Evaluating Optimal Detention Pond Locations at a Watershed Scale

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Abstract

Structural BMPs like stormwater basins (detention and retention basins), wetlands, filter strips and grassland swales are extensively used as stormwater runoff controls. BMPs are often designed for peak flow reduction or pollution control or can be considered for dual purpose in that they provide both water quality and quantity benefits by relying upon storage allocation and key mechanisms of setting filtration, sorption, biodegradation and evapotranspiration. In spite of previous studies, there exists neither a methodology nor a generalized model for selecting, placing, and sizing BMP combinations that cost- effectively promotes achievement of treatment goals at larger spatial scales. This paper presents part of an ongoing research effort to develop a new, comprehensive decision support tool for watershed-scale BMP design. The current model is designed to identify detention pond sizes that best achieve target peak flow reduction criteria. It is developed by coupling the U.S. Department of Agriculture's (USDA) Soil and Water Assessment Tool (SWAT) and a genetic algorithm. The model is applied to Silver Creek watershed, a subbasin of the larger Lower Kaskaskia watershed in Illinois. The results show that detention ponds can be designed at a holistic, watershed scale to more effectively achieve peak flow reduction goals. Future work will focus on expansion of the model, which will also be disseminated through outreach workshops in portions of Illinois and surrounding states.

Introduction

Potential impacts of stormwater runoff include the altered hydraulic characteristics of receiving streams, including higher peak flows, increased duration and frequency of bankfull flows and sediment transport capacity, public health effects caused by contact with surface contaminants that have been transported to receiving waterways and raw water supplies, recreational impacts such as beach closures and fishing restrictions, changes in fish and macroinvertebrate populations, and loss of aquatic species. In recent years, the U.S. Congress has implemented a number of regulatory programs aimed at reducing these impacts. One of the most significant outcomes of these programs has been an increased emphasis on the application of Best Management Practices (BMPs) as runoff controls. BMPs represent a variety of abatement procedures, devices, restrictions, or management activities designed to minimize the negative impacts of watershed development or landscape change without altering riparian morphology.

Many current and past approaches to water quality protection and the maintenance of natural runoff rates have resulted in a patchwork of control measures that focus on individual properties or "on-site" sources. Emerson et al. (2005) showed that for detention-based systems, this approach is not particularly effective in collectively reducing watershed-wide peak flows and can potentially increase peak flow rates. These and other structural BMPs are instead most cost-effective when designed and implemented in regionally-strategic combinations (i.e., basin-wide treatment trains) to meet related stormwater treatment goals. Previous studies focusing on watershed-scale design and placement of BMPs have concentrated primarily on water quality (e.g. Zhen et al., 2004) in conjunction with land use (Harrell and Ranjithan, 1997; 2003). Yeh and Labadie (1997) used a multi-objective genetic algorithm to optimize locations and sizes of BMPs for flood control. Despite these efforts, there exists neither a methodology nor a generalized model for selecting, placing, and sizing BMP combinations that cost effectively promote achievement of treatment goals at the watershed scale. This paper presents ongoing research to develop a new, comprehensive decision support tool for watershed-scale BMP design. The current model identifies detention pond sizes that best achieve target peak flow reduction criteria.

Silver Creek Watershed

The model is developed and applied to the 1,189 km^2 Silver Creek watershed, a subbasin of the larger Lower Kaskaskia watershed in Illinois (see Figure 1). Silver creek watershed consists primarily of cropland, grassland, and forest. Like many of the nation's watersheds, this area is currently experiencing moderate to high levels of urbanization. This statement is supported by recent census data and 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.

Climate data for this region was obtained from the National Climate Data Center (NCDC). Hydrologic data and a 30-m resolution Digital Elevation Model (DEM) were downloaded from United States Geographical Society (USGS) website. The digital soil maps and land use maps were obtained from the Natural Resources Conservation Service (NRCS).

