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Assessing the Impact of Contour Strips of Perennial Grass with Bio-fuel Potentials on Aquatic Environment

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Abstract**—**The use of contour strips of perennial vegetation with bio-fuel potential can improve surface water quality by reducing NO_3-N and sediment outflow from cropland to surface water-bodies. It also has economic benefits of producing ethanol. In this study, The Soil and Water Assessment Tool (SWAT) model was applied to a watershed in Iowa, USA to examine the effectiveness of contour strips of switch grass in reducing the NO_3-N outflows from crop fields to rivers or lakes. 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 on NO_3-N reduction under various meteorological conditions, i.e. dry, average and wet years. Useful information was obtained for the evaluation of economic feasibility of growing switch grass for bio-fuel in contour strips. The results can assist in cost-benefit analysis and decision-making in best management practices for environmental protection.

Keywords**—**ethanol, modeling, water quality, NO_3-N, watershed.

I. 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 [1], [2]. 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 [3], [4]. An average annual export of nitrate nitrogen from Iowa in surface water ranges 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 and ethanol industry 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. Additional amount of land will be required to meet the corn demand of ethanol plants and farmers have already started to respond to this. In Iowa farmers had 17% increased land under corn in 2007 compared to the previous year; and it is believed that the trend may continue to grow. Therefore, where will the additional amount of land come from? Majority of the USA baseline projection of 90 million acres under corn required to meet the ethanol and other demands by 2010 would come from the Midwest. Increased farming of corn will significantly 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.

It may be feasible to use biomass for ethanol production. Perennial grass such as switch grass is a good source of biomass that can be grown in the field that currently produce corn and use it to produce cellulosic ethanol instead of corn ethanol. From the environmental perspective, burning of cellulosic ethanol from switch grass is found to produce 94% less greenhouse gas (GHG) compared to GHG from gasoline. While the economic outputs of corn and switch grass 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.

Best management practices, such as grassed waterway, riparian buffer, contour strips, field border etc., were used for reducing pollutant yields from agricultural lands. The impacts of best management practices on water quality can be considerable. However, these measures are expensive to put it on the field and take the land out of production. Therefore, farmers are reluctant to put it on their farm without appropriate subsidy. A new way of farming is needed for water quality improvement without significantly increased compromise in agricultural economy. An emerging option can be bio-mass yielding crops such as switch grass that is grown in contour strips and can be used for ethanol production. Replacing the crop production by contour strips of switch grass having bio-fuel potential can have a positive impact in reducing the nitrate and sediment yield and meanwhile compensate the loss of land production values by bio-fuel from the switch grass. This can be a both environmentally and economically promising solution and creates a need for setting up scientific investigations. The benefits of conversion from corn fields to contour strips with bio-fuel potential include the reduction of nitrate and sediment yield to the river resulting in better water quality, economic benefits of producing ethanol, low greenhouse gas (GHG) emitting cellulosic ethanol, and direct

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carbon sequestration that contributes positively to the global climate change.

When flow from a crop area carrying nutrients passes through the filter strip, the perennial plant will be able to use up some of the nutrients and net outflow of nutrients will be reduced. Larger the area and longer the contact time (or lower flow velocity) within the filter strip more will be the use-up of nutrients by the perennial plants. 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 trade-off 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. The objective of this study is to investigate the effectiveness of contour strips of perennial plants having bio-fuel potential in reducing nutrient (NO_3-N) loading to streams in an agricultural watershed. The Soil and Water Assessment Tool (SWAT) is applied to the Walnut Creek, Iowa for this purpose. 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 the 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.

II. METHODOLOGY

A. The 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 [5]. 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 [6], Srinivasan et al. [7], Arnold et al. [8], Saleh et al. [9], Santhi et al. [10] and Jha et al. [11] for various watersheds throughout USA. Model components are described in detail by Arnold et al. [5], [8] and Srinivasan et al. [7].

