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Basin Scale Water Quality Conservation: Impacts of filter strips, bio-fuel development and hydrological parameters

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Basin Scale Water Quality Conservation: Impacts of filter strips, bio-fuel development and hydrological parameters

By

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ABSTRACT

Excessive nutrient and sediment export from agricultural basins with intensive row crop cultivation have been identified as persistent problems leading to higher levels of nitrate nitrogen and reduced levels of dissolved oxygen in the water bodies. Water quality thus gets degraded and becomes less suitable for human use and potential threat to the aquatic life and environment. Development of bio-fuel technology further increases the demand of grain that will result in more land under row crop cultivation, which supposedly would worsen the situation regarding water quality. In this study, application of contour and riparian buffer strips and strategic conversion of row crop to biomass yielding switchgrass to conserve the basin scale water quality is evaluated using the Soil and Water Assessment Tool (SWAT) model. Finally SWAT hydrological parameters have been developed for a small portion of Iowa that would be instrumental in development of TMDL's.

The use of contour and riparian buffer strips planted with perennial vegetation has been found to improve surface water quality by reducing NO_3-N and sediment outflow from cropland to a river. Modeling such a system to compare alternative layout and different strip sizes often faces challenges in flow routing scheme. The hillslope scheme in Soil and Water Assessment Tool (SWAT) offers the flexibility of allowing the flow from a crop area to be routed through a buffer and/or contour strip, in which a thin sheet flow represents more closely the natural condition of a watershed. SWAT was applied to the Walnut Creek Watershed and the hillslope option was used to examine the effectiveness of contour and riparian buffer strips in reducing NO_3-N outflows from crop fields to the river. Numerical experiments were conducted to identify potential subbasins in the watershed that have high

water quality impact and to examine the effects of strip size and location on NO_3-N reduction in the subbasins under various meteorological conditions (dry, average and wet). Variable sizes of contour and riparian buffer strips (10%, 20%, 30% and 50%, respectively, of a subbasin area) planted with perennial switchgrass were used to simulate the effects of strip size on stream water quality. Simulation results showed that a filter strip having 10%-50% of the subbasin area could lead to 55%-90% NO_3-N reduction in the subbasin during an average rainfall year. Strips occupying 10-20% of the subbasin area were found to be more efficient in reducing NO_3-N when placed along the contour than that when placed along the river. Varying the area and location of the contour and buffer strip affects NO_3-N outflow and crop yields as well since it takes the land out of production. The size of the filter strip has economic implications in deciding how much land area to dedicate to prevent NO_3-N loss to a desired limit or vice versa. The results of this study can assist in cost-benefit analysis and decision-making in best management practices for environmental protection.

SWAT was then applied to the Upper Mississippi River (UMRB) to study the perpetuation of the current trend of growing corn to meet the increasing corn demand for ethanol industry. A hypothetical case of converting the entire UMRB agricultural land into corn production was simulated by SWAT. Though very unlikely, this study provided a guideline to identify the highest nitrate contributing subbasins that could be used for switchgrass production instead of corn. Such conversion would yield economic value from cellulosic ethanol from swtichgrass and at the same time there would be an improvement in water quality. High impact subbasins were identified based on the total nitrate output of each subbasin. Converting them to switchgrass production was found to reduce nitrate nitrogen yield of up to 14 kg/ha and sediment reduction of up to 5 tons/ha. In many cases, switchgrass

reduced up to 71% of total nitrate nitrogen yield and almost 99% of sediment. The Production-Economy-Environment matrix analysis of growing switchgrass for various rates of fertilizer application and its consequences on the yield of biomass and environment was performed. It demonstrated that the efficacy of rate of fertilizer application and its relationship to economy and environment was not proportionate. It underscores the importance of such analysis to design an optimum amount of fertilizer to be used. Conversely, it can be used to determine the rate of fertilizer application for a desired gain or desired target in environmental quality. A simple economic analysis found out that there was a significant economic gain from the cellulosic ethanol compared to corn ethanol. It was concluded that even though the economic benefits of bio-energy crops were marginal, the bio-energy crops are yet a potentially viable solution for the degrading water environment in the waterways of Upper Mississippi River Basin and the Gulf of Mexico.

Finally, Soil and Water Assessment Tool (SWAT) was set up, calibrated and validated for the Maquoketa (4867 km^2) and Beaver Creek (905 km^2) watersheds to develop SWAT hydrologic parameters specific to one of the six principal Iowa landform regions. These landforms (eco-regions) cover the majority of the intensively cropped regions in the state and are based on similar bio-physical characteristics that are assumed to have a corresponding specific range of SWAT input parameters unique to each one of them. Having a readily usable set of SWAT hydrological parameters would make the modeling part of TMDL development easier. Using the observed data of 1995-2008, calibration of SWAT for Maquoketa gave the annual and monthly flow Nash-Sutcliffe's efficiency (E) of 0.89 and 0.83 and coefficient of determination (R^2) value of 0.94 and 0.86. Without making any further changes to the model parameters, model validation on Beaver Creek gave the monthly flow E of 0.73 and 0.82 and R^2 value of 0.96 and 0.87 that was well over acceptable limit. A sensitivity analysis on Beaver Creek was performed by modifying the land use distribution similar to Maquoketa and the results showed that SWAT model was performing coherently in both the watersheds. Thus a SWAT hydrological parameter set was recommended for the Iowan Surface landform region.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

Nutrient, sediment and pesticides outflows from agricultural watersheds are often attributed as non-point source of pollution to the streams and natural waterways, resulting in depleted dissolved oxygen and higher level of nitrates and pesticides than the permitted standard (Humenik et al. 1987, Burgoa and Wauchope 1995). Water quality in rivers and streams of Iowa and Midwest in general, where the landscape is dominated by agriculture, is experiencing higher level of nitrate causing hypoxic conditions in rivers that flow into the Gulf of Mexico threatening the marine ecosystems (US EPA 1992, Rabalais et al. 1996, Mitsch et al. 2001). Other implications of higher nitrate level in the rivers are that it violates the drinking water standard for the source of raw water supply. Keeney and DeLuca (1993) found that NO_3-N concentrations in Des Moines River water in Central Iowa were above 10 mg L^{-1} for an average of 14 days per year, generally in spring. Libra (1998) has reported an average annual export of nitrate nitrogen from Iowa in surface water ranging approximately from 225,000 to 245,000 tons, which is about 25% of the nitrate that the Mississippi River delivers to the Gulf of Mexico, despite Iowa occupying less than 5% of its drainage area. Thus the excessive export of nutrient and sediment from crop zone has remained as a persistent problem for the aquatic environment.

Recent development in bio-fuel technology will lead into higher demands of grain for ethanol production. Corn ethanol is an attractive source of energy in terms of energy independence of the nation and cleaner air. Study conducted by USDA suggests that additional amount of land will be required to meet the corn demand of ethanol plants and farmers have already started to respond to this. One study in Iowa showed that farmers had 17% increased land under corn in 2007 compared to the previous year (USDA Baseline Projection 2007) and the researcher believed that the trend may continue to grow. So where will the additional amount of land come from? Majority of the USDA baseline projection of 90 million acres under corn required to meet the ethanol and other demands by 2010 would come from the Midwest, converting the typical corn-soybean rotation to continuous corn production and from other crops. Increased farming of the row crop will increase the export of nitrate and sediment to waterways of Upper Mississippi River Basin (UMRB) ultimately contributing to the hypoxia in the Gulf of Mexico.

Last couple of decades has seen a growing concern of understanding and mitigating the problem of non-point source of pollution. Best management practices (such as grassed waterway, riparian buffer, contour strips, field border, etc. have been suggested for reducing the pollutant yield from the agricultural land. Modeling studies (Osborne and Lewis 1993, Vache et al. 2002, Chaplot et al. 2004, Santhi et al. 2002, Syversen 2005, Sahu and Gu 2009) have shown that the impacts of best management practices on water quality is considerable; however, its application on filed scale and every farm plot seems to be very unlikely. Part of the reason is that it is expensive to put it on the field. Secondly, it takes the land out of production and farmers will be reluctant to put it on their farm without appropriate subsidy. Monitoring side of the conventional BMP’s will be even more challenging on farm to farm basis.

Recently, researchers have found that biomass can be used for ethanol production. Perennial grass such as switchgrass is a good source of biomass that can be grown in the fields that currently produce corn and use it to produce cellulosic ethanol instead of corn ethanol. From the environmental perspective, cellulosic ethanol from switchgrass is found to produce 540% more renewable than the nonrenewable energy consumed and burning of cellulosic ethanol produces 94% less greenhouse gas (GHG) compared to GHG from gasoline (Schmer et al. 2008). While the economic outputs of corn and switchgrass in terms of ethanol production needs to be compared to design the subsidies, the environmental benefits are significant in terms of water quality and greenhouse gas emission contributing positively to the global climate change. From management perspective, it will be like normal planting operation for the farmers to grow switch grass and it will be a lot easier for the authorities to monitor. This can be named as a macro level Best Management Practice (Macro BMP).

Majority of the agricultural land in Iowa, Illinois and other mid-western agricultural states are heavily tile drained because of the low lying ground and smaller valley formation. Tile drains short circuit the flow and siphon most of the nutrients directly into the river. In that sense, the tile drainage in effect bypasses the micro-level BMP's (the traditional BMP's such as field border, grassed waterway, filter strip, contour strip, etc.) and would be unable to mitigate the problem of pollutant export to the water bodies. Replacing the row crop production by biomass yielding crop such as switchgrass, which is very closely grown, can have a positive impact in reducing the nitrate and sediment yield from such region. It seems to be one of the promising solutions for the tile drained area and creates a need to be examined scientifically.

Numerical modeling of the possible future scenarios is very important to provide alternatives in terms of Production, Economy and Environment (PE^2) that will form the basis for policy making. Production of corn must be met for domestic human and animal consumption, for ethanol industry and for export. The production part of corn for ethanol can be replaced by switchgrass for cellulosic ethanol. This replacement of corn ethanol by cellulosic ethanol (Production) will have their corresponding impact on economy and environment that needs to be quantified and examined numerically. A number of mathematical models such as SWAT, SWIMM, BASINS, and REMM etc are available for the watershed and environmental water quality modeling. Among them, Soil and Water Assessment Tool (SWAT) (Arnold et al. 1995) is a more comprehensive watershed scale model that can simulate the hydrological processes along with the nutrient, sediment and pesticides in a watershed and river network. It can work on small to large scale watersheds over long period of continuous time simulation incorporating high level of spatial details. Therefore SWAT model will be used a numerical tool for this study.

Selection of hydrologic parameters for physically based models has significant effect on model performance. Generally, measured values may not be available for all the parameters for the entire region of a watershed to be modeled and analyzed. Hence the model parameters are often calibrated with respect to the observed data on flow and other hydrological and water quality components. To have a readily usable SWAT for the development of TMDL’s, a known set parameter range for the individual watersheds would be essential. An available set of such parameters for the intensively cropped regions would be very instrumental to perform the TMDL studies. Smaller studies performed all around the cropped region of the Midwest integrated together could yield a very robust tool for water quality studies on large scale basin such as UMRB. Results of such integrated model can be fed to a hydrodynamic model and the dynamics of Gulf hypoxia can be predicted.

Objectives

1. Set up SWAT model, calibrate and validate for the Walnut Creek watershed, Ames, Iowa with respect to the historical data.
2. Use the model to evaluate the effectiveness of Micro BMP's such as filter strips used as contour and riparian buffer strips planted with perennial vegetation such as switch grass and compare their efficacies in pollutant reduction. Examine the effects of strip size and location on nitrate reduction under various meteorological conditions, such as dry, average and wet years.
3. Identify the high impact subbasins of the UMRB i.e. the subbasins having the highest nitrate yield. Study the water quality impact due to Macro BMP's such converting them to switchgrass. Conduct numerical experiments and analyses to identify potential subbasins in the watershed, which have high water quality impact.
4. Perform the Production, Economy and Environment matrix study for switchgrass production.
5. Set up, calibrate and validate the SWAT model for Maquoketa and Beaver Creek, Iowa to develop the SWAT hydrological parameters for future TMDL studies.

Dissertation Organization

This dissertation is organized in five chapters. The first chapter includes the general introduction and general study objectives. The second, third and fourth chapter contains three different journal article manuscripts containing the above mentioned study objectives. The second chapter presents the calibration and validation of SWAT for Walnut Creek watershed, Ames, Iowa to study the effects of contour and riparian buffer strips on water quality. It contains a journal article manuscript entitled “Modeling the effects of contour and riparian buffer strips on stream water quality” published in Ecological Engineering. The third chapter contains the manuscript entitled “Water quality conservation for UMRB – Transition from Micro to Macro level BMP’s and bio-fuel development scenario” submitted to the ASCE Journal of Water Resources Planning and Management. The fourth chapter consists of a journal article manuscript entitled “Development of SWAT hydrologic parameters for specific Iowa landforms” that will be submitted to the Journal of American Water Resources Association. The fifth and the final chapter include general conclusions and recommendations based on this study.

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CHAPTER2. MODELING THE EFFECTS OF RIPARIAN BUFFER ZONE AND CONTOUR STRIPS ON STREAM WATER QUALITY

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(A paper published in Ecological Engineering 35(2009), 1167-1177)

Abstract

The use of contour and riparian buffer strips planted with perennial vegetation has been found to improve surface water quality by reducing NO_3-N and sediment outflow from cropland to a river. Modeling such a system to compare alternative layout and different strip sizes often faces challenges in flow routing scheme. The hillslope scheme in Soil and Water Assessment Tool (SWAT) offers the flexibility of allowing the flow from a crop area to be routed through a buffer and/or contour strip, in which a thin sheet flow represents more closely the natural condition of a watershed. In this study, SWAT model was applied to the Walnut Creek Watershed and the hillslope option was used to examine the effectiveness of contour and riparian buffer strips in reducing NO_3-N outflows from crop fields to the river. Numerical experiments were conducted to identify potential subbasins in the watershed that have high water quality impact, and to examine the effects of strip size and location on NO_3-N reduction in the subbasins under various meteorological conditions (dry, average and wet). Variable sizes of contour and riparian buffer strips (10%, 20%, 30% and 50%, respectively, of a subbasin area) planted with perennial switchgrass were used to simulate the effects of strip size on stream water quality. Simulation results showed that a filter strip having 10%-50% of the subbasin area could lead to 55%-90% NO_3-N reduction in the subbasin during an average rainfall year. Strips occupying 10-20% of the subbasin area were found to be more efficient in reducing NO_3-N when placed along the contour than that when placed along the river. Varying the area and location of the contour and buffer strip affects NO_3-N outflow and crop yields as well since it takes the land out of production. The size of the filter strip has economic implications in deciding how much land area to dedicate to prevent NO_3-N loss to a desired limit or vice versa. The results of this study can assist in cost-benefit analysis and decision-making in best management practices for environmental protection.

Keywords: Modeling, SWAT, water quality, NO_3-N, contour strip, buffer strip, watershed

1. Introduction

Nutrient, sediment and pesticide outflows from agricultural watersheds are often attributed as non-point source pollutants to streams and natural waterways, resulting in depleted dissolved oxygen, and higher level of NO_3-N and pesticide than the permitted standard ([Humenik et al., 1987], [Burgoa and Wauchope 1995]). Water quality of rivers and streams in Iowa and the Midwest, where the landscape is dominated by agriculture, is experiencing a higher level of NO_3-N causing hypoxic conditions in rivers that flow into the Gulf of Mexico threatening the marine ecosystems ([US EPA, 1992], [Rabalais and Turner 1996], [Mitsch et al., 2001]). Keeney and DeLuca (1993) found that NO_3-N concentrations in Des Moines River water in Central Iowa were above 10 mg L^{-1} for an average of 14 days per year, generally in spring. Libra (1998) has reported an average annual export of NO_3-N from Iowa in surface water ranging approximately from 225,000 to 245,000 tons, which is about

25% of the NO_3-N that the Mississippi River delivers to the Gulf of Mexico, despite Iowa occupying less than 5% of its drainage area.

Nitrogen fertilizers, livestock manure application, nitrogen fixation by legumes and mineralization of soil nitrogen are the primary sources of NO_3-N in agricultural watersheds. Part of the NO_3-N are utilized by crops and other plants and excess of it become available to be carried by the surface and groundwater flow into the river and other water bodies as pollutants. Ecologically engineered solutions and Best Management Practices (BMP’s) that comprise crop rotation, no till cultivation, application of filter strips along a river and along the contour in a crop field, field border and wetlands are often employed to reduce and or capture the nutrients and sediments from getting into the stream. Performance of such ecologically engineered systems has been studied by Mitsch and Mander (1997), Hernandez and Mitsch (2007), Meier at al. (2005), Lin et al. (2004) and Anbumozhi et al. (2005). It is important to numerically simulate the effects on NO_3-N outflow due to alternative land-use/management scenarios containing the ecological solutions. A wide range of numerical models have been developed to study non-point source pollution, however most of these models are designed to assess the pollutant outflow at a field scale. The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1995) is a more comprehensive watershed scale model that can simulate the hydrological processes along with nutrient, sediment and pesticides in a watershed and river network. It can work on small to large scale watershed with key features such as continuous time simulation over longer periods, high level of spatial details, various levels of watershed subdivisions, and efficient computation and capability to directly simulate the likely water quality at the outlet of a watershed due to existing or changed land-use scenarios.

Vache et al. (2002) have applied SWAT to the Walnut Creek Watershed, Ames, Iowa and have reported that a significant reduction (54-75%) in NO_3-N occurred when the BMP's were employed in conjunction with wider riparian buffer strip. Chaplot et al. (2004) has applied SWAT to model the effect of reduced application in agriculture and found that lessening the nitrogen (N) application rate by 20, 40 and 50% decreased the mean NO_3-N loads by 22, 50 and 95% respectively. Field experiments by Dillaha et al. (1989) showed that a filter strip with a width of 9.1 m and 4.6 m removed an average of 84 and 70% of suspended solids, 79 and 61% of phosphorus (P), and 73 and 54% of N, respectively. They also found that occasional release of the nutrient from the VFS were even higher than the incoming one underscoring the fact that removal efficiency can be low due to nutrient saturation in the filter strip. Their observations indicated that on-farm VFS may not perform as good as experimental one or as the one simulated by numerical models. In a field experiment on small plots, Lee et al. (1999) found that 6-m and 3-m filter strips removed 42% and 25% of NO_3-N, respectively. Syversion (2005) studied the effect of buffer strip in a field experiment under Nordic climate and found that 10 m and 5 m wide buffer zones reduced the phosphorus, nitrogen and sediment by 60-89%, 37-81% and 81-91% respectively. Santhi et al. (2002) used SWAT model to simulate filter strips using trap efficiency for sediments and nutrients based on strip's width. The selection of the coefficient that would replicate the trapping efficiency of a buffer strip is critical to the results of previous studies and could be under- or over-predicted depending on the local conditions (Barlund et al, 2007). However, the trapping efficiency may be different depending upon the type of vegetation and watershed parameters such as slope and soil type. Hence the challenge in application of SWAT model remains when applied to simulate the riparian buffer and contour strips.

The objective of this study is to investigate the effectiveness of contour and riparian buffer strips having perennial plant cover in reducing nutrient (NO_3-N) loading to streams in an agricultural watershed. SWAT2003 and its hillslope scheme are applied for this purpose in which the type of vegetation is specified to avoid the potential problem of selecting incorrect trapping efficiency. Hillslope scheme of SWAT allows the routing of overland flow from one unit through another. When the flow from a crop area carrying nutrients passes through the filter strip, perennial plant will be able to use up some of the nutrients and net outflow of nutrients will be reduced. When the area of the filter strip is large and velocity of surface flow through it is low, the perennial plants in the filter strip will be able to use up more nutrients. This in turn takes the land out of production and will have economical impact. Compensation for farmers for not growing crop is a direct cost of environmental protection and a tradeoff needs to be examined. It can be based on the relative efficacy of increasing the area under filter strip and its effect on NO_3-N outflow reduction. In this study, SWAT simulations of the Walnut Creek watershed were conducted to identify high impact subbasins based on total and per unit area NO_3-N yield, to compare the response of the two types of high impact subbasins to selected management practices, and to evaluate the reduction of NO_3-N load due to varying the area of filter strip. Numerical experiments on different scenarios were carried out to examine the effectiveness of filter strips on water quality improvement under various weather conditions and to determine more effective location for the placement of filter strips, i.e. contour strip or riparian buffer strip.

2. Methodology

2.1 Model

SWAT is designed to operate on a continuous daily time step basis to simulate the hydrological processes and fate and transport of nutrients, sediments and pesticides in a watershed along with flow routing of the river network (Arnold et al. 1995). The GIS version of SWAT makes the model more user-friendly to enter and manipulate the input data. The model takes topography, soil, land-use, crop management practices, and climate as input data and produces the stream flow and its water quality as output. SWAT model has been validated by Arnold and Allen (1996), Srinivasan et al. (1998), Arnold et al. (1998), Saleh et al. (2000), Santhi et al. (2001) and Jha et al. (2004) for various watersheds throughout USA. Model components are described in detail by Arnold et al. (1995, 1998) and Srinivasan et al. (1998).

Hydrology component of the model calculates the water balance of a system based on the following equation:

$$SW_t = SW + \sum_{i=1}^{t}(R_i - Q_i - ET_i - P_i - QR_i) \qquad (1)$$

where SW is the soil water content, t is time in days and R, Q, ET, P and QR are daily amounts of precipitation, runoff, evapo-transpiration, percolation and return flow respectively. All units are in mm. SWAT balances the amount of water, thereby updating the soil moisture content for every time step.

Surface runoff is computed in SWAT by using the SCS curve number equation (SCS, 1972) that estimates a retention parameter for the watershed from the curve number based on slope, land-use, soil type and antecedent moisture condition. Percolation component of the model uses a storage routing technique combined with a crack-flow model to predict flow through each soil layer. Lateral subsurface flow in the soil profile for 0-2 m depth is calculated simultaneously with percolation using a kinematic storage model (Sloan et al., 1983). SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) (Williams and Brendt, 1977) to calculate sediment yield for each subbasin.

Nitrogen cycle in SWAT considers three major forms of nitrogen in mineral soils, i.e. organic nitrogen associated with humus, mineral forms of nitrogen held by soil colloids, and mineral forms of nitrogen in solution. They are monitored in five different pools of nitrogen in the soil. Details of the nitrogen cycle in SWAT can be found in Neitsch et al. (2005). SWAT considers the addition of nitrogen by fertilizer, manure or residue application, fixation by symbiotic or non-symbiotic bacteria and rain. Nitrogen is removed from the soil by plant uptake, leaching, volatilization, denitrification and erosion. Fate and transport of nitrate nitrogen in SWAT is explained by Neitsch et al. (2005) and in Jury et al. (1991) and Thomas and McMahon (1972).

In its present setup, SWAT utilizes trapping efficiency based solely on the strip's width to simulate the nutrient capturing capability of filter strips. Mathematical modeling of a watershed with contour and buffer strips using SWAT poses a challenge to the flow scheme adopted in the current SWAT model. In a riparian buffer zone, flow from a crop area passes through the buffer and contour strip; where buffer zone and/or contour strip act as filter between crops and waterways. The effectiveness of a filter strip depends on many factors, including vegetation type, soil type, flow velocity, and slope. In the previous studies, crop area and buffer and/or contour strip were treated as separate HRU's (Hydrologic Response Units) in parallel and outflow from these units were taken into the river. The overland flow from one unit through the other is not considered. HRU is a hydrological computational unit having a unique land use, soil type and management practices.

2.2 Hillslope Scheme

The hillslope scheme feature in SWAT is a mechanism to discretize the watershed into individual spatially explicit units. In this scheme, overland flow can be routed from one subbasin into another (adjacent) subbasin, thus allowing SWAT to model hillslope processes (Neitsch et al., 2002). Figure 1(a) shows the schematic flow pattern in SWAT where HRU contribute separately to the river. In case of riparian buffers and contour strips, this method of approximation does not adequately represent the actual flow pattern occurring in the natural condition. Figure 1(b) and (c) show the schematic flow pattern in hillslope SWAT for a riparian buffer and contour strip (shown in Figure 1(d)), where water flowing from the crop area passes through the buffer or contour strip. The hillslope scheme allows the flow to be routed as shown in Figure 1(b) and (c) where flow from the crop area carrying nutrients passes through the buffer or contour strip as overland flow. Thus there is a washout of nutrients from the crop area and supplied to the buffer or contour strip having perennial vegetations that in turn use up the nutrients. SWAT uses a crop-growth model to simulate the growth of perennial vegetation in the contour or buffer strips with the supply of nutrient from the upland crop areas. Nutrients utilized by the perennial vegetation are the reduction of nutrient flowing into the river. Figure 1(d) shows a watershed having contour and buffer strip proposed in this study. Perennial vegetation such as switchgrass or forest can be planted in the buffer or contour strips, which act as a filter between cropland and river. In this study, filter strips were assumed to be planted with switchgrass that can uptake the nutrients in the surface runoff for its growth and slows down the flow to reduce the sediment yield.

2.3 Study Domain: Walnut Creek Watershed

Walnut Creek watershed (Figure 2) has an area of 51.3 km^2 and is located near Ames in central Iowa extending from $41^{\circ}55'$ to $42^{\circ}00'$ North latitude and $93^{\circ}32'$ to $93^{\circ}45'$ longitude. Elevation of this watershed ranges from 267 m to 320 m, however, it has little topographic relief and poorly naturally drained soils. Most of the upper part of the watershed is tile drained to make it suitable for agriculture and drain the pot holes. This is an intensively farmed watershed comprising over 83% of its area under row crop of corn/soybean. Small portion (about 5%) of the watershed is under pasture and grassland having livestock operation. This watershed is highly monitored under MSEA (Management Systems Evaluation Area) of U.S. Department of Agriculture (USDA).

