Designing BMPs at a watershed-scale using SWAT and a genetic algorithm

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Abstract. An optimal control model (OCM) is developed by coupling a semi-distributed hydrological model, Soil and Water Assessment Tool (SWAT), with a genetic algorithm (GA) to identify the least cost design (sizes, types, and locations) of structural best management practices (BMPs) while meeting treatment goals at a watershed-scale. Treatment goals considered are constraints on daily peak flow values and annual sediment load. SWAT performs the hydrological simulation incorporating combinations of BMPs while the GA searches for the least cost combination. Structural BMPs included in the OCM include detention ponds, infiltration ponds, parallel terraces, filter strips, grade stabilization structures, and grassed waterways. The model is demonstrated on Silver Creek watershed, a sub-watershed of the Lower Kaskaskia basin in Illinois. The OCM is able to find optimal or near optimal solutions for different scenarios of treatment goals.

Keywords. Genetic algorithm, optimal control model, SWAT, Silver Creek, BMPs.

Introduction

Section 303 (d) of the Clean Water Act mandates states, territories and tribes to develop a list of impaired waters. According to the US Environmental Protection Agency (USEPA), over 20,000 river segments, lakes and estuaries, which account over 40% of assessed waters, still do not meet the water quality standards. The states, territories and tribes are required to develop a Total Maximum Daily Load (TMDL) that specifies the maximum amount of a pollutant that a water body can receive and still meet water quality standards and allocates pollutant loadings among point and non-point pollutant sources for these impaired waters.

Generally, structural Best Management Practices (BMPs) are used to control runoff, sediments and nutrients both in urban and rural or agricultural watersheds. Structural BMPs normally applied in agricultural watershed include detention and retention basins, filter strips and field terracing. On-site design is a common practice for BMP design, but it could lead to implement many BMPs in the watershed and still can not assure that the treatment goals at the watershed outlet are achieved. Emerson (2005) pointed out that the on-site approach is not particularly effective in collectively reducing watershed-wide peak flows and can potentially increase peak flow rates for detention-based systems by negatively impacting each other. Harrell et al. (2003) emphasized that fewer regional basins can be implemented in place of many on-site basins to achieve the same treatment goals when they are implemented at a watershed scale. To address these issues, a single objective optimal control model (OCM) is developed by selecting, placing, and sizing BMP combinations that cost- effectively promotes the achievement of treatment goals at larger spatial scales. The OCM couples the U.S. Department of Agriculture's (USDA) hydrological model, Soil and Water Assessment Tool (SWAT) and a genetic algorithm (GA). The model is applied to Silver Creek watershed, which is a sub watershed of Lower Kaskaskia watershed in Illinois. SWAT performs the hydrological simulation incorporating different BMPs, while GA explores the least cost combination of BMPs (type, location and size) to meet treatment goals. The treatment goals considered are reduction on peak flow and sediment load at the watershed outlet. The model is run for different treatment scenarios (5%, 15% and 25% reduction of peak flow and annual sediment load) and the results are compared. This work is an extension from Kaini et al. (2007) where the cost of a combination of detention ponds in a watershed was optimized to reduce the peak flow. Where the OCM finds a single optimal or near optimal solution that achieves the target treatment goals, Artita et al (2008) presents the simultaneous generation of near-optimal alternative design strategies using a cost-based distance metric considering similar BMPs for the same watershed.

Problem Formulation

The current problem can be stated as the design of BMPs (type, size and location) at a watershed scale that:

Minimize: Total cost of BMPs

Subject to the following constraints:

(1) Water balance in the watershed
(2) BMP size constraints
(3) Landuse constraints
(3) Meets peak flow and sediment load reduction criteria

Mathematically, this can be expressed as

Minimize: $BMPC = \sum_i \sum_j BMPC_{ij}$

Subject to:

