)

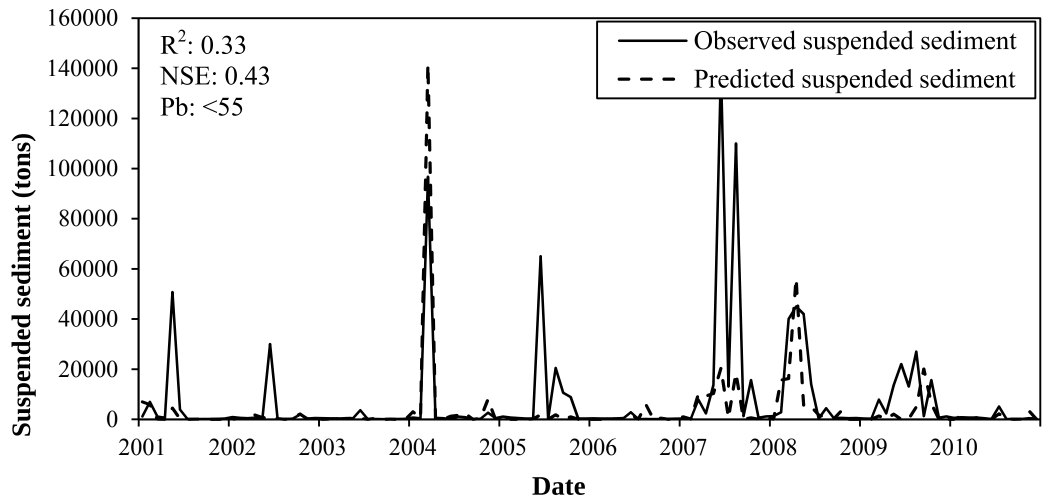


Figure 7. Observed and validated SWAT simulated suspended sediment concentration at Cobb Creek near Eakley, OK (2001-2010)

Crop yield and biomass production affect watershed hydrology through altered erosion and water balance (Hu et al. 2007; Ng et al. 2010a; Andersson et al. 2011; Nair et al. 2011). A combination of the OSU variety trial data from 2001 to 2016 (http://croptrials.okstate.edu/), and the county level NASS data (1986–2005) were used to calibrate yield of three different crops (winter wheat, grain sorghum, cotton- both dryland and irrigated) (USDA-NASS, 1986 to 2005, http://digitalprairie.ok.gov/cdm/ref/collection/stgovpub/id/11177). The variety trial crop yields were collected from sites in seven counties (Apache, El Reno, Homestead, Chickasha, Altus, Tipton, and Thomas) that are located within and nearby the study area. A list of crop yield parameters with their initial and calibrated values is provided in Appendix 2, 3. In this study the coefficient of determination (R) was used as an indicator to compare the SWAT simulated crop yields with the observed yields. The values of R for cotton, grain sorghum and winter wheat, grain sorghum, and cotton were 0.4, 0.32 and 0.61 respectively which are deemed satisfactory as reported by other studies.

Based on the previous research in this area, the average yields of hay, alfalfa, rye, native pasture, and Bermuda grass yields in the study area were held constant at 2,000, 3,000, 3,000, 1,500, and 6,500 kg/ha respectively. When used with the adjusted parameters for these crops, lead to satisfactory results.

Crop-BMP scenarios

In this study, five conservation practices were considered for three mains crops (winter wheat, cotton, and grain sorghum) and cropland conversion to pasture. Table 3 shows the explanation of each scenario.

Table 3. Crop-BMP Scenarios

No.	Conservation practice	Explanation	Abbreviation for different crops in different BMPs		
			Winter wheat	Grain sorghum	Cotton
1	Conservation tillage	The conservation tillage system was considered for all crops except hay and alfalfa	**WhCv**	**GRSG**	**CtCv**
2	Conservation tillage in combination with contour farming	The contour conservation tillage was used following the operations-crop calendars for all crops except hay and alfalfa	**WhCC**	**GSCC**	**CtCC**
3	No-Till farming non-contour cropping	No-till was simulated in regular crop calendars for all crops except hay and alfalfa*: - Cotton no-till was simulated in irrigated areas with wheat as a cover crop - Wheat no-till was simulated in rotations/cover crop with canola, cotton, and grain sorghum	In rotation with grain sorghum: **WGNS** In rotation with cotton: **WCNS** In rotation with Canola: **WKNS**	**GSNS**	**CtNS** (notill irrigate cotton covered with wheat: **CNWc**)
4	No-Till farming on the contour	It is the combination of two management practices (no-till and contour farming).	In rotation with grain sorghum: **WGNC** In rotation with cotton: **WCNC** In rotation with Canola: **WKNC**	**GSNC**	**CtNC**
5	Conversion crop lands to pasture (Bermuda grass)	replaces all crop land uses (except hay and alfalfa) into Bermuda grass pasture**	Grazing starts in May, bio-min: 1200 kg **BERM1-1** Grazing starts in Jun, bio-min: 1200 kg **BERM2-1**	Grazing starts in July , bio-min: 1200 kg **BERM3-1** Grazing starts in May, bio-min: 1600 kg **BERM1-2**	Grazing starts in Jun, bio-min: 1600 kg **BERM2-2** Grazing starts in July, bio-min: 1600 kg **BERM3-2**

*Note: Continuous no-till wheat is not really feasible because of weed and disease problems and was replaced by rotations of wheat with canola and as cover crop for cotton and grain sorghum.
**According to the result of a meeting with Nolan (2017), Caddo and Grady counties agent, producers are having success in cropland conversion to Bermuda grass in the FCR watershed. So, this scenario has been divided to 6 scenarios which includes different stocking rate by changing BIO_MIN and starting grazing time has been considered.

Optimization

In this study Linear Programing (LP) was used as an optimization method in the General Algebraic Modeling System (GAMS), to find the most cost effective selection and location of livestock-crop-BMPs in agricultural fields. LP is one of the mathematical programming techniques for achieving the best outcome (in our case maximum profit or lowest cost) subjects a set of linear requirements on the use of land, water and other resources. The objective function was to maximize net revenue per hectare based on crops produced and livestock supported by changing agricultural management practices subject to constraints on sediment and phosphorous. Hence, the objective function had two parts; maximizing producer's income and minimizing public charge which is based on constraints on sediment and phosphorous losses. The producer's income was calculated using crop yield, crop price, value of livestock, and costs of production. The public cost is from the charge on total sediment and/or phosphorous loss. Constraints on sediment and phosphorous in the LP model are implemented as taxes which are used to calculate subsidies from government to producers. Constraints are considered in different tax scenarios to estimate different incentive programs from government.

The optimization model is stated mathematically as shown:

$$Maximize\ revenue = \sum_{s=1}^{S}\left[\sum_{h=1}^{H}\sum_{i=1}^{I}\sum_{k=1}^{K}\left((P_i.Y_{shik}) - C_{shik}\right)\times X_{ik} + V_{Cu}Cu_s - \sum_{m=1}^{12} Fh_{sm}\,.Chay\right] - SED_{tot}\times Schg - Ph_{tot}\times Pchg \quad (1)$$

Subject to:

$$\sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{h=1}^{H}\sum_{i=1}^{I} SED_{shik}\times X_{ik} = SED_{tot} \quad (2)$$

$$\sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{h=1}^{H}\sum_{i=1}^{I} Ph_{shik}\times X_{ik} = Ph_{tot} \quad (3)$$

$$\sum_{k=1}^{K}\sum_{i=1}^{I} X_{ik} \le Ta_{sh} \qquad \text{for all sub-basins, HRUs and k} \quad (4)$$

$X_{ik} \geq 0$ (5)

Cattle feed balance for each month in each sub-basin:

$$\left[\sum_{h=1}^{H}\sum_{i=1}^{I} DMg_{shikm}.X_{ik}\right] + Fh_{sm} \geq DMc_{sm}.Cu_s \tag{6}$$

$$\left[\sum_{h=1}^{H} Yhay.X_{ik}\right] \geq \sum_{m=1}^{12} Fh_{sm} \tag{7}$$

Where:

s: Sub-basin, h: HRU, i: crop, K: BMP

P_i: Price of pasture and Crop_i

Y_{shik}: Yield of pasture and Crop_i on HRU_h with BMP_k on one hectare in subbasin_s