2.4 Input data

Required data by SWAT model include topography as Digital Elevation Model (DEM), soil, land-use, management practices in the watershed and climate data. Daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity are required for the climate data input. Data for the Walnut Creek watershed were obtained from the Soil Tilth Lab (USDA/ARS), Ames, Iowa. Data on flow and water quality is available for the watershed since 1990 (Hatfield et al., 1999). The Clarion-Nicollet-Canisteo soil association characterizes the soils within the watershed. Well-drained Clarion and Webster soils are found on higher or sloping areas; somewhat poorly drained Nicollet soils are found on the convex side slopes; Canisteo and Webster soils on poorly drained low areas and drainage ways and very poorly drained Okoboji and Harps soils are found enclosed in depressional areas (Hatfield et al., 1999). State soil geographic (STATSGO) soil map developed by USDA was linked to the SWAT soil database.

The watershed has a cold winter and warm summer climate. Precipitation during the winter is usually snow whereas the rain events during the spring and summer often occur as thunderstorms with brief intense showers. Total annual precipitation for the Ames, IA area for the 30-yr average is 818 mm, of which the year 1993 had recorded precipitation of 1290 mm (Hatfield et al., 1999).

Temperature ranges from an average monthly minimum of -13.4^{0}C in January to an average monthly maximum of 29.4^{0}C in July. Relative humidity in the watershed varies from 60% in the afternoon to 80% at dawn (Hatfield et al., 1999).

Land-use within the watershed is predominantly row crop production with more than 85% of the land under corn-soybean rotation. Chemical fertilizers of N and P are applied at a highly variable rate among different farms and from year to year. Nitrogen application rates vary from 3.4 kg ha^{-1} to 336 kg ha^{-1}. Chisel-plow operations are used for primary tillage operation within the watershed after harvest. Moldboard plowing is used on a very small portion (less than 220 ha) of the watershed (Hatfield et al., 1999). The number of tillage passes applied to each field varies with the operator and ranges from three to six tillage operations for corn and three to eight tillage operations for soybean fields in the fall as well as in the spring.

2.5 Experimental Design

Historical data of flow and NO_3-N are used to calibrate and validate the SWAT model for the Walnut Creek watershed. Tile drainage was simulated by default SWAT parameters for tile drainage function. It is then used to conduct three numerical experiments to test the effectiveness of contour and buffer strip on water quality improvement under various scenarios. The first experiment is to look for the high impact subbasins based on total NO_3-N outflow and NO_3-N outflow on per unit area (kg/ha) basis. Performance of buffer and contour strips are supposed to be more effective in high impact subbasins. Once the high impact subbasins are identified, two subbasins - one on the basis of total NO_3-N outflow and the other on the basis of per unit area NO_3-N outflow (kg/ha), are selected to examine the reduction of NO_3-N outflow due to contour and riparian strips. In the second experiment, a filter strip is placed mid-way on the slope as a contour strip. Four different sizes of the contour strip having 10%, 20%, 30% and 50% of the subbasin area are simulated to determine the efficiency of each scenario. In the third experiment, filter strips are put next to the river as a buffer strip having 10%, 20%, 30% and 50% of the subbasin area and are simulated to investigate and compare the effectiveness of strips of different sizes. The results from experiments 2 and 3 are analyzed and compared to quantify the impact of strip size and location on the efficiency of nutrient reduction by buffer and contour strips.

3. Results and Discussion

3.1 Model Calibration and Validation

Stream flow and NO_3-N data for 1996-2000 at the outlet of the Walnut Creek watershed were used to calibrate the SWAT model. Automatic calibration of SWAT 2003 was used to calibrate the model. The automatic calibration procedure is based on the Shuffled Complex Evolution algorithm (SEA-UA). It is a global search algorithm that minimizes a single objective function for up to 16 model parameters (Duan et al., 1992). The SCE-UA has been applied with SWAT successfully for hydrologic parameters (Eckhardt and Arnold, 2001) and hydrologic and water quality parameters (van Griensven et al., 2002). In this study, the objective function was the sum of squared residuals, observed minus simulated flow. The sum was minimized while adjusting the values of curve number and groundwater delay factor to a final value of 60.0 and 0.179 days respectively.

Curve Number (CN) is directly related to how much surface runoff will be produced from the watershed and depends on land use, farming practice, hydrologic condition and soil type. Standard recommendations are available for the curve number however these values are general recommendations and need to be adjusted to match the measured flow from a particular watershed. Groundwater delay factor is related to base flow of the river. It affects the groundwater contribution to the river flow. One of the components of how much will be the contribution to the river flow from groundwater is the time delay between water percolating through the root zone and ultimately reaching the river via shallow aquifer. It is directly related to groundwater flow response and will affect the recession limb of the flow hydrograph after a rainfall event has passed. A direct measure of this factor is not possible and hence was selected as one of the variables for model calibration.

Figures 3 and 4 demonstrate the results of model calibration and validation using flow data for the Walnut Creek, in which observed and simulated flows are compared. Presented in Figure 3 are annual totals and average annual flows over the periods of calibration and validation, respectively. Observed and simulated monthly flows at the outlet of the watershed for 1996 to 2000 were used for model calibration and 1992 to 1995 was used for model validation (Figure 4). Calibration period was chosen after the validation period to avoid the very high flow of 1993 in the model calibration process since the model is not very good at dealing with the extreme events (i.e. flooding and drought). Regardless of those limitations, SWAT can still be used for long-term simulations such as those conducted in this study. Initial trials were made to use 1992-1995 as calibration period and automatic calibration of the model apparently tried to match the very high peak flow of 1993 that affected the calibration of other years and did not give a very good fit. Statistical analysis showed the coefficient of determination (R^2) to be 0.62 for model calibration and 0.59 for model validation. Corresponding Nash-Sutcliffe coefficient of efficiency (E) (Nash and Sutcliffe, 1970) for model calibration and validation was 0.56 and 0.54. The peaks of the observed and simulated flows however match better except the high flow year 1993. Wet year 1993 was a very extreme event that would be difficult to be predicted by the model.

Observed and simulated cumulative NO_3-N flow at the outlet of the watershed is plotted in Figure 5. Model was calibrated for flow only and no model parameters were adjusted for NO_3-N. Plots of observed and simulated NO_3-N for 1994-1998 show a similar pattern and a reasonably good match between the two. The Nash-Sutcliffe coefficient of efficiency for monthly observed and simulated NO_3-N was found to be 0.87. The accumulated small discrepancy might have come from various sources, including the assumption of average NO_3-N fertilizer application rate. In practice, the field application rate of fertilizers could be different from plot to plot and year to year. Hatfield et al (1999) reports a variation from 3.4 kg/ha to 336 kg/ha from field to field and year to year. An average value of 220 kg/ha of anhydrous ammonia was assumed for this study. NO_3-N outflow from the watershed will also be dependent on the timing of fertilizer application and the following rainfall event for which exact data is rarely available. Farming practices may vary from field to field in terms of fertilizer application such as some plots may get the fertilizer before cropping in spring while others may receive in early fall. All these factors can significantly affect the net NO_3-N outflow from the watershed. However, results of this study can still be useful in evaluating the relative reduction of NO_3-N outflow due to filter strips. Results of the validated model serve as the base-line scenario for analysis and comparison of the effects of strip size and location on water quality improvement.

3.2 Identification of high impact subbasins

The Walnut Creek watershed was divided into 23 subbasins in SWAT simulations based on topography and flow concentration points (Figure 2). Depending on the slope, soil type and other hydrological parameters (Table 1), each subbasin has different NO_3-N contributions to the river. As listed in Table 1, major watershed parameters include size (area), shape which is described by channel density--the ratio of channel length to subbasin area, slope, soil type and land-use. It is important to identify the subbasins that contribute high amounts of NO_3-N to the river so that they can be targeted as the primary areas to employ the management practices. These high impact subbasins were identified on the basis of two criteria, namely, the high total NO_3-N contributing subbasins and the high per-unit-area NO_3-N contributing subbasins. This was done to compare the response of the two types of high impact subbasins to the management practices.

Annual average NO_3-N contributions (1992-2000) of the 23 individual subbasins of the Walnut Creek Watershed under existing land-use/cover are plotted in Figures 6 and 7 from the SWAT output. The results presented in Figure 6 indicate that subbasins 4, 8 and 14 are the high impact subbasins based on total NO_3-N contribution. As shown in Table 1, these three subbasins have the top three largest sizes. Therefore, it can be concluded that more NO_3-N can be generated from a subbasin with a larger area. Per-unit-area NO_3-N contributions are displayed in Figure 7, which indicate that Subbasins 11, 13, 14, 19, 20 and 22 are the high impact subbasins based on per-unit-area NO_3-N contribution. Subbasin 8, identified according to total NO_3-N contribution, and subbasin 19, according to per-unit-area NO_3-N contribution, was chosen to examine the effects of buffer and contour strips on water quality improvement.

The high impact subbasins with respect to per-unit-area NO_3-N contribution are those having relatively steeper slopes compared to the other subbasins and a soil type of moderate porosity, i.e. IA115--Hayden soil (Table 1), which result in greater and faster surface runoff. The shape of a subbasin can also affect per-unit-area NO_3-N yield by the subbasin. As listed in Table 1, majority of the six high impact subbasins have a high channel density, which leads to a greater per-unit-area NO_3-N contribution. Per-unit-area NO_3-N outflow from a subbasin can be affected by several watershed parameters, including size, shape, slope, soil, and land-use or land-cover. A single parameter may not be able to play a dominating role in NO_3-N contribution by a subbasin. A parameter can be overridden by a combined impact of other factors. An interesting observation is that Subbasin 17 is not a high impact subbasin although it has the values of watershed parameters to qualify it as a high impact subbasin. It is found that Subbasin 17 is the only subbasin in the Walnut Creek watershed that has a land-cover type of forest, which is a major player in reducing NO_3-N outflow from the subbasin, overriding the impact of all other factors.

3.3 Scenario 1: Filter strips located mid-way of the slope

Filter strips are placed along the contour at a location mid-way of the slopes of subbasins 8 and 19. SWAT simulations are carried out and NO_3-N outflows from each of the subbasins with and without the filter strip are compared. Figures 8(a) and 8(b) show the percentage reduction of NO_3-N in surface water from the individual subbasins due to filter strip compared to the base case with no filter strip. Actual NO_3-N yields of subbasins 8 and 19 with contour strips are presented in Tables 2 and 3. Three different scenarios of weather and flow, namely – wet year (1993), dry year (1994) and average year (1996) and four different sizes (10%, 20%, 30% and 50% of subbasin area) of the filter strip are chosen for this comparison to see how different sizes of filter strips are functioning in NO_3-N reduction under different runoff scenarios. The weather scenarios were classified by analyzing long-term annual rainfall data. In the time series studied, a year having a relatively low annual rainfall was designated as dry year, and similarly a wet year was selected from years with relatively high annual rainfall. A year of average weather condition is represented by an average annual rainfall. Data for the three different weather scenario years were extracted from the continuous model simulations for year 1992-2000. Contour strips were found to be more effective in NO_3-N reduction in average precipitation year than in wet and dry years when there are more extreme events (storm duration and intensity). During wet year, the overland flow is high that results in fast and diluted runoff from the crop field through the filter strip, and thus NO_3-N carried by the surface runoff gets short contact time with plant roots. Short contact time reduces the chances of NO_3-N being taken up by the plants and hence there is higher yield of NO_3-N to the river. Increase in the area of contour strip is less effective in further NO_3-N reduction compared to that achieved by 10% of the area underscoring the point that the filter strips are less effective during wet year. During the dry year, on the other hand, overland flow is low and thus less NO_3-N is carried by the overland flow through the filter strips that becomes available for the perennial vegetation. During the average flow year, there is good balance between the available NO_3-N and plant uptake due to moderate flow and longer contact time of nutrients with the plant roots, and hence the filter strip works much effectively.

Higher reduction in nitrate outflow for 50% area of contour strip in average weather scenario is due to the fact that there is more perennial vegetation available to receive the NO_3-N in the overland flow and will be more effective in reducing the NO_3-N in surface runoff. Therefore 50% area of the contour strip could have a significant effect on reducing NO_3-N. The grassed filter strip will have a high potential of up taking the nutrient and possibly removing most part of it (in this study 94%) if the opportunity is more favorable such as in the average flow year. Literatures do not provide a direct experimental result of this kind of set up; however, some similar field experimental studies by Dillaha et al. (1989) and Syversen (2005) have suggested nutrient reductions of up to 54-73% and 37-81% with different width of vegetative filter strips. Hence the modeled reduction of 94% in the surface runoff NO_3-N by 50% of the filter strip area seems to be reasonable compared to these field experimental data.

The larger size of the filter strip leads to a higher reduction of NO_3-N yield. However the efficacy of NO_3-N reduction is much higher for the contour strip having 10-20% than 30-50% of the subbasin area, i.e. a small increase in the filter strip area leads to relatively large NO_3-N reduction as shown in Figures 8(a) and (b). The NO_3-N reduction due to filter strip works in two fold – one is due to reduced application and the other is due to uptake of the part of NO_3-N in the runoff by the perennial plants in the filter strip. Larger area of the filter strip means reduced application of total NO_3-N to the subbasin since no fertilizer is applied to the filter strip. There are more perennial plants but less NO_3-N available for them. In this way, when the area of the filter strip gets larger, the dominant factor in reducing the NO_3-N yield is the reduced application rate. When the filter strip area is 10-20% of the subbasin area, nitrate uptake by the plants is significant compared to the nitrate application reduction due to filter strip replacing crop fields. But when the area of filter strip further increases, the plants in filter strip are either in short supply of nutrients or have smaller contact time depending on the climate parameters. Thus as the area of filter strips increase, percentage reduction of nitrate outflow is smaller and the curve gets flatter for 20%-50% filter area. It is evident that a large increase in the area of filter strip leads to only a small increase in NO_3-N reduction. In this study, applications of strip size of over 30% of the subbasin area were found to be less effective as the increase in NO_3-N reduction is diminishing when strip size is over 30% and NO_3-N available for plant uptake is limited.

Plots of NO_3-N reduction per unit area of filter strips are shown in Figures 9 (a) and (b). The per-unit-area reduction of NO_3-N decreases with increasing area of the filter strips in all cases of average flow year, wet and dry years.

3.4 Scenario 2: Filter strips next to the river

Filter strips in this case are placed along the channels of subbasins 8 and 19. Results of the model simulations for three different flow scenarios - wet year (1993), dry year (1994) and average year (1996); and four different strip areas (10%,20%, 30% and 50%) are presented in Figure 10 (a) and (b). The actual NO_3-N yields of the subbasins 8 and 19 with and without the buffer strips are presented in Tables 4 and 5.

Larger size of the filter strip lead to a higher reduction of NO_3-N yield in both the cases of subbasins 8 and 19. However, the rate of NO_3-N reduction decreases as the area of filter strip increases to 30% and over. It is evident in the later part of the curves (Figures 10 (a) and (b)) in average flow year cases. The dynamics of reduction in NO_3-N outflows from the subbasin has two major components: direct reduction of NO_3-N application (since no fertilizer is applied in the filter strip area) and the uptake of NO_3-N by the vegetation in the filter strip. In the earlier part of the curve (Figure 10), when the area within filter strip is small (20% or less), there is more opportunity and availability of nutrients to be used up by the plants. In this case, the NO_3-N reduction is both due to reduced application and uptake by plants. When the area within the filter strip increases, there is higher direct reduction in NO_3-N application. However there is more vegetation in the filter strip as candidate to use up the NO_3-N if enough nutrients were available in their root zone. Due to reduction in the crop area, less fertilizer is applied to the subbasin and hence smaller amount of nutrient is available to be used by the filter strip vegetation. In this case (large strip size), reduction in NO_3-N application to the subbasin dominates the process of NO_3-N outflow from the subbasin and flatter curve is observed particularly when the area of filter strip increases from 30% to 50%. However, the dynamics of nutrient in the surface runoff and its interaction with the vegetation in the filter strip is somewhat different in the wet or dry year. When the flow is too high in case of a wet year, nutrients are carried away at a faster rate along with huge amount of water and there is not enough opportunity for the vegetations to use up the nutrient. Increasing the area within the filter strip still has some room for additional nutrients to use up as shown in Figures 10 (a) and (b). In case of dry year, the amount of flow is not enough to wash the nutrients from the crop area through the filter strip and there is always enough room for the additional nutrient to be utilized by the filter strip vegetation.

Plots of NO_3-N reduction per unit area of filter strips are shown in Figures 11 (a) and (b). This show that the per unit area reduction of NO_3-N decreases with increasing area of the filter strips. NO_3-N reduction per unit area in subbasin 19 appears to increase slightly when the area of filter strip increases initially from 10 to 20% (Figure 11 (b)). Subbasin 19 has relatively steeper slope and average flow year on steep slope might provide enough nutrient to be captured by a wider riparian buffer.

Comparing the results of subbasins 8 and 19, subbasin 8 has higher effective reduction in NO_3-N outflow compared to subbasin 19. Subbasin 8 is a high impact subbasin based on total NO_3-N contribution, and it could be the prime target for conservation of water quality.

Filter strip with an area of 10% of the subbasin reduces about 72% of NO_3-N when placed mid-way the slope compared to 55% when placed along the river for subbasin 8 during average flow year. This shows that the filter strip placed mid-way of the slope is more effective than when placed along the river, which is true for subbasin 19 as well.

3.5 Uncertainty in effectiveness of filter strips

One of the underlying presumptions in this study was that the overland flow from the upslope cropland flows as a uniform thin sheet distributed equally through the filter strips. In this way, this study overlooks the possibilities of concentrated flow through small gully or channel formation within the filter strips. Concentrated flow entering the filter strip makes it less effective for water quality improvement. Field observations have indicated that as much as 60% of the flow could enter the filter strip as concentrated flow and will depend on several factors such as field size, slope and rainfall pattern (Dillaha et al., 1989). It will be difficult to predict beforehand how such concentrated flows may occur in the field and simulating such situation will lead to modeling complications. Field experiments will be helpful to estimate the uncertainty of the effectiveness of filter strips. However, with filter strip area of 10% or higher, it gives some confidence that the concentrated flows will be minimized. A monitoring system at regular interval will further take care of the occurrence of concentrated flow in the field.

4. Conclusions

SWAT model was used to investigate the fate and transport of NO_3-N in an agricultural watershed through a contour strip, placed mid-way of the slope, and a riparian buffer strip planted with perennial vegetation such as switchgrass. In this study, the hillslope descretization feature of SWAT was employed to simulate the contour and riparian buffer strips and their effects on NO_3-N yield.

High impact subbasins were identified based on NO_3-N contribution per unit area (kg/ha) and total NO_3-N contribution (kg) from each subbasin of the Walnut Creek watershed. Subbasins 11, 13, 14, 19 and 20 were found to contribute most to the river on the basis of per-unit-area NO_3-N yield; while subbasins 4 and 8 were identified as big contributors in term of total NO_3-N yield. These subbasins would be the priority subbasins in the watershed, which should be addressed first to have the maximum environmental impact with minimum economical effort.

Based on the evaluation of two filter strip locations, i.e. the contour strip placed midway in the subbasin and buffer strip along the river, contour strips were found to be more effective in both cases of subbasins 8 and 19. It can be concluded that it would be much effective to have multiple strips of perennial vegetation along the contour instead of having one riparian buffer strip.

Strip sizes of 10%, 20%, 30% and 50% of the subbasin area were considered for the simulations. In general, larger the size of filter strip, more was the reduction in NO_3-N outflow. However, the rate of NO_3-N reduction became milder when size of the strip was in 30-50% range. Filter strips having 10-20% area were found to be more efficient in case of contour strips whereas filter strips having 10-30% area were still considerably effective in case of buffer strips.

Results of hillslope SWAT application to the Walnut Creek Watershed, Ames, Iowa have shown that a filter strip having 10%-50% of the subbasin area with a perennial cover of switchgrass could potentially lead to 55%-90% NO_3-N reduction in outflows from the subbasin in an event of average rainfall year.

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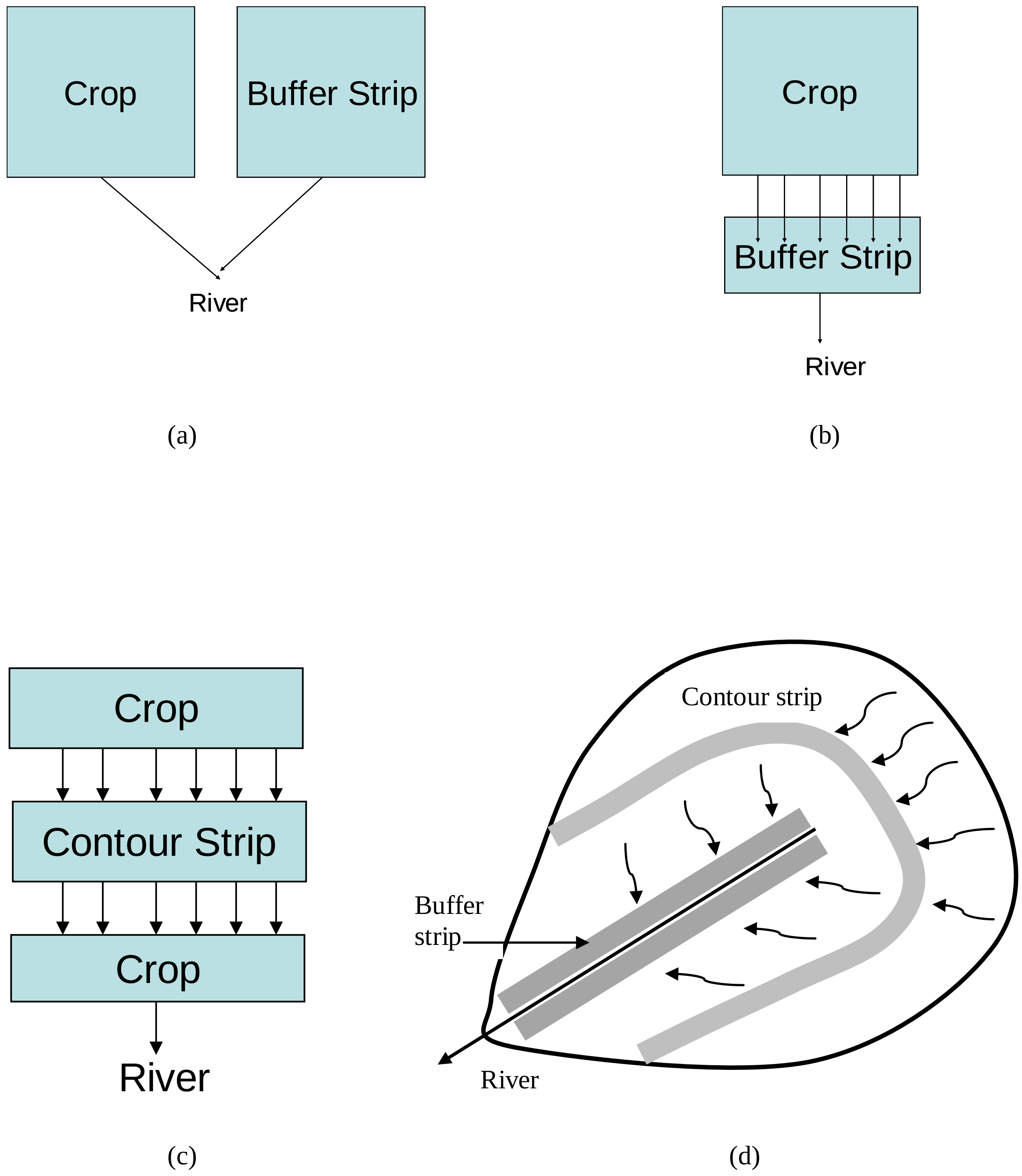


Figure 1. Flow scheme in SWAT for (a) default filter strip routine (b) Hillslope scheme for buffer strip (c) Hillslope scheme for Contour strip (d) A typical watershed having contour and riparian buffer strips

