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Evaluating Effectiveness of Unconfined Livestock BMPs using SWAT

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Abstract

Innovative market-based approaches for environmental management, such as Best Management Practice (BMP) auctions, have recently gained more attention due to their cost-effectiveness and practical success dealing with specific pollution problems. In a BMP auction, agricultural or livestock producers submit their own BMP proposals that are ranked based upon the quantity of pollutant reduction per dollar. Winning bids are awarded accordingly to achieve the greatest environmental impact for the least cost. This study presents a field-scale modeling approach to assess effectiveness of livestock BMP proposals using SWAT. A pasture field used to represent an actual bid was divided into floodplain, riparian buffer, and multiple grazing land areas having unique land characteristics similar to the Hydrologic Response Units (HRU) in SWAT. Multiple sets of grazing operation scenarios with a range of applied stocking rates within each pasture area were simulated by running the SWAT model in a Lower Marais des Cygnes watershed located at the Kansas and Missouri border. The collected annual average nutrient loads for every HRU in the watershed were statistically analyzed, and the least-square error trends were determined. Given the unique pasture features in each submitted bid, including pasture geometry, land characteristics, and management operation schedule, the BMP effectiveness index was calculated based on the pollutant load values interpolated from the trend charts and an expert-formed ranking table. A stand-alone user-friendly interface was developed to help the bid evaluation expert team pre- and post-process individual BMP proposals.

Keywords: SWAT, Livestock, BMP, Auction

Introduction

Grazing management on livestock pasture highly affects sediment and nutrient loads coming off to the streams (Haan *et al.*, 2006). To minimize the loads many incentive programs have been established to motivate producers to adopt pollution prevention BMPs. Among other programs, there has been an increased interest in market-based approaches such as BMP auctions. To date, three BMP auctions have taken place in Kansas and four more are scheduled. As an example, $70,000 is committed to be awarded to producers through an auction in the Lower Marais des Cygnes watershed (410,700 ha), located at the Kansas and Missouri border.

In a BMP auction, the producers submit bids to an agency investing in BMPs. An expert team is formed to assess the BMP proposals and rank their water-quality impact based upon the nutrient and sediment loads. The most cost-effective and environmentally efficient proposals are awarded. To quantify the environmental impact, the expert team requires a hydrologic modeling tool to provide rapid assessment of the livestock BMP proposal. While there are many models available for evaluation of agricultural BMPs, the number of models for livestock/pasture assessment is limited (White *et a.l*, 2009). The unique pasture features, including pasture geometry, land characteristics, and management operation schedules, must be accounted in determining the BMP effectiveness.

The objective of this study is to develop a framework that utilizes pasture unique features to determine average annual pollutant loads and to calculate a BMP effectiveness index that helps a bid evaluation expert team rank BMP proposal. Application of this framework to Lower Marais des Cygnes watershed and computed results will also be discussed.

Methodology

In this study we use the following pasture layout. The pasture is split into the following four subareas as shown in Fig. 1: a floodplain (area 1), riparian buffer (area 2), and two grazing lands (areas 3 and 4). The floodplain represents a flat area along both sides of the stream. If grazing occurs in the floodplain it is assumed that majority of the manure deposition is introduced directly into the stream. Area 2 is a riparian buffer that separates the grazing land from the stream and serves as a buffer for runoff. Most times the buffer may be a part of the floodplain, but in this setup we assume it is an independent area. Areas 3 and 4 both are part of the grazing land where livestock spends most of the time during the day. Splitting the grazing areas into two subareas serves purpose to manage spatial distribution of the cattle. All areas in the pasture may have different soil types, average slopes, and land cover conditions.