C_{shik}: Total Cost to produce pasture and Crop_i on HRU_h with BMP_k on one hectare in subbasin_s

X_{ik}: The number of hectares of pasture and Crop_i with BMP_k on one hectare

V_{Cu}: The value of cow unit

Cu_s: Number of cow herd animal units

Fh_{sm}: Fed hay in subbains_s in month m on one hectare in subbasin_s

$Chay$: Cost of hay

SED_{shik}: Sediment runoff from HRU_h with pasture and Crop_i and BMP_k on one hectare in subbasin_s

Ph_{shik}: Phosphorous runoff from HRU_h with pasture and Crop_i and BMP_k on one hectare in subbasin_s

Ta_{sh}: Total acres in HRU_h

DMg_{shikm}: Grazed out dry matter

DMc_{sm}: Dry matter required per cow unit in a month_m in subbasin_s

$Yhay$: Yield of hay

SED_{tot}: Total amount of sediment leaving HURs in the watershed

Schg: Charge or tax on each ton of sediment leaving fields in the watershed

Ph_{tot}: Total amount of phosphorous leaving HRUs in the watershed

Pchg: Charge on each kg of phosphorus leaving fields in the watershed

Each crop-BMP was simulated separately in a SWAT run. The mean HRU specific values for crop yield, phosphorus, and sediment loads for each livestock-crop-BMP obtained from the SWAT simulations were used as coefficients in the LP model described above.

The principal approach in the US toward control of NPS pollutions from agricultural fields has been to subsidize adoption of BMPs or provide funds for land retirement and crop rotation, rather than taxing inputs such as nitrogen and fertilizer (Shortle and Horan, 2001). In this regard, the charges of $100, $200, and $300 per ton of sediment and $300 per ton of phosphorous (bold numbers in Table 4) were applied in the LP model to reduce the sediment and phosphorous loads. Theoretically, these charges or shadow prices in the LP model could be considered as government subsidies paid to farmers to adapt the optimal crop-livestock-BMPs.

One of the objectives of this research is to define more specific incentive payment programs for producers and landowners to adopt the most cost effective BMPs. Therefore, different charges on sediment and phosphorous loads were defined to evaluate the impacts of charges or subsidies on sediment and phosphorous abatement rates. Table 4 shows alternative charges used in LP optimization to determine the amount of phosphorus and or sediment that could be abated.

Table 4. Charges ($) used for alternative sediment and phosphorous abatement in the FMC

	a	b	**c**	d	e	a	b	**c**	d	e	a	b	**c**	d	e
Sediment ($/tons)	100	100	**100**	100	100	200	200	**200**	200	200	300	300	**300**	300	300
Phosphorous ($/ton)	0	100	**300**	600	1000	0	100	**300**	600	1000	0	100	**300**	600	1000

Crop budget and crop price

The OSU Enterprise Budgets tool (Sahs and Doye, 2017) was used to estimate the basic quantities and management costs included costs of seed, fertilizer, custom harvest, pesticide, harvest aids, crop insurance, annual operating capital, machinery labor, machinery fuel, irrigation costs for the study area. The management costs were generated with the Machsel program and the Oklahoma State University's enterprise budget generating software, developed by Kletke and Sestak (Kletke and Sestak, 1991). Average crop prices obtained from the Oklahoma Agricultural Statistics 2010-2017 are shown in Table 5.

The average costs ($/hectare) for each management practice (contour farming, conservation tillage, and no-tillage) in Oklahoma were obtained from Oklahoma Enterprise Budgets for 2017 (Doye et al., 2004) and are shown in Tables 6 and 7. The net revenue from the Cow calf enterprise was estimated to be $520 per cow unit.

Table 5. Average net returns per acre, using (2011 - 2016) Oklahoma crop prices and 2017 OSU budget costs

Crop	Alfalfa	Bermuda	Canola	Corn	Cotton	Grain Sorghum	Hay	Rye	Soybean	Winter Wheat
Price ($/unit ton)	203.67	88.69	461.65	216.21	1525.6	201.68	88.69	88.69	424.76	248.68

Table 6. Management cost ($/hectare) for three major crops in the study area

Crop	**Conservation tillage**		**Conservation tillage+Contour**		**No-till**		**Contour+No-till**	
	Dry	**Irrigated**	**Dry**	**Irrigated**	**Dry**	**Irrigated**	**Dry**	**Irrigated**
Cotton	754.0	1,612.0	798.1	1,721.0	769.7	1,612.5	779.4	1,690.3
Grain Sorghum	308.5	422.2	327.4	441.8	383.2	401.9	399.8	418.6
Winter Wheat	355.2	365.3	372.7	383.9	341.8	352.8	354.0	335.2

Table 7. Management cost ($/hectare) for rotation of wheat and canola in the study area

Rotation straight row		**Rotation contour farming**	
Dryland		**Irrigated**	
Canola	Wheat	Canola	Wheat
388.3	350.1	407.5	367.3

Results

A livestock-crop-BMP Linear Programming model was designed to identify the most cost-effective crop-livestock-BMPs and their locations in the study area. All 22 crop-BMPs were simulated in each cropland HRU in the study area. The SWAT simulated results of crop yield, sediment and phosphorous loads in each HRU were combined with the crop price, management cost, and monthly feed balances for livestock. Then, the LP model was used to estimate producer's income along with sediment and phosphors loads under two scenarios: market solution and tax solution (pollutant charges). In market solution, no charge was considered for sediment and phosphorous loads, which means just producer's benefits were considered without environmental aspects consideration. In the tax solution, the charges of \$100, \$200, and \$300 per ton of sediment leaving the field were considered in the way that maximizes the producer's income with sediment and phosphorous constraints. The charge on each ton of phosphorus leaving the field was \$300 per ton of phosphorous. At the end, the impact of other different combination of taxes on sediment and phosphorous abatement was discussed.

Baseline

In the baseline scenario and other scenarios a minimum of 40.1% of the FMC watershed area was in permanent pasture. In the baseline, 30% of the area (3,388 ha) was in wheat, and 15.6% of the area (1,766 ha) was in cotton. Irrigated cotton occupied 12% of the FMC watershed area. Using the average SWAT crop yields, the OSU budget costs, and average prices received by Oklahoma farmers (2011- 2016), the net revenue for the FMC watershed was estimated to be \$3,026,795. At the outlet of watershed, there were 16,513 tons of sediment and 69 tons of phosphorous from all above fields. Some 52% of the area planted to cotton (irrigated and dryland) was on land with 0–2% slope. Only 8% of the cotton was planted on land with more than a six percent slope. Thirty percent of grain sorghum was planted on land with a 0–2% slope. More than half of the wheat was planted on lands with 0–2% slope, 26% was planted on land with a 2–4% slope, while 20% was planted on land with more than a four percent slope. Forty percent of the pasture was on land with more than six percent slope.

Market solution

This solution estimates changes in crops and BMPs that have incentives for adoption because of changes in market prices. Table 8 shows the land use with their associated BMPs in this economic scenario and its comparison with the baseline scenario.

Table 8. Comparison of hectares of each crop in market solution and baseline scenarios in the Five-Mile Creek watershed

Land use	Rye	Canola	Soybean	Grain sorghum	Wheat			Cotton	
				GRSG	WhCv	WKNC	WKNS	CtCv	Irrigated Cotton
Market solution	2.8	1107.7	1.5	3.1	3597.1	227.0	877.7	1012.9	8.9
Baseline	71.3	373.6	43.6	92.8	3387.7	-	-	398.5	1367.1

In the market solution scenario, 42% of the area was wheat, and 9% was cotton. Since the native pasture area modified by the model, the area of pasture remains constant except for possible conversion of cropland to Bermuda grass pasture. The data showed that with average 2010–2016 market prices, the optimal crop choice, from among the conventional crops and added BMPs, would increase net revenue (producer's income) in the watershed by 29% over the conventional crops in the baseline solution ($870,482). The market choice of crops and BMPs also reduced total sediment and phosphorous loads at the outlet of watershed by 11% and 6.5% respectively from the baseline. Changes in relative input prices have increased returns from no-till methods relative to conventional reduced tillage methods. There were 1,341 cow units in the study area. This is about 1 cow unit for each 7 ha of land rangelands. The rate of monthly fed hay using livestock is in Figure 8.