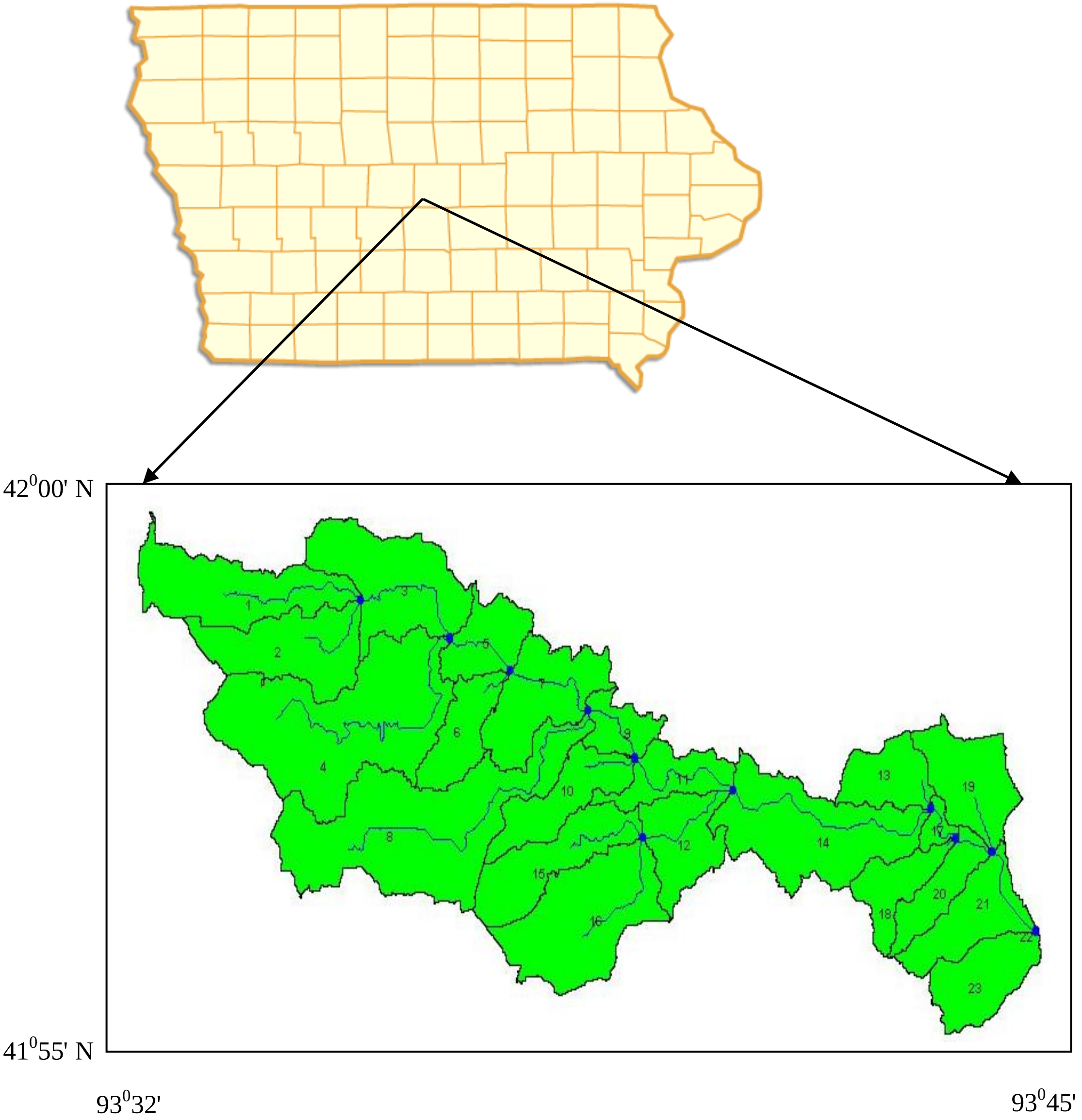
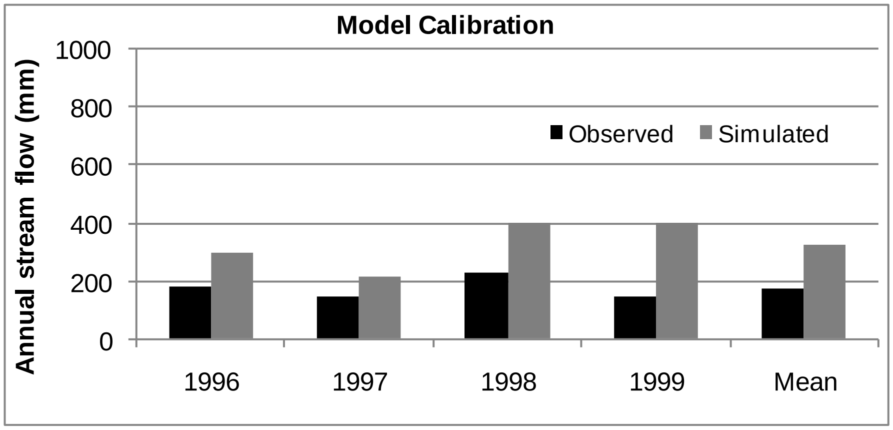
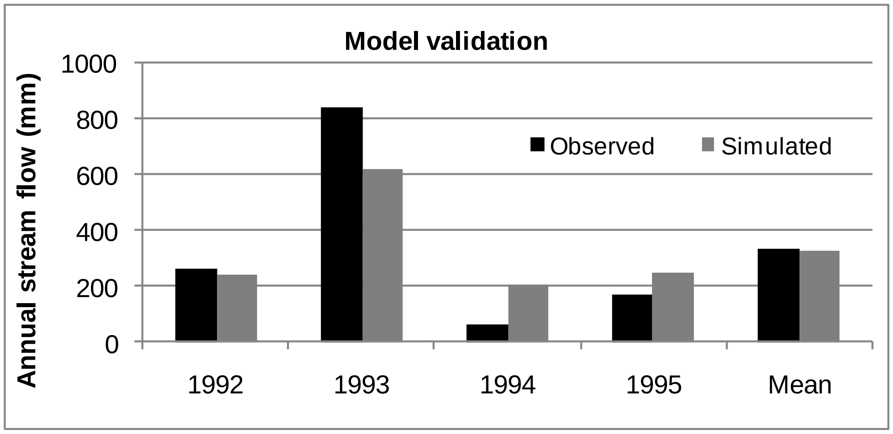


Figure 2. Maps of Iowa and the Walnut Creek Watershed with its subbasins delineated by SWAT

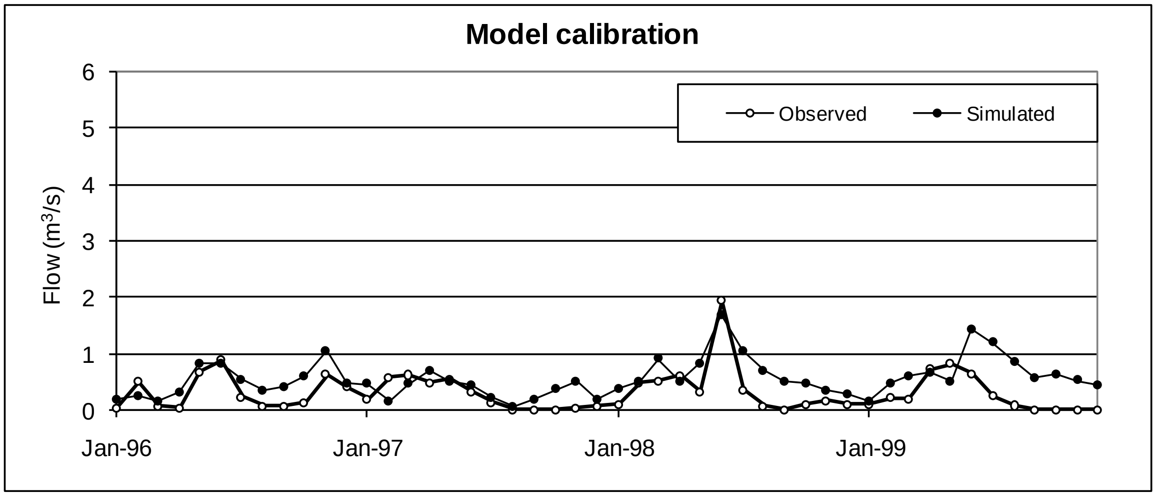


(a)

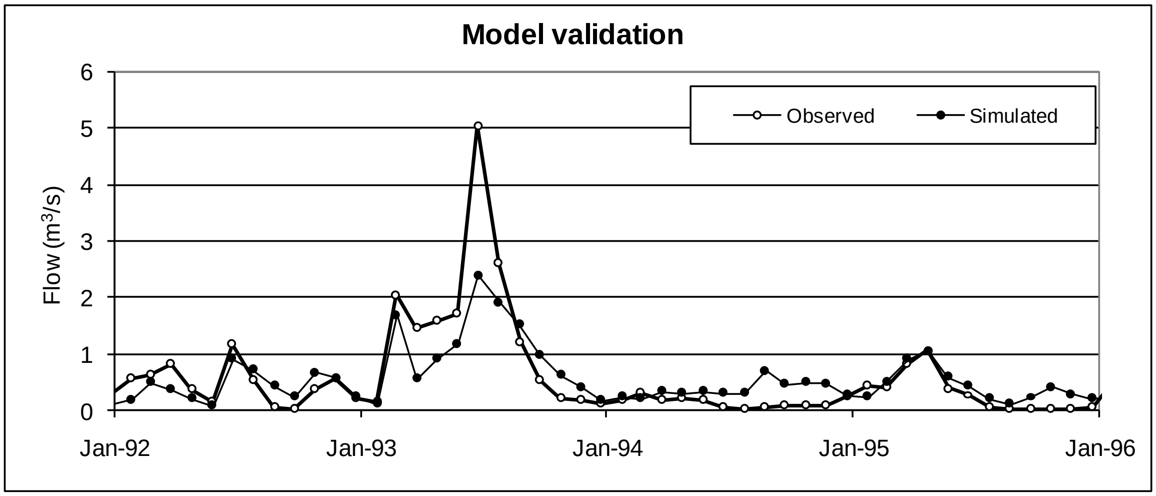


(b)

Figure 3. Observed and simulated flows (mm) in Walnut Creek Watershed (a) Model calibration (b) Model validation



(a)



(b)

Figure 4. Model calibration and validation – Time series of observed and simulated flows in Walnut Creek, Iowa

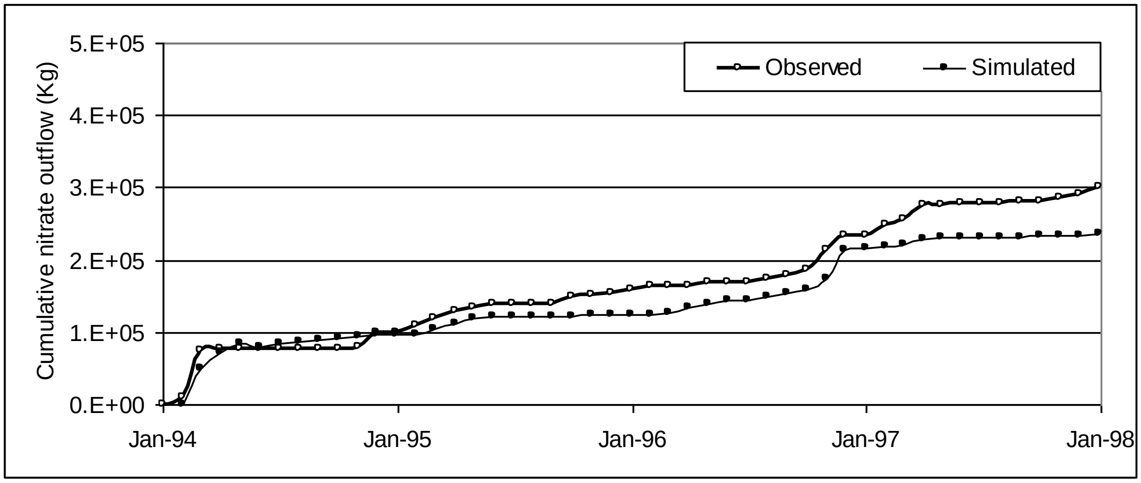


Figure 5. Observed and simulated cumulative NO_3-N outflows at the outlet of the Walnut Creek Watershed

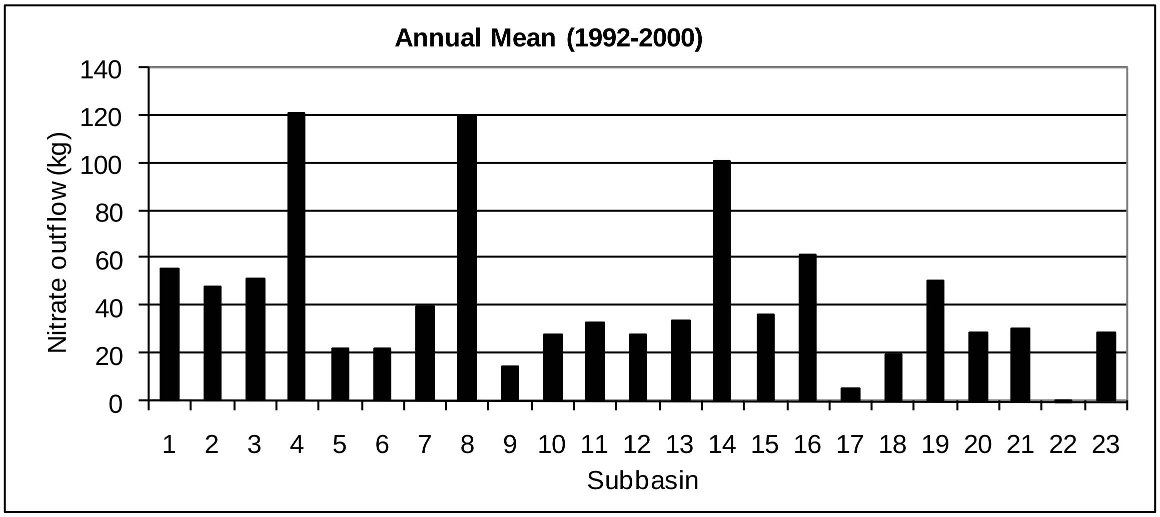


Figure 6. Simulated annual average of total NO_3-N outflow from each subbasin under existing land use/cover condition

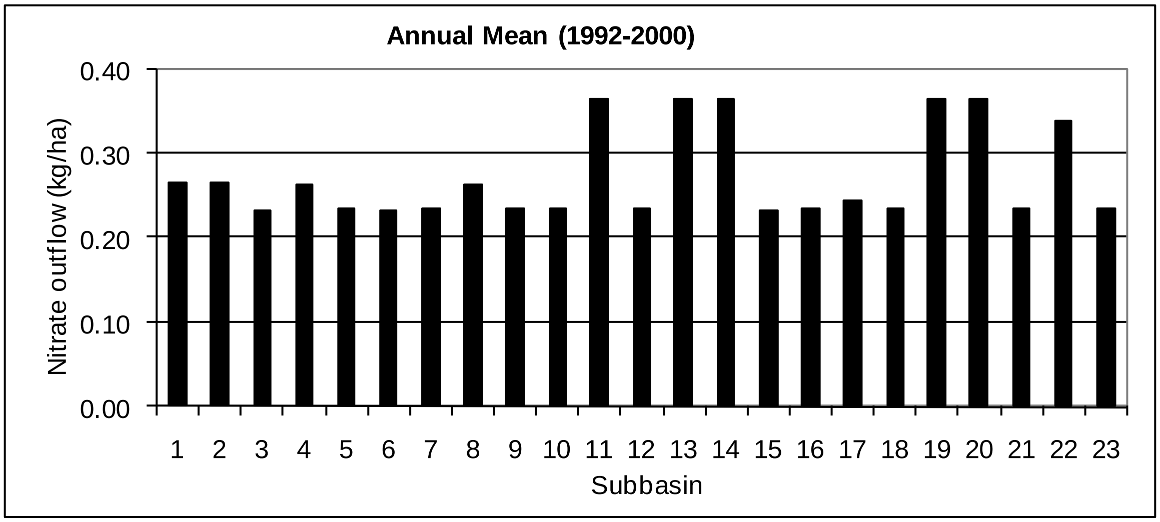


Figure 7. Simulated annual average of per-unit-area NO_3-N outflow from each subbasin under existing land use/cover condition

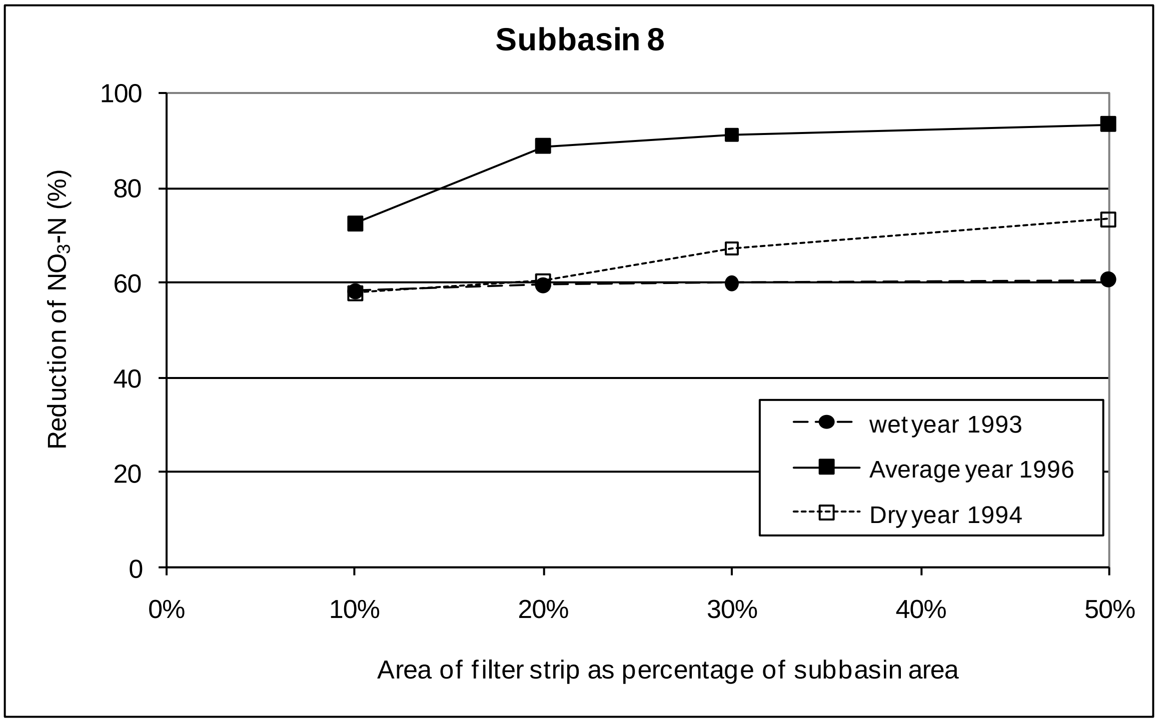


Figure 8(a). Reduction of NO_3-N contribution of subbasin 8 due to filter strip located midway of the slope

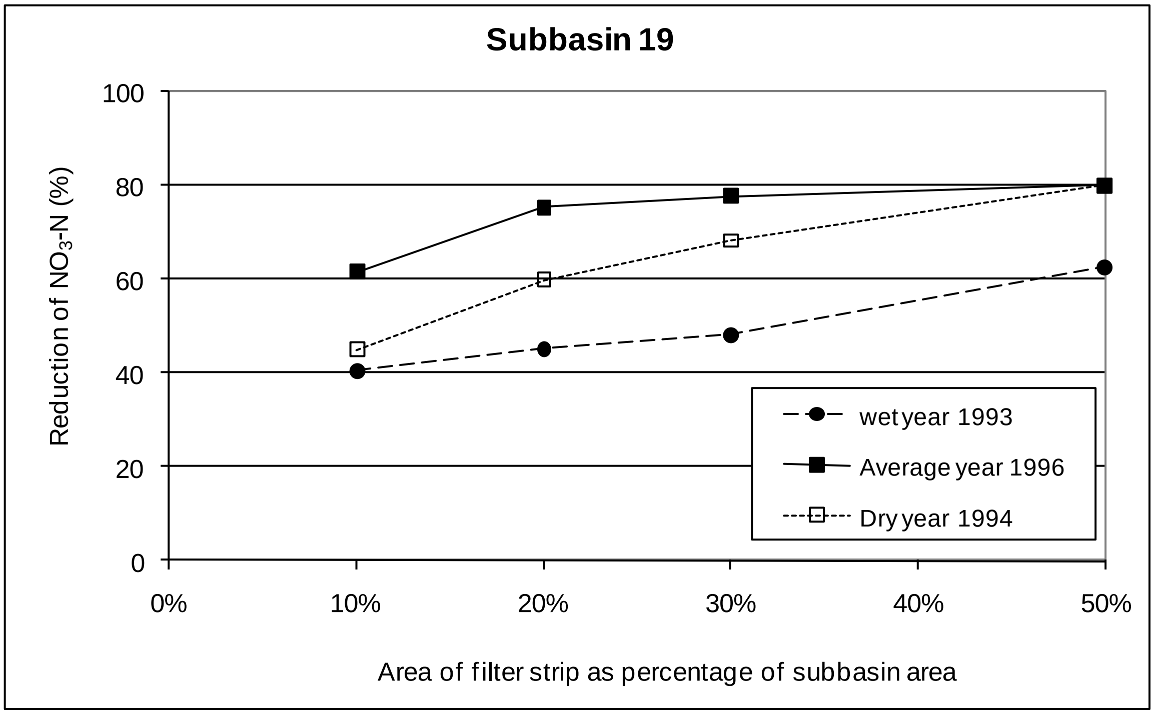


Figure 8(b). Reduction of NO_3-N contribution of subbasin 19 due to filter strip located midway of the slope

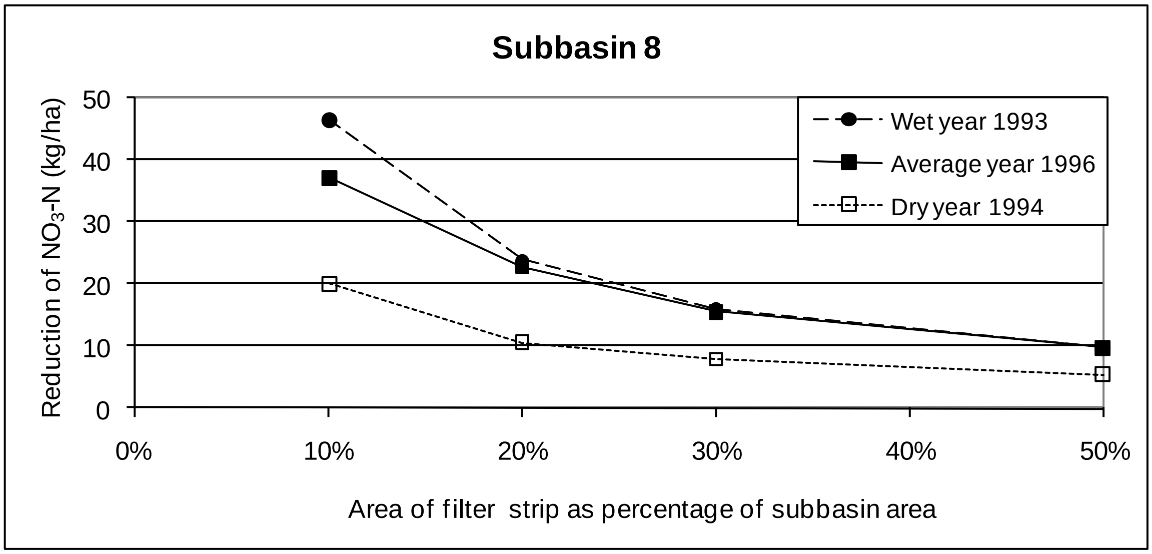


Figure 9(a). Reduction of NO_3-N per unit area of the contour strip for subbasin 8

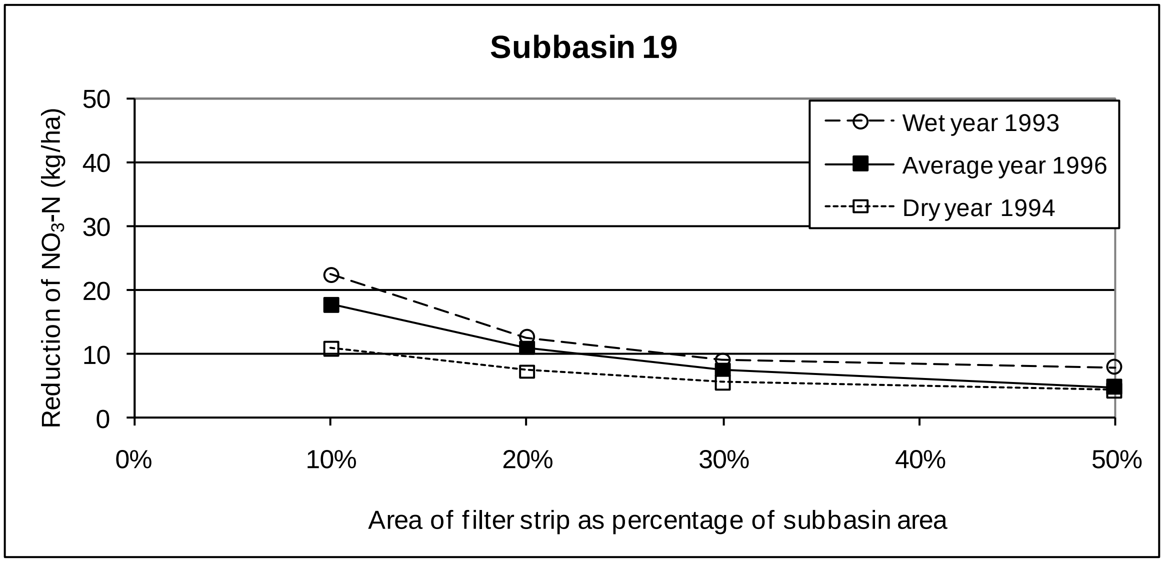


Figure 9(b). Reduction of NO_3-N per unit area of the contour strip for subbasin 19