$$\sum_{k=1}^{n} A_k \le A_{\max}$$

$$A_k = A_{k,sb} \times fr$$

$$PF_{\max} \le PF_{\max\lim}$$

$$SedL_{\max} \le SedL_{\max\lim}$$

$$PF_{\max} = g_1(x,u,t)$$

$$SedL_{\max} = g_2(x,u,t)$$

Where, $BMPC$ is the total cost of BMPs implemented in a watershed. $BMPC_{ij}$ is the cost of a j type of BMP implemented in a subbasin i. A_k is the area of the pond in subbasin k whose value lies within the user-defined maximum and minimum limits, A_{max} is the maximum limit of the total pond area assigned to the watershed, $A_{k,sb}$ is the area of subbasin k, and fr is the fraction of the subbasin area that drains to the pond. PF_{max} is the maximum daily flow of the simulation period, $PF_{max\ lim}$ is the user defined limit of peak flow, $SedL_{max}$ is the maximum annual sediment load and $SedL_{max\ lim}$ is the user defined maximum limit of annual sediment load. The final two relationships represent simulation constraints, where g generally represents all pertinent hydrologic and hydraulic relationships, as a function of dependent (state) and independent (decision) variables, x and u, respectively, and time, t. BMPs are not implemented in a subbasin where the dominated land use is either forest or water body.

Silver Creek Watershed

The model is developed and applied to the 1,189 km^2 (459 sq. miles) Silver Creek watershed (Figure 1). The primary landuses in the watershed are cropland, grassland, and forest. Due to the eastward expansion of the Metro Link light rail system, an indication that the region is growing "bedroom communities" for the city of St Louis, Missouri and the Metro East Region, the area is currently experiencing moderate to high levels of urbanization.

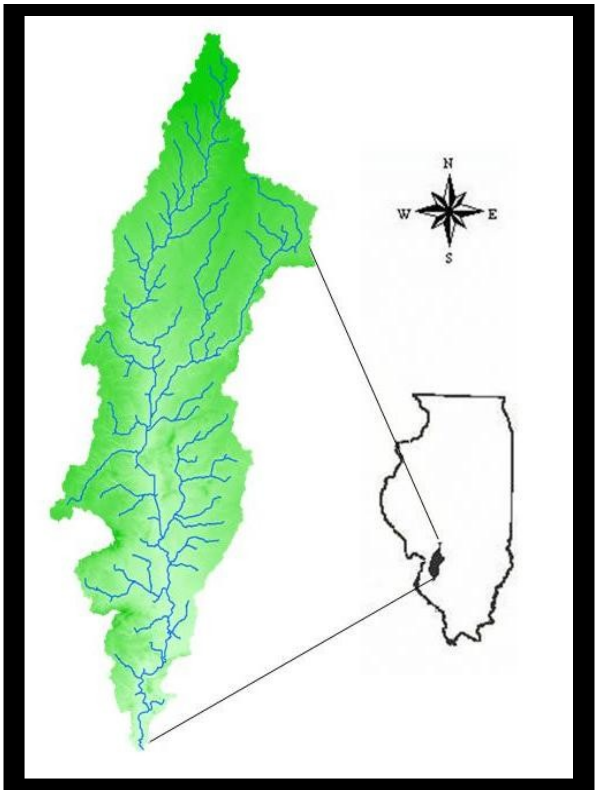

Figure 1: Location of Silver Creek Watershed, Illinois

Climate data for the study area, which include the daily precipitation and maximum and minimum daily temperatures, were obtained from the National Climate Data

Center (NCDC). A 30-m resolution Digital Elevation Model (DEM) and hydrologic data (daily flow) for the hydrological station USGS-05594800, located near Freeburg (St Clair County) in Illinois were obtained from US Geological Survey (USGS). The digital soil map and the land use map were obtained from the Natural Resources Conservation Service (NRCS).

SWAT

SWAT is a physically based, spatially-distributed, continuous-time watershed model that operates on an ArcView GIS (i.e., AVSWAT) platform. It was developed by the USDA to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Arnold, 2005). The main purpose of SWAT is the computation of runoff, sediment and nutrient loads from a watershed. SWAT requires specific information about climate, topography, soil properties, land use and management of a watershed for simulation (Arnold, 2002). To account for the spatial heterogeneity of climate, topography, land use and soil, SWAT delineates the watershed into spatially defined sub basins by using Digital Elevation Model (DEM). Each subbasin is further sub-divided into hydrologic response units (HRUs). A HRU is the total area in a subbasin with a particular land-use, management and soil type. SWAT simulates the surface and subsurface flow accounting for rainfall/snowfall and snow melt and sub surface flow processes.