Comparison of market solution with baseline:

The results of comparison between baseline and market solution are shown in Figure 9. According to the results of market solution, the optimal area of rye and soybean decreased by 96% and 96% from the baseline respectively and canola increased by 104% from the baseline. There was a 100% decrease in the grain sorghum area from the baseline. There was also a 28% increase in wheat from the baseline scenario. Twenty-two percent of the wheat was planted using non-contour conservation tillage, 19% with rotation with canola with non-contour no-till, 5% with rotation with canola with contour no-till, and 54% was planted with conservation tillage in the market solution. The area for all cotton (irrigated and dryland) declined 42.6% from the baseline. However, the areas of dryland cotton with conventional reduced tillage increased by 133.5% while the irrigated cotton area decreased by 99%.

Tax solution

This solution is presenting the most cost efficient crop-BMPs first with \$100/ton sediment and \$300/ton phosphorous charges on edge of field loss and then present results for \$200 and \$300/ton of sediment charge. Table 8 shows the land use with their associated BMPs in this tax solution scenario and its comparison with the baseline and market solution scenarios.

Table 8. Comparison of hectares of crop-BMP choices between the baseline, market, and $100 sediment tax scenarios for the Five-Mile Creek watershed

Land use	**Rye**	**Canola**	**Soybean**	**Grain sorghum**	**Wheat**				**Cotton**		
				GRSG	**WhCv**	**WhCC**	**WKNC**	**WKNS**	**CtCv**	**Irrigated Cotton**	**CtNC**
Tax solution	3	761	1.5	3	3484	1278	698	60	79	0.5	124
Market solution	3	1108	1.5	3	3597	-	227	878	1013	9	-
Baseline	71	374	44	93	3388	-	-	-	398	1367	-

In this scenario, as compared to the baseline, the area in wheat increased from 30% to 49%. The area in cotton declined from nearly 16% to only 2%. The uncompensated or market value of net revenue after tax of selected crops and BMPs declined to $2,701,050 or 10% less than the baseline ($3,026,795). However with the compensation to adopt the BMPs, the compensated producer's income would be ($3,899,777) or 29% more than baseline. The sediment and phosphorous loads at the outlet of watershed were 28% and 24% lower respectively than the baseline, and 19.5% and 18.3% lower than the market solution. Table 9 shows the new crop-BMPs and the associated crops that were converted to them in tax solution scenario.

Table 9. New crop-BMP scenarios in tax solution

New crop-BMP	**CtCv		**CtNC			**WhCC			
Area (ha)	69.6		124.1			1277.7			
Baseline crop	Wheat	Other*	Wheat	Dryland cotton	Other*	Wheat	Cotton Irrigated	Cotton Dryland	Other*
Area (ha)	59.3	10.3	100.4	8	15.4	933	153	59.6	132

New crop-BMP	**WhCv			**WKNC			
Area (ha)	1232.5			698.2			
Baseline crop	Cotton Irrigated	Cotton Dryland	Other*	Cotton Irrigated	Cotton Dryland	Wheat	Other*
Area (ha)	515.3	318.3	398.8	638.2	2.9	43.3	15.8

*Note: Other means canola, rye, and grain sorghum
**CtCv means cotton with non-contour conservation tillage, CtNC means cotton with contour no-till farming, WhCC means wheat with contour conservation tillage, WhCv means wheat with non-contour conservation tillage, and WKNC means wheat in rotation with canola with contour no-till farming.

Table 9 shows there was some shifting between crops and production practices. The total area in cotton declined from 15.6% in the baseline to 1.7 % of the total watershed area. The percent of the watershed area in no-till contour cotton was (CtNC) (1.1%) and 0.6 % of that was in in non-contour conservation tillage cotton (CtCv) (0.6%). The total area in wheat increased from 30% in the baseline to 5,520 hectares or 48.8 % of the total watershed area. Wheat with contour conservation tillage (WhCC) (11.3%), and wheat with non-contour conservation tillage (WhCv) (10.9%), non-contour no-till wheat in rotation with canola (WKNS) (0.5%) and contour no-till wheat in rotation with canola (WKNC) (6.2%) were new crop-BMPs that have been suggested to be implemented as additional strategies to abate 28% of sediment and 24% of phosphorous loads from agricultural lands. Eighty-one percent of CtNC was from conversion of wheat, 8.2% from canola, 6.6% from dryland cotton, and 4.2% from rye and grain sorghum conversion to CtNC. Eighty five percent of CtCv was from conversion of wheat, 8.8% from canola, and 6.0% from rye and grain sorghum conversion to CtCv. Seventy three percent of WhCC was from conversion of wheat with conventional reduced tillage, 12% from irrigated cotton, 5.8% from canola, 4.7% from dryland cotton, and 4.5% from rye and grain sorghum conversion to WhCC. Forty two percent of WhCv was from conversion of irrigated cotton, 25.8% from dryland cotton, 22.4% from canola, 3.6% from grain sorghum, and 6.4% from rye and soybean conversion to WhCv. Ninety-two percent of WKNC was from conversion of irrigated cotton, 6% was from wheat with non-contour conservation tillage, and other was from grain sorghum and rye conversion. 100% of WKNS was from conversion of irrigated cotton.

For these new conservation strategies, it was found that 80% of cotton (CtNC) would be planted on the almost flat areas with slopes from 2-4%, while the non-contour conservation tillage (CtCv), 100% was limited to fields with a 0-2% slope. Ninety-three percent of continuous contour conservation tillage wheat (WhCC) was planted on steeper slopes, soils with more than four percent slope, which shows for wheat with contour conservation tillage it was better crop to be planted on with 0-4% slopes. Most of the no-till wheat-canola, (WKNC) (60 %) was planted on soils with a with a 0-2% slope, 24% was planted on lands with 2-4% slope, 11% on lands with 4-6% slope, and 5% on lands with more than six percent slope.

The number of cow-units with the $100 sediment tax solution declined to 958 units. This is about 1 cow unit for each 11 ha of land rangelands. The rate of hay fed monthly to livestock is in Figure 8.

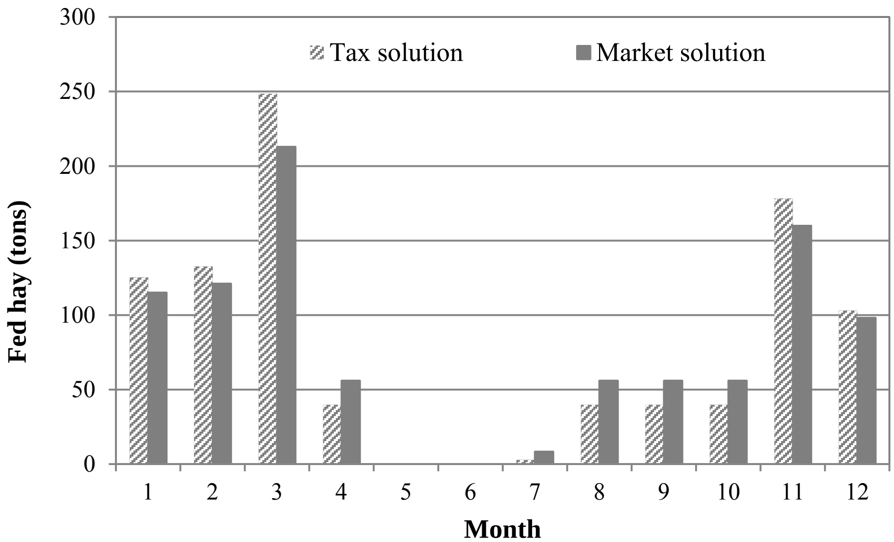


Figure 8. Comparison of monthly average quantities of hay fed in Five-Mile Creek watershed between the market and $100 per ton of sediment charge scenario

According to Figure 8, March and November were the months where the maximum quantity of hay was fed to livestock. It means that in these months there was not enough grazing to support the number of cattle, so the feeding of harvested hay is required. In May, June, and July all feed is supplied by grazing.