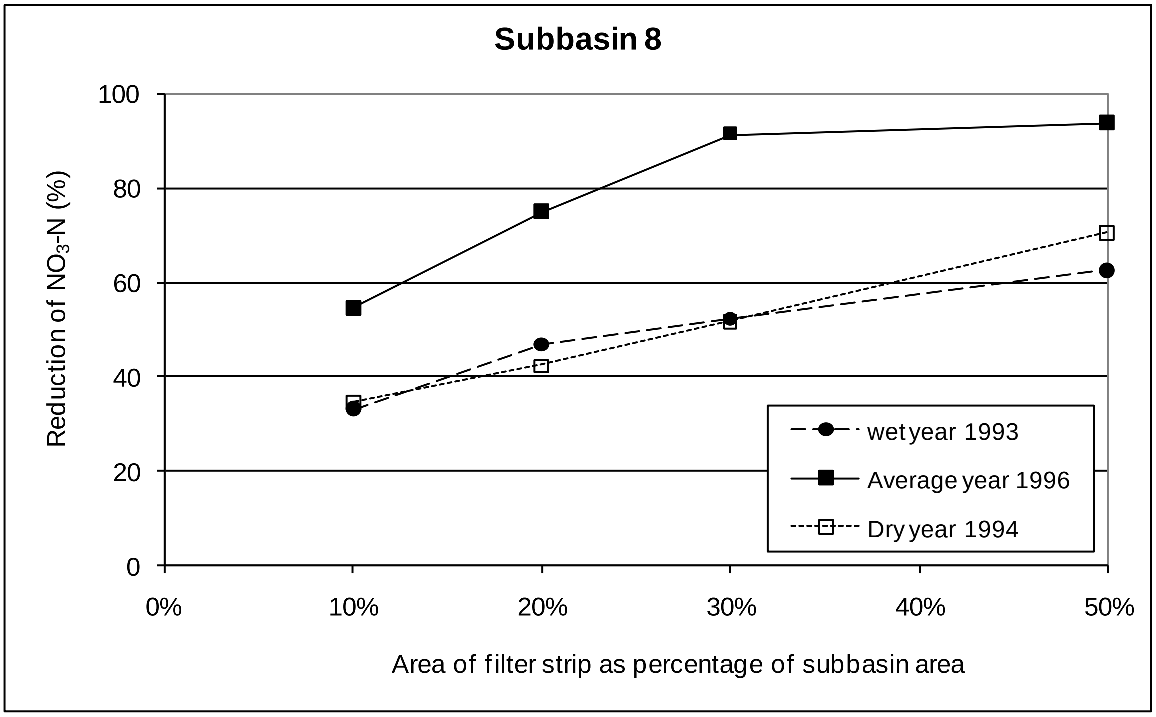


Figure 10(a). Reduction of NO_3-N contribution of subbasin 8 due to buffer strip located next to the river

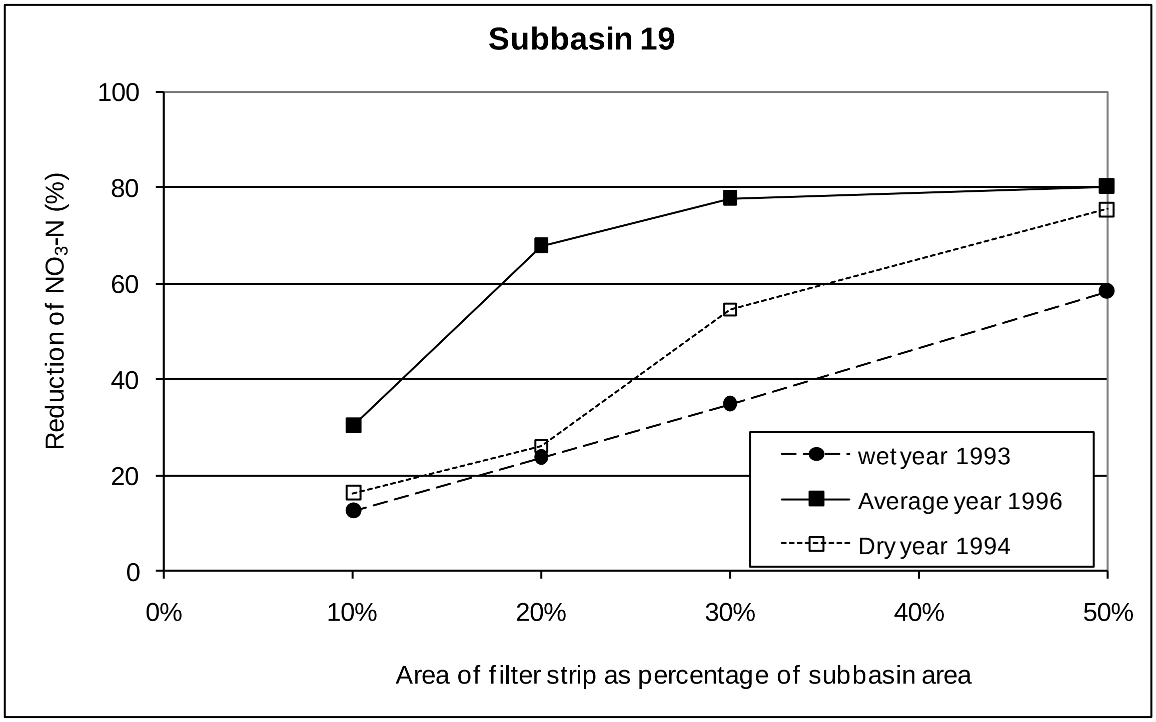


Figure 10(b). Reduction of NO_3-N contribution of subbasin 19 due to buffer strip located next to the river

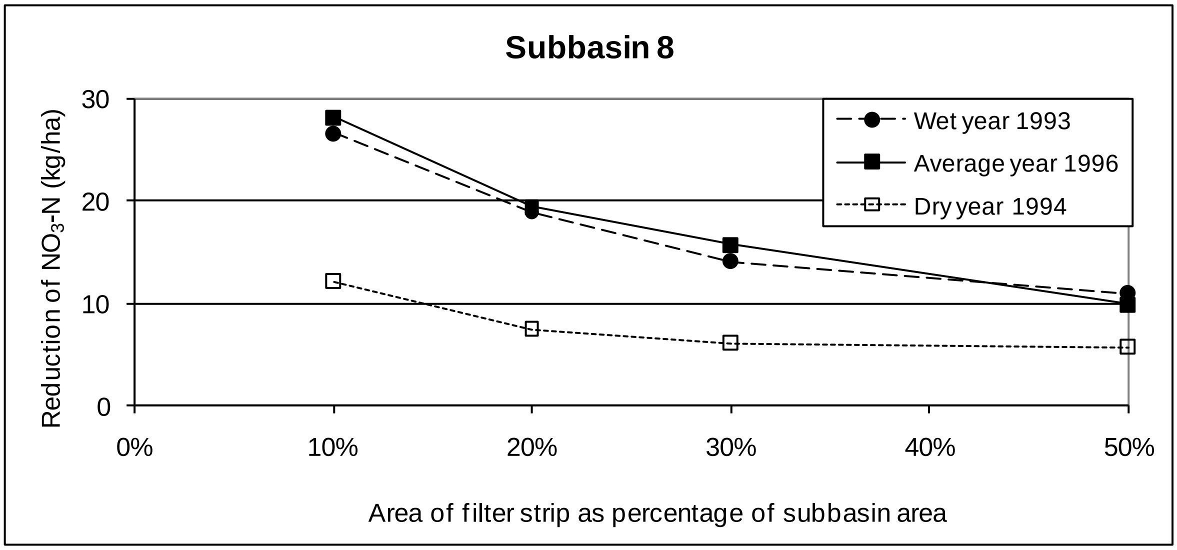


Figure 11(a). Reduction of NO_3-N per unit area of the riparian buffer strip for subbasin 8

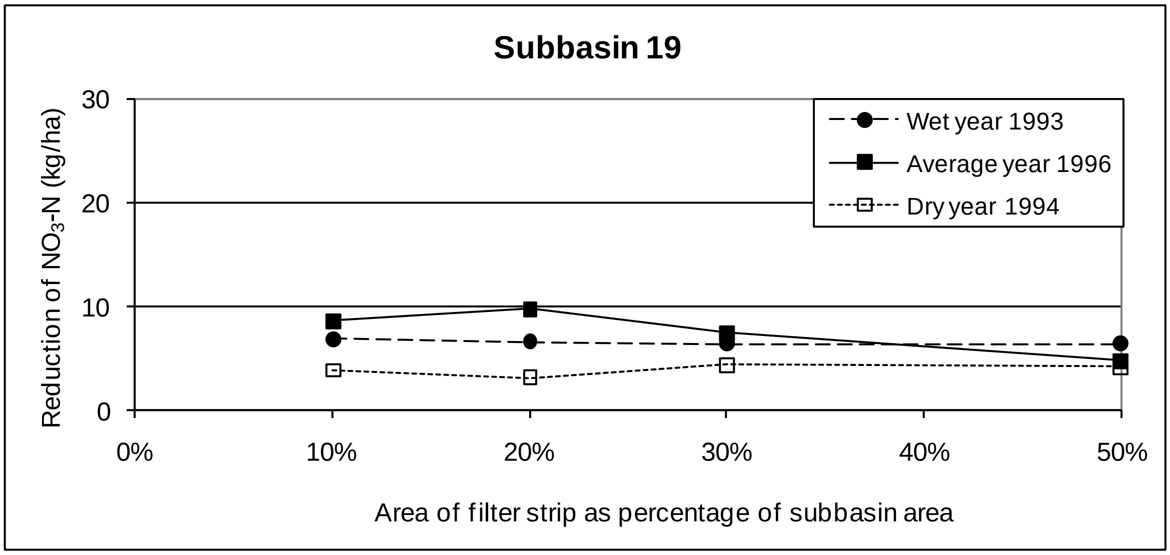


Figure 11(b). Reduction of NO_3-N per unit area of the riparian buffer strip for subbasin 19

Table 1 Characterizing parameters for subbasins of the Walnut Creek Watershed

Sub-basin	Area (km^2)	Channel length, (km)	Channel Density (km/km^2)	Slope	Slope Length (m)	Soil Type and Name	Land use
1	2.086	4.689	2.248	0.009	122.0	IA 111 Clarion	Agriculture
2	1.812	3.726	2.056	0.007	122.0	IA 111 Clarion	Agriculture
3	2.217	3.294	1.486	0.012	122.0	IA 110 Caniseto	Agriculture
4	4.581	6.920	1.511	0.008	122.0	IA110 (50%) + IA111 (50%)	Agriculture
5	0.938	1.666	1.776	0.015	122.0	IA 110 Caniseto	Agriculture
6	0.955	2.710	2.837	0.011	122.0	IA 110 Caniseto	Agriculture
7	1.687	3.124	1.852	0.015	122.0	IA 110 Caniseto	Agriculture
8	4.554	7.230	1.588	0.009	122.0	IA 111 Clarion	Agriculture
9	0.598	1.480	2.475	0.030	91.5	IA 110 Caniseto	Agriculture
10	1.189	3.015	2.537	0.019	122.0	IA 110 Caniseto	Agriculture
11	0.898	2.906	3.238	0.067	60.1	IA 115 Hayden	Agriculture
12	1.195	2.669	2.234	0.041	91.5	IA110 (50%) + IA111 (50%)	Agriculture
13	0.912	2.478	2.717	0.037	91.5	IA 115 Hayden	Agriculture
14	2.779	4.413	1.588	0.083	61.0	IA 115 Hayden	Agriculture
15	1.538	3.498	2.274	0.011	122.0	IA 110 Caniseto	Agriculture
16	2.609	3.690	1.415	0.017	122.0	IA 110 Caniseto	Agriculture
17	0.211	1.121	5.303	0.102	36.6	IA 115 Hayden	Forest
18	0.813	2.332	2.868	0.057	61.0	IA110 (60%) + IA115 (40%)	Agriculture
19	1.387	2.406	1.734	0.024	91.5	IA 115 Hayden	Agriculture
20	0.782	2.485	3.178	0.047	91.5	IA110 (50%) + IA115 (50%)	Agriculture
21	1.272	3.336	2.622	0.046	91.5	IA110 (50%) + IA115 (50%)	Agriculture
22	0.003	0.296	92.500	0.041	91.5	IA 119 Coland	Agriculture
23	1.214	2.275	1.875	0.046	91.5	IA110 (50%) + IA119 (50%)	Agriculture

Table 2 Simulated nitrate outflow from subbasin 8 for various contour strip areas

Filter strip area			NO_3 Output (kg)			NO_3 reduction per unit area of filter strip (kg/ha)		
sq. km	ha	% of subbasin	1993 (wet)	1996 (average)	1994 (dry)	1993 (wet)	1996 (average)	1994 (dry)
0.000	00.0	0%	3520	2260	1540			
0.439	43.9	10%	1480	626	653	46.6	37.2	20.2
0.878	87.8	20%	1430	258	611	23.8	22.8	10.6
1.317	131.7	30%	1420	205	508	16.0	15.6	7.8
2.195	219.5	50%	1380	126	365	9.8	9.7	5.4

Table 3 Simulated nitrate outflow from subbasin 19 for various contour strip areas

Filter strip area			NO_3 Output (kg)			NO_3 reduction per unit area of filter strip (kg/ha)		
sq. km	ha	% of subbasin	1993 (wet)	1996 (average)	1994 (dry)	1993 (wet)	1996 (average)	1994 (dry)
0.000	00.0	0%	764	398	331			
0.139	13.9	10%	455	153	182	22.2	17.6	10.7
0.278	27.8	20%	419	98	133	12.4	10.8	7.1
0.417	41.7	30%	396	88	105	8.8	7.4	5.4
0.695	69.5	50%	230	74	46	7.7	4.7	4.1

Table 4 Simulated nitrate outflow from subbasin 8 for various buffer strip areas

Filter strip area			NO_3 Output (kg)			NO_3 reduction per unit area of filter strip (kg/ha)		
sq. km	ha	% of subbasin	1993 (wet)	1996 (average)	1994 (dry)	1993 (wet)	1996 (average)	1994 (dry)
0.000	00.0	0%	3520	2260	1540			
0.439	43.9	10%	2360	1030	1010	26.5	28.1	12.1
0.878	87.8	20%	1880	570	892	18.7	19.3	7.4
1.317	131.7	30%	1690	197	749	13.9	15.7	6.0
2.195	219.5	50%	1150	118	310	10.8	9.8	5.6

Table 5 Simulated nitrate outflow from subbasin 19 for various buffer strip areas

Filter strip area			NO_3 Output (kg)			NO_3 reduction per unit area of filter strip (kg/ha)		
sq. km	ha	% of subbasin	1993 (wet)	1996 (average)	1994 (dry)	1993 (wet)	1996 (average)	1994 (dry)
0.000	00.0	0%	764	398	331			
0.139	13.9	10%	670	280	278	6.8	8.5	3.8
0.278	27.8	20%	584	128	246	6.5	9.7	3.1
0.417	41.7	30%	500	90	151	6.3	7.4	4.3
0.695	69.5	50%	325	74	46	6.3	4.7	4.1

CHAPTER 3. WATER QUALITY CONSERVATION FOR UMRB – TRANSITION FROM MICRO TO MACRO BMP'S BIO-FUEL DEVELOPMENT SCENARIO

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(A paper submitted to ASCE Journal of Water Resources Planning and Management)

Abstract

SWAT was applied to the Upper Mississippi River Basin (UMRB) to study the perpetuation of the current trend of growing corn to meet the increasing corn demand for ethanol industry. A hypothetical case of converting the entire UMRB agricultural land to corn was simulated by SWAT. Though very unlikely, this study provided a guideline to identify the highest nitrate contributing subbasins that could be used for switchgrass production. Such conversion would yield economic value from cellulosic ethanol and at the same time a significant improvement in water quality. High impact subbasins were identified based on the total nitrate output of each subbasin. Converting them to switchgrass production was found to reduce nitrate nitrogen yield of up to 14 kg/ha and sediment reduction of up to 5 tons/ha. In many cases, switchgrass reduced up to 71% of total nitrate nitrogen yield and almost 99% of sediment. The Production-Economy-Environment matrix analysis of growing switchgrass for various rates of fertilizer application and its consequences on yield and environment demonstrated that the efficacy of rate of fertilizer application and its relationship to economy and environment was not proportionate. It underscores the importance of such analysis to design an optimum amount of fertilizer or even the rate of

fertilizer application for a desired gain in environmental quality. Even though the economic benefits of bio-energy crops were marginal, the bio-energy crops are yet a potentially viable solution for the degrading water environment in the waterways of Upper Mississippi River Basin and the Gulf of Mexico. A simple economic analysis suggests that it is equally or even more profitable in many cases to grow switchgrass for cellulosic ethanol than corn for ethanol. The high nitrate yielding subbasins can be kept under switchgrass production while still getting all the economic benefits without any direct subsidy. If corn grains are only considered for ethanol, the production of switchgrass is more beneficial with minimum agricultural inputs compared to corn.

Introduction

The agricultural land of the Upper Mississippi River Basin (UMRB) is dominated by row crop cultivation such as corn and soybean. Excessive nitrate and sediment export from the area has been identified as a persistent problem, causing higher levels of nitrate nitrogen and reduced levels of dissolved oxygen (a hypoxic condition) in the aquatic environment of the region and the Gulf of Mexico (US EPA 1992; Rabalais and Turner 2006; Mitsch et al. 2001). Conventional Best Management Practices (BMP’s) referred as micro BMP’s in this study, consisting of riparian buffers, filter strips, engineered wetlands, grassed waterways, field borders etc, have been employed to reduce nitrate and sediment outflow from the agricultural land (Osborne and Kovacic 1993; Vache et al. 2002; Chaplot et al. 2004; Santhi et al. 2002; Syversen 2005; Sahu and Gu 2009). In spite of the research and application of conventional BMP’s, pollutant (nitrate and sediment) yield to the river and waterways continue to increase, resulting in the increased size of hypoxia in the Gulf of Mexico

(Rabalais 2008). The size of hypoxia (bottom water oxygen less than 2 mg/l) has increased from 8,500 km^2 in the year 2003 to 22,500 km^2 in the year 2007. The application of micro level BMP's is expensive, difficult to put in place and challenging to monitor at the field level. They may not be fully functional due to lack of maintenance (Dillaha et al. 1989). The presence of tile drainage, which is common in the Corn Belt, acts like a siphon and bypass the pollutants quickly and directly into the river. Randall and Mulla (2001) found that the subsurface tile drainage is a key conduit of nitrate transport to the Mississippi River. Micro BMP's thus become further less effective while taking the land out of production and farmers will be reluctant to put it on their farm without appropriate subsidy.

Recent development in bio-fuel technology leads into higher demands of grain for ethanol production. Corn ethanol is an attractive source of energy in terms of energy independence of the nation and cleaner air. Study conducted by USDA suggests that additional amount of land will be required to meet the corn demand of ethanol plants and that farmers have already started to respond to this. One study in Iowa showed that farmers had 17% increased land under corn in 2007 compared to the previous year (USDA Baseline Projection 2007), and the researcher believed that the trend may continue to grow. Therefore, where will the additional acreage of corn land come from? The majority of USDA baseline projection of 90 million acres required to meet the ethanol and other demands by 2010 would come from the Midwest, possibly converting the typical corn-soybean rotation to continuous corn production and from other crops. Increased farming of the row crop will increase the export of nitrate and sediment to the waterways of Upper Mississippi River Basin (UMRB), ultimately contributing to the hypoxia in the Gulf of Mexico.

Here the problem appears to be threefold – the existing problem of excessive nutrient and sediment from the agricultural land, mitigation measures (micro BMP's) not working effectively and additional nutrient and sediment to come from the increased row crop farming for ethanol.

Therefore, alternative ways of farming that can replace the row crops (rotation of corn-soybean) needs to be evaluated for water quality protection and improvement. One such emerging option is bio-mass yielding crops such as switchgrass or hybrid grasses that can be used for cellulosic ethanol production. Switchgrass or other bio-mass yielding crops can be grown with minimum agricultural inputs to reduce nutrient and sediment export to the water bodies while still being able to supply the needs of ethanol. The benefits of such conversion will be multifold – such as reduction of nitrate and sediment yield to the river resulting in better water quality, economic benefits of producing ethanol, and economic benefits on not requiring heavy subsidy. Farm subsidy may or may not be required at all. From the environmental perspective, cellulosic ethanol from switchgrass is found to produce 540% more renewable energy than the nonrenewable energy consumed, and burning of cellulosic ethanol produces 94% less greenhouse gas (GHG) compared to GHG from gasoline (Schmer et al. 2008). While the economic outputs of corn and switchgrass in terms of ethanol production needs to be compared to design the subsidies, the environmental benefits are significant in terms of water quality, greenhouse gas emission and direct carbon sequestration contributing positively to the global climate change. From the farm management perspective, it will be cheaper planting operation for the farmers to grow switchgrass, and it will be much easier for the authorities to monitor. It is referred as macro level Best Management Practices

(Macro BMP's) in this study where a large area will be converted to managed bio-energy yielding switchgrass production.

The objectives of this study are (1) to simulate the likely water quality due to perpetuation of the current trend of increased corn production, (2) to identify the locations where additional corn can be grown to meet the increasing grain demand for ethanol that will have least impact on water quality in terms of nitrate and sediment, and (3) to evaluate the environmental and economic benefits of macro BMP's, i.e. replacing the corn by switchgrass production that can be used for cellulosic ethanol. The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) is used in this study to simulate the alternative land use scenarios of the Macro BMP's. A simple economic model is adopted to compute the ethanol equivalents of corn and switchgrass to assess the economical aspects of macro BMP's. A Production-Economy-Environment (PE^2) matrix analysis study is carried out to examine the effects of varying agricultural inputs and its effect on yield and environment. The three dimensional evaluation matrices will yield an instrument where the impact of choosing the value of one parameter in a certain range can be evaluated on other dimensions. It is anticipated that the conversion to switchgrass will yield better water quality while still bring the economic benefit of ethanol production which may encourage the production of switchgrass or other biomass yielding crops.

Materials and Methodology

SWAT

The Soil and Water Assessment Tool (SWAT) is a comprehensive watershed scale model that can simulate the hydrological processes along with nutrient, sediment and pesticides in a watershed and river network. It is a physically based model that works well for the long term continuous simulation of watershed with different land use and climate scenario. In this model, the watershed is divided into sub-watersheds and then into Hydrologic Response Units (HRU's) with similar soil type, land use and management practices. Thus a very high level of spatial details can be incorporated at the watershed, sub-watershed and/or HRU level (Arnold et al. 1998; Neitsch at al. 2002).

The model takes account of water balance at HRU level and routes through the main channel of a subbasin by Muskingum method. Surface runoff is estimated by modified SCS curve number method. SWAT uses the modified universal soil loss equation (MUSLE) (Williams and Brendt 1977) to calculate the sediment yield for each HRU. Crop growth in the model is estimated by simplified EPIC crop model (Williams et al. 1984). SWAT uses the concept of phenological crop development based on daily accumulated heat units, interception of solar radiation, harvest index for partitioning grain yield, and water and temperature stress adjustments to compute the potential biomass. SWAT can simulate both annual and perennial crops. Annual crop grows from planting to harvest date where as the perennial crop maintain their root system throughout the year but plant becomes dormant after certain temperature. Crop yield is rarely compared and matched in SWAT modeling; however, the model yields for crop and biomass are comparable with the typical yield in the region.

Study area: Upper Mississippi River Basin

Upper Mississippi River Basin has been chosen in this study to evaluate the impact of the perpetuation of corn production and alternative farming system to replace the corn ethanol by cellulosic ethanol. A baseline scenario is established for the present land use, management and climate data scenario. SWAT model has been set up, calibrated and validated by Jha et al. (2004) for the entire Upper Mississippi River Basin. Fig. 1 shows the UMRB and its 131 subbasins (8 digit HUC's) delineated by SWAT. The 131 subbasins contain 2730 hydrological response units (HRU) that has similar land use and soil type. The UMRB database system developed by Jha et al. (2004) is used in this study.

UMRB has a drainage area of 492,000 km^2 and includes parts of Minnesota, Wisconsin, Iowa, Illinois and Missouri. Landscape is dominated by agriculture such as row crop production of corn and soybean followed by pasture land. Heavy tile drainage is present in parts of Minnesota, Iowa and Illinois

Simulation Scenarios

<u>Perpetuation of Current Trend</u>

A typical cropping trend in Iowa and Upper Midwest is the alternative corn and soybean rotation. However, grain demand for ethanol industry is shifting the cropping pattern of the region. Baseline projections of USDA reported that acreage moved back to corn are more likely to come from the Midwest regions as well as from the crop rotations. In the same study, an increase of 19% in the corn acreage was reported for Iowa in 2007 compared to 2006. However, the increased corn production will lead to poor water quality in terms of nitrate and sediment. Modeling the perpetuation of current trend will evaluate the likely water quality degradation due to increased corn production. All the cropland in this scenario is converted to continuous corn and water quality impacts of each subbasin is evaluated.

Another question is where should the additional amount of corn be grown within the vast area of UMRB? Answer to this would be to grow it in the area that will have least nutrient and sediment yield. Perpetuation of current trend study will answer this question as well.

High Impact Subbasins

Few watersheds such as Raccoon River and Walnut Creek watersheds (which are part of UMRB) have already been identified as high nitrate yielding regions. Identifying other high nitrate yielding subbasins will flag the potential candidates (the high impact subbasins) as focus area for water quality improvement plan.

Macro BMP's and Bio-fuel Scenario

The crop area of high impact subbasins is converted to switchgrass instead of existing crops. It is expected that the water quality in terms of nitrate and sediment outflow will be improved under the bio-fuel scenario. Nitrate and sediment yields of the two different land use will be compared.

Economic Analysis

A simple economic analysis will be carried out to evaluate the monetary return from bio-fuel produced from corn and switchgrass grown on the same land and will be compared along with the nitrate and sediments. Difference between the two will be the cost of environmental protection. That will help evaluate the economic feasibility of growing switchgrass for bio-fuel and designing the farmer compensations program based on the cost of environmental benefits.

