Optimal Location and Sizing of Stormwater Basins at Watershed Scale

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Abstract: Nonpoint source pollution control requires the implementation of best management practices (BMPs) at various locations in a watershed. One important aspect of the watershed strategy is to find the optimal placement and design of BMPs so that their combined effect is most cost-effective. An innovative method is presented for optimizing the placement and configurations of BMPs at the watershed scale. Heuristic optimization techniques are coupled with a watershed model, which is the agricultural Nonpoint Source Pollution model (AnnAGNPS) in this case, and BMP simulation module to find a least cost set of solutions that meet the pollutant load reduction requirements. An impoundment module imbedded in AnnAGNPS, and modified to address the sediment accumulation and resuspension effect, is used to provide the means of evaluating the long-term performance of detention ponds. A scatter search algorithm is applied to finding the least cost solution. The optimization framework developed herein provides a tool for stormwater management practitioners to examine and analyze the treatment efficiencies of stormwater control alternatives and to determine a robust and cost-effective design of stormwater treatment systems.

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Introduction

To mitigate nonpoint source pollution caused by stormwater runoff, various regulations require the use of stormwater control systems or best management practices (BMPs). These systems can be expensive and have for years represented a significant public investment. Since the stormwater regulations enacted in the late 1980s and early 1990s, runoff water quality control has attracted more public attention due to increased awareness and understanding of the seriousness of nonpoint source pollution (NPS). The need for water quality controls or BMPs will keep increasing with the implementation of more stringent regulations, e.g., the propagation of total maximum daily load (TMDL) program and the establishment of the final rules for Phase II of the National Pollutant Discharge Elimination Program for stormwater. Best management practices implementation will represent a significant public and private expenditure for many years to come.

Remedies for NPS pollution are very complicated because of its diffuse and time-varying characteristics. As a result, NPS pollution control presents a formidable challenge to policy makers. Presently, most, if not all, stormwater controls have been designed and implemented at the local or "on-site" level based on the so-called "performance based" criteria, and not at the regional or watershed level in a comprehensive and systematic manner. In other words, the controls are applied individually, without considering the overall combined or synergetic treatment effect of all controls within the watershed or area of interest. The disadvantage of the "on-site," rather than watershed level, approach is its inherent inability of comparing alternative BMP placements and obtaining the most cost-effective stormwater control system design for the watershed as a whole.

For the implementation of stormwater controls, it has been recognized that effective stormwater management is often achieved from a synergetic, management system approach, as opposed to focusing on individual practices. However, even though the concept is available and accepted, there is a lack of applicable and practical methodologies, or tools, to assist and fulfill its implementation. Considering that enormous public investment may be needed for NPS pollution control, it is therefore even necessary to develop a systematic approach for the stormwater control systems planning and design at the watershed level, which could lead to significant cost savings. Motivated by such considerations, the study presented herein develops and demonstrates a holistic approach and framework for objectively determining a cost-effective placement and sizing of structural BMPs by using a long-term simulation and scatter search optimization technique.

The objective of this study is to develop and demonstrate a holistic approach and framework for objectively determining a cost-effective placement and design of structural BMPs by using a long-term simulation approach and scatter search optimization technique. The effectiveness is evaluated at the watershed scale using a "long-term" simulation method. It is envisioned that a long-term simulation method can cover the various dynamic conditions under which the BMP performs, and therefore have better accuracy than event-based evaluation. Two major issues addressed in the framework development are: (1) coupling of a con-

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tinuous watershed simulation model annualized agricultural non-point source (AnnAGNPS) with the scatter search optimization algorithm; and (2) demonstrate the impact of considering sediment resuspension in ''long-term'' evaluation of stormwater ponds on optimization results.

Literature Review

As early as 1976, Loucks pointed out that ''developing management plans of river basin systems is an art. There is no single best way to do it, there only exists some good approaches for specific problems. System analysis approach is an effective way for finding, if not the best solution, at least for eliminating from further consideration the bad solutions'' (Loucks 1976). Research efforts have been made to solve stormwater management problems by using optimization techniques, even though it was considered difficult due to the complexity of environmental problems, especially when using classical optimization techniques because of their inability to handle complicated, i.e., nonlinear, discrete, environmental systems. In most of the studies that applied classical optimization techniques (Kao and Tsai 1997; Behera et al. 1999), significant simplifications were necessarily made for problem formulation because of the complexity of stormwater management systems and limitations on the use of optimization methods. In these cases, even though the optimal solutions found were mathematically feasible, their practical usage in the real world was usually questionable. In recent years, the development of modern meta-heuristic search techniques, such as genetic algorithms and scatter search, has attracted much attention from researchers wanting to address the real world planning/design issues. The meta-heuristic techniques are much less restrictive in problem formulation, and are therefore better suited for tackling complex systems. One major drawback of these new techniques is the demand of extensive computing time. However, due to the rapid development of computer power and speed, this weakness becomes less of a hinderance.

Genetic Algorithms (GAs) are the most commonly used techniques for optimal stormwater management planning at the present time. Basically, GAs are stochastic search procedures that use probabilistic rather than deterministic search rules and are based on the ''survival of the fittest'' principle. The objective function magnitude, instead of derivative information, is used directly in the search, therefore allowing GAs to be applied to non-convex, highly nonlinear, and complex problems (Goldberg 1989). Several applications of GA to controlling nonpoint source pollution have been found in the literature. For example, Dorn et al. (1995) developed a GA based search method for determining a cost-effective configuration of wet detention basin systems in response to a prescribed land use plan to provide a desired system-wide or watershed level of total suspended solid removal for a design storm event. This method was extended by Harrell (1998) to incorporate long-term removal efficiency of pollutants using the Driscoll sedimentation model, which is also called the environmental protection agency (EPA) model (USEPA 1986). The EPA model uses a statistical and probabilistic approach presented in the form of a series of dimensionless curves for estimating the long-term average sediment removal efficiency of wet detention ponds. Lippai and Heaney (1996) and Heaney et al. (