Comparison of baseline and tax solution:

Table 10 shows the changes in the hectares of the main crops in the FMC watershed to different crop-BMPs by soil texture and slope class. The results of tax solution indicated that grain sorghum, rye, and soybean decreased 97%, 96%, and 96% from the baseline respectively and canola increased by 196% from the baseline. Results indicated that for a 28% and 24% increase in sediment and phosphorous abatement, wheat should increase by 63% (2,132 hectares) from the baseline. Thirty-six percent of the wheat would be planted on contour, 14% of wheat would be in rotation with canola, and some 92% of the wheat-canola would be planted on the contour. According to Table 10, 97% of conversion of wheat to CtCv was on lands with FS soil texture with a slope of two percent or less. However, there were also some smaller areas converted from conventional wheat to cotton. Nearly 60 ha of conventional wheat on FS soils with slopes of 2% or less were switched to conventional cotton. Another 94 hectares of conventional wheat on FS soils with slopes of 2-6 % were converted to no-till contour cotton. Five hundred hectares of the conventional tilled wheat were converted to contour-conservation tillage on FS and FSL soils with slopes of 4% or more. Conversion to wheat with contour conservation tillage was on FSL soil texture which 50% of it was on land with more than six percent slope. Also, 100% of wheat to WKNC was on lands with FSL soils, and 50% of that was on land with 2-4% slopes.

For the cotton, there was an 88.5% decrease in the total cotton area (irrigated and dry). All of the irrigated cotton in the baseline solution was replaced by wheat. Meanwhile, 61% of the dryland cotton was planted with a no-till contour system and 39% was planted with non-contour conservation tillage. Forty-seven percent of irrigated cotton was converted to no-till contour wheat in rotation with canola. Forty percent of the irrigated cotton was converted to wheat with non-contour conservation tillage system (WhCv) and 13% was planted to wheat with contour conservation tillage (WhCC). Fifty-five percent of irrigated cotton converted to WhCv was on FSL soils with slopes of two percent of less. Forty-five percent of the irrigated cotton that was converted to WKNS was on SICL soils where the slope was 2% or less. For dryland cotton, 96% of that converted to CtNC was on FS soils with slopes of 4 % or less. Forty-five percent of the dryland cotton converted to WhCC was on FSL soils with 2-4% slopes. Forty-nine percent of dryland cotton converted to WhCv was on SICl soils, 77% of which had slopes of 2 % or less. All the dryland cotton converted to WKNC was on FSL soils. Some 58% of these soils had 4-6% slopes. All the grain sorghum converted to cotton was on FS soils. Ninety-one percent of this area had slopes of four percent or less. Grain sorghum on FSL soils that was converted to wheat was mainly on land with more than a four percent slope. All conversion of grain sorghum to WKNC was on lands with a FSL soil texture and 4-6% slopes. Figure 9 shows the area of each land use in baseline (2014), market solution, and tax solution scenarios.

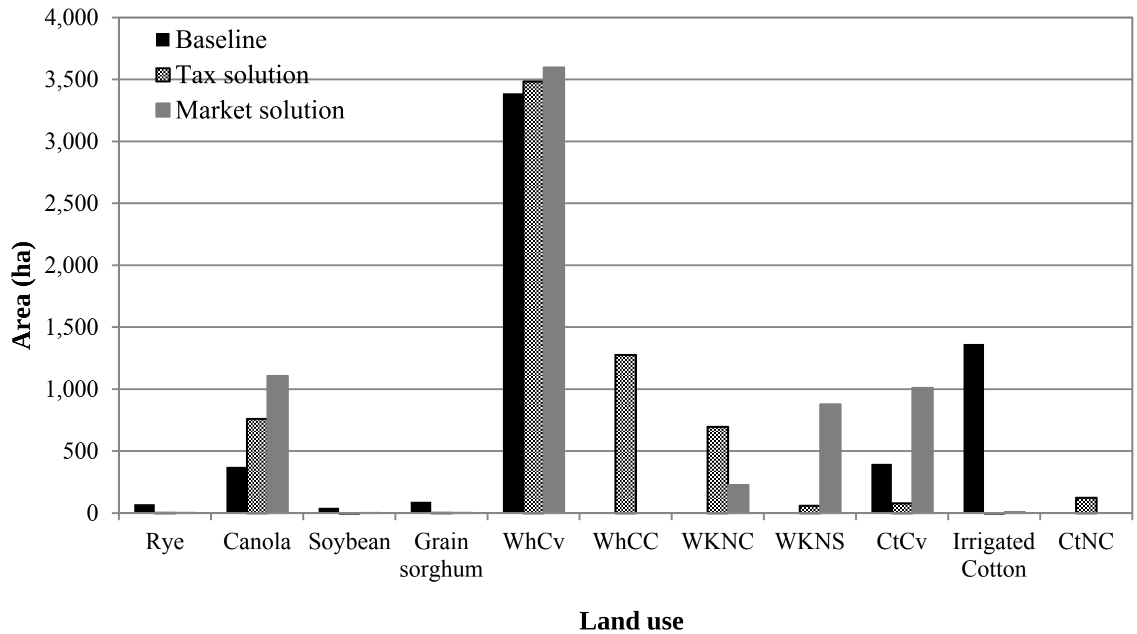


Figure 9. Land use variation in baseline and LP solutions

The results show that continuous minimum till wheat remains the dominant crop in the FMC area (until problems with continuous no-till wheat can be solved). Simulations with winter wheat as a cover crop or double crop in rotation with cotton or grain sorghum gave lower economic returns and some increase in erosion, but rotation of no-till wheat with canola especially with contour farming was economically viable.