Production-Economy-Environment Matrix

A Production-Economy-Environment (PE^2) Matrix analysis will be developed for different amounts of fertilizers applied to the switchgrass to assess its effect on production and environment (nitrate export). It will be useful tool in devising optimal fertilizer application and design farm subsidy program if needed.

Results and Discussion

SWAT simulations of the UMRB under the existing conditions of land use, management practices and climate were carried out for twenty four years (1981 to 2004). Historical weather data were used to drive SWAT model. A base-line scenario was established using current management practices to which the results of various simulation scenarios were compared.

Perpetuation of the Current Trend

All the agricultural land in the subbasins was hypothetically converted to continuous corn with the current typical fertilizer input of 256 kg/ha. Fertilizers were applied either in two applications (fall and spring) or in one application before planting. Land use under non-crop sections such as urban, pasture, forest etc. was kept unchanged. SWAT simulations were conducted for the period of 1981 - 2004. Comparisons of the results with the baseline scenario for nitrate are shown in Fig. 2 (a) and (b) and for sediment in Fig. 3 (a) and (b). It shows serious water quality degradation in terms of nitrate and sediment. Some of the subbasins would be yielding as high as 5000 tons of additional nitrate nitrogen and up to 700,000 tons of additional sediment annually compared to the base line scenario if they are kept under continuous corn. It was found that the highest total nitrate contributing subbasins and highest per unit area nitrate contributing subbasins are not the same. It is because of the difference in the area of the agricultural land in particular subbasins. Subbasins were found to respond differently to the continuous corn, depending on characteristics of the subbasin such as soil type, slope, geometry etc. This result provides a hierarchy of the subbasins based on their additional nitrate and sediment yield if they are kept under continuous corn.

From these results, candidates for conversion to corn only production can be selected as the low additional nitrate yielding subbasins. Higher additional nitrate yielding areas must not be kept for additional acreage under corn. Compensation program for the farmers who want to grow additional corn but do not because their land falls in one of the high additional nitrate yielding zone can be developed on this basis. Required additional acreage under corn can thus be designed to minimize the nitrate and sediment yield, thus maximizing the benefits from the compensation program.

In this study of 131 subbasins, if there is requirement of increased area under corn, the additional acreage under corn should come from subbasin 123 and then move subsequently to subbasins 121, 124, 59 and so on according to their additional per unit area nitrate contribution (Fig 2(b)). It is very unlikely that the entire UMRB will be converted to continuous corn production; however this study provides a guideline for choosing additional corn acreage from the subbasins that have lowest per-unit-area nitrate contribution in hierarchical fashion. The high nitrate yielding subbasins could be kept under perennials such as switchgrass that can yield better water quality along with the ethanol benefits from switchgrass.

High Impact Subbasins

Subbasins having the highest total nitrate yield from the baseline scenario are considered as the high impact subbasin presuming that they will be the target candidates for water quality conservation program. Twenty four year annual average nitrate contributions of each individual subbasin (Fig. 4) were considered for this ranking. Table 1 shows the list of three groups of high impact subbasins. There are four subbasins in the first group of high impact subbasins contributing over 7,000 tons/year of nitrate. Second group of high impact subbasins consists of ten subbasins contributing 5,000-7,000 tons/year of nitrate. Third group consists of fourteen subbasins contributing 3,000-5,000 tons/year. For this study, only these three groups of subbasins consisting of twenty eight subbasins were considered. Subbasins contributing less than 3000 tons/year were not considered in this study for macro BMP’s.

Bio-fuel Scenario and MacroBMP’s: Conversion to Switchgrass

The four group I high impact subbasins were converted to switchgrass production instead of corn or soybean. Anhydrous ammonia application of 156 kg/ha were considered for all the subbasins studied for this purpose. Nitrate and sediment yield of each subbasin were compared to the baseline scenario (Fig. 4). Fig. 5 (a), (b) and (c) show the per unit area reduction of nitrate due to conversion of current practices of corn and soybean to switchgrass production. Listed in Table 2 are the per unit area, total and percentage reduction of nitrate due to the conversion of current practices of corn and soybean to switchgrass production. Fig. 6 (a), (b) and (c) display per unit area reduction of sediment due to conversion of current practices of corn and soybean to switchgrass. Presented in Table 3 are the per unit area, total and percentage reduction of sediment after the conversion of current practices of corn and soybean to switchgrass. It was found that there is significant reduction of both nitrate (up to 71.4%) and sediment (up to 99%) yield of the subbasin because of macro BMP's.

Reduction of nitrate by switchgrass is mainly due to reduced input of nitrate, modified runoff pattern from the land and less bare soil containing nitrate exposed directly to the rainfall. The root zone of switchgrass will be much denser due to the closely packed roots that will slow down the percolation of water and consequently reduce the amount of nitrate that is carried through the groundwater system into the river. The root zone of switchgrass thus delays and attenuates the surface runoff that retains the nitrate for relatively longer period resulting in the smaller loss of nitrate.

The comparison of switchgrass scenario to the baseline scenario demonstrates that switchgrass is very effective at reducing the sediment yield from the cropland. Almost 99% of the sediment is reduced compared to the base case of corn-soybean rotation. The process can be explained by that erosion is computed in SWAT by modified universal soil loss equation (MUSLE) that has many factors including land cover and management - it considers the canopy height and soil covering by the plant canopy. For row crop such as corn, canopy is high as well as there is enough bare soil between the rows. This means the rain drop will have high energy to disturb the soil particles to be eroded. Additionally the rain drops intercepted by corn canopy will ultimately fall down to the soil and will still regain higher energy compared to switchgrass. For switchgrass case, canopy is relatively short and it is so closely grown that less bare soil is exposed to get the impact of rain that imparts energy for soil erosion. Besides all these factors, the runoff pattern is attenuated by switchgrass since the curve number reduces. These factors combine together to attenuate the sediment yield.

Economic Analysis of Bio-fuel Development Scenario

A simple model was used to evaluate the economic benefits of switchgrass versus corn for ethanol production. The yield of both switchgrass and corn were multiplied by the conversion rate of 0.38 liter per kg of biomass and 0.4 liter per kg of grain (Renewable and Applicable Energy Laboratory 2007) to get the ethanol equivalent of switchgrass and corn. Since the whole plant of switchgrass can be used for ethanol production, not just the grain as in the case of corn, it was found that the switchgrass managed for bio-energy can produce even more ethanol compared to corn (Table 4). However, considering the corn stalks also being used for cellulosic ethanol production, the benefits from switchgrass and corn can be comparable. Schmer et al. (2008) reported that managed bio-energy crops such as switchgrass can have equal profitability with corn. Leaving the corn stalks on the field also protects the nutrient, reduces soil erosion and preserves soil moisture. Growing switchgrass instead of corn will, however, give better water quality which is of major concern at this time. Ethanol from corn grain and stalks will involve more harvesting operations and two different plants (cellulosic ethanol production plant and grain ethanol production plant) which may add more costs. Farm inputs for the production of corn will be higher compared to that for switchgrass that will be a topic of further research. Recent efforts have been to increase the use of bio-energy and protect the degrading water quality. Huge amount of money could have been spent on subsidy for CRP's but this study shows a positive result that economically beneficial and environmental friendly perennial crops such as switchgrass can be grown as managed bio-energy crop to meet the energy demand. Underlying assumption of this study is that production cost of grain ethanol and cellulosic ethanol is the same and could be studied in detail which is beyond the scope of this study.

The Production, Economy and Environment (PE^2) Matrix

Application of different rates of fertilizer to switchgrass production will affect the yield of switchgrass bio-mass and the resulting water quality. Higher fertilizer rates will give higher yield and hence more economical benefits but at the same time it yields more nitrate nitrogen to the river. Hence a relationship was established among the production, economy and environmental quality to evaluate the yield and water quality response of five different rates of 0, 52, 104, 156 and 208 kg/ha of anhydrous ammonia application for the production of switchgrass. Fig. 7 and Table 5 show the results of this analysis. Considering the yield corresponding to no fertilizer application as 100%, the yield increased up to 541% for 208 kg/ha of fertilizer application and the corresponding nitrate reduction changed from 91% to 26%. Considering a $2/gallon price of ethanol, the economical benefit increased from $4.46 billion to 24.2 billion dollars from the three groups of high impact subbasins listed in Table 3. From this study, it is shown that the economic benefits of growing switchgrass is significant compared to if the same land were under corn production (Table 4). Hence the additional environmental benefit can be converted to monetary equivalent to promote the research and development of cellulosic ethanol.

From the Production-Economy-Environment matrix in Fig. 7, it is found that increasing the fertilizer application by 28% (from 156 kg/ha to 200 kg/ha), there is only 25% increase in yield and about 20% less nitrate reduction. Similarly cutting the fertilizer to 95 kg/ha from 156 kg/ha (by 39%), there is about 120% loss of yield but 20% increase in nitrate reduction. So increasing the fertilizer by 28% adds only 25% to the yield but 20% increased nitrate export. However, for the same 20% gain in nitrate reduction, there will be a 120% loss of yield by reducing the fertilizer use by 39%. Thus this analysis can be very much beneficial in designing optimum fertilizer input or even to design the rate of fertilizer application for a desired gain in environmental quality. It can serve as a robust tool for the TMDL studies.

Conclusions

SWAT simulations were conducted for Upper Mississippi River Basin (UMRB) for the year 1981 -2004. The perpetuation of current trend of growing corn to meet the increasing corn demand for ethanol showed general water quality degradation in UMRB compared to the baseline scenario. The simple economic analysis suggests that it’s equally or even more profitable in many cases to grow switchgrass for cellulosic ethanol than corn for ethanol. The high nitrate yielding subbasins can be kept under switchgrass production while still getting all the economic benefits without any direct subsidy. If corn grains are only considered for ethanol, the production of switchgrass is more beneficial with minimum agricultural inputs compared to corn.

High impact subbasins were identified based on the total nitrate output of each subbasin. Converting them to switchgrass production was found to reduce nitrate nitrogen yield of up to 14 kg/ha and sediment reduction of up to 5 tons/ha. In many cases, switchgrass reduced up to 71% of total nitrate nitrogen yield and almost 99% of sediment. Economically beneficial and environmental friendly perennial crops such as switchgrass can be grown as managed bio-energy crop to meet the energy demand. However a more detailed economic investigation is needed to evaluate the economic benefits that were beyond the scope of this study.

The Production-Economy-Environment matrix analysis of growing switchgrass for various rates of fertilizer application and its consequences on yield and environment demonstrated that the efficacy of rate of fertilizer application and its relationship to economy and environment is not proportionate. It underscores the importance of such analysis to design an optimum amount of fertilizer or even the rate of fertilizer application for a desired gain in environmental quality. It is concluded that even though the economic benefits of bio-energy crops were marginal, the bio-energy crops are yet a potentially viable solution for the degrading water environment in the water ways of Upper Mississippi River Basin and the Gulf of Mexico. Despite the research work of decades, the problem seems to be increasing. With all the tile drains in, which siphons the nitrate nitrogen into the river very quickly; the conventional best management practices have not produced much satisfactory result. It is suggested that without investing too much money into it, and in fact having all of the economical benefits, the macro BMP’s suggested in this study will bring positive changes in the water environment of the region. The research can be further verified by comparison with the field experimental data and detailed economic analysis in future investigation.

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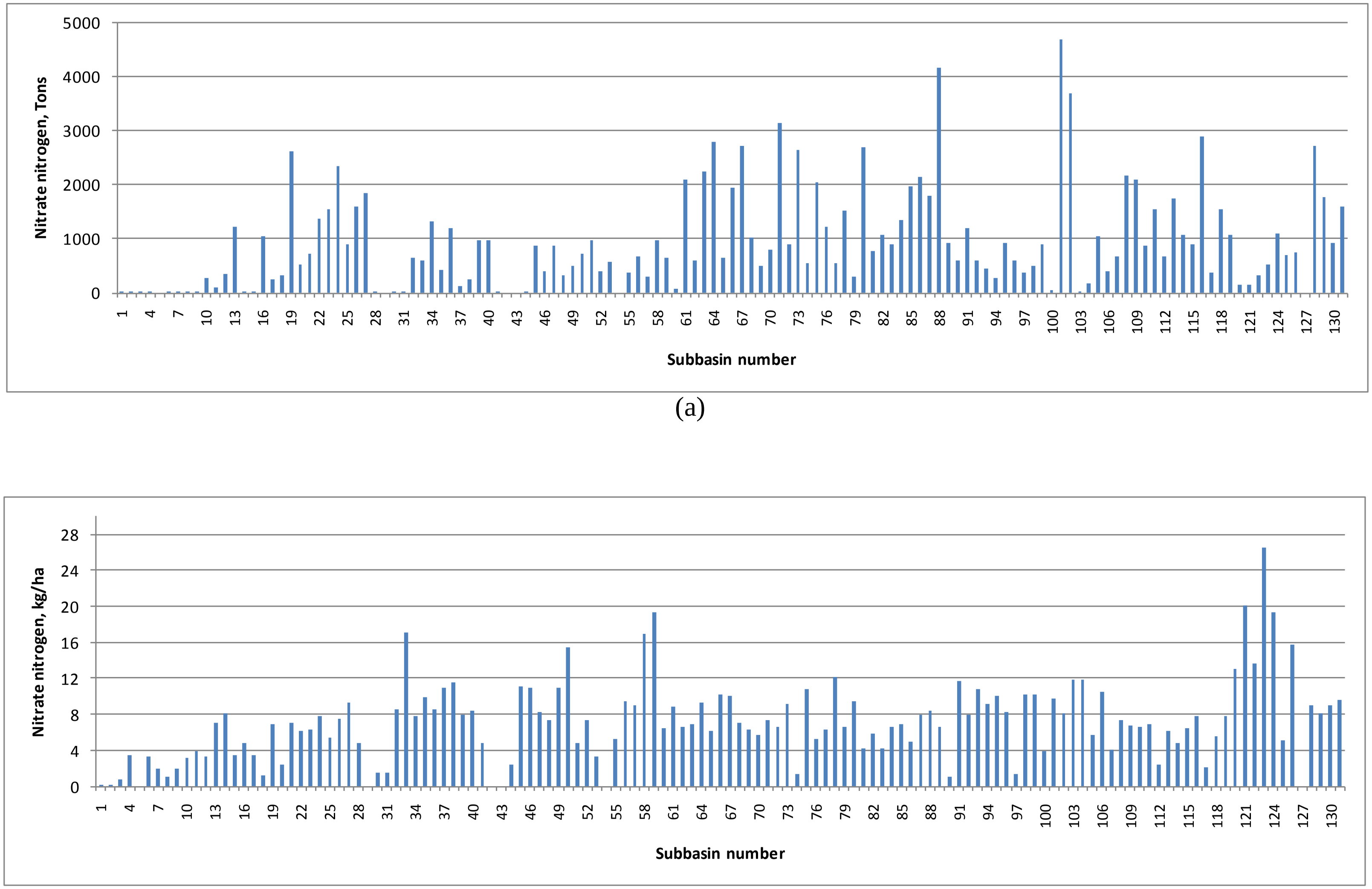
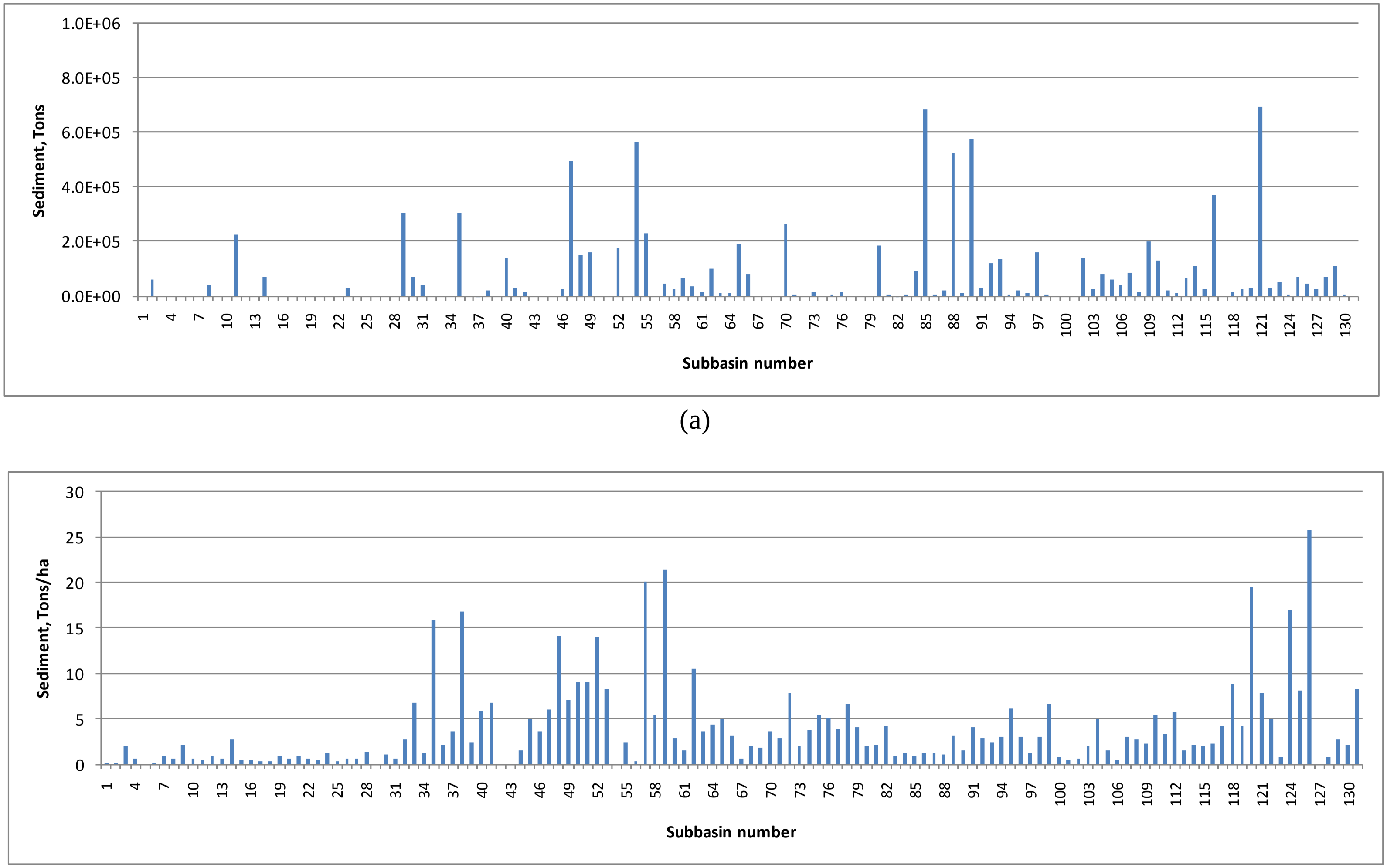
Figure 1 Upper Mississippi River Basin and sub-watersheds



(a)

(b)

Fig. 2 Additional nitrate contributions (compared to the baseline) of individual subbasins due to conversion of agricultural land to corn production only (a) Annual total (b) Per unit area



(a)

(b)

Fig. 3 Additional sediment contributions (compared to the baseline) of individual subbasins due to conversion of agricultural land to corn production only (a) Annual total (b) Per unit area

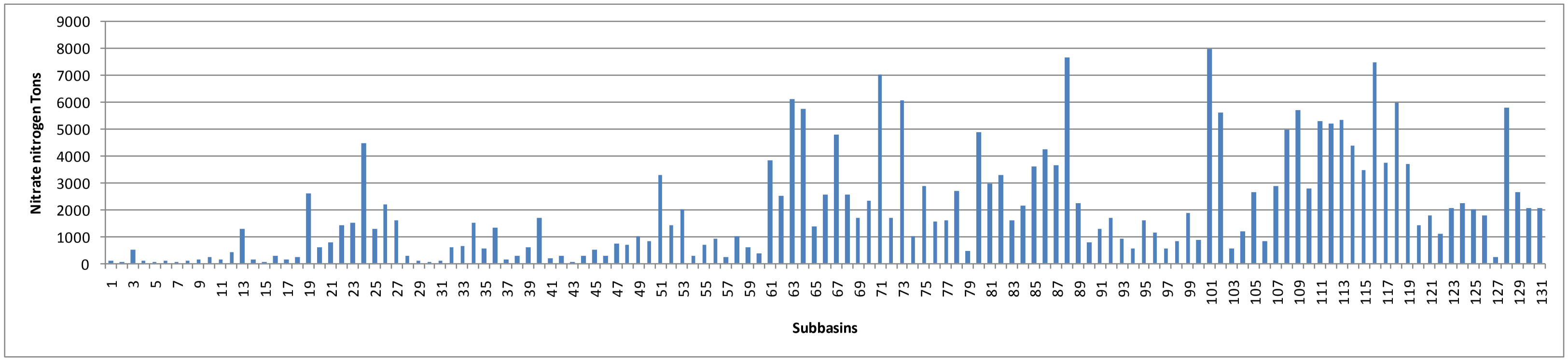
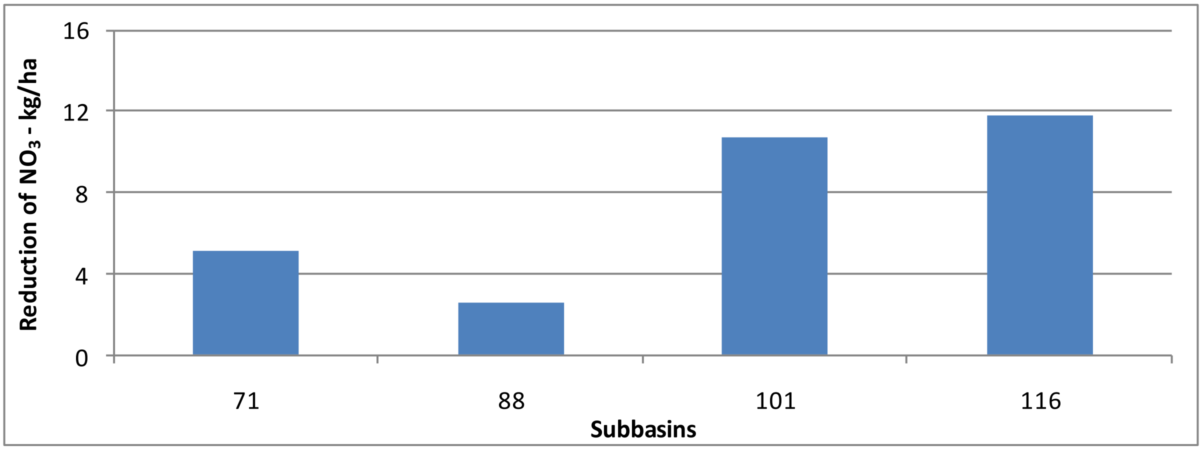
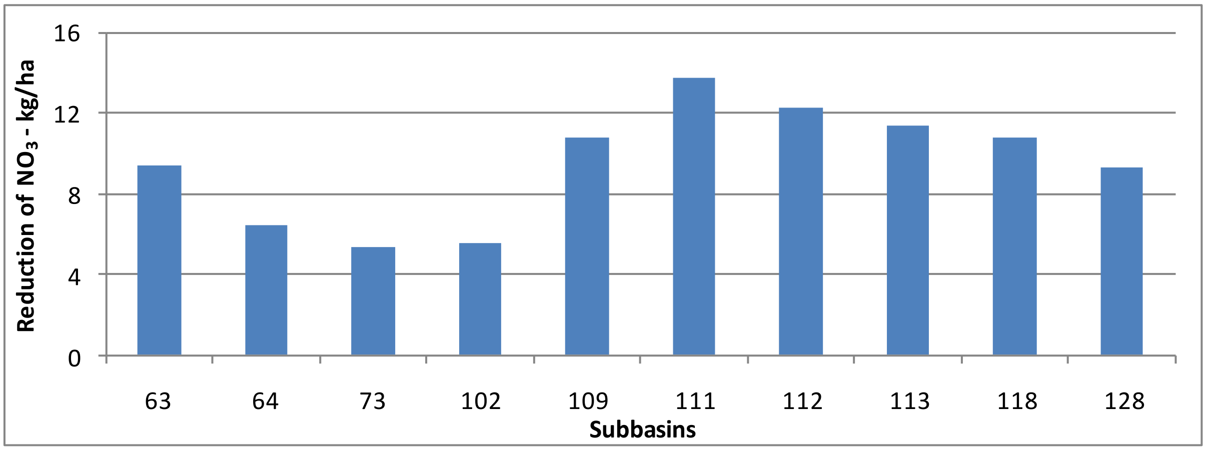


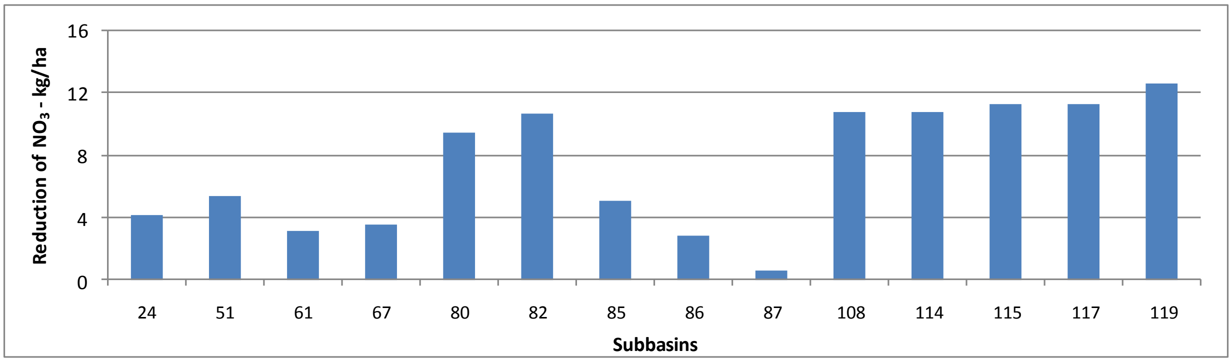
Fig. 4 Annual average (baseline) nitrate nitrogen contributions of individual subbasins (1981-2004)