Main source of water for the livestock is a stream within the area 1 or a watering site located in areas 2, 3, or 4. Watering site can be represented by a trough, or a pond, or any other watering facility. Pastures with an access to the stream are known to produce higher sediment loading due to cattle eroded stream bank and higher water-quality concerns due to direct deposition of manure into the stream. Nutrient flows from congregated locations in the buffer where livestock rest in shade in summer can also decrease quality of the land cover and have significant environmental effects. To prevent such conditions and block the access to the streams, the recommended BMPs include fencing the stream or the buffer accompanied with the altering of grazing management practices by attracting livestock to the areas farther away from the stream by creating alternative watering sites (Ohlenbusch and Harner, 2003).

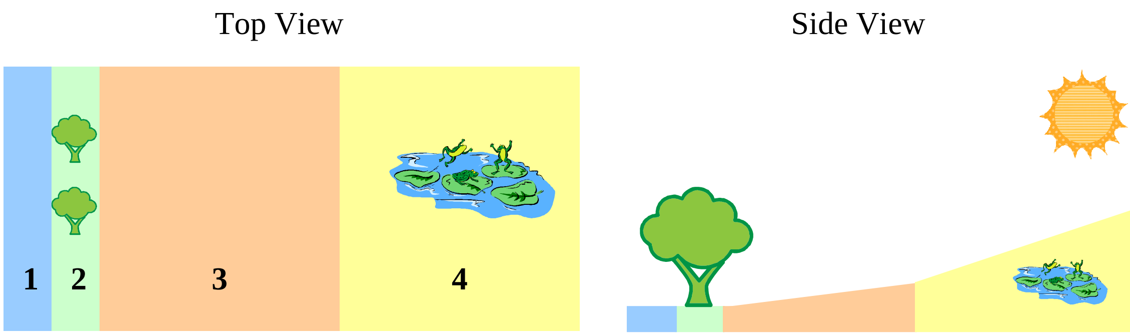

Figure 1 Schematic of the pasture split into four subareas. Area 1 is a floodplain with a stream, Area 2 is a riparian buffer that separates the grazing land from the stream, and Areas 3 and 4 represent the grazing land with unique soil and slope characteristics.

Spatial and temporal distribution of cattle within the pasture is difficult to model because of limited knowledge of what affects the grazing patterns. Many factors may include (Ohlenbusch and Harner, 2003):

- Location of preferred watering site,
- Location of preferred shade,
- Prevailing wind direction,
- Quality of available forage in grazing areas,
- Topography.

One simple way to account for different distributions within the pasture is to assume a uniform spatial distribution within individual areas of pasture. The stocking rate within each subarea can be used as the distribution input parameter, and it is defined as the number of animal units (1 AU = 1,000 lbs) allocated in a given land area for a day (Ohlenbusch and Watson, 1994). Knowing total number of animal units grazing in the pasture gives an average pasture stocking rate Sr_{AVE} that is related to subarea i stocking rates Sr_i and areas A_i by the following formula:

$$Sr_{AVE} = \sum_{i=1}^{4} \left(Sr_i A_i\right) \Big/ \sum_{i=1}^{4} A_i$$

For individual pasture scenarios the stocking rates will be specified for each area during the grazing season.

Soil and Water Assessment Tool (SWAT) model (Arnold *et al.*, 1998) is used to simulate livestock grazing in the pasture and make a quantitative prediction of average annual sediment loss and nutrient loadings at the pasture and basin scales. SWAT is a complex continuous basin-scale model that incorporates a set of both physically and empiricallybased equations to calculate a large variety of hydrologic parameters. SWAT uses Hydrologic Response Units (HRU) as main footprints for hydrologic simulations. Each HRU represents spatially aggregated parts of land within a watershed with unique combinations of soil type, land cover, and average slope. Applying SWAT approach to the pasture we state that subareas within the pasture are represented by their corresponding HRUs; more specifically, the riparian buffer is represented by the HRU formed with deciduous forest (classified as FRSD) and pastureland (classified as HAY) refers to the grazing areas. SWAT results are not applied to the floodplain, as its loadings are calculated directly based on amount of manure applications.

