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Water and Soil Environment Pollution Reduction by Filter Strips

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Abstract**—**Contour filter strips planted with perennial vegetation can be used to improve surface and ground water quality by reducing pollutant, such as NO_3-N, and sediment outflow from cropland to a river or lake. Meanwhile, the filter strips of perennial grass with bio-fuel potentials also have economic benefits of producing ethanol. In this study, The Soil and Water Assessment Tool (SWAT) model was applied to the Walnut Creek Watershed to examine the effectiveness of contour strips in reducing NO_3-N outflows from crop fields to the river or lake. Required input data include watershed topography, slope, soil type, land-use, management practices in the watershed and climate parameters (precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity). 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 strips (10%, 20%, 30% and 50%, respectively, of a subbasin area) planted with perennial switchgrass were selected for simulating the effects of strip size and location 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. The results of this study can assist in cost-benefit analysis and decision-making in best water resources management practices for environmental protection.

Keywords—modeling, SWAT, water quality, NO_3-N, watershed.

I. Introduction

NUTRIENT 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 [1], [2], [3], [4]. The efficiency of pollutant reduction may be different depending upon the type of vegetation, the size and location of the strips, and watershed parameters such as slope and soil type. It is important to numerically simulate the effects on NO_3-N outflow due to alternative land-use/management scenarios containing the ecological solutions. The Soil and Water Assessment Tool (SWAT) [5] is a comprehensive watershed scale model that can simulate the hydrological processes along with nutrient, sediment and pesticides in a watershed and river network.

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. 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.

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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 et al. [6], Santhi et al. [7] and Jha et al. [8] for various watersheds throughout USA. Model components are described in detail by Arnold et al. [5], [6].

B. Study Area

Figure 1 shows a typical watershed having contour and riparian buffer strips. Walnut Creek watershed (Figure 2) has an area of 51.3 km^2 and is located near Ames in central Iowa extending from 41°55' to 42°00' North latitude and 93°32' to 93°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).

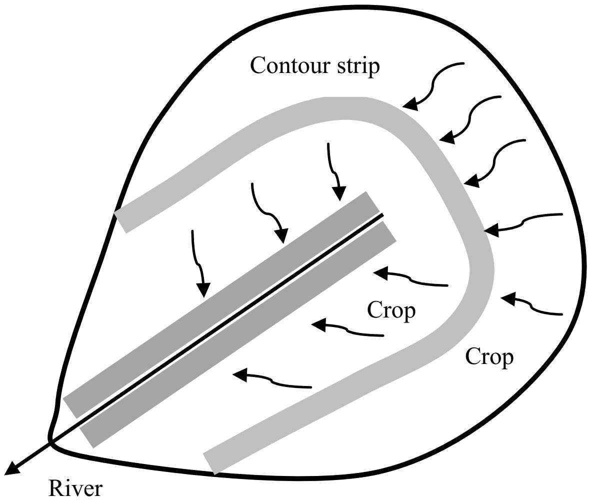

Fig. 1 A typical watershed with contour strips

C. 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. 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 [9]. State soil geographic (STATSGO) soil map developed by USDA was linked to the SWAT soil database. 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.

D. 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.

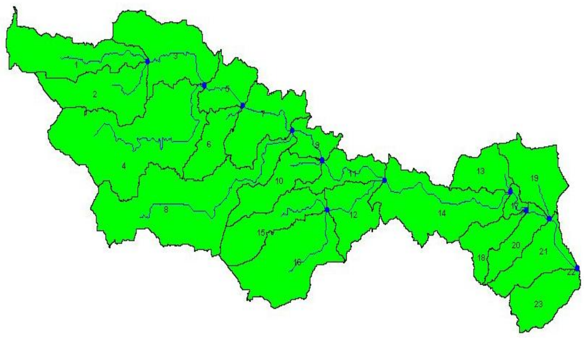

Fig. 2 Walnut Creek watershed with its subbasins

III. Results and Discussion

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, each subbasin has different NO_3-N contributions to the river. 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 Figure 3 from the SWAT output. The results presented in Figure 3 indicate that subbasins 4, 8 and 14 are the high impact subbasins based on total NO_3-N contribution. 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. Simulated per-unit-area NO_3-N contributions indicated 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.

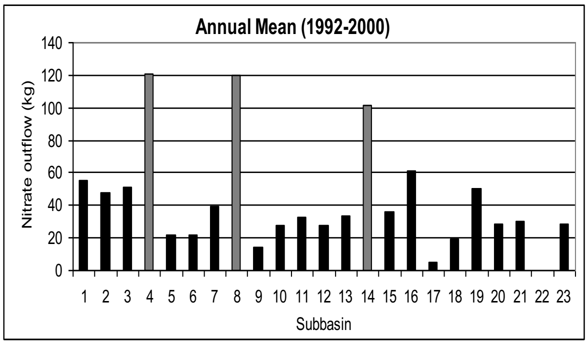

Fig. 3 Simulated annual average of total NO_3-N outflow under existing land-use/cover condition

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, 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. 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.