Reduction of NO_3 - kg/ha
16
12
8
4
0
71
88
101
116
Subbasins

(a)

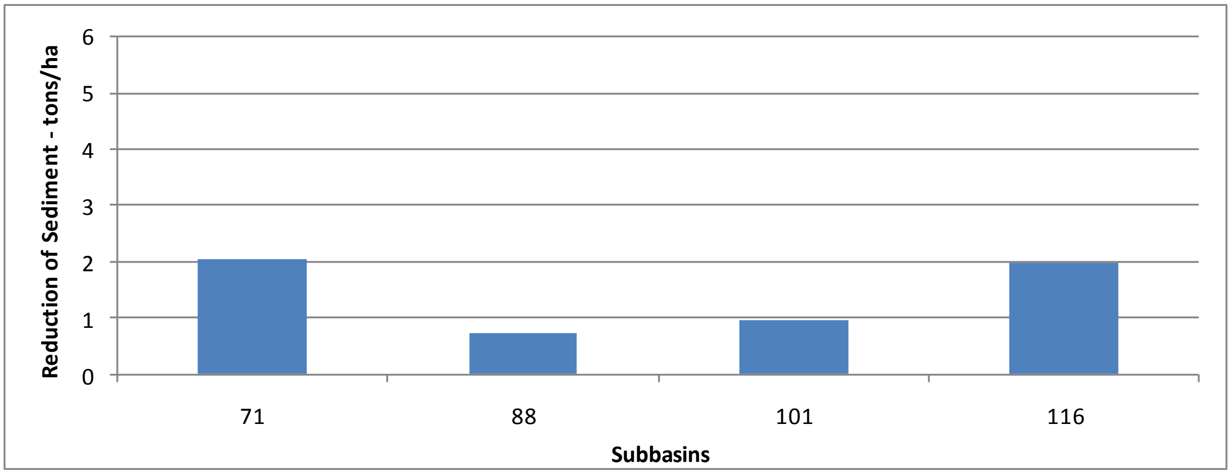

Reduction of NO_3 - kg/ha
16
12
8
4
0
63
64
73
102
109
111
112
113
118
128
Subbasins

(b)

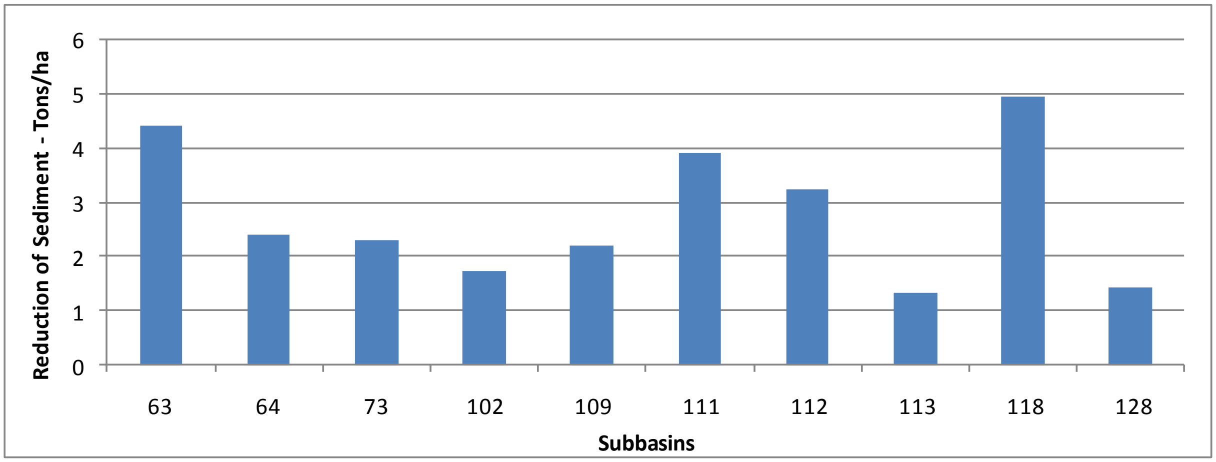


(c)

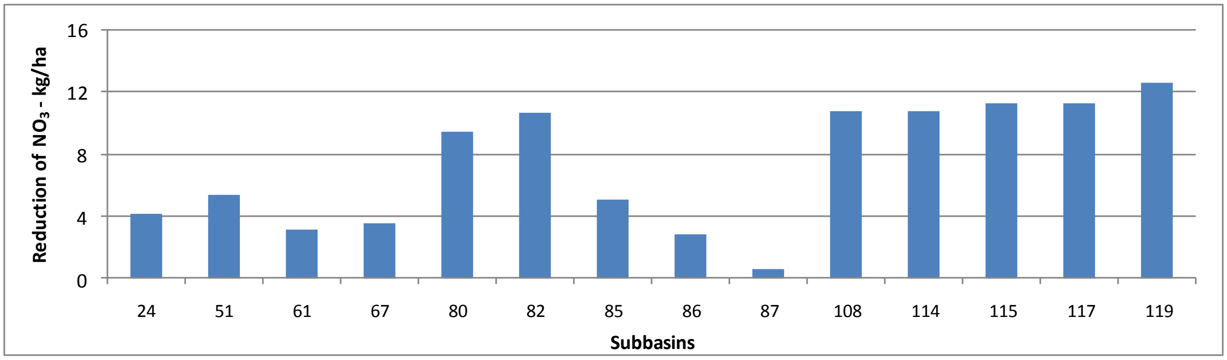
Fig. 5 Per-unit-area reduction of nitrate yield after the conversion of agricultural land of high impact subbasins to switch grass production (a) Group I (b) Group II (c) Group III


Reduction of Sediment - tons/ha
6
5
4
3
2
1
0
71
88
101
116
Subbasins

(a)


Reduction of Sediment - Tons/ha
6
5
4
3
2
1
0
63
64
73
102
109
111
112
113
118
128
Subbasins

(b)



(c)

Fig. 6 Per-unit-area reduction of sediment yield after the conversion of agricultural land of high impact subbasins to switch grass production (a) Group I (b) Group II (c) Group III

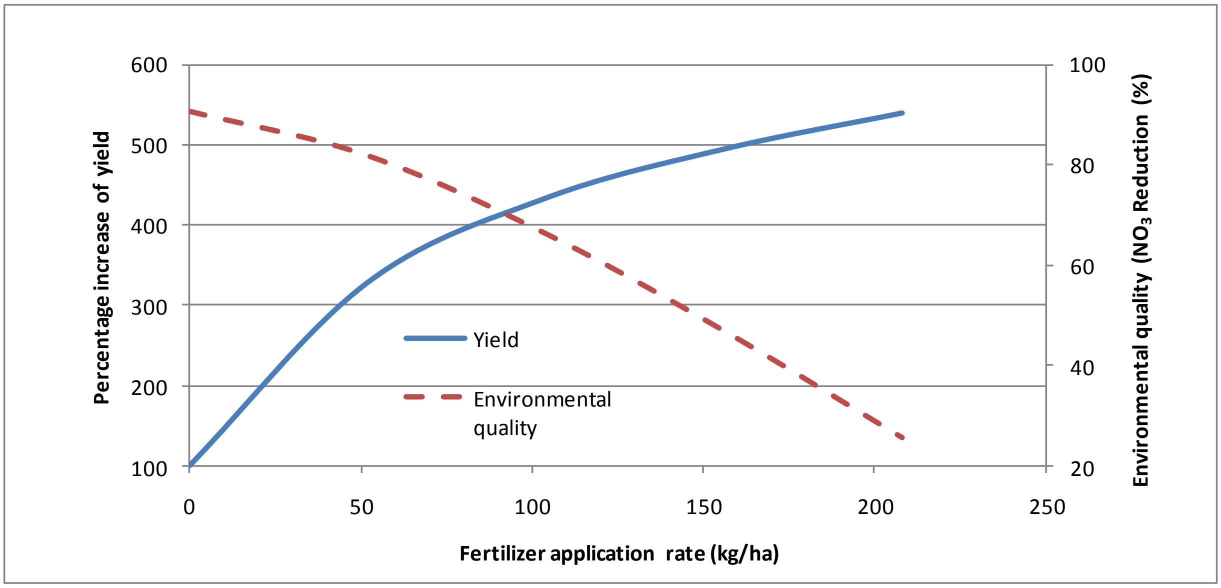


Figure 7 Production-Economy-Environment Matrix: Grass yield and nitrate reduction response of various fertilizer application rates for switchgrass production

Table 1 High impact sub basins

Group I – Nitrate Yield Over 7,000 tons/yr		Group II – Nitrate Yield 5000-7000 tons/yr		Group III – Nitrate Yield 3000-7000 tons/yr	
HUC	Subbasin no.	HUC	Subbasin no.	HUC	Subbasin no.
7080205	71	7080104	63	7020009	24
7100006	88	7080105	64	7060004	51
7120001	101	7080207	73	7080102	61
7130009	116	7120002	102	7080201	67
		7130002	109	7090005	80
		7130004	111	7090007	82
		7130005	112	7100003	85
		7130006	113	7100004	86
		7130011	118	7100005	87
		7140201	128	7130001	108
				7130007	114
				7130008	115
				7130010	117
				7130012	119

Table 2 Nitrate reductions due to high impact sub basin converted to switch grass

Group 1: High Impact subbasins converted to switchgrass				
	Nitrate Reduction			
Subbasin	**Area, km2**	**Total - kg**	**kg/ha**	**% Reduction**
71	4289.8	2.21E+06	5.1	34.2
88	4936.3	1.29E+06	2.6	17.4
101	4804.1	5.15E+06	10.7	68.9
116	3741.8	4.40E+06	11.8	60.8
Group 2: High Impact subbasins converted to switchgrass				
63	3217.8	3.04E+06	9.5	54.7
64	2998.9	1.93E+06	6.4	34.8
73	2883.4	1.56E+06	5.4	26.4
102	4555.9	2.52E+06	5.5	46.9
109	3107.9	3.35E+06	10.8	60.6
111	2259.9	3.11E+06	13.8	61.9
112	2861.0	3.51E+06	12.3	71.4
113	2859.3	3.24E+06	11.3	63.1
118	2839.7	3.07E+06	10.8	58.2
128	3005.2	2.79E+06	9.3	50.3
Group 3: High Impact subbasins converted to switchgrass				
24	3054.0	1.27E+06	4.2	29.0
51	2005.4	1.07E+06	5.3	34.9
61	2377.8	7.44E+05	3.1	21.9
67	2706.3	9.52E+05	3.5	21.2
80	2872.2	2.70E+06	9.4	62.2
82	1854.5	1.97E+06	10.6	62.4
85	2857.7	1.44E+06	5.0	40.4
86	4333.7	1.24E+06	2.9	29.1
87	2262.3	1.41E+05	0.6	3.9
108	2944.2	3.17E+06	10.8	67.1
114	2209.6	2.39E+06	10.8	55.7
115	1394.2	1.57E+06	11.2	48.3
117	1793.3	2.03E+06	11.3	59.0
119	1380.2	1.74E+06	12.6	53.2

Table 3 Sediment reduction due to high impact sub basin converted to switch grass

Group 1: High Impact subbasins converted to switchgrass				
	Sediment Reduction			
Subbasin	**Area, km2**	**Total - tons**	**Tons/ha**	**% Reduction**
71	4289.8	8.78E+05	2.0	97.9
88	4936.3	3.52E+05	0.7	98.4
101	4804.1	4.63E+05	1.0	98.5
116	3741.8	7.38E+05	2.0	98.2
Group 2: High Impact subbasins converted to switchgrass				
63	3217.8	1.42E+06	4.4	98.5
64	2998.9	7.15E+05	2.4	97.8
73	2883.4	6.61E+05	2.3	98.5
102	4555.9	7.89E+05	1.7	99.0
109	3107.9	6.84E+05	2.2	98.4
111	2259.9	8.83E+05	3.9	98.3
112	2861.0	9.29E+05	3.2	97.6
113	2859.3	3.78E+05	1.3	98.4
118	2839.7	1.41E+06	5.0	98.0
128	3005.2	4.28E+05	1.4	98.7
Group 3: High Impact subbasins converted to switchgrass				
24	3054.0	1.42E+06	4.7	98.8
51	2005.4	7.27E+05	3.6	96.6
61	2377.8	3.93E+05	1.7	98.4
67	2706.3	4.76E+05	1.8	98.9
80	2872.2	1.08E+06	3.7	98.8
82	1854.5	7.38E+05	4.0	98.6
85	2857.7	7.54E+05	2.6	98.9
86	4333.7	3.74E+05	0.9	98.3
87	2262.3	2.97E+05	1.3	98.5
108	2944.2	8.45E+05	2.9	98.6
114	2209.6	3.48E+05	1.6	98.4
115	1394.2	2.25E+05	1.6	98.1
117	1793.3	4.55E+05	2.5	98.1
119	1380.2	3.25E+05	2.4	97.5

Table 4 Economic analysis

	Yield (million tons)			Ethanol (million liters) from			Additional benefit due to switchgrass			
Subbasin	switch grass	Corn grain	Corn Biomass	Switchgrass	Corn grain	Corn Biomass	Ethanol (mil. ltr.)	Dollars (mil.)	NO_3 red. (tons)	Sed. red. (tons)
71	4.2	2.5	2.6	1586.9	984.6	1001.4	-399.1	-211.2	2207.0	8.78E+05
88	4.5	2.9	3.1	1720.0	1176.9	1194.8	-651.8	-344.9	1285.8	3.52E+05
101	5.5	2.3	2.5	2095.3	929.9	944.0	221.4	117.2	5146.8	4.63E+05
116	6.8	1.9	2.0	2584.1	745.7	760.9	1077.5	570.1	4398.9	7.38E+05
63	5.9	1.6	1.8	2238.8	655.9	667.8	915.1	484.2	3042.4	1.42E+06
64	4.0	1.6	1.8	1516.2	657.7	668.0	190.5	100.8	1928.3	7.15E+05
73	2.5	1.6	1.8	958.1	658.7	669.0	-369.7	-195.6	1557.0	6.61E+05
102	7.4	2.6	2.8	2819.0	1046.1	1062.8	710.1	375.7	2520.6	7.89E+05
109	5.2	1.6	1.7	1958.8	645.7	656.3	656.8	347.5	3353.4	6.84E+05
111	4.0	1.1	1.2	1509.6	453.5	460.9	595.2	314.9	3113.0	8.83E+05
112	4.1	1.6	1.7	1553.6	634.8	645.8	273.0	144.5	3506.0	9.29E+05
113	5.2	1.5	1.6	1991.2	595.0	605.8	790.3	418.1	3242.5	3.78E+05
118	5.6	1.5	1.6	2130.7	594.4	605.8	930.5	492.3	3066.8	1.41E+06
128	5.7	1.5	1.6	2184.2	613.6	624.3	946.2	500.7	2785.4	4.28E+05
24	1.7	1.8	2.0	637.6	733.6	744.6	-840.7	-444.8	1268.8	1.42E+06
51	1.0	1.2	1.2	369.6	462.7	471.7	-564.9	-298.9	1071.7	7.27E+05
61	1.7	1.4	1.4	647.3	540.7	549.4	-442.9	-234.3	743.8	3.93E+05
67	1.6	1.6	1.7	597.3	650.4	660.2	-713.3	-377.4	951.9	4.76E+05
80	4.9	1.4	1.5	1843.1	557.6	567.3	718.3	380.0	2703.4	1.08E+06
82	3.1	1.0	1.0	1162.1	392.3	398.7	371.1	196.4	1972.5	7.38E+05
85	2.1	1.8	1.9	790.2	710.3	720.4	-640.5	-338.9	1435.7	7.54E+05
86	3.4	2.0	2.1	1293.2	784.2	795.5	-286.5	-151.6	1242.0	3.74E+05
87	1.6	1.4	1.5	610.0	555.5	563.2	-508.8	-269.2	140.9	2.97E+05
108	4.9	1.4	1.5	1869.3	575.4	584.9	709.1	375.2	3174.7	8.45E+05
114	4.5	1.2	1.3	1716.4	470.6	479.6	766.1	405.4	2389.0	3.48E+05
115	2.8	0.7	0.8	1057.9	287.9	292.8	477.2	252.5	1565.5	2.25E+05
117	3.4	1.0	1.1	1276.2	397.0	403.6	475.6	251.6	2029.3	4.55E+05
119	2.7	0.7	0.8	1044.2	285.1	290.2	468.9	248.1	1737.3	3.25E+05

Table 5 The Production-Economy-Environment Matrix analysis

Fertilizer application (Kg/ha)	Switchgrass Biomass yield (mil. tons)	Ethanol (bil. ltr.)	Benefit from ethanol (bil. $)	NO_3 red. (x10^3 tons)	NO_3 red. (%)	Increase of yield (%)
0	22.2	8.4	123.0	123.0	91	100
52	73.0	27.7	111.0	111.0	82	329
104	96.4	36.6	89.9	89.9	66	434
156	110.0	41.8	63.6	63.6	47	495
208	120.0	45.7	34.7	34.7	26	541

CHAPTER 4. DEVELOPMENT OF SWAT HYDROLOGIC PARAMETERS FOR SPECIFIC IOWA LANDFORM REGIONS

Mahesh Sahu, Roy R Gu, Philip W Gassman, Manoj Jha, Keith E Schilling and Calvin F Wolter

(To be submitted to the Journal of the American Water Resources Association)

Abstract

Soil and Water Assessment Tool (SWAT) was set up, calibrated and validated for the Maquoketa (4867 km^2) and Beaver Creek (905 km^2) watersheds to develop SWAT hydrologic parameters specific to one of the six principal Iowa landform regions. These landforms (eco-regions) cover the majority of the intensively cropped regions in the state and are based on similar bio-physical characteristics that are assumed to have a corresponding specific range of SWAT input parameters unique to each one of them. Having a readily usable set of SWAT hydrological parameters would make the modeling part of Total Maximum Daily Load (TMDL) development easier. Using the observed data of 1995-2008, calibration of SWAT for Maquoketa gave the annual and monthly flow Nash-Sutcliffe's coefficient of efficiency (E) of 0.89 and 0.83 and R^2 value of 0.94 and 0.86. Without making any further changes to the model parameters, model validation on Beaver Creek gave the monthly flow E of 0.73 and 0.82 and R^2 value of 0.96 and 0.87 that was well over acceptable limit. A sensitivity analysis on Beaver Creek was performed by modifying the land use distribution similar to Maquoketa and the results showed that both the SWAT model was performing coherently on the two watersheds. Thus a SWAT hydrological parameter set was recommended for the Iowan Surface landform region.

Introduction

Selecting hydrologic parameters for physically based models has significant effect on model performance. Generally, measured values may not be available for all the parameters for the entire region of a watershed to be modeled and analyzed. Hence the model parameters are often calibrated with respect to the observed data on flow and other hydrological and water quality components. The Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998) is a physically based watershed scale model, which can be applied to large watersheds. This model uses a significant number of parameters to simulate the hydrological and water quality processes in a watershed. Application of this model or any other physically based model is based on the assumption that the selected parameters are valid for the entire region of interest. Thus, an uncertainty always remains as an integral part of such modeling practices. However, within some acceptable limits, this uncertainty is considered outweighed by the efficacy of strategically important findings that come as an output. Some earlier studies have been conducted to evaluate the effects of such assumption in hydrological modeling. Heuvelmans et al. (2004) studied the transferability of parameters and suggested that there is decline in model performance when parameters are transferred in time and space. Regionalization of parameters was studied by Seibert (1999), Heuvelmans et al. (2006) where the parameters are linked to the catchment characteristics using the linear regression techniques or artificial neural network techniques based on sufficient numbers of catchment data that may not be available often times. Heuvelmans et al. (2004) found that clustering of model parameters gives more accurate results than the single parameter approach. Regardless of which of the above mentioned technique is employed, calibrated model parameter values may go beyond the realistic range in order to match the observed and simulated data while calibrating the model for a limited number of sensitive parameters. Therefore it is important to make the most appropriate choices of SWAT hydrologic parameter for performing hydrologic assessments.

SWAT has been extensively used for a wide variety of water quality analysis (Gassman et al. 2007) including the production of Total Maximum Daily Loads (Borah et al. 2006). To have a readily usable SWAT for the development of TMDL's, a known set parameter range for the individual watersheds would be essential. A study is being carried out at the Center of Agriculture and Rural Development (CARD) to determine the most appropriate choices of input parameter ranges for performing hydrologic assessments in six principal Iowa landform regions (Figure 1) of which this study constitutes a portion. The six landform regions cover the majority of the intensively cropped regions in the state and are based on patters of biological and physical characteristics including geology, physiography, vegetation, climate, soils, land use, wild life and hydrology. It is assumed that these distinctive characteristics of each of the landform would predispose each of these landform regions to have a specific range of SWAT input parameters unique to that landform. This study focuses on one of the landform regions, namely the Iowan Surface landform. Walnut Creek and Beaver Creek watersheds were chosen as a pair of watersheds to develop the hydrologic parameters for this particular landform. The objective of this study are to set up and calibrate the SWAT model for Maquoketa watershed, validate it on Beaver Creek watershed and thus devise a range of most appropriate SWAT hydrological parameter set for this landform. The recommended SWAT hydrological parameter set will serve as a guideline for future Iowa Department of Natural Resources (IDNR) TMDL studies for the gauged or ungauged watersheds in the same landform region.

Materials and Methods

SWAT

SWAT (Arnold et al. 1998) is a physically based hydrologic and water quality model developed by the USDA Agricultural Research Services. It operates on long term continuous daily time step basis to simulate the hydrological processes and the fate and transport of nutrients, sediments and pesticides in a watershed along with flow routing of the river network. It takes topography, soil, land-use, farm management practices and climate as input data and gives flow and water quality parameters as output. Both the input and output can be incorporated at high level of spatial details. A more common application of this model is to study the impacts of changes in any of the inputs on the flow and water quality at any desired location. Hence it becomes a comprehensive tool to study the water quality impacts of changes in land-use and climate.

In SWAT, a user friendly ArcGIS platform is employed to prepare and manipulate the input data and to run the simulations. It divides a watershed into subbasins and then further subdivides into smaller Hydrological Response Units (HRU's) based on threshold for land use and soils. The hydrologic and other water quality computations are based on this HRU's and then aggregated at the subbasins and watershed level. SWAT uses Manning's equation to define rate and velocity of flow. Water is routed through the channel network using the variable storage routing method or the Muskingum river routing method. More details on SWAT model can be found in Arnold et al. (1998), Gassman et al. (2007), Jha et al. (2007), Schilling and Wolter (2009), Sahu and Gu (2009).

Maquoketa River watershed

Maquoketa watershed and its subbasins are shown in Figure 2. It has an area of 4867 km^2 dominated by row crop (58%), grassland (25%), forests (9%) and pasture (7%). Land use distribution for this watershed is given in Table 1. About 5% of the watershed area is tile drained that is under the row crop production of corn and soybean. It is identified as one of the high level nutrient contributing tributaries of the Mississippi River basin mainly through agricultural nonpoint source pollution. It was listed in 1998 as a priority watershed within the Iowa Department of Natural Resources Unified Watershed Assessment program. This watershed has significant livestock operation with the 7% pasture land, mainly for the production of swine, dairy cows, beef cattle, feeder cattle, calves and heifers. Major source of nutrient to the river is the non-point source from agriculture and livestock operation. Presence of tile drainage might be further worsening the situation. Developing TMDL will thus enable the design of a nitrate nitrogen load reduction program and assistance in the conservation of water quality of the Mississippi River Basin.

Beaver Creek watershed

The Beaver Creek watershed (Figure 3) has an area of 905 km^2 having agriculture as the predominant land-use. It is a tributary of the Skunk River that is one of the sources of drinking water supply for Des Moines, Iowa. Land use distribution of the Beaver Creek watershed is given in Table 1. Approximately 86% of the watershed is devoted to corn and soybean farming; followed by 10% under brome grass, 2% of pasture, 1% grassland and 1% forest. About 27% of the watershed is tile drained to make it suitable for row crop cultivation. Majority of the nutrient source is believed to be the agricultural non-point source which is further worsened by the presence of the tile drainage that siphons out the nitrate quickly into the river. Water quality in the River has thus degraded over time.

Input Data

Major input data required for SWAT modeling are topography, soil, land use, climate and farm management. The primary data used to develop SWAT set up in this study and their sources are listed in Table 2. These data were selected based on accuracy, resolution, and most recently compiled data available. The cropland portion of the landuse cover is updated in SWAT simulations to reflect the dominant corn-soybean rotation used in Iowa cropped landscapes. The pair of watershed chosen for the SWAT simulations has long-term stream flow data. The Iowa Environmental Mesonet climate data provides continuous daily precipitation and temperature data required to drive the SWAT simulations.