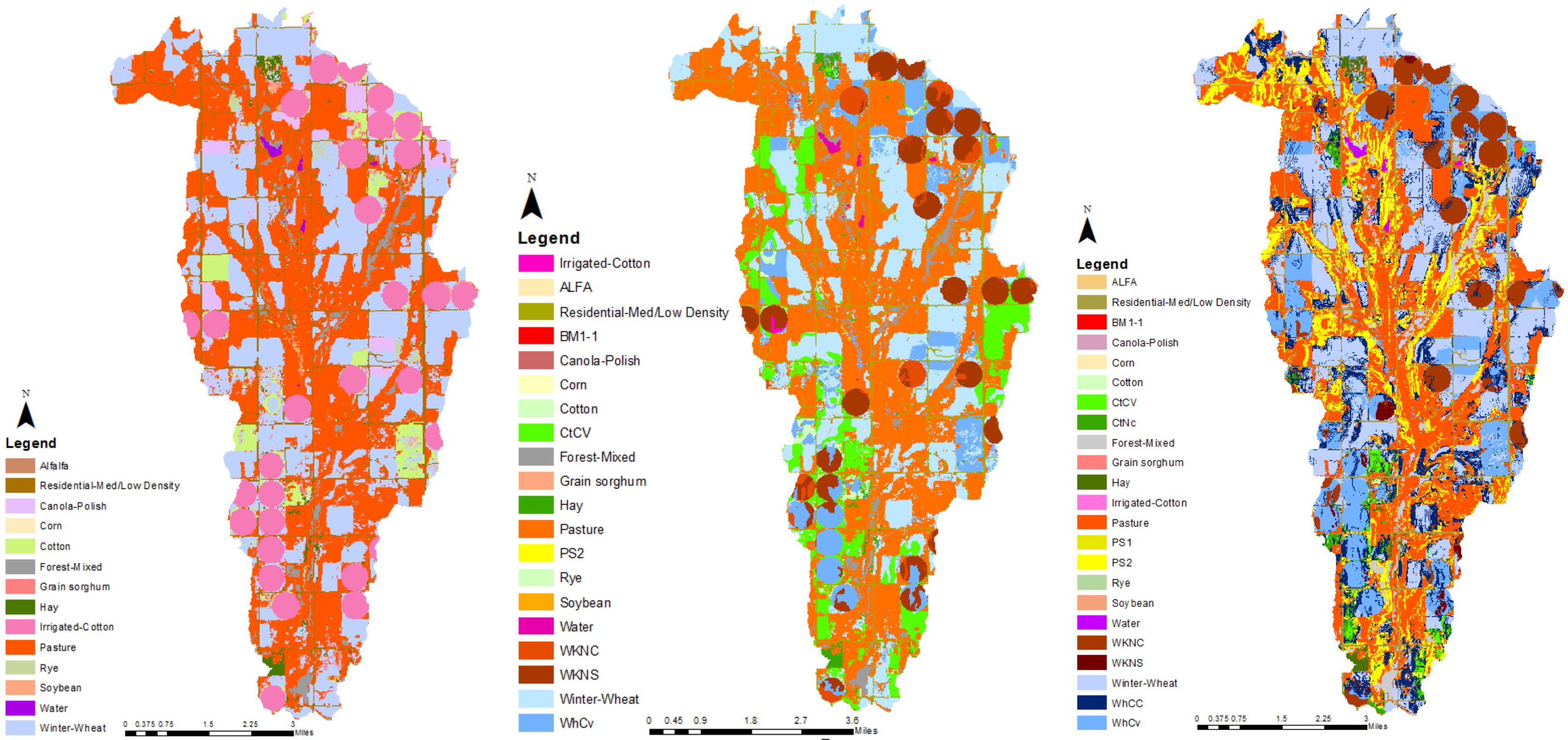
According to Figure 9, wheat was dominate (both economically and environmentally) crop. Osei (2016) applied three conservation practices in the FCR watershed to find the optimal distribution of conservation practices and indicated that no-till winter wheat production in central Oklahoma lead to a small cost reduction while maintaining yields and was the win-win option. But since continuous no-till wheat is not possible because of weeds and other disease, it is not a good choice for adoption. He also indicated that although conversion to pasture entails a significant cost to farmers, it resulted in substantial and consistent reductions in all environmental indicators (runoff volumes and sediment and nutrient losses). However it was not economical and efficient strategy in our results.

Figure 10 shows the crop-BMP distribution in the FMC area of FCR watershed in baseline, market solution, and tax solution for different sediment and phosphorous abatement scenarios. Figure 13-b illustrates optimal crop-BMPs for 11% sediment and 6.5% phosphorous abatement (Market solution). Figure 13-c illustrates optimal crop-BMPs for 28% sediment and 24% phosphorous abatement (tax solution).

Table 10. Areas of baseline crops conversion to different crop-BMPs based on soil texture and land slope in tax solution scenario

Soil texture	**Slope (%)**	**Conversion of irrigated cotton to**				**Conversion of dryland cotton to**				**Conversion of grain sorghum to**					**Conversion of conventional wheat to**			
		WhCC	WhCv	WKNC	WKNS	CtNC	WhCC	WhCv	WKNC	CtCv	CtNC	WhCC	WhCv	WKNC	CtCv	CtNC	WhCC	WKNC
CL	Total							2.5					0.1				0.1	
	0-2							2.1					0.1					
	2-4							0.4										
	4-6																0.1	
	>6																	
FS	Total	55.7	185.9		20.3	7.7	11.0	6.9		3.5	4.1	7.2	2.2	0.5	**57.7**	**94.4**	124.8	0.1
	0-2		86.3		11.7			2.4		3.5			0.9		57.7			
	2-4		86.6		8.6	7.1		4.6		0.1	3.7		1.3			79.1		
	4-6	27.8	13.0			0.6	4.7				0.4	3.3				15.3	52.3	
	>6	28.0					6.3					3.9		0.5			72.5	0.1
FSL	Total	65.5	**283.9**	41.6	12.9		**27.1**	58.1	2.9			**16.6**	13.9	**2.2**	1.2		**442.1**	**43.2**
	0-2		172.2	8.5	4.3			24.8	0.1				5.5		1.2			4.5
	2-4		101.5	6.1	4.7			29.2	0.9				8.1				62.3	21.6
	4-6	31.2	7.4	13.6	1.6		16.4	2.3	1.7			5.8	0.3	2.2			171.8	13.9
	>6	34.3	2.8	13.4	2.3		10.7	1.9	0.3			10.9					208.0	3.2
LFS	Total	11.4	45.5				2.4	9.9				0.3	0.8		0.5		14.9	
	0-2		28.4					4.1					0.6		0.5			
	2-4		16.7					5.8					0.3					
	4-6	6.9	0.4				2.1					0.1					8.4	
	>6	4.5					0.3					0.2					6.5	
SICL	Total	0.9		**443.4**	**27.0**	0.3	8.1	**155.1**				3.0	**19.5**			6.0	69.1	
	0-2			344.0	27.0	0.3		118.6					13.4			5.2		
	2-4			80.3				34.4					6.1			0.8		
	4-6			14.7			6.0	1.8				2.2					50.1	
	>6	0.9		4.4			2.2	0.3				0.8					19.1	
SIL	Total	19.5		134.9			10.4	82.3				7.3	7.3				199.7	
	0-2			61.4				38.0					3.1					
	2-4			49.8				30.2					3.7				3.8	
	4-6			23.7			6.9	10.0				3.5	0.4				102.1	
	>6	19.5					3.5	4.0				3.8					93.7	
VFSL	Total			18.3			0.7	3.4				0.5	0.5				82.4	
	0-2			4.4				1.9					0.2					
	2-4			5.9			0.3	0.9				0.1	0.3				24.1	
	4-6			3.4			0.2	0.6				0.2					26.8	
	>6			4.6			0.1	0.1				0.2					31.5	

*Note: CL is clay loam, FS and FSL are fine sandy loam, LFS is loamy fine sand, SICL is silty clay loam, SIL is silt, and VFSL is very fine sandy loam.



a) Baseline land use

b) Optimal crop-BMPs for 11% sediment and 6.5% phosphorous reduction

c) Optimal crop-BMPs for 28% sediment and 24% phosphorous reduction

Figure 10. FMC crop-BMP map in the baseline, market, and $100/ton of sediment charge scenarios

Different sediment charge scenarios

Table 11 shows the comparison of sediment, phosphorous, net revenue, producer's compensated income, and producer's compensation subsidy for baseline, market solution, and \$100, \$200, and \$300 per ton of sediment charge and \$300 per ton of phosphorous charge. According to results, an additional 2,873 and 3,140 and 3,215 tons of field sediment loss could be prevented for \$100, \$200, and \$300 per ton of sediment respectively. Figure 11 shows the area of main crops in different scenarios.