SWAT simulations of subbasin 8 were carried out and NO_3-N outflows from the subbasins with and without the filter strip were compared. Figure 4 show the percentage reduction of NO_3-N in surface water from the subbasin due to filter strip compared to the base case with no filter strip. 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 were 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.

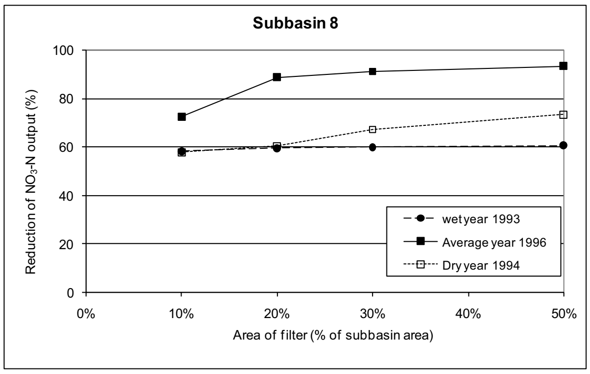

Fig. 4 Reduction of NO_3-N in subbasin 8 by filter strip

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 Figure 4. 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 Figure 5. 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.

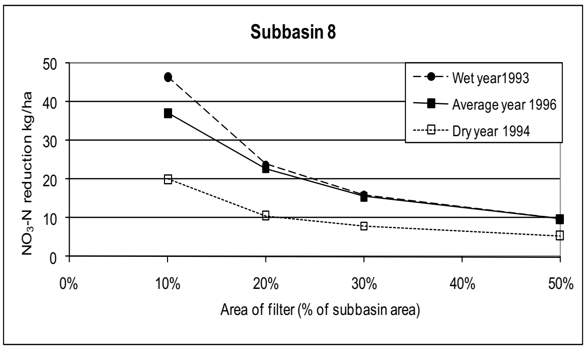

Fig. 5 Reduction of NO_3-N per unit area of the contour strip in subbasin 8

IV. Conclusions

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.

In general, larger the size of a 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. It is found 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.

References

[1] Hernandez, M.E. and Mitsch, W.J., 2007. Denitrification in created riverine wetlands: Influence of hydrology and season. *Ecological Engineering* 30(1): 78-88.

[2] Meier, K., Kuusemets, V., Luig, J., and Mande, U. 2005. Riparian buffer zones as elements of ecological networks: Case study on *Parnassius mnemosyne* distribution in Estonia. *Ecological Engineering* 24(5), 531-537.

[3] Lin, Y., Lin, E., Chou, W., Lin, W., Tsai, J. and Wu, C. 2004. Modeling of riparian vegetated buffer strip width and placement: A case study in Shei Pa National Park, Taiwan. *Ecological Engineering* 23(4-5), 327-339.

[4] Anbumozhi V., Radhakrishnan, J. and Yamaji, E. 2005. Impact of riparian buffer zones on water quality and associated management considerations. *Ecological Engineering* 24: 517–523.

[5] Arnold, J.G., Williams, J.R., and Maidment, D.R., 1995. Continuous – Time Water and Sediment-Routing Model for Large Basins. Journal of Hydraulic Engineering, 121(2), 171-183.

[6] Arnold, J.G., Srinivasan, R., Muttiah, R.S. and Williams, J.R., 1998. Large Area Hydrologic Modeling and Assessment Part I: Model Development. Journal of American Water Resources Association, 34(1), 73-89.

[7] Santhi, C., Arnold, J.G., Williams, J.R., Dugas, W.A. and Hauck, L., 2001. Validation of the SWAT model on a large river basin with point and nonpoint sources. Journal of the American Water Resources Association, 37(5), 1169-1188.

[8] Jha, M., Pan, Z., Takle, E.S. and Gu, R., 2004. Impacts of climate change on stream flow in the Upper Mississippi River Basin: A regional climate model perspective. Journal of Geophysical Research, 109, D09105, doi: 10.1029/2003JD003686.

[9] Hatfield, J.L., Jaynes, D.D., Burkhart, M.R., Cambardella, C.A., Moorman, T.B., Prueger, J.H. and Smith, M.A., 1999. Water Quality in Walnut Creek Watershed: Setting and Farming Practices. Journal of Environmental Quality, 28, 11-24.