Modeling Procedure

SWAT model was set up for Maquoketa and Beaver Creek watersheds using ArcSWAT. The watersheds were delineated into subbasins and then further subdivided into hydrological response units (HRU's) based on 5% threshold for both soils and land use by using the NRCS Soil Survey Geographical Database (SUURGO). The interactive SWAT (i_SWAT) interface developed at CARD (CARD 2009) was then used to manage the input and output data as well as to run the simulations. An uncalibrated model (out of the box) was run for both the watershed without adjusting any of the model parameters. Model simulated flows at the outlet of each watershed were compared to the observed historical data at the same point. SWAT model was then calibrated for Maquoketa River watershed by adjusting the hydrologic parameters such as soil evaporation compensation factor (ESCO), daily curve number calculation method (ICN), plant curve number evaporation coefficient (CNCOEFF), curve number (CN2), depth to tile drain (DDRAIN), time to drain the soil to field capacity due to the presence of tile (TDRAIN) and depth to impervious layer (DEPIM) manually. The observed and simulated monthly and annual flows at the outlet of the watershed were compared. SWAT model gives breakdown estimates of the hydrological budget of the watershed that includes surface flow, base flow, evapotranspiration, groundwater contribution and lateral flow contribution as major constituent. The calibration process was initiated by maintaining the base flow and surface flow ratio around the base flow separated by two different programs – PART and BFLOW. The model parameters were further adjusted until a reasonably good match between the observed and simulated total flows at the outlet of the watershed was attained. The calibrated model was then validated on Beaver Creek watershed without changing any of the calibrated parameters. Observed and simulated flows at the outlet of Beaver Creek watershed were compared to determine the validity of the model parameters recommended for the given landform.

Model performance was measured by two statistical criteria, namely the coefficient of determination (R^2) and Nash-Sutcliffe simulation efficiency (E) (Nash and Sutfliffe 1970). The R^2 value is a measure of how well the simulated flow correlates with the observed data over the period of simulation. The E value is a measure of how well the simulated flow values agree with the observed values on the same date or over a period of time given by following equation:

$$E = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2}$$

where n is the number of observations in dataset, i is the i^{th} observation, O is the observed flow value, S is the simulated flow value and O_{avg} is the average of the observed flow data.

The E value ranges from 0 to 1, 0 meaning the worst and 1 meaning the best match of the observed and simulated values. Model performance criteria of E and R^2 values of over 0.50 was suggested by Moriasi et al (2007) and of 0.75 was suggested by Van Liew et al. (2005).

Results and Discussion

Uncalibrated Model

Uncalibrated model was run for year 1995 to 2008 for both the Maquoketa and Beaver Creek watershed. Observed and model simulated flows at the outlet of the watersheds are shown in Figures 4 and 5. Uncalibrated model over-predicted the flows for Maquoketa and under-predicted for Beaver Creek watershed. Performance of the uncalibrated model was evaluated for the annual and monthly flows by statistical analysis using the coefficient of determination (R^2) and the Nash-Sutcliffe simulation efficiency (E). Table 3 shows the statistical comparison of the annual and monthly simulated and observed flows. The E and R^2 values of the uncalibrated model were 0.60 and 0.91 for the annual flow and 0.65 and 0.84 for the monthly flow respectively for Maquoketa watershed. This is better than the acceptable limits of 0.50 suggested by Moriasi et al (2007); however it should be adjusted further during the model calibration process to improve the annual average flows and monthly peak values and seek an improvement of statistical measurement of the fit. For Beaver Creek watershed, the E and R^2 values were 0.84 and 0.96 for the annual flow and 0.80 and 0.83 for the monthly flow. Model performance seems to be better than the criteria of 0.50 suggested by Moriasi et al (2007). The model will have to be validated for the Beaver Creek watershed. It will also serve as a test of validity of SWAT hydrological parameters suggested for the Iowan Surface landform based on Maquoketa watershed.

Calibration and Validation

Model calibration was performed by adjusting the hydrologic parameters such as ESCO, ICN, CNCOEFF and CN2, DDRAIN, TDRAIN, DEPIM. Final calibrated values of these parameters are shown in Table 4. The monthly and annual model predicted flows were compared to the observed data at the outlet of the Maquoketa River watershed as shown in Figure 6. SWAT seems to predict the annual balance of average flow very well for this watershed i.e. 284 mm of simulated flow versus 286 mm of observed flow. As shown in Figure 6(a), the annual observed and predicted flows seem to be in good agreement for both the high and low flow years. Statistical analysis (Table 3) shows the Nash-Sutcliffe simulation efficiency (E) and coefficient of determination (R^2) values of 0.89 and 0.94 respectively that are better than the acceptable limits of 0.50 suggested by Moriasi et al (2007). The monthly flows seem to be well predicted by the model as shown in Figure 6(b). The peaks and low flows are generally well depicted by the model and supported by the statistical parameter values of E and R^2 of 0.83 and 0.86. These values are slightly lower than that for the annual flows.

Calibration process enhanced the model performance compared to the uncalibrated model (out of the box). This is shown by increase in annual E value from 0.60 to 0.89 and R^2 value from 0.91 to 0.94. Similarly, the monthly E value increased from 0.65 to 0.83 and R^2 value increased from 0.84 to 0.86. There was also a significant improvement in the model predicted total annual average flow of 350 mm in the uncalibrated model to 284 mm in the calibrated model versus the observed data of 286 mm. The monthly flow distribution, including the base flow and the peaks, were found to be better simulated by the calibrated model compared to the uncalibrated model (Figures 4(b) and 6(b)).

Model validation results for Beaver Creek watershed are shown in Figure 7. Annual flow (Figure 7(a)) was consistently under-predicted by the model whereas the pattern of monthly flow (Figure 7(b)) was well captured, including the high and the low flows. Statistical analysis (Table 3) shows the Nash-Sutcliffe simulation efficiency (E) and coefficient of determination (R^2) to be 0.73 and 0.96 for annual flow and 0.82 and 0.87 for the monthly flow respectively. Statistical measures of the model simulated flows are well above the acceptable level (0.50) suggested by Moriasi et al (2007). Thus the model can be considered validated for practical purposes.

Hydrological component of the calibrated model for the two watersheds are shown in Table 5. Although the two watersheds are in the same landform region, land uses are slightly different in Beaver Creek compared to Maquoketa (Table 1). Maquoketa has 58.4% of row crop and 9.1% of forest compared to 86.1% of row crop and 0.7% forest in Beaver Creek. Similarly there are differences in the percentage of area of land under brome grass and pasture. This might have lead to higher evapotranspiration in the Beaver creek (644mm) compared to Maquoketa (627 mm) as shown in Table 5. Thus the model might have resulted in under-prediction of the flow. Tile flow contribution of Maquoketa is 7 mm compared to 36 mm of Beaver Creek watershed. This is because only 5% of Maquoketa is tile drained compared to 27% in the Beaver Creek (Table 1). The depth of tile flow is expressed as depth over the entire watershed. Due to the presence of the tile, the lateral flow seems to be reduced greatly in the Beaver Creek.

Some of the modeling limitations, such assumption of the data being the perfectly representative of the study area, might be causing or contributing to the discrepancy in the results especially for the validation phase on Beaver Creek watershed. Climate data is one of the major drivers of SWAT and it appears in Figure 3 that there is no climate station within the boundary of the Beaver Creek watershed; however there are a number of them around it. Therefore, it's quite possible that the climate stations are capturing the weather parameters in the watershed; however there is some underlying uncertainty is this assumption. In addition, small land cover areas less than the threshold might not get captured by the model. The assumption of perfectly uniform HRU's is not possible in the nature and that could lead to modeling error.

Sensitivity Analysis

The difference in land use distributions of the two watersheds is shown in Table 1, which is also reflected by the comparison of the validated model results for Beaver Creek to the uncalibrated model results. The Uncalibrated model gave an average annual flow of 239 mm which is much closer to the observed flow of 290 mm than the validated model average annual flow of 212 mm (Figures 5(a) and 7(a)). The E value of annual flow went down from 0.84 for the uncalibrated model to 0.73 for the validated model. Moreover, the validated model consistently under-predicts the flow in Beaver Creek watershed. Therefore, a sensitivity analysis was performed to evaluate if the model response of Beaver Creek with calibrated parameters was coherent with the Maquoketa watershed. This was done by hypothetically changing the land use distribution of Beaver Creek so that it is equivalent to that of Maquoketa watershed. Targeted amounts of land under each land-use type in Beaver Creek watershed were determined based on land use distribution of Maquoketa watershed. A proportional conversion of land use was then made on the basis of slope; such as the highest slopped croplands were converted into brome grass followed by pasture and forest at the lowest slope. Original and modified land use distribution for Beaver Creek and its comparison with Maquoketa land use distribution are shown in Table 6. Land use were converted on HRU's basis, hence modified land use of Beaver

Creek are approximately in the same range to that of Maquoketa watershed. Model was run for this changed land use but with the same values of the calibrated model parameters.

Statistical evaluation of the results in Table 7 shows that the sensitivity analysis run has a consistent improvement on the model performance compared to the validation run with actual land use. The E values for annual and monthly flows increased from 0.73 to 0.88 and 0.82 to 0.85 respectively while the R^2 did not change. Comparing the uncalibrated and sensitivity model runs, annual E value increases from 0.84 for the uncalibrated model to 0.88 for the sensitivity run where as the R^2 remained the same at 0.96. For the monthly flow, however, both the E and R^2 values changed from 0.80 to 0.85 and 0.83 to 0.87 respectively.

Plots of the observed and simulated (sensitivity run) annual and monthly flows for the Beaver Creek watershed are shown in Figure 8. It gave an annual average flow of 247 mm which is much closer to the observed annual average flow of 290 mm. It is also an improvement over the results of the validated model annual average flow of 239 mm with the actual land use. The correlation and closeness of the simulated monthly flows to the observed flows are enhanced as evident from the statistical analysis.

Development of SWAT Hydrologic Parameters

SWAT Hydrologic parameters (Table 4) developed from the calibration of SWAT on Maquoketa watershed and validated on Beaver Creek watershed can be suggested for this landform. However, it appears that the model performance for the Beaver Creek watershed has reduced slightly with the calibrated parameters compared to the uncalibrated model. There was a reduction in the annual flow E value from 0.84 to 0.73 supporting the consistent under-prediction of annual total flows. It is opposed to the expectation that there should be no degradation in model performance, if not improved over the uncalibrated model, even though the statistics are well over the acceptance criteria. This is yet apparently compensated by a gain in the monthly flow E value from 0.80 to 0.82 and R^2 value from 0.83 to 0.87 indicating that the monthly flows are predicted much closely and are better correlated to the observed values compared to the uncalibrated model. It shows that the model is sensitively responding through the enhancement in the ‘details’ of the model performance although the annual totals seem to remain conservative.

Considering the different land use distribution and presence of tile drainage in different proportions in the two watersheds, the results are acceptable. Sensitivity analysis on the change of land use of Beaver Creek watershed in proportion to Maquoketa watershed further endorses the fact that the model is actually responding consistently for both of the watersheds. The E value of annual results for sensitivity run changed to 0.88 compared to that of the uncalibrated model (0.84) (Table 7). Similarly, the E and R^2 values for monthly results changed from 0.80 to 0.85 and 0.83 to 0.87. Additionally, the statistics of the Beaver Creek sensitivity run results were very much comparable to the results of Maquoketa calibration runs as shown in the last two columns of Table 7. It indicates that the model is performing coherently in the Iowan surface landform. The overall flow is still being under-predicted by the sensitivity run (Figure 8(a)). However, it can be accepted on the ground of considering parameter choices for the similar land use that remains always different in the nature.

Conclusions

SWAT hydrological parameters were developed for the Iowan Surface landform, one of the six principal landforms of Iowa. Maquoketa and Beaver Creek watersheds were selected for this study. SWAT model was set up for these two watersheds and the simulation was driven by the historical flow data of 1995 to 2008. Simulation was first conducted with an uncalibrated model without changing any parameters of the model. Calibration was then performed on Maquoketa watershed. The calibrated model was then applied to Beaver Creek watershed without any further adjustment of model parameters for validation. Observed and simulated flows at the outlet of each watershed were compared and model performance was evaluated by using the statistical parameters, the coefficient of determination (R^2) and Nash-Sutcliffe efficiency (E).

Uncalibrated model gave E values of 0.60 and 0.65 and R^2 values of 0.91 and 0.84 for the annual and monthly flows respectively for the Maquoketa watershed. Calibration of the model improved the model performances. The E values reached to 0.89 and 0.83 and R^2 values to 0.94 and 0.86 for the annual and monthly flows respectively. The annual average flow simulated by the calibrated model was 284 mm compared to the observed data of 286 mm. Similarly the uncalibrated model for Beaver Creek watershed gave E values of 0.84 and 0.80 and R^2 values of 0.96 and 0.83 for the annual and monthly flows respectively. Model validation runs gave E values of 0.73 and 0.82 and R^2 values of 0.96 and 0.87 for the annual and monthly flows respectively. The annual average flow simulated by the model was 212 mm compared to the uncalibrated model of 239 mm versus the observed data of 290 mm. Thus there was a slight decline in the model performance with reference to the decline in annual E value for annual average flow; however a gain in model performance for the monthly flow was observed. The E and R^2 changed from 0.80 to 0.82 and 0.83 to 0.87 for the monthly flows, indicating that the validated model is responding better in the ‘details’ of the model performances. Due to the difference in land use distribution in the two watersheds and presence of different amount of tile drainage, the validated model for Beaver Creek consistently under-predicted the flow.

A sensitivity analysis was performed by changing the land use distribution of Beaver Creek in proportion to the Maquoketa watershed. Without changing any of the model parameters, the sensitivity run for Beaver Creek watershed yielded E values of 0.88 and 0.85 and R^2 values of 0.96 and 0.87 for the annual and monthly flow results. The model performance of sensitivity run was found to be about the same level of Maquoketa calibration run, indicating that the SWAT model with the given set of parameters is performing coherently in the Iowan Surface landform. Thus a set of SWAT hydrological parameters are recommended for this landform.

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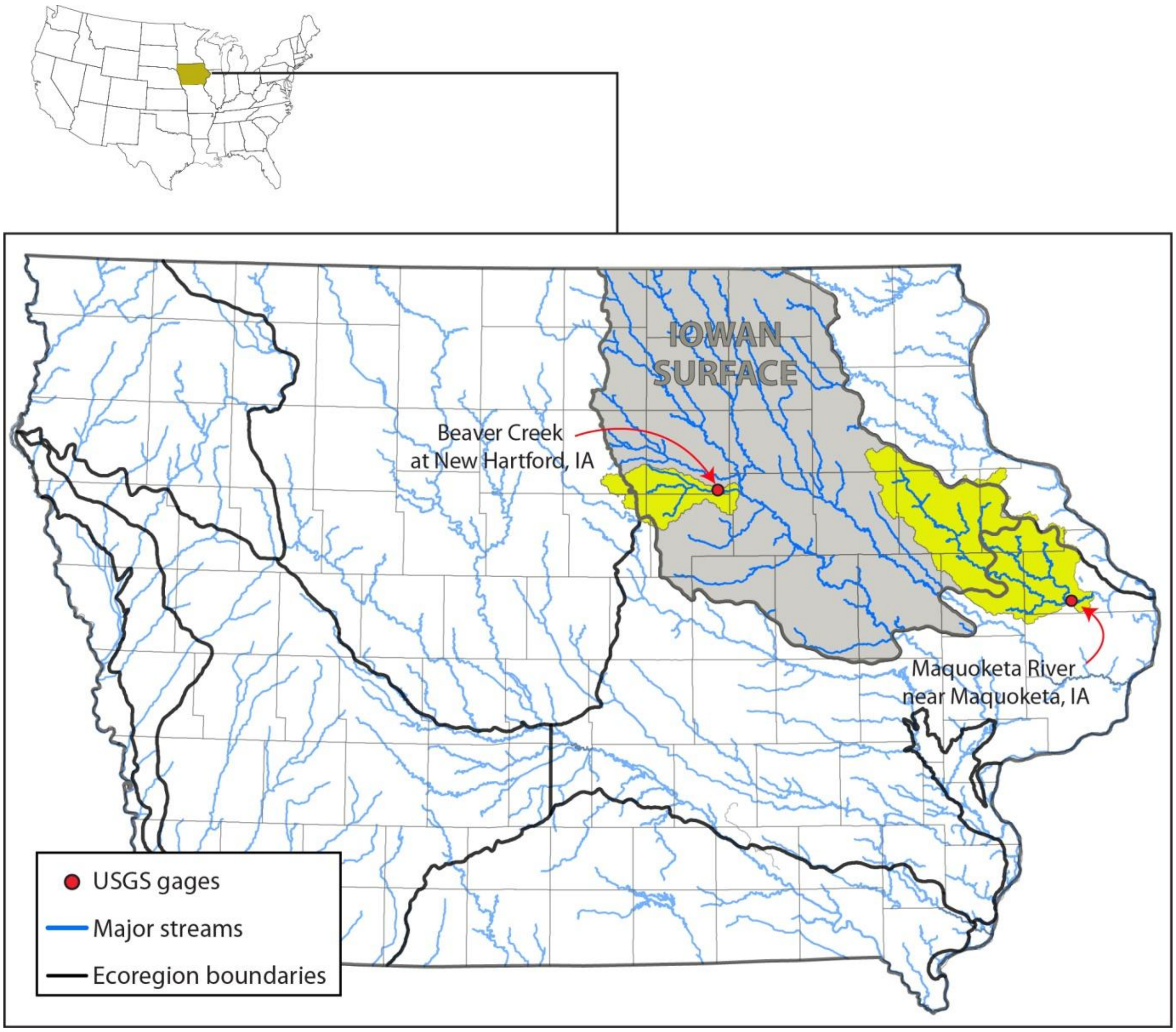


Figure 1 Six principal Iowa Landforms (Ecoregions) including the Iowan Surface Landform

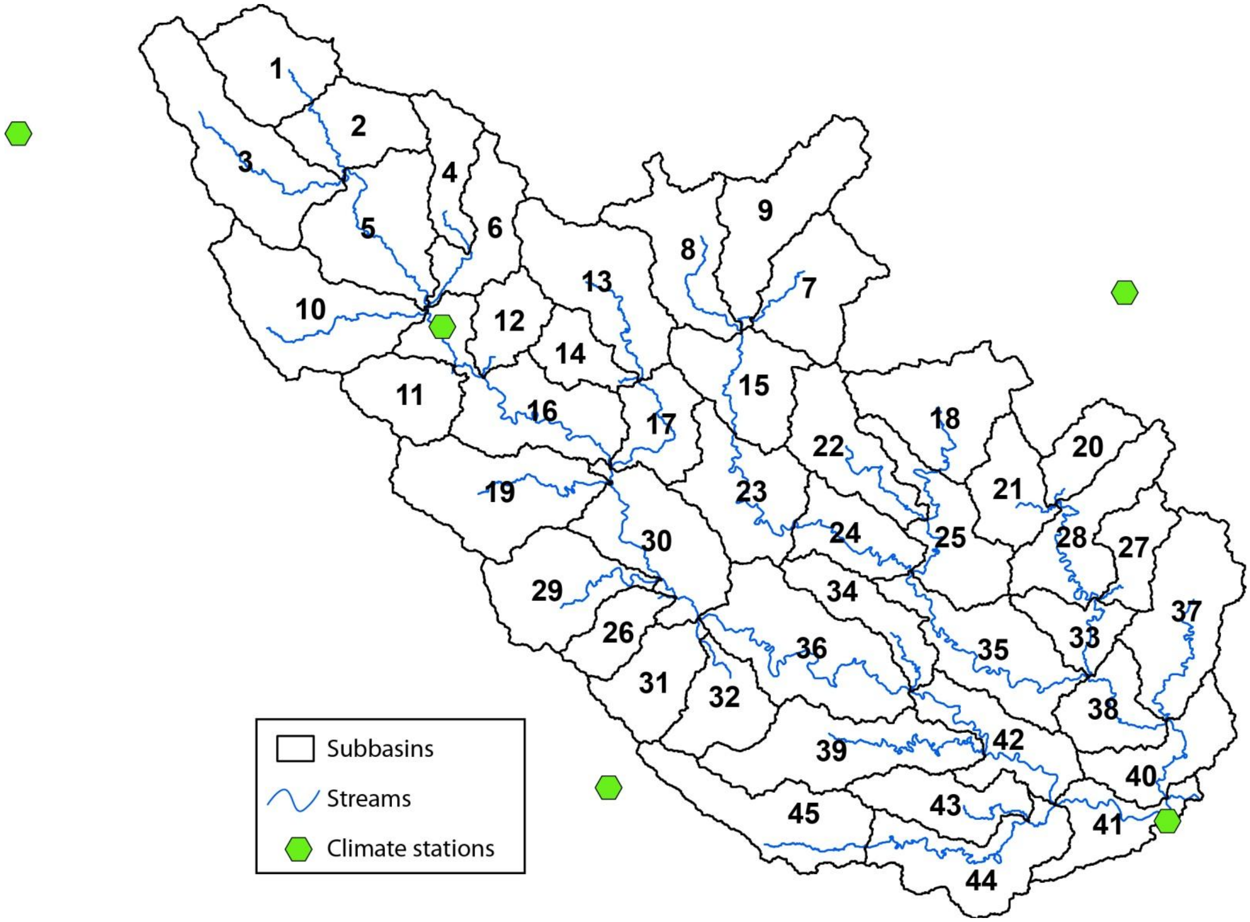


Figure 2 Maquoketa River watershed and its subbasins along with the climate stations

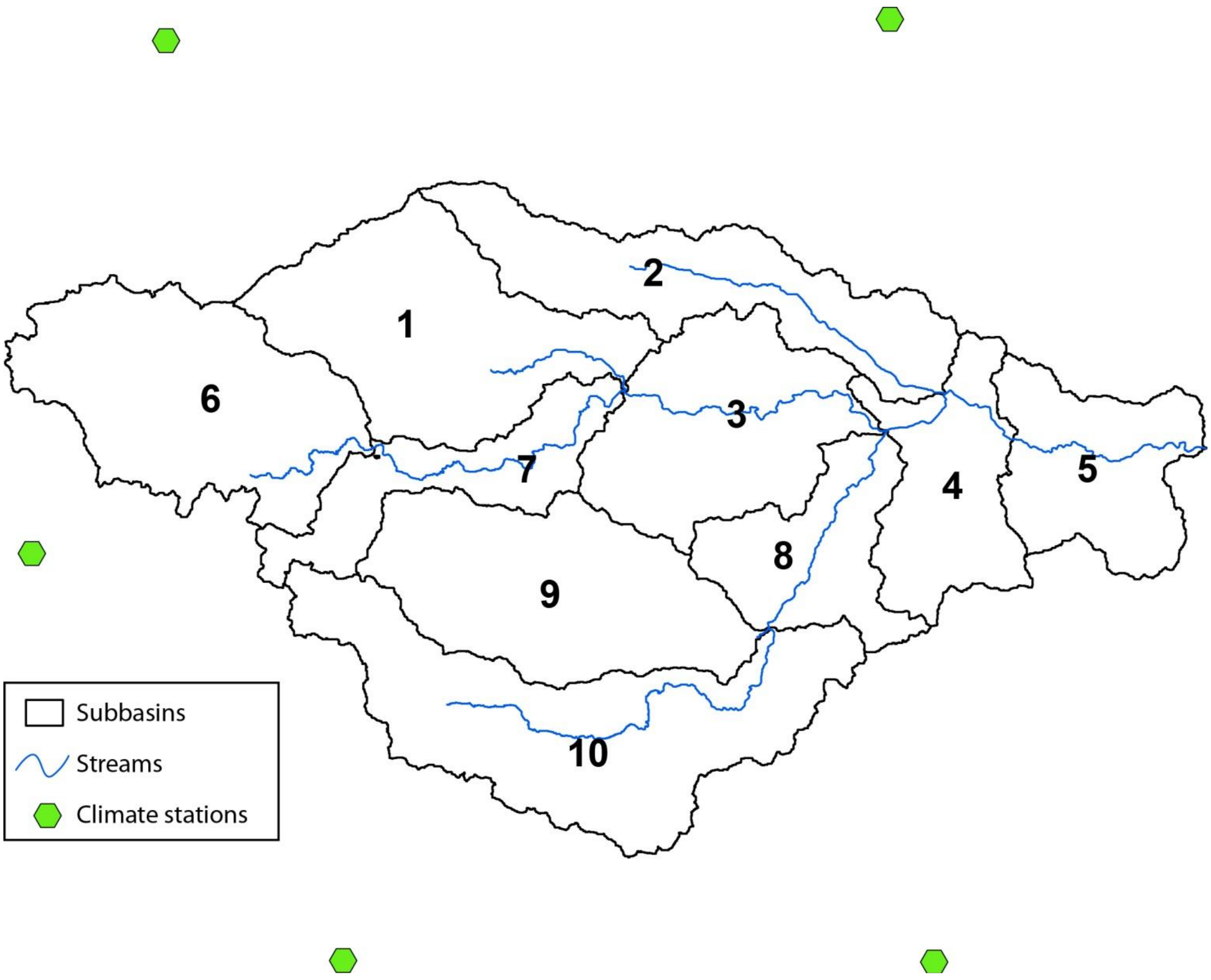
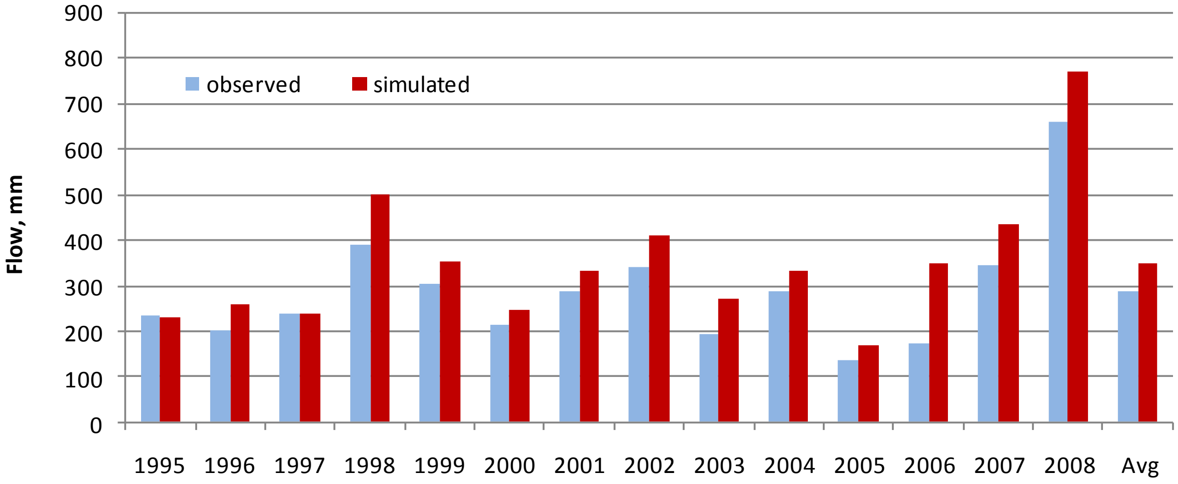