Problem Formulation

The current problem can be stated as the determination of detention pond locations that:

Minimize: Maximum daily flow at the watershed outlet

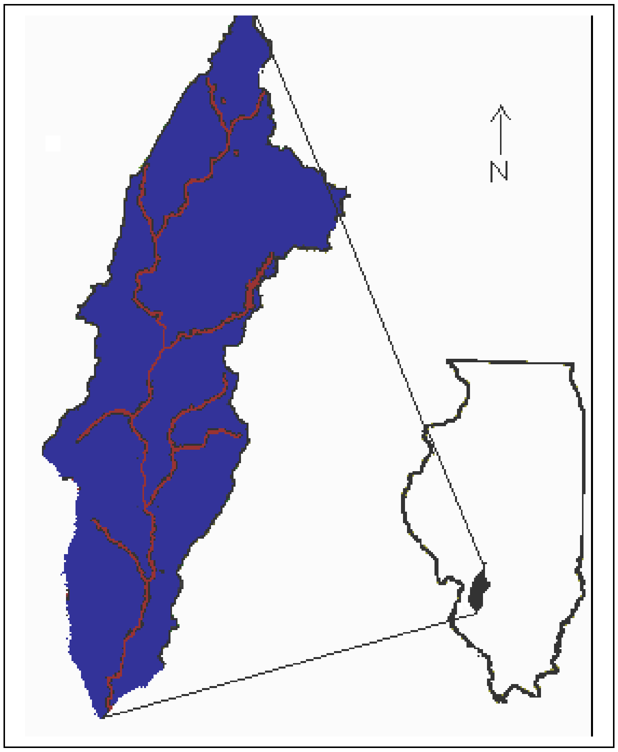

Figure 1: Location of Silver Creek Watershed, Illinois.

Subject to the following constraints:

1. Water balance in the watershed
2. Detention pond sizes less than the user-defined maximum limit
3. Total area of detention pond area in the entire watershed is less than a user-defined maximum size

Mathematically, this can be expressed as

$$\textit{Minimize: } PF_{max}$$

$$\textit{Subject to: } \sum_{k=1}^{n} A_k \le A_{\max}$$

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

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

where, PF_{max} is the maximum daily flow of the simulation period, A_k is the area of the pond in subbasin k to be randomly assigned 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. The final relationship represents a simulation constraint, where g generally represents all pertinent hydrologic and hydraulic relationships, as a function of dependent (state) and independent (decision) variables, x and u, and time, t.

An optimal control approach capable of solving this BMP design problem is implemented by coupling the U.S. Department of Agriculture's (USDA) Soil and Water Assessment Tool (SWAT) with a genetic algorithm (GA). SWAT is used to solve the simulation constraint, thus yielding maximum daily flow, while the GA solves the overall optimization problem. Figure 2 illustrates a schematic of this approach when applied for the current formulation, and the following paragraphs briefly describe SWAT and the GA as applied herein.

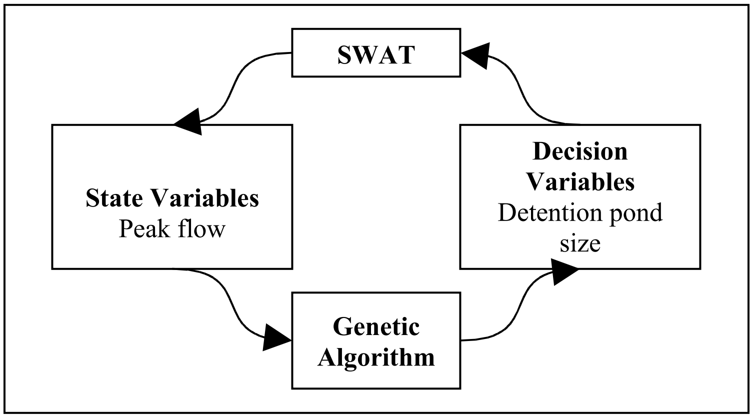

Figure 2: Optimal Control Model

Watershed Simulation model (SWAT)