Calibration of SWAT

An automatic calibration routine that makes use of the GA to adjust model parameters has been used to calibrate SWAT for Silver Creek watershed. A single objective GA is applied where Root Mean Square Error (RMSE) between the observed and simulated flow is considered as an objective function considering 11 SWAT parameters which influence flow (Bekele, 2007; Muleta, 2005; Arnold, 2002). Nash-Sutcliffe Efficiency (NSE) is calculated to check the model performance as defined by Nash and Sutcliffe (1970). SWAT is simulated for the duration of 1990 through 1996 where calibration is performed for the period of 1992 through 1994. Simulation from 1990 through 1991 is considered as the warm up period to reduce the initial condition impacts, whereas the simulation from 1995 through 1996 is used for verification.

The RMSE for calibration and verification are found to be 1.4155 and 1.7831 respectively whereas, NSE for calibration and verification are found to be 0.42 and 0.64 respectively. According to Moriasi (2007), NSE value between 0 and 1 is acceptable. The results obtained here, NSE equal to 0.42 for calibration and 0.64 for validation, are considered satisfactory.

BMP Representation in SWAT

A detention pond is a permanent pool which treats storm water by retaining flow for certain time. A pond reduces suspended sediments, metals and dissolved nutrients by sedimentation and biological processes. It also helps to attenuate storm peaks by delaying the surface runoff to the river. In this study, the infiltration type of detention pond is represented with the bottom permeability coefficient (K) of 0.1 where as normal detention pond is represented with the value of K equal to 0. A detention pond is represented by assigning appropriate parameters including pond area and volume corresponding to maximum and emergency spillway levels, fraction of subbasin that drains to the pond in the pond subroutine.

A filter strip, also known as field border, is a uniformly graded and densely vegetated area at the border of the field where excessive sheet and rill erosion is likely to occur. A filter strip is represented by the width of the edge of field filter strip (FILTERW). The value of FILTERW is 0 for no filter strip and 5 m if a filter strip is applied (Bracmort et al. 2006). The trapping efficiency of the strip is a function of the filter width and is calculated in SWAT by (Arnold, 2002);

$$Trap_{eff} = 0.367 \times (Width_{filter})^{0.2967}$$

where, $\mathrm{Trap}_{\mathrm{eff}}$ is the trapping efficiency of the filter strip and $\mathrm{Width}_{\mathrm{filter}}$ is the width of the filter strip in m.

A grassed waterway is a natural or constructed watercourse consisting of vegetation and is designed to accommodate concentrated flows without erosion. Grassed waterways reduce runoff velocity, filter sediment and absorb chemicals from sheet erosion, and deliver intermittent flows to streams. It is represented by the channel erodibility factor (CH_EROD), channel cover factor (CH_COV) and Manning's n value for main channel in the subbasin (CH_N2) in SWAT. The values of CH_COV and CH_EROD should be adjusted during the model calibration for sediment. As the calibration for sediment is not carried out here, value of CH_EROD is considered to be 0.2157 and CH_COV to be 0.4855 where as CH_N2 to be 0.0158 (from calibration) for the base case (without grassed waterways). The manning's coefficient affects the flow velocity, which is obtained by using Manning's equation;

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$

where V is the flow velocity, n is the Manning's coefficient, R is the hydraulic radius of a channel and S is the channel slope. Grassed waterway in the main channel is represented by CH_N2, equal to 0.24 and CH_COV and CH_EROD equal to zero (Bracmort et al., 2006).

Terraces are formed by earthen embankments or channels or a combination of the two to reduce the sheet and rill erosion, peak flow, retain moisture and reform the farm to increase the productivity. Bracmort et al. (2006) identified parameters initial SCS runoff curve number for moisture condition II (CN2), USLE equation support practice factor (USLE_P) and average slope length (SLSUBBSN) to represent the effects of parallel terrace in a HRU scale in SWAT. Arnold (2002) recommends the adjustment of CN2 for parallel terraces. USLE_P for the terrace implemented case is recommended to be 0.2 (Bracmort et al., 2006), whereas the initial value is 0.3 (without parallel terrace). To represent the parallel terrace, SLSUBBSN is defined as (ASAE, 2003);

$$SLSUBBSN = (X \times S + Y)\frac{100}{S}$$

where, X and Y are constants. X depends on location of the watershed; it is 0.21 for the watershed considered (ASAE, 2003). The value of Y depends on the soil erodibility, cropping system and management and the value varies from 0.3 to 1.2 (ASAE, 2003), with lower values for more erodible soil. It is assumed to be 0.9 for the case considered.