Figure 3 Beaver Creek watershed and its subbasins along with the climate stations



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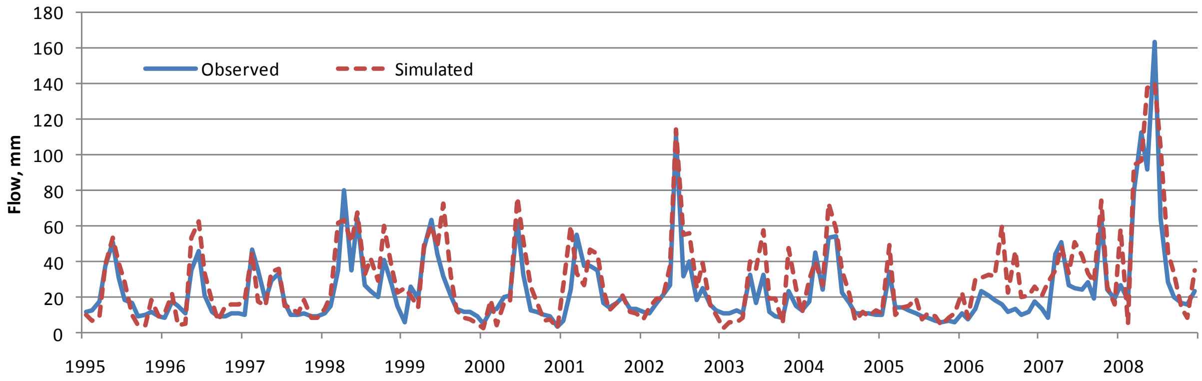
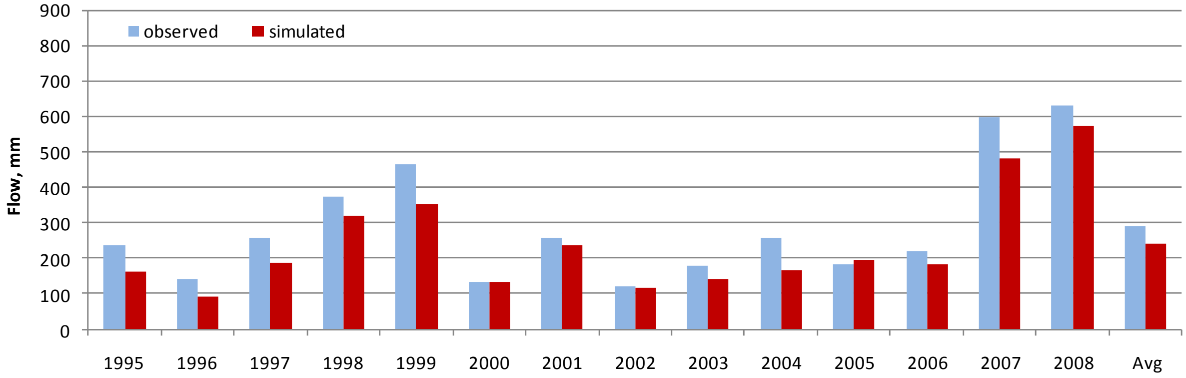


(b)

Figure 4 Observed and simulated flow from the uncalibrated model for Maquoketa River watershed (a) annual (b) monthly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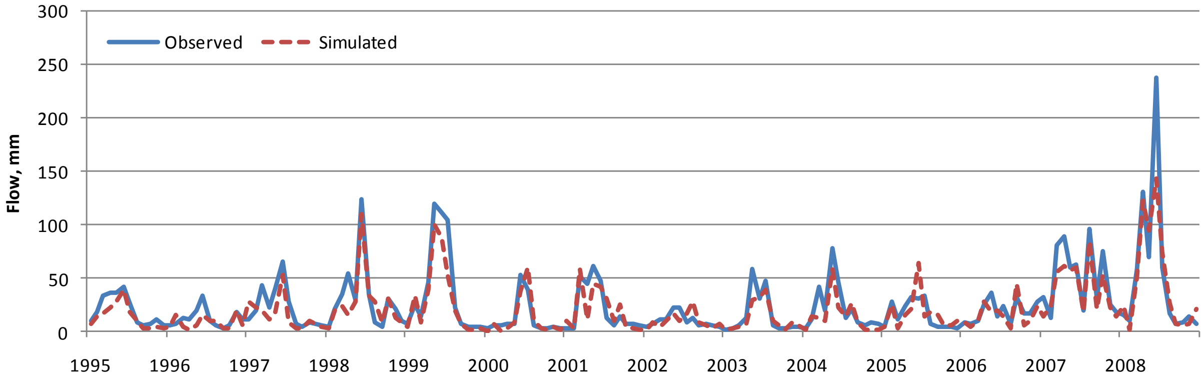
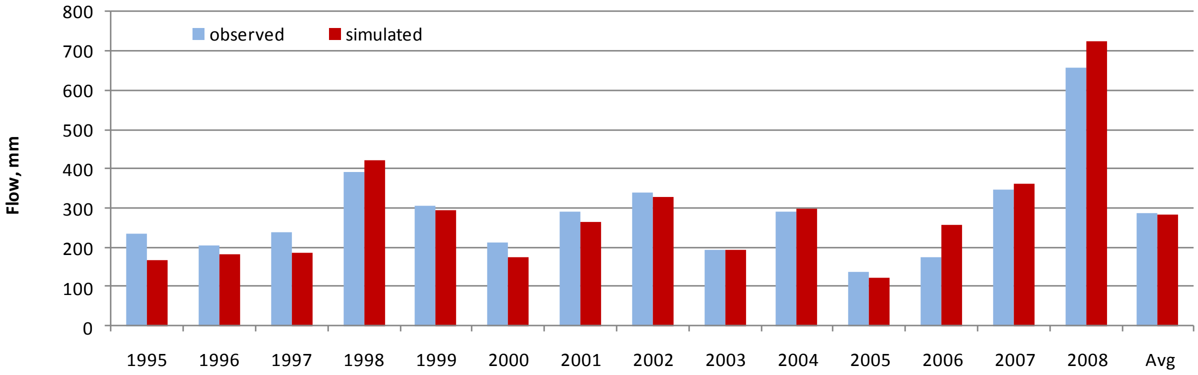


(b)

Figure 5 Observed and simulated flow from the uncalibrated model for Beaver Creek watershed (a) annual (b) monthly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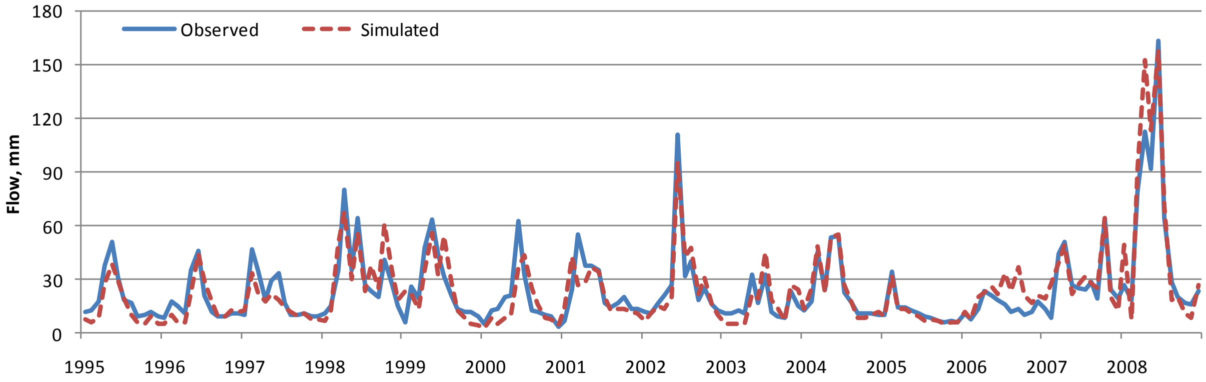
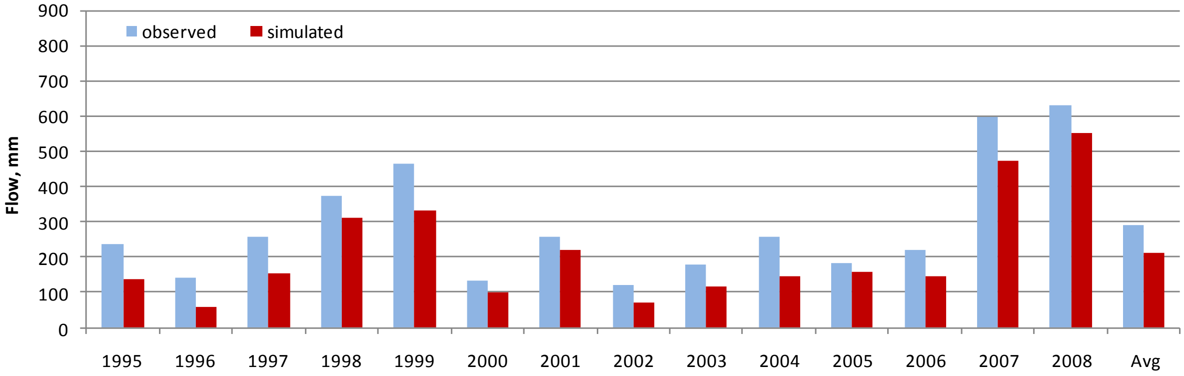


(b)

Figure 6 Observed and simulated flow from the calibrated model for Maquoketa watershed (a) annual (b) monthly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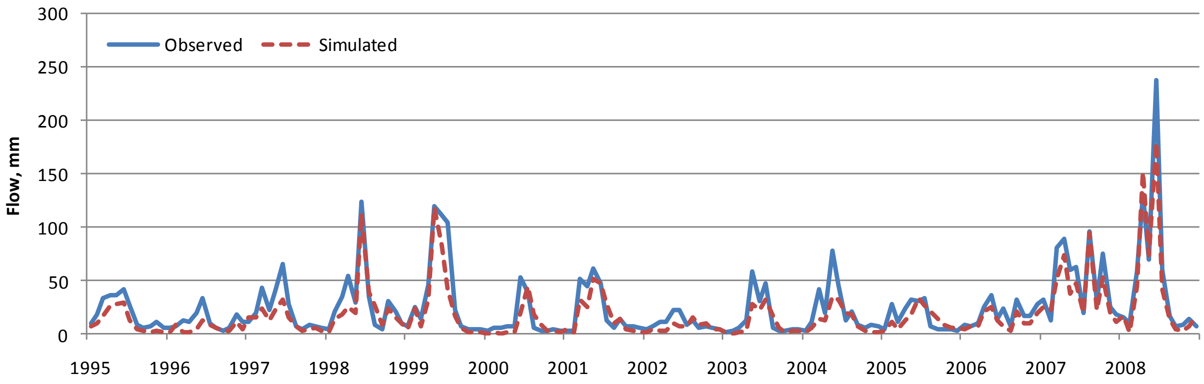
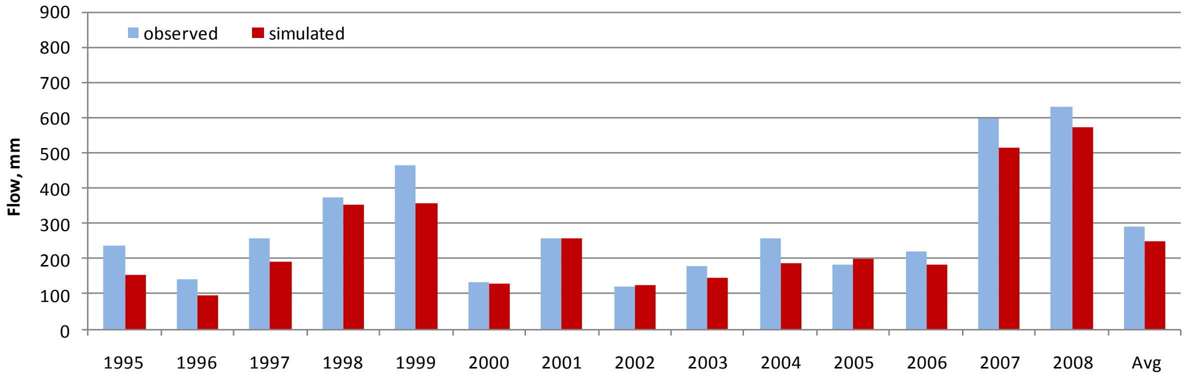
Avg

(a)

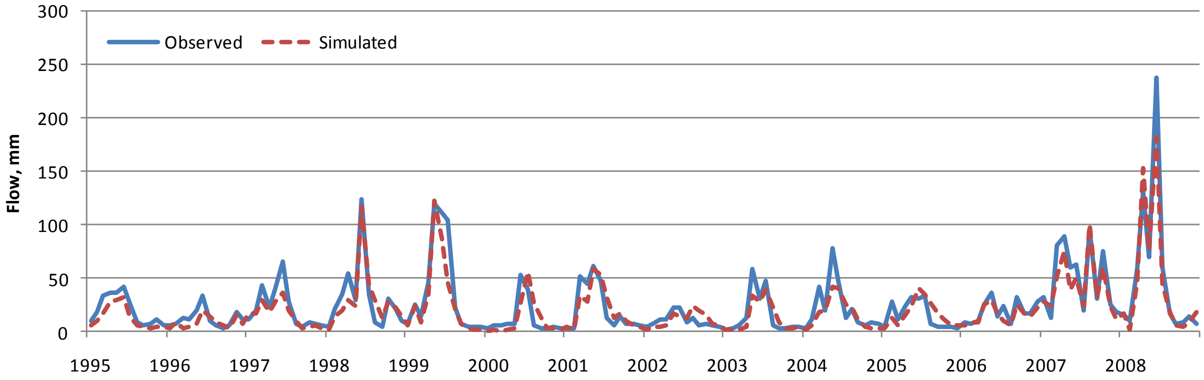


(b)

Figure 7 Observed and simulated flow for model validation for Beaver Creek watershed (a) annual (b) monthly


900
800
700
600
500
400
300
200
100
0
Flow, mm
observed
simulated
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
Avg

(a)



(b)

Figure 8 Observed and simulated flow for sensitivity analysis for Beaver Creek watershed (a) annual (b) monthly

Table 1 Land use for Maquoketa and Beaver Creek watershed

	Maquoketa watershed		Beaver Creek watershed	
	Area (km$^{2)}$	Area (%)	Area (km$^{2)}$	Area (%)
Alfa Alfa	53	1.3	0	0.0
Brom grass	858	21.4	95	10.5
Row crop	2345	58.4	776	86.1
Forest	366	9.1	6	0.7
Pasture	268	6.7	17	1.9
Switchgrass	128	3.2	7	0.8
Tile drainage	184	4.6	242	26.9

Table 2 Input data and their sources for SWAT model set up

Data type	Source
Soil	Soil Survey Geographic (SSURGO) Database[a]
Climate	Iowa Environment Mesonet[b]
Land use	2002 Land Cover Grid of Iowa[a]
Topographic	Resampled 30 m Digital Elevation Model[c]

[a] http://www.igsb.uiowa.edu/nrgislibx

[b] http://mesonet.agron.iastate.edu/COOP

[c] The 30 m DEM was resampled from 10 m DEM topographic data (internal IDNR dataset).

Table 3 Statistics of uncalibrated, calibrated and validated model

		Uncalibrated Model for		Calibration	Validation	
		Maquoketa	Beaver Creek	Maquoketa	Beaver Creek	
Annual	E	0.60	0.84	0.89	0.73	
	R^2	0.91	0.96	0.94	0.96	
Monthly	E	0.65	0.80	0.83	0.82	
	R^2	0.84	0.83	0.86	0.87	

Table 4 Final calibrated values of SWAT parameters

SWAT Parameter	Calibrated value
Soil evaporation compensation factor (ESCO)	0.8
Daily curve number calculation method (ICN)	1
Plant curve number ET coefficient (CNCOEFF)	0.35
Curve Number (CN2) for row crop	77
Depth to tile drain (DDRAIN), mm	1200
Time to drain soil to field capacity (TDRAIN), hrs	24
Depth to impervious layer (DEPIM), mm	1500

Table 5 Hydrological budget of calibrated model for Maquoketa and Beaver Creek watershed

Hydrological component	Maquoketa	Beaver Creek
Precipitation (mm)	946	903
Snow melt (mm)	102	95
Total water yield (mm)	308	246
Evapotranspiration (mm)	627	644
Surface runoff (mm)	125	100
Groundwater contribution (mm)	77	98
Lateral flow contribution (mm)	100	13
Tile flow (mm)	7	36

Table 6 Original and Modified land use distribution for Beaver Creek and Maquoketa watershed

	Beaver Creek watershed				Maquoketa watershed	
	Original landuse		Modified landuse			
	Area (km$^{2)}$	Area (%)	Area (km$^{2)}$	Area (%)	Area (km$^{2)}$	Area (%)
Alfa Alfa	0	0.0	0	0.0	53	1.3
Brom grass	95	10.5	193	21.4	858	21.4
Row crop	776	86.1	550	61.0	2345	58.4
Forest	6	0.7	90	10.0	366	9.1
Pasture	17	1.9	61	6.8	268	6.7
Switchgrass	7	0.8	7	0.8	128	3.2

Table 7 Statistics of model sensitivity results for Beaver Creek watershed

		Beaver Creek watershed			Maquoketa
		Uncalibrated Model	Model validation	Sensitivity run	Calibration run
Annual	E	0.84	0.73	0.88	0.89
	R^2	0.96	0.96	0.96	0.94
Monthly	E	0.80	0.82	0.85	0.83
	R^2	0.83	0.87	0.87	0.86

CHAPTER 5. GENERAL CONCLUSIONS

Application of contour and filter strips for stream water quality protection

SWAT model was used to investigate the fate and transport of NO_3-N in an agricultural watershed through a contour strip, placed mid-way of the slope, and a riparian buffer strip planted with perennial vegetation such as switchgrass. Hillslope descretization feature of SWAT was employed to simulate the contour and riparian buffer strips and their effects on NO_3-N yield.

High impact subbasins were identified based on NO_3-N contribution per unit area (kg/ha) and total NO_3-N contribution (kg) from each subbasin of the Walnut Creek watershed. These subbasins would be the priority subbasins in the watershed, which should be addressed first to have the maximum environmental impact with minimum economical effort.

Based on the evaluation of two filter strip locations, i.e. the contour strip placed midway in the subbasin and buffer strip along the river, contour strips were found to be more effective. It was concluded that multiple strips of perennial vegetation along the contour would be more effective in nitrate reduction instead of having one riparian buffer strip along the river.

Strip sizes of 10%, 20%, 30% and 50% of the subbasin area were considered for the simulations. In general, larger the size of filter strip, more was the reduction in NO_3-N outflow. However, the rate of NO_3-N reduction became milder when size of the strip was in 30-50% range. Filter strips having 10-20% area were found to be more efficient in case of contour strips whereas filter strips having 10-30% area were still considerably effective in case of buffer strips.

Results of hillslope SWAT application to the Walnut Creek Watershed, Ames, Iowa have shown that a filter strip having 10%-50% of the subbasin area with a perennial cover of switchgrass could potentially lead to 55%-90% NO_3-N reduction in outflows from the subbasin in an event of average rainfall year.

Macro level BMP's, bio-fuel development and water quality conservation

SWAT simulations were conducted for Upper Mississippi River Basin (UMRB) for the year 1981 -2004. The perpetuation of current trend of growing corn to meet the increasing corn demand for ethanol showed general water quality degradation in UMRB compared to the baseline scenario. The simple economic analysis suggests that it's equally or even more profitable in many cases to grow switchgrass for cellulosic ethanol than corn for ethanol. The high nitrate yielding subbasins can be kept under switchgrass production while still getting all the economic benefits without any direct subsidy. If corn grains are only considered for ethanol, the production of switchgrass is more beneficial with minimum agricultural inputs compared to corn.

Converting some high nitrate yielding portions of the UMRB to switchgrass production was found to reduce nitrate nitrogen yield of up to 14 kg/ha and sediment reduction of up to 5 tons/ha. In many cases, switchgrass reduced up to 71% of total nitrate nitrogen yield and almost 99% of sediment. Economically beneficial and environmental friendly perennial crops such as switchgrass can be grown as managed bio-energy crop to meet the energy demand.

A Production-Economy-Environment matrix analysis of growing switchgrass for various rates of fertilizer application and its consequences on yield and environment was developed. It demonstrated that the efficacy of rate of fertilizer application and its relationship to economy and environment is not proportionate. It underscores the importance of such analysis to design an optimum amount of fertilizer or even the rate of fertilizer application for a desired gain in environmental quality. It is concluded that even though the economic benefits of bio-energy crops were marginal, the bio-energy crops are yet a potentially viable solution for the degrading water environment in the water ways of Upper Mississippi River Basin and the Gulf of Mexico.

Development of SWAT hydrologic parameters

SWAT hydrological parameters were developed for the Iowan Surface landform, one of the six principal landforms of Iowa. Maquoketa and Beaver Creek watersheds were selected for this study. SWAT model was set up for these two watersheds and the simulation was driven by the historical flow data of 1995 to 2008. Simulation was first conducted with an uncalibrated model without changing any parameters of the model. Calibration was then performed on Maquoketa watershed. The calibrated model was then applied to Beaver Creek watershed without any further adjustment of model parameters for validation. Observed and simulated flows at the outlet of each watershed were compared and model performance was evaluated by using the statistical parameters, the coefficient of determination (R^2) and Nash-Sutcliffe efficiency (E).

Calibration of SWAT model on Maquoketa watershed significantly improved the model performances compared to the uncalibrated model with final E values of 0.89 and 0.83 and R^2 values to 0.94 and 0.86 for the annual and monthly flows respectively. The annual average flow simulated by the calibrated model was 284 mm compared to the observed data of 286 mm.

Calibrated model was then validated on Beaver Creek watershed that gave E values of E values of 0.73 and 0.82 and R^2 values of 0.96 and 0.87 for the annual and monthly flows respectively. The annual average flow simulated by the model was 212 mm compared to the uncalibrated model of 239 mm versus the observed data of 290 mm. Thus there was a slight decline in the model performance with reference to the decline in annual E value for annual average flow; however a gain in model performance for the monthly flow was observed. It indicated that the validated model was responding better in the 'details' of the model performances. Due to the difference in land use distribution in the two watersheds and presence of different amount of tile drainage, the validated model for Beaver Creek consistently under-predicted the flow.

A sensitivity analysis was performed by changing the land use distribution of Beaver Creek in proportion to the Maquoketa watershed. Without changing any of the model parameters, the sensitivity run for Beaver Creek watershed yielded E values of 0.88 and 0.85 and R^2 values of 0.96 and 0.87 for the annual and monthly flow results. The model performance of sensitivity run was found to be about the same level of Maquoketa calibration run, indicating that the SWAT model with the given set of parameters is performing coherently in the Iowan Surface landform. Thus a set of SWAT hydrological parameters are recommended for this landform. An available set of such parameters for the intensively cropped regions would be very instrumental to perform the TMDL studies for individual smaller units. Smaller scale studies performed all around the cropped region of the Mid-west integrated together could yield a very robust tool for water quality studies on large scale basin such as UMRB. Impacts of perpetuation of current trend of increasing corn production, bio-fuel scenario or any other land use changes could be evaluated more accurately at the watershed scale to have more meaningful insight into the Gulf hypoxic zone.

Recommendations

The Production-Economy-Environment (PE^2) Matrix can be studied on much detailed basis of economical analysis that was beyond the scope of this study.

Development of SWAT hydrologic parameters will be instrumental in development of TMDL's that can be back tracked in the Production, Economy and Environment (PE^2) Matrix study to design the corresponding fertilizer application rate and evaluate economic consequences.

A more comprehensive and robust tool for the water quality evaluation and conservation for the entire UMRB can be developed by integrating the smaller scale studies related to the development of SWAT hydrological parameters for TMDL studies. While these studies serve the localized purposes, their ultimate impact on basin scale water quality can be evaluated. Results from the integrated basin scale modeling could be linked to the hydrodynamic model to simulate the dynamics of Gulf hypoxic zones.