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 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. A hillslope scheme is used in this study, which 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 [12]. Figure 1 shows the schematic flow pattern in hillslope SWAT for a contour strip, where water flowing from the crop area passes through the contour strip. The scheme route the flow from the crop area through the contour strip as an overland flow. Perennial vegetation (switch grass) is planted in the contour strips, which act as a filter between cropland and river and can uptake the nutrients in the surface runoff for its growth and slows down the flow to reduce the sediment yield.

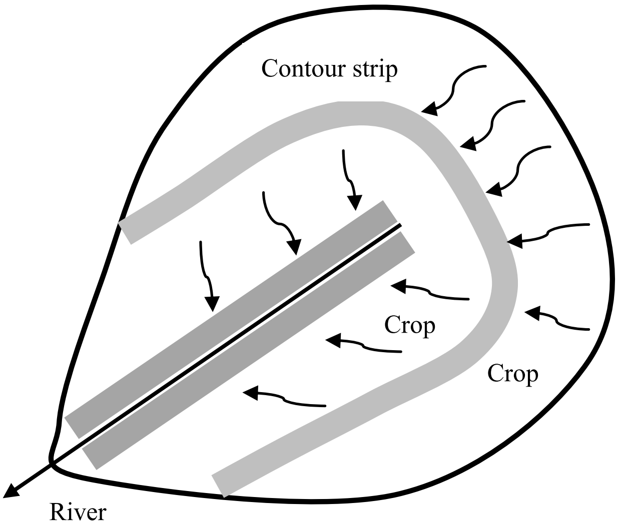

Fig. 1 A typical watershed having contour strips

B. Study Area and Input Data

Walnut Creek is a tributary to the Mississippi River. Walnut Creek watershed has an area of 51.3 km^2 and is located in central Iowa, USA. 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).

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 [13]. 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

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depressional areas [13]. 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 [13].

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 [13].

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 [13]. 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.

C. *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 numerical experiments to test the effectiveness of contour 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 contour strips is 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 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. The results are analyzed and compared to quantify the impact of strip size on the efficiency of nutrient reduction by contour strips.

III. RESULTS AND DISCUSSION

A. *Model 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 [14]. The SCE-UA has been applied with SWAT successfully for hydrologic parameters [15] and hydrologic and water quality parameters [16]. 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.

Figure 2 demonstrates the results of model calibration and validation using flow data for the Walnut Creek, in which observed and simulated flows are compared. Observed and simulated monthly flows at the outlet of the watershed for 1996 to 2000 (Figure 2) were used for model calibration and 1992 to 1995 was used for model validation. Calibration period was chosen after the validation period to avoid the very high flow of 1993 in the model calibration process. 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) 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 3. 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 [13] reported 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 on water quality improvement.

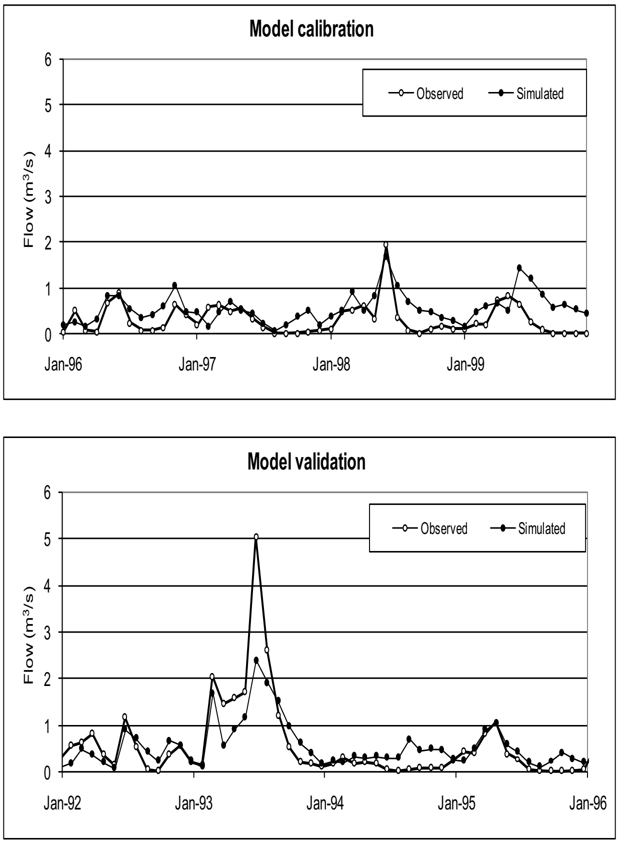

Fig. 2 Model calibration and validation – Time series of observed and simulated flows in Walnut Creek, Iowa