SWAT is a physically based, spatially-distributed watershed model that operates on an ArcView GIS (i.e., AVSWAT) platform. It was developed by 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. The model delineates the watershed into subbasins based on the user defined critical source area. Input information for each subbasin is organized into the following categories: climate; hydrologic response units (HRUs); ponds/wetlands; groundwater; and the main channel or reach draining the subbasin (Arnold, 2002). An HRU is the total area in the subbasin with a particular land-use, management and soil type. Hydrological processes that are modeled include; the surface runoff using the SCS curve number or Green & Ampt infiltration method, potential evapotranspiration, estimated by Penman-Monteith, Hargreaves or Priestley method; percolation, simulated by a combination of a layered routing technique with a crack flow model; lateral subsurface flow or interflow, simulated by a kinematic storage model; and ground water flow. The water balance through a detention pond is simulated as;

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep}$$

Where V is the volume of water (m^3, H_2O) in the impoundment at the end of the day, V_{stored} is the volume of water stored in the water body at the beginning of the day, V_{flowin} is the volume of water entering the water body during the day, V_{pcp} is the volume of precipitation falling on the water body during the day, V_{evap} is the volume of water removed from the water body by evaporation during the day, V_{seep} is the volume of water lost from the water body by seepage.

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 the cost. The operating components of a GA are illustrated in Figure 3 (Haupt and Haupt, 1998).

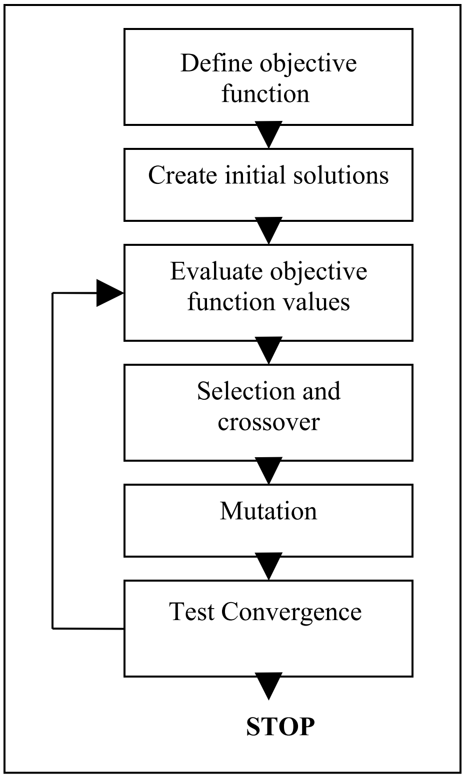

Figure 3: Framework of Genetic Algorithm

GAs do not require derivative or gradient information to evaluate optimal solutions. After defining optimization parameters and the objective function, potential solutions are generated in the initial generation. On the basis of the objective (maximum or minimum), the solutions are ranked. The best solutions are kept for the next generation while the weak solutions are discarded. The GA finds and sorts the solutions with the objective of identifying the combination of detention pond sizes that has the maximum peak flow reduction.

The initial generation consists of 200 sets of solutions where the different sizes of detention ponds are applied randomly in all the subbasins. Individual pond sizes are based on a percentage of the subbasin's area. With ponds matched to their respective subbasins, SWAT generates the daily flow at the watershed outlet. The maximum daily flow is the objective function value. After ranking solutions, the new sets of solutions are found by applying binary tournament selection with replacement and uniform crossover.

Mutation is then applied at the rate of 0.2 to ensure that the search will not converge in the local maxima/minima. The search is stopped based on the convergence criteria, in this case, a maximum generation.