Table 1. SWAT Input Parameters for Grazing Management Operation

Description	Parameter	Units
Grass type	CROP	—
Daily manure	MANURE_KG	kg/ha
Start of grazing	YEAR,MONTH,DAY	—
Number of grazing days	GRZ_DAYS	—
Type and amount of fertilizer	FRT_ID, FRT_KG	—, kg
Biomass consumed and trampled daily	BIO_EAT, BIO_TRMP	kg/ha
Initial pasture and buffer conditions	CN2	—

SWAT requires a large number of input parameters. Default values for many parameters can be found in SWAT database. Some parameters represent user inputs, and their values rely on the local knowledge. Parameters related to grazing management (operation OPNUM=9) within the pasture are listed in Table 1. Values of these parameters are modified to accommodate grazing in FRSD and HAY HRUs. The specified minimum amount of dry forage at which grazing is permitted and the initial condition of the riparian buffer are defined by the curve number value (CN2) for the corresponding HRU. Amount of biomass consumed and trampled daily, fertilizer application date, type, and amount are also entered into the project input database based on the grazing operation.

Daily precipitation and temperature data is collected from National Climatic Data Center while other weather daily information is generated by the weather prediction model embedded in SWAT. For each HRU, SWAT calculates average loadings per hectare of a HRU land ω_i. Total loadings of each output variable W for entire pasture are calculated as a sum of the loadings for each subarea in the pasture:

$$W_{past} = \chi M \, Sr_1 A_1 + \omega_2 A_2 + \omega_3 A_3 + \omega_4 A_4$$

The floodplain loadings shown as the first term in the formula are estimated based on amounts of nitrogen and phosphorous in the directly applied manure, where $M = 8.5$ kg is amount of solid manure produced by 1000 kg of live animal mass, χ is percent of the selected constituent or SWAT variable in solid manure. If floodplain and buffer are fenced then the corresponding areas are assumed to be not contributing to the total pasture loadings due to the grazing.

Combination of stream and buffer fencing and relocation of a watering site composes a set of nine BMP scenarios assessed in this study (see Table 2). Soil and topography in pasture subareas significantly affect efficiency of the BMP. Stocking rate within each area determines daily amount of manure applied to the land. High stocking rates and lack of available forage decrease quality of the pasture through higher curve number values, increase soil erodibility, and produce higher nutrient loads.

Table 2. Grazing Management Scenarios and Associated Stocking Rates for Four Subareas in Pasture (F refers to floodplain, B to buffer, and G1 and G2 to two grazing subareas). Average stocking rate is equal to 1 AU/acre.

			Stocking Rates			
	Fence	**Watering Site**	**F**	**B**	**G1**	**G2**
1	-	F	2.00	2.00	0.96	0.96
2	-	B	1.50	2.00	0.97	0.97
3	-	G1	0.93	2.00	1.50	0.00
4	-	G2	0.26	0.50	0.80	1.45
5	F	B	0.00	1.40	1.40	0.28
6	F	G1	0.00	1.50	1.50	0.09
7	F	G2	0.00	0.51	0.51	2.00
8	B	G1	0.00	0.00	1.60	0.00
9	B	G2	0.00	0.00	0.53	2.00

To assess water-quality efficiency for the BMP proposal during the bid evaluation process, the following approach is developed. First, the expert team specifies a realistic range of stocking rates for each subarea in the pasture and identifies grazing management practices for entire range of the stocking rates that are converted to SWAT inputs for HAY and FRSD HRUs. Secondly, the stocking rate ranges are divided into 20 equal intervals and the previously defined inputs applied to the SWAT model. At last, the SWAT model runs consecutively 21 times with the inputs changed according to the assigned stocking rate. For each run the outputs for all HAY and FRSD HRUs are collected and stored in a separate database. Once all runs are completed, outputs of all HRUs with similar characteristics from various subwatersheds are plotted for each output variable on one chart, and the least-square error polynomial trend is determined. Pollutant load values W_i are interpolated from these trends for each subarea in the pasture according to subarea stocking rate.