B. *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 4). Depending on the slope, soil type and other hydrological parameters, each subbasin has different NO_3-N contributions to the river. 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 5 and 6 from the SWAT output. The results presented in Figure 5 indicate that subbasins 4, 8 and 14 are the high impact subbasins based on total NO_3-N contribution. Similarly, per-unit-area NO_3-N contributions displayed in Figure 6 indicate that subbasins 11, 13, 14, 19, 20 and 22 are the high impact subbasins based on per-unit-area NO_3-N contribution. These subbasins have relatively steeper slopes compared to the other subbasins and have a soil type of IA115 (Hayden soil), which result in greater and faster surface runoff. 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 contour strips on water quality improvement.

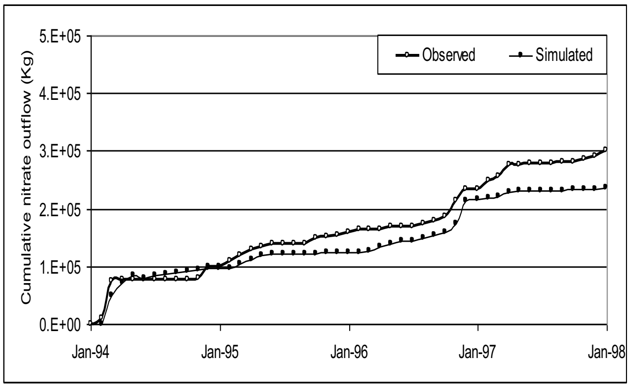

Fig. 3 Observed and simulated cumulative NO_3-N outflows at the outlet of the Walnut Creek Watershed

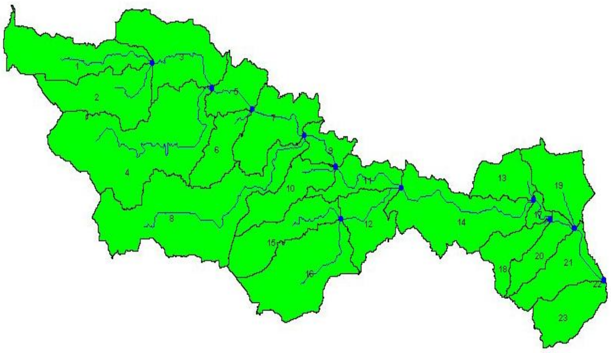

Fig. 4 Subbasins of the Walnut Creek watershed delineated by SWAT

C. *Effects of Contour Strip Size and Weather Conditions*

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 7 and 8 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 I and II. 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. Plots of NO_3-N reduction per unit area of filter strips are shown in

Figures 9 and 10. 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.

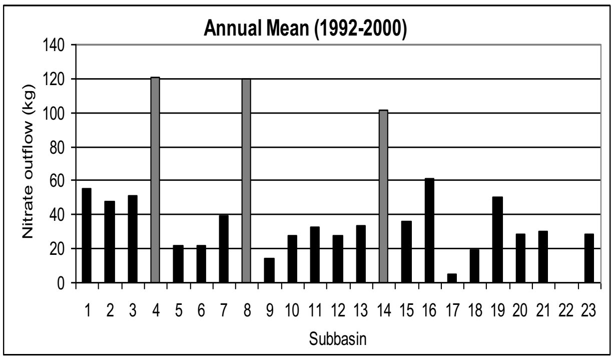

Fig. 5 Simulated annual average of total NO_3-N outflow from each subbasin under existing land use/cover condition