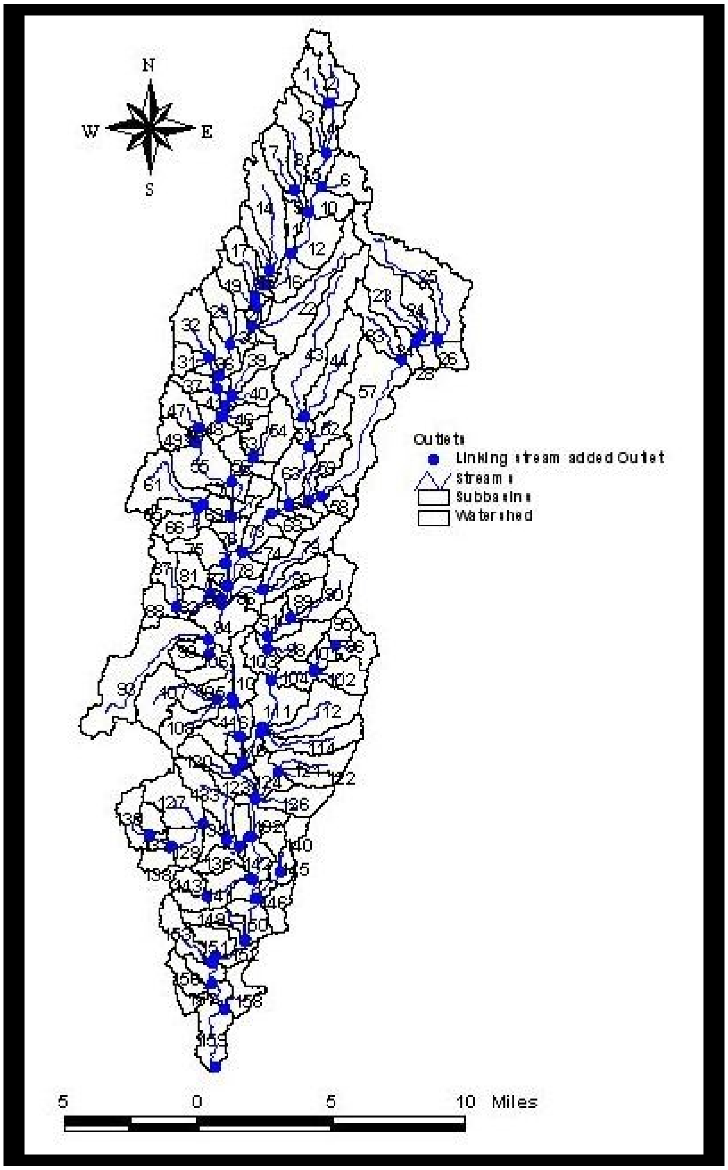

Figure 4: Subbasin delineation

Application to Silver Creek watershed

Using the DEM, AVSWAT delineates the watershed into 159 subbasins, as shown in Figure 4, with an average subbasin area of 7.48 km^2. Each subbasin is considered as a site for a detention pond within the optimization process. The pond sizes are randomly chosen within the considered upper and lower limits. The maximum total pond area has been set by the user. When a pond is included in a subbasin, water from a certain fraction of the subbasin, will route through the pond. Based on the depth, area, volume, spillway level, hydraulic conductivity of the detention pond and the inflow, SWAT models the flow through the set of ponds located in different subbasins.

Results and Discussion

The model can evaluate different scenarios of maximum limiting total pond area. In this study, the optimal total pond area is found to be 891 ha, where the maximum pond area limitation was set to be 892 ha and the maximum daily flow is $3.14 \text{ X } 10^7 m^3$ in 50th generation. Without a detention pond, the maximum daily flow from the watershed is $3.78 \text{ X } 10^7 m^3$ over a two year simulation period which is the base case. Although these results are not particularly surprising, the associated model provides the basis for an expanded methodology for more comprehensive BMP design.

Conclusion

An optimal control model is constructed by coupling the distributed hydrological model, SWAT, with a GA. The combined model can evaluate the optimum total detention pond area in the watershed scale for the reduction of maximum daily flow. The solution primarily finds optimum size of all the detention ponds in the sub watersheds and the total pond size for the entire watershed. In this case, the optimum solution reduces the maximum daily flow by 16.8%.

In addition, Harrell and Ranjithan (2003) concluded that incorporating land use allocation associated with future growth into the system wide design of detention pond can lead to lower cost designs than those achieved using other procedures. Thus, future work will add land use allocation into the model. Furthermore, other types of BMPs will be added as decision vectors, and sediment concentration and nutrients as will be added as state variables.

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