In determining the BMP effectiveness index, scenario 1 with no fencing and stream being used as a primary watering site is considered as a baseline. BMP effectiveness index I_{EFF} is calculated relative to the baseline scenario output values by the following formula

$$I_{EFF} = \frac{1}{N}\sum_{j=1}^{N}\phi_j\left(1-\frac{W_j}{W_j^{base}}\right)$$

with superscript *base* defining the baseline and *N* representing a total number of output SWAT variables. Based on the main environmental goal of the livestock BMP auction process, various weights ϕ_j in the formula above can be assigned to SWAT variables. Table 3 presents a list of SWAT output variables and an example of the weighting factors skewed toward importance of phosphorous reduction in implementation of the BMP.

The BMP effectiveness index is calculated for each BMP proposal, and then all proposals are ranked from the most to the least water-quality efficient with the proposals exhibiting higher effectiveness have higher probability to get awarded. We note, that the technical expert team must consider other aspects, such as cost-effectiveness of BMP investments and TMDL priorities in that area among others, before making a final decision on which proposal to award.

Table 3. Weighting Factors ϕ_j for SWAT Variables in Ranking Index Calculations (SWAT variable abbreviations shown in the lower row)

Sediment **SYLD**	Organic Nitrogen **ORGN**	Organic Pho **ORGP**	Mineral Pho **SEDP**	Nitrates in Surface Runoff **NSURQ**	Nitrates in Lateral Flow **NLATQ**	Nitrates with Ground water **NO3GW**	Soluble Pho **SOLP**	Total
0.05	0.10	0.20	0.20	0.10	0.05	0.05	0.25	1.00

A spreadsheet tool was developed to assist the expert team with bid evaluation process. SWAT model executable file is called many times from this spreadsheet tool to conduct multiple model runs and collect the output data. Each individual BMP proposal is entered into the spreadsheet and BMP effectiveness index is evaluated.

Application and Results

The approach presented in the previous section was applied to the Lower Marais des Cygnes watershed which was selected by the Kansas Department of Health and Environment to conduct a livestock BMP auction in 2009. Lower Marais des Cygnes watershed is a part of the Marais des Cygnes river basin and located south of the Kansas City metropolitan area with 60% of its land in Kansas and 40% in Missouri. Three counties (Miami and Linn Counties in Kansas and Bates County in Missouri) cover 90% of the entire watershed. Total drainage area of the watershed is 410,700 ha with almost 50% (49.81% = 204,582 ha) of it used for rangeland and pastures.

After researching the watershed land use maps and communicating with the extension specialists in that area, total area of representative pasture was chosen to be 16.2 hectares (40 acres) with a floodplain being 300 meters long and 10 meters wide (area of 0.3 ha) and a riparian buffer of 12 meters wide (area of 0.36 ha). The grazing land were split into 10 ha for area 3 and the remaining 5.54 ha for area 4. The floodplain length was determined as an average stream length per total pasture area in the whole watershed.

The watershed was delineated into 45 subwatersheds with total of 2833 HRUs. The STATSGO soil database identified 13 soils predominantly of C and D hydrologic soil type, and the watershed was divided into areas with less and more than 3 percent slope. The same weather data was applied to all subwatersheds belonged in each of three counties which allowed having three independent subsets of output data. Within each subset outputs from all similar HRUs were collected for FRSD and HAY land uses.

Stocking rates for all pasture subareas are presented in Table 2 for 9 different BMP scenarios assuming $Sr_{AVE} = 1$ as a reference value. For the studied watershed the average stocking rate is equal to 0.5 thus all stocking rates in Table 2 must be scaled down by half. Based on the management practices in that watershed, the grazing season starts in mid-April and ends in the beginning of December. Pasture has perennial grasses like brome or tall fescue growing in it that are fertilized in mid-February with 50 lbs of Nitrogen fertilizer applied to each acre of land. The amount of forage consumed by 1 AU is 14 lbs dry matter per day with 7 lbs dry matter per day wasted or trampled.