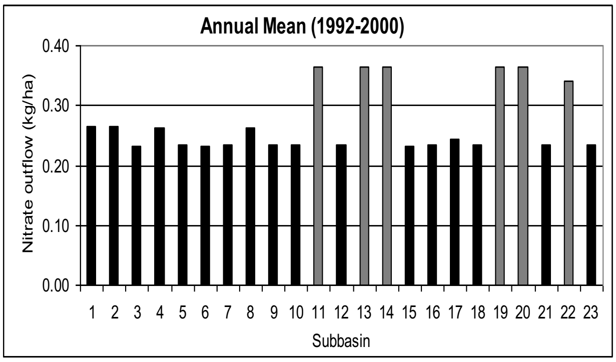

Fig. 6 Simulated annual average of per-unit-area NO_3-N outflow from each subbasin under existing land use/cover condition

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.

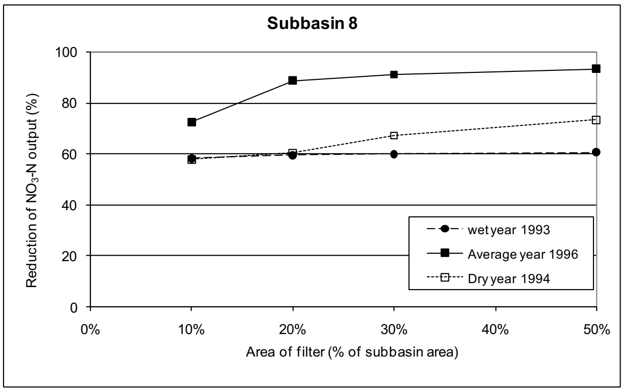

Fig. 7 Reduction (%) in NO_3-N contribution of subbasin 8 due to filter strip

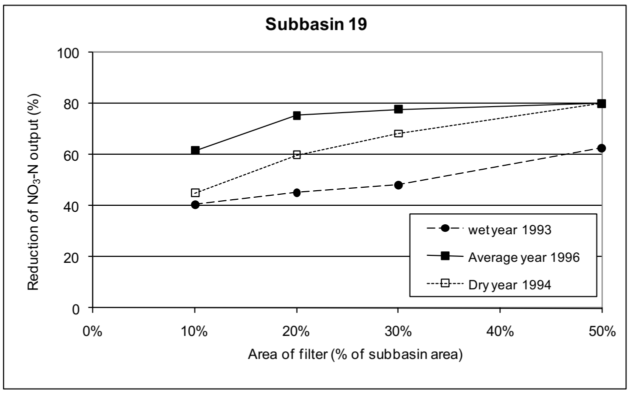

Fig. 8 Reduction (%) in NO_3-N contribution of subbasin 19 due to filter strip

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 studies by Dillaha et al. [17] have suggested nutrient reductions of up to 54-73% and 37-81% with different width of vegetative filter strips. Hence a 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

7 and 8. 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. 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.