Table 11. Net revenue, sediment, and phosphorous variation in baseline, market, and different sediment charge scenarios

Scenarios			**Net revenue (uncompensated income) ($)**	**Tax cost (producer's compensation subsidy) ($)**	**Producer's income (compensated income) ($)**	**Sediment (ton)**	**Phosphorous (kg)**
Baseline			3,026,795	_	_	16,513	62,572
Market solution			3,879,895	_	_	14,717	58,510
Tax solution	**\$100/ton of sediment, \$300/ton of phosphorous**	**Tax solution (100)**	2,689,002	1,198,728	3,887,730	11,844	47,779
	\$200/ton of sediment, \$300/ton of phosphorous	**Tax solution (200)**	1,581,240	2,329,489	3,910,730	11,577	46,807
	\$300/ton of sediment, \$300/ton of phosphorous	**Tax solution (300)**	484,229	3,464,499	3,948,728	11,502	46,330

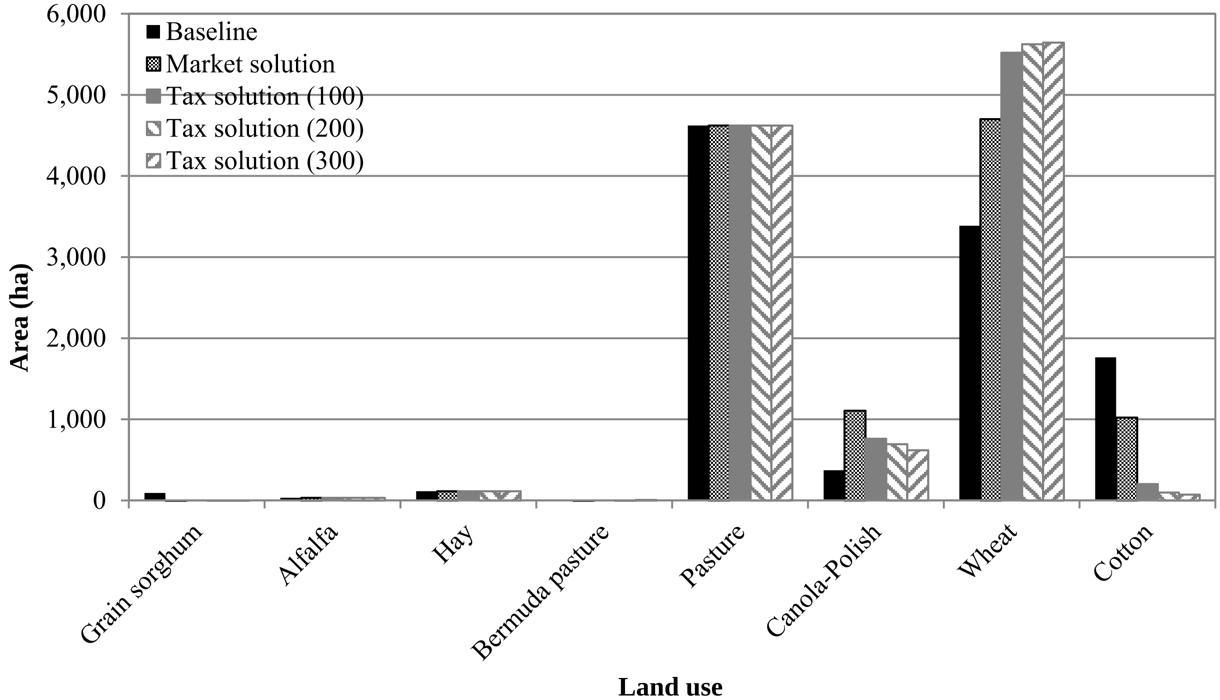


Figure 11. Land use variation in baseline, market solution and LP solutions for $300/ton of phosphorous charge and three different sediment charge scenarios

The main point of Figure11 is that by increasing charge for sediment the wheat area increased from the baseline to the market solution and the $100/ton of sediment charge. However, there was only a slight increase in the wheat area with the $200 and $300 per ton of sediment charge solutions. Meanwhile, by increasing charge for sediment the cotton area decreased from the baseline through the market and tax solutions. The percentage of the area in cotton declined from 15.6% in baseline to 9.0%, 1.8%, 0.9%, and 0.7% in market and $100, $200, and $300/ton of sediment charge solutions. Also, by increasing the charge, there were 8.6 hectares of crop conversion to Bermuda grass, which 100% of this conversion was from wheat with conventional reduced tillage conversion to Bermuda grass. Meanwhile, by increasing sediment and phosphorous abatement, cotton with conventional tillage in dryland in removing and cotton with no-till covered with wheat is becoming better choice.

Table 12 shows the change of cropping system (tillage and contour farming) for cotton and wheat in baseline, market solution, and different sediment charge scenarios.

Table 12. Change of cropping system (tillage and contour farming) for cotton and wheat in baseline, market solution, and different tax solution scenarios

Scenario	**Area (ha)**		**Area (%)**		**Contour farming**		**No-till**	
	Wheat	Cotton	Wheat	Cotton	For wheat (% of total wheat)	For Cotton (% of total cotton)	For wheat (in rotation) (% of total wheat)	For cotton (% of total cotton)
Baseline	3,387.7	1,765.6	30.0	15.6	-	-	-	-
Market solution	4,701.8	1,021.8	41.6	9.0	4.8	-	23.5	0.0
Tax solution 100	5,519.8	203.9	48.8	1.8	35.8	60.9	13.7	60.9
Tax solution 200	5,624.7	98.2	49.8	0.9	54.3	89.5	12.4	93.1
Tax solution 300	5,644.7	74.0	49.9	0.7	56.8	86.8	11.0	98.5

According to the results, by increasing the sediment charge, contour farming was increased for wheat and cotton, but no-till was decreased for wheat and increased for cotton. The reason for decreased no-till farming for wheat was that its rotation with other crops which makes it expensive and also erosive.

Results of different tax scenarios

This part presents results of different combination of tax (Table 4) for both sediment and phosphorous charges. The phosphorous charges considered were; a. $0; b. $100; c. $300; d. $600; and e. $1000 per ton on three scenarios of sediment charge; $100, $200, and $300 per ton (Table 4). Graph 12 and 13 show changes in phosphorous and sediment reduction with changes in costs. Figure 12 shows the cost to remove on additional 2-3 tons of phosphorous at each sediment charge.