SWAT model were ran for 17 years from 1992 to 2008 with first 5 years used as a warm-up period. After the SWAT simulations with stocking rates ranging from 0 to 4 AU/acre were completed, the average annual values for phosphorous constituents listed in Table 3 were collected for each of the three subsets of output data, and polynomial trends and coefficient of determination R^2 were calculated. The results are shown in Fig. 2 for the grazing land (a) and the buffer subarea (b). For both land uses the output values increase as stocking rate grows.

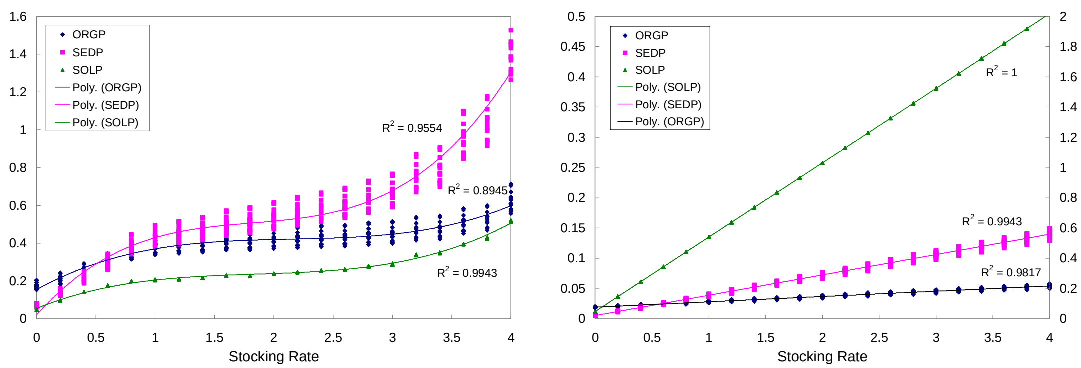

Figure 2. Phosphorous loads in kg/ha for grazing land (a) and buffer (b) HRUs with "Summit" soil (hydrologic group D) and slope more (a) and less (b) than 3%.

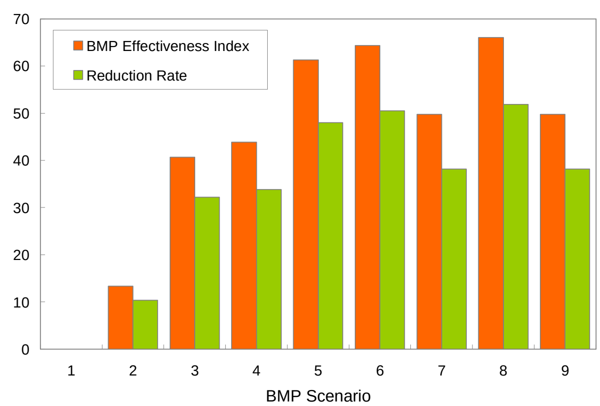

Figure 3. BMP effectiveness index and cumulative pollutant reduction rates for various scenarios

Constructing a pasture of D group soil and flat subareas 1, 2, and 3, and high slope subarea 4 as an example of an actual BMP bid proposal, we calculated the BMP effectiveness index and pollution reduction rates for all 9 scenarios shown in Fig. 3 with stocking rates presented in Table 2. Effectiveness of the BMP reaches its highest value for scenarios 6 and 7 where the stream is fenced and watering site is located in flat subarea 3. Fencing the stream appears to be the most effective conservation practice for small livestock operations.

Conclusions

A modeling framework to support livestock BMP auctions is developed and applied to Lower Marais des Cygnes watershed in the U.S. Midwest. The framework includes running a SWAT model with the input pasture data provided by the expert team, processing the SWAT output data and determining the least-square error trends for each of the output variables, and then interpolating the trend charts to fit the pasture design in the submitted BMP proposal. The expert-formed ranking table is established and used to calculate the BMP effectiveness index that is utilized by the expert team to rank the bids on environmental and water-quality effectiveness. A stand-alone user-friendly spreadsheet tool was developed to help the bid evaluation expert team pre- and post-process individual BMP proposals.

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