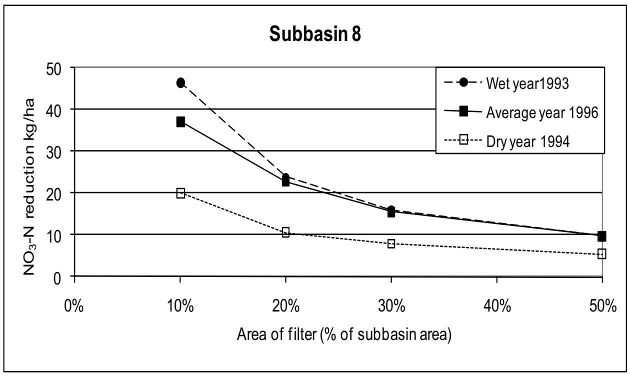

Fig. 9 NO_3-N reduction per unit area of the contour strip for subbasin 8

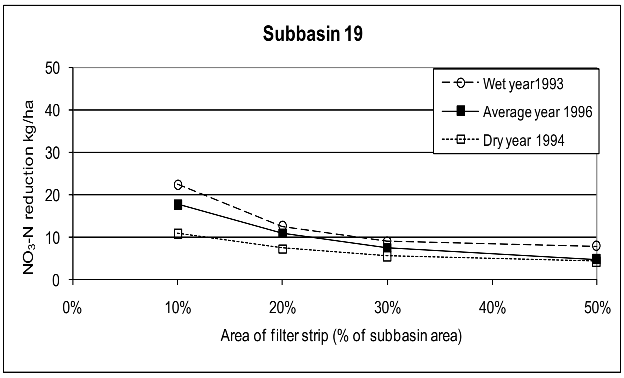

Fig. 10 NO_3-N reduction per unit area of the contour strip for subbasin 19

IV. CONCLUSIONS

SWAT model was used to investigate the fate and transport of nutrient (NO_3-N) in an agricultural watershed through contour strips planted with perennial vegetation, such as switch grass, with bio-fuel potential 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. Subbasins 11, 13, 19 and 20 were found to be contributing the highest NO_3-N to the river on per unit area basis and subbasins 4 and 8 were identified as highest total NO_3-N contributing subbasins. These subbasins would be priority subbasins in the watershed to be addressed first to have the maximum environmental impact with minimum economical effort.

TABLE I
SIMULATED NITRATE OUTFLOW FROM SUBBASIN 8 FOR VARIOUS CONTOUR STRIP AREAS

FILTER STRIP AREA			NO_3 Output (kg)		
sq. km	ha	% of subbasin	1993 (wet)	1996 (average)	1994 (dry)
0.000	00.0	0%	3520	2260	1540
0.439	43.9	10%	1480	626	653
0.878	87.8	20%	1430	258	611
1.317	131.7	30%	1420	205	508
2.195	219.5	50%	1380	126	365

TABLE II
SIMULATED NITRATE OUTFLOW FROM SUBBASIN 19 FOR VARIOUS CONTOUR STRIP AREAS

FILTER STRIP AREA			NO_3 Output (kg)		
sq. km	ha	% of subbasin	1993 (wet)	1996 (average)	1994 (dry)
0.000	00.0	0%	764	398	331
0.139	13.9	10%	455	153	182
0.278	27.8	20%	419	98	133
0.417	41.7	30%	396	88	105
0.695	69.5	50%	230	74	46

Strip sizes of 10%, 20%, 30% and 50% of the subbasin area were considered for the simulation. Varying the area of the contour strip affects the loss of NO_3-N to the river outflow reduction and the crop yield 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 the loss of NO_3-N to a desired limit or vice versa. In general, larger the size of filter strip, higher was the reduction in NO_3-N outflow. However, the rate of NO_3-N reduction gets milder when size of the strip gets in 30-50% range. Contour strips having 10-20% area were found to be more efficient. Results have shown that a filter strip having 10%-50% of the subbasin area with a perennial cover of switch grass could potentially lead to 55%-90% reduction in the NO_3-N outflows from the subbasin in an event of average rainfall year. However, dynamics of nutrient in the runoff and its interaction with the vegetation in the filter strip is somewhat different in wet or dry year. In case of wet year, very high flow carrying nutrients does not provide enough opportunity to the filter strip vegetation to use up the nutrients, whereas in case of a dry year, there is not enough supply of nutrient to the filter strip vegetation. Thus in dry year, there remains enough additional capacity of the filter strip to remove the nutrients that is not fully utilized.

In future work, this study is to be extended to large-scale watersheds, such as the Upper Mississippi River Basin, to examine NO_3-N reductions by the application of contour strips. An economic (or cost vs. benefit) analysis is also needed to compare the monetary returns from the same land under corn and contour strips of switch grass for bio-fuel. Difference between the two is the cost of environmental protection. The results are expected to be useful in evaluating the economic feasibility of growing switch grass for bio-fuel and designing a farmer compensation program based on the cost of environmental benefits.

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