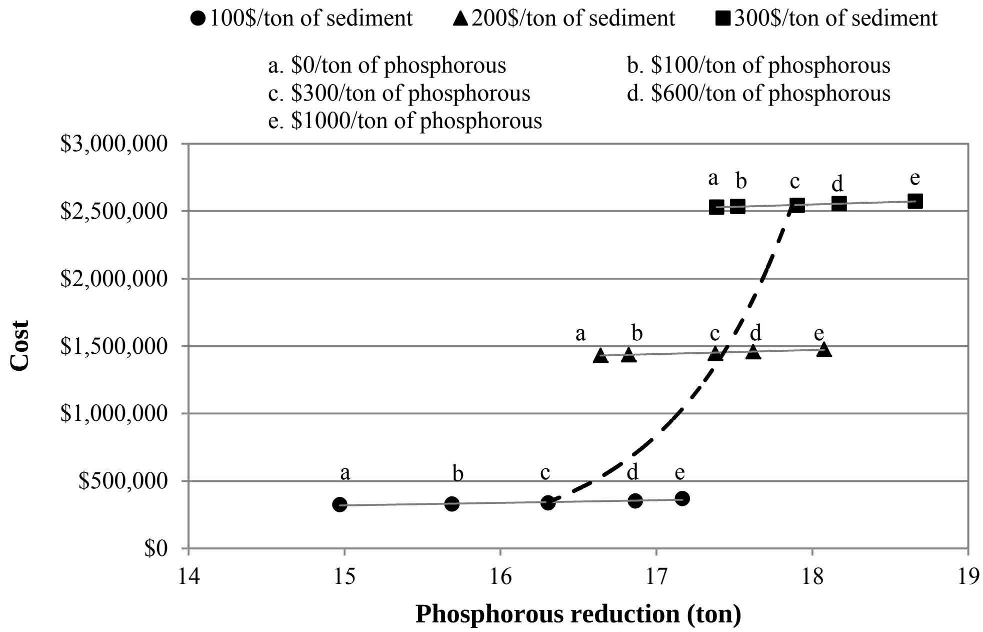


Figure 12. Variation of cost with changing phosphorous abatement rates

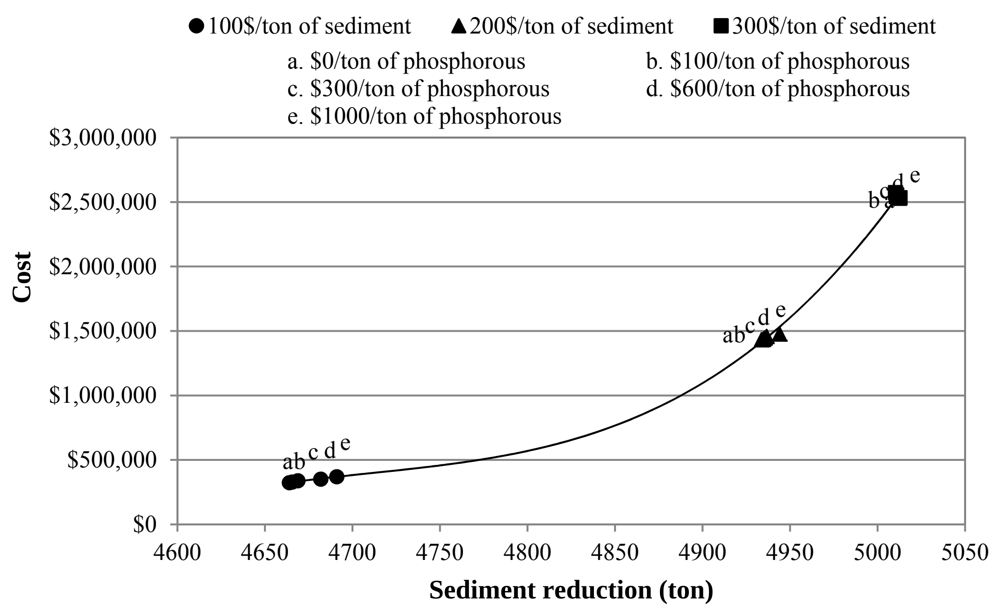


Figure 13. Variation of cost with changing sediment abatement rates

With increasing sediment and phosphorous abatement, total abatement cost was increased. It means that while BMPs can reduce sediment and phosphorous, pollution reduction will be costly to producers. Thus, reduced pollution probably will require some type of government intervention and incentive programs. The other point is that concentrating on phosphorous reduction only was not changing crop system much and was not effective solution. Since much of the phosphorous is attached to the sediment, so concentrating on sediment will affect phosphorous as well. This result could be seen in the number of livestock in different tax solutions (Figure 14). The number of livestock varied by 10 head or less when the sediment tax was held constant and only the tax rate on phosphorus was varied. However, the number of livestock declined as the charge on sediment was increased from $100 to $300 per ton.

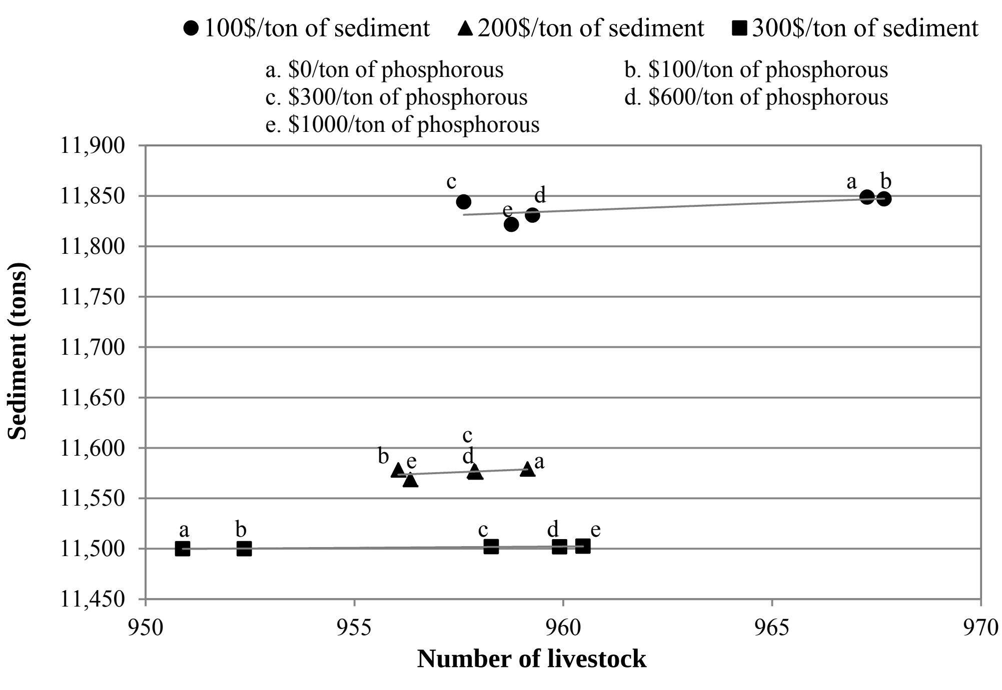


Figure 14. Livestock numbers and their associated sediment rate

Conclusion

Twenty two crop-livestock/BMP combinations, including no-till and conservation practices with contour and non-contour farming on grain sorghum, cotton, and winter wheat were simulated in 5,750 HRUs of FMC area of FCR watershed to estimate the most cost efficient crop-BMP and number of supported livestock with their associated grazing operation in each HRU with considering existing BMPs in the watershed. Since no-till wheat is a common suggested crop-BMP that can reduce sediment and phosphorous effectively and since the continuous no-till wheat is not possible because of weeds and diseases problems, no-till wheat was considered as cover crop for grain sorghum and cotton and in rotation with canola. The conversion of cropland to Bermuda grass because of substantial and consistent reductions in all environmental indicators was one of the other conservation practices considered in this study. Average crop yield, sediment, and phosphorous loads and grazing amount from each HRU were estimated under each scenario using SWAT and fed into LP written in GAMS. At the end, the soil textures and slope that should be targeted was determined.

It was noted that market changes could reduce field losses of sediment and phosphorous by 1,796 and 4.1 tons respectively over the 2014 baseline cropping pattern. An additional 2,873 and 3,140 and 3,215 tons of field sediment loss could be prevented for \$100, \$200, and \$300 per ton of sediment respectively. By maximizing net revenue with considering \$100/ton of sediment and \$300/ton of phosphorous, sediment decreased 28% and phosphorous decreased 24% compare to the current land use with existing BMPs in the watershed. In this scenario, producer's income increased 29%, but net revenue totally decreased 29%. According to this solution, most of the new strategies for replacement of row crops with new conservation practices are wheat with contour and non-contour conservation tillage, no-till wheat in rotation with canola and no-till cotton with contour farming. The results show that continuous minimum till wheat remains the dominant crop in the FMC area (until problems with continuous no-till wheat can be solved). Also, by increasing sediment abatement, contour farming is increased for wheat and cotton, but not-till is decreased for wheat and increased for cotton. This was because simulations with winter wheat as a cover crop or double crop in rotation with cotton or grain sorghum gave lower economic returns and some increase in erosion, but rotation of no-till wheat with canola especially with contour farming was economically viable.

The number of livestock varied by 10 head or less. They also increased by 10 head or less with increasing tax for sediment reduction. March and November were the months where the maximum quantity of hay was fed to livestock. It means that in these months there was not enough grazing to support the number of cattle, so the feeding of harvested hay is required. In May, June, and July all feed is supplied by grazing.

Fine sandy loam soils are the targeted soils for changing tillage system of wheat to conservation or no-till and once the contour tillage are the most effective solution, these changes should be implemented more on steep slope areas. For cotton the targeted soils for conversion of cotton to wheat were the fine sandy and silty clay loams. The silty clay loam soil, where wheat in rotation with canola, had a comparative advantage. Fine sandy loam was targeted soil for conversion of cotton to wheat with conservation tillage. Again contour was the selected on the steep slopes.