A grade stabilization structure is a structure designed to reduce the channel grade in natural or constructed water course. It reduces or prevents the erosion due to higher grade on the channel bed. This practice is applicable where structures are required to prevent head cutting or stabilize gully erosion and also where the intersecting channels have different elevations. They may be vertical drop, weir spillways, chutes, or pipe drop structures and may be made of reinforced concrete, steel sheet piling, concrete block, riprap, corrugated metal, plastic, or concrete pipe, depending on-site conditions. The structure is represented by a CH_EROD value equal to zero and by reducing the average slope of a subbasin main channel (CH_S2) by 10%.

Genetic Algorithm

GAs are a subset of evolutionary algorithms that mimic biological processes to optimize an objective function (Haupt and Haupt, 1998). Developed by Holland (1975), a GA allows a population composed of many individuals to evolve under specified selection rules to a state that maximizes/minimizes the cost. GAs do not require derivative or gradient information to evaluate optimal solutions (Goldberg, 1989). After defining optimization parameters and the objective function, potential solutions are randomly generated in the initial generation. Selection, crossover and mutation are the GA operations which generate new solutions. While crossover selects properties from parent solutions to the offspring solutions, mutation ensures that the search will not converge in local maxima/minima. The search is stopped based on selected convergence criteria.

Methodology

A single-objective OCM is developed by coupling SWAT with GA to design BMPs at a watershed scale. The model is designed to search for the least cost combination of BMPs in a watershed ensuring that the peak flow and sediment load reduction criteria are met. SWAT is run for a 2 years, from 2001 through 2002.

SWAT delineates the watershed into 159 subbasins, and each subbasin is considered as a HRU. Types of structural BMPs considered in the study are detention ponds, infiltration ponds, filter strips, grassed waterways, grade stabilization structures and parallel terraces. The GA operation starts with a random generation of an initial set of solutions which consists of a combination of different BMPs located in different sub basins. The objective function, the sum of the cost of the BMPs implemented, is evaluated based on their size. SWAT performs the watershed simulation and determines peak flow and sediment load at the watershed outlet. The GA ranks the solutions based on the cost function. Solutions which do not meet the peak flow and sediment load reduction criteria are highly penalized so that they are forced out of the competition. GA operations (selection, crossover and mutation) are applied to produce a new set of solutions. The search is stopped when the iterations reach the maximum number of generations.

The unit costs of BMPs considered in the study are summarized in Table 1. As the real cost of BMPs for the study area is difficult to access, these cost figures represent the best assumption of the authors'.

Table 1 Unit Costs of BMPs

BMP	**Unit**	**Unit Cost ($)**	**BMP**	**Unit**	**Unit Cost($)**
Detention pond	m^3	20	Grade stabilization structure	No.	6000
Filter strip	Acre	900	Grassed waterway	m	10
Parallel terrace	Acre	190			

Results and Discussion

The OCM is run with a population of 100 chromosomes in the initial generation and 50 chromosomes from the second to the maximum of 400 generations for three different scenarios of peak flow and sediment load reduction (case 1- 5%, case 2-15% reduction and case 3-25% reduction). Comparisons of BMP allocation in the first and last generations for three cases of target treatment goals are presented in Table 2.

Table 2 Number of BMPs on the best solution of first and last generation (10% case)

Case	**Gen**	**Number of**					**Cost (mill USD)**
		DP	**FS**	**PT**	**GWW**	**GSS**	
5% reduction	1	136	61	69	83	44	305.9
	400	62	123	5	62	49	41.8
15% reduction	1	128	60	78	70	49	311.3
	400	59	121	4	79	36	51.5
25% reduction	1	139	60	76	79	45	332.0
	400	69	112	4	59	35	56.7

The minimum cost found by the model for case-1, case-2 and case-3 are 41.8 million USD, 51.5 million USD and 56.7 million USD respectively. The change in number and locations of different BMPs between the best solutions of the 1st and last generation for the 25% reduction case is shown in Figure 2. The best cost found over the generations is plotted in Figure 3. In the search process, the number of detention ponds and parallel terraces were reduced whereas the number of filter strips was increased significantly with an insignificant change in the number of other two types of BMPs.

The peak flow for the base case (without BMPs) is 7.6 mm per day per square km, whereas the annual sediment load at the watershed outlet is 34,566 tons per year. The best solution found by the algorithm in case-1, case-2 and case-3 reduces the peak flow to 5.5, 5.3 and 5.3 mm per day per square km, respectively and the annual sediment load to 14,547, 15,117 and 14,145 tons per year respectively. These results show that both peak flow and sediment loads are reduced to levels that are much lower than the set limit, particularly for case 1 and 2. Therefore it can be anticipated that further search could find an even better solution.

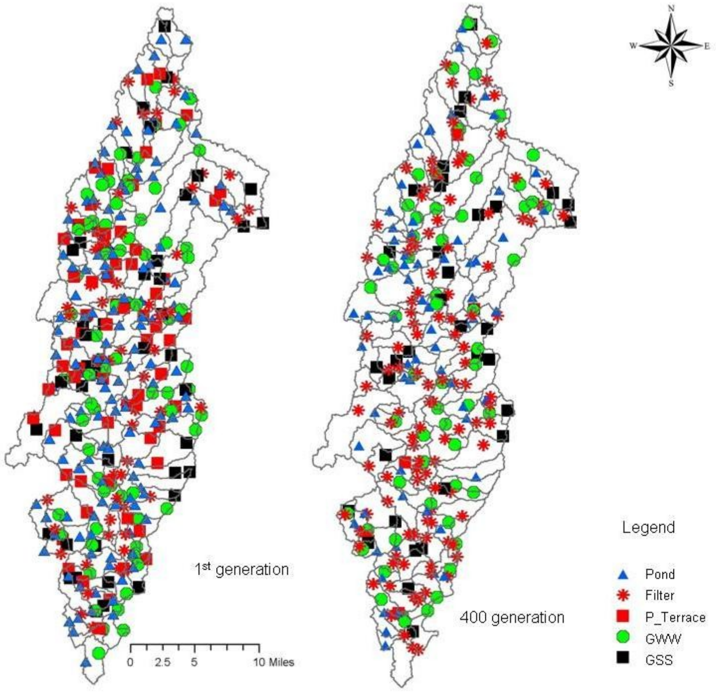

Figure 2: Comparison of BMPs locations between the best solutions of 1st and 400th generation (25% reduction case)

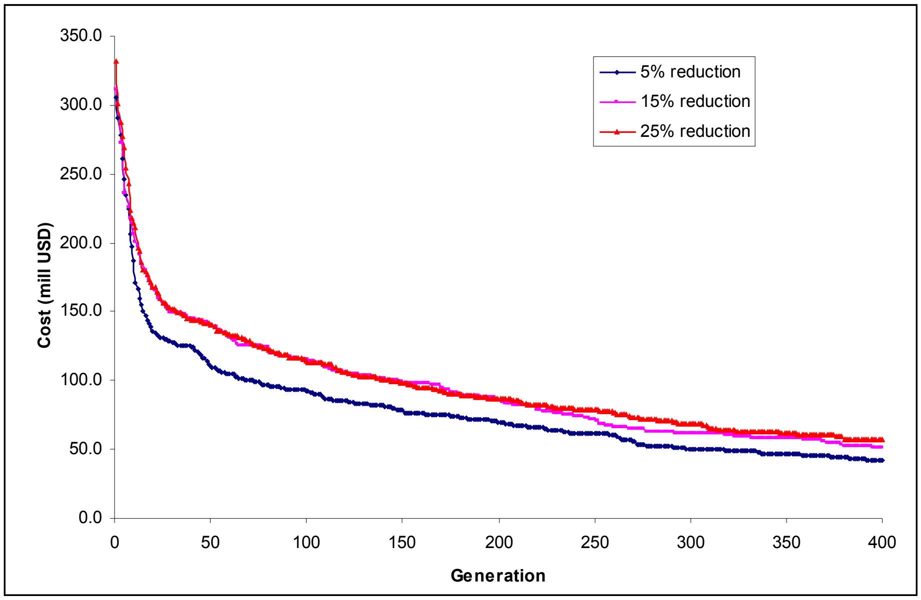

Figure 3: Cost variation of best solution through generations

Conclusion

The model effectively searched for the BMP combination that reduces the target peak flow and sediment load. However, in cases of 5% and 15% target reduction, the model reduced peak flow and sediment load to a significant lower level than the target. This shows that there is still a potential to find better solutions (with lower cost) when the model is run with larger population and/or for a higher number of generations. Because costs are based on the users' best guess, the results are meaningful only in terms of methodological development. It is likely, however that the model can predict useful results when it is run using real unit cost figures.

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