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Appendix

Appendix 1. Conventional (reduced) tillage for dryland crops and pasture

Crop	Date	Operation
Cotton	1.1	Tillage operation (Disk Plow Ge23ft)
	3.15	Tillage operation (Disk Plow Ge23ft)
	5.15	Tillage operation (Springtooth Harrow Ge15ft)
	6.1	Tillage operation (Finishing Harrow Lt15ft) Pesticide Operation (Pendimehalin, 0.25 kg)
	6.10	Fertilizer application (Elemental Nitrogen, 50 kg)
	6.11	Plant
	7.1	Tillage operation (Row Cultivator Ge15ft)
	11.15	Harvest and kill
Pasture	1.1	Plant
	3.1	Auto fertilization
	5.1	Grazing operation (Beef-Fresh Manure, GRZ_DAYS*: 180, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Winter wheat	3.15	Fertilizer application (Elemental Nitrogen, 80 kg)
	6.1	Harvest and kill
	7.1	Tillage operation (Chisel Plow Gt15ft)
	8.1	Tillage operation (Offset Dis/heavduty Ge19ft)
	9.20	Fertilizer application (Elemental Nitrogen, 80 kg) (Elemental Phosphorus, 35 kg)
	9.22	Tillage operation (Disk Plow Ge23ft)
	9.24	Tillage operation (Springtooth Harrow Lt15ft)
	9.25	Plant
	12.1	Grazing operation (GRZ_DAYS*: 90, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)
Grain sorghum	5.1	Plant
	5.27	Fertilizer application (Elemental Nitrogen, 150 kg)
	5.28	Tillage operation (Springtooth Harrow Ge15ft, Disk Plow Ge23ft, Mecoprop Amine, 125), Pesticide Operation (Mecoprop Amine, 125 kg)
	10.18	Tillage operation (Disk Plow Ge23ft)
	10.20	Tillage operation (Springtooth Harrow Ge15ft)
	10.30	Harvest and kill
Alfalfa	4.1	Harvest only
	5.15	Harvest only
	7.1	Harvest only
	8.29	Fertilizer application (Elemental Nitrogen, 50 kg), (Elemental Phosphorous, 20)
	9.7	Plant
	10.15	Harvest only
Hay	4.1	Harvest only
	7.1	Harvest only
	8.29	Auto fertilization
	9.7	Plant
	10.15	Harvest only
Rye	6.10	Harvest only
	8.10	Fertilizer application (Elemental Nitrogen, 80 kg), (Elemental Phosphorous, 35)
	9.20	Plant

	9.15	Grazing operation (GRZ_DAYS*: 150, BIO_EAT*: 3, BIO_TRMP*: 0.47, MANURE_KG*: 1.5)

*AUTO_NSTRS: Nitrogen stress factor of cover/plant triggers fertilization. This factor ranges from 0.0 to 1.0 where 0.0 indicates there is no growth of the plant due to nitrogen stress and 1.0 indicates there4 is no reduction of plant growth due to nitrogen stress.
*GRZ_DAYS: Number of consecutive days grazing takes place in the HRU
*BIO_EAT: dry weight of biomass consumed daily ((kg/ha)/day)
* BIO_TRMP: dry weight of biomass trampled daily ((kg/ha)/day)
*MANURE_KG: dry weight of manure deposited daily ((kg/ha)/day)

Appendix 2. Cotton yield calibration parameters

Parameter	Parameter definition	Default value	Calibrated value
BIO_E [(kg/ha)/(MJ/m^2)]	Radiation use efficiency or biomass energy ratio	15	14
USLE_C	Minimum value of USLE C factor for water erosion	0.2	0.1
HVSTI [(kg/ha)/(kg/ha)]	Harvest index for optimal growing season	0.4	0.3
OV_N	Manning's "n" value for overland flow	0.14	0.12
BLAI (m^2/m^2)	Maximum potential leaf area index	4	3
FRGRW1(fraction)	Fraction of plant growing season to the first point on the optimal leaf area development curve	0.15	0.14
FRGRW2 (fraction)	Fraction of plant growing season to the second point on the optimal leaf area development curve	0.5	0.3
LAIMX1 (fraction)	Fraction maximum leaf area index to the first point on the optimal leaf area development curve	0.01	0.005
CNYLD (kg N/kg seed)	Normal fraction of nitrogen in yield	0.015	0.018
CPYLD (kg P/kg seed)	Normal fraction of Phosphorus in yield	0.0025	0.0027

Appendix 3. Wheat, pasture, and grain sorghum yield calibration parameters

Parameter	Winter wheat		Pasture		Grain sorghum	
	Default value	Calibrated value	Default value	Calibrated value	Default value	Calibrated value
BIO_E [(kg/ha)/(MJ/m^2)]	30	29	35	28	33.5	37
USLE_C	0.03	0.02	0.003	0.003	0.2	0.2
HVSTI [(kg/ha)/(kg/ha)]	0.4	0.3	0.8	0.8	0.45	0.3
OV_N	0.14	0.12	0.3	0.25	0.14	0.12
BLAI (m^2/m^2)	4	3	4	2.5	3	4.5
FRGRW1(fraction)	0.05	0.03	0.05	0.03	0.15	0.15
FRGRW2 (fraction)	0.45	0.35	0.49	0.35	0.5	0.5
LAIMX1 (fraction)	0.05	0.03	0.05	0.03	0.05	0.05
CNYLD (kg N/kg seed)	0.025	0.02	0.0234	0.0134	0.0199	0.02
CPYLD (kg P/kg seed)	0.0022	0.0018	0.0033	0.0022	0.0044	0.0032

CHAPTER VII

LIMITATION OF STUDY AND FUTURE RESEARCH

Limitation of study

There are some technical and theoretical limitations to this study, which most of them come from both the SWAT and the economic models. Although SWAT is a reliable modeling tool, there are many assumptions and uncertainties especially in calibration and validation process. One of the points that contributed to the uncertainty about the calibration process was that the SWAT model can be constructed based on one year of landuse data (2014). SWAT was then calibrated for ten years and validated for the next ten years. Of course, there are landuse changes during these time periods and the model was calibrated based on just one year landuse data. The second point in making uncertainty in calibration process for sediment was use of bi-weekly grab sample data which was used to generate daily sediment data for use observed data in the calibration and validation process. Other reasons could be dispersed nature of the sediment data and poor accuracy of the measured data. However, the largest error in sediment prediction was associated with errors of peak flow estimation. The second storm effect problem in the hydrological model could not be tested in calibration process since there were no observed sediment data representing flood events (May 1993, June 1995, June 2007) during the model calibration-validation period. It is assumed the first storm event caused a larger sediment transport and made the remaining surface layers more difficult to mobilize. As a result, the second and third storm events regardless of their event sizes would result in smaller sediment loads. The simulated sediment data failed to accurately capture these events, resulting in uncertainty in sediment calibration. The over-and under-estimation of sediment during flood events has been reported in other SWAT based studies (Oeurng et al., 2011). Because of the same problems in sediment calibration process, phosphorous could not be calibrated and just the simulated phosphorous data were compared to the observed phosphorous data to be sure that SWAT phosphorous outputs are reasonable.

One of the other limitations of this study was about the weakness of SWAT in process of calculating crop yield once there is rotation of two crops with no-till farming. In no-till farming there is a problem of crop resistance to the diseases from using herbicides and pesticides. One of the limitations of this study was that in the modeling part using SWAT, this resistance was not considered in crop yield calculation. One of the other assumptions was related to phosphorous calculation process. The model assumed that harvested hay was not consumed in the farms and the phosphorous loss from consuming harvested hay was not added to the phosphorous leaving from fields.

The economic model had some limitations due to the assumption of profit maximization, which may not always be an appropriate assumption for the real world. For example, the changes in relative crop prices or proven yields and crop insurance rates will also affect producers' ability to change crops. Time did not allow for an analysis of the effect of alternative crop process on BMP adoption.

Future research

There are several areas of this dissertation where further research is needed. One of the areas needing more consideration is impact of drought and even severe floods on the economics of BMP adoption. Since in this study the average of 25 years hydrologic simulation was used in economic analysis, and since there are specific years in the historical data that there was drought in the region, it would be beneficial to reduce the time frame and evaluate the most cost efficient BMPs that were effective in drought conditions. Additional, applying different Global Climate Models (GCM) can help to work on future weather conditions and evaluate the most cost effective crop-BMPs which would minimize the sediment and phosphorous losses from agricultural fields in this region. The results of working with future climate data can be beneficial for decision makers to know that with adopting which conservation practices and planting which crops they will have the most economic results for producers while spending less funding to support them in the future once there will be more drought and flood, and consequently, more NPS pollution loads.

CHAPTER VIII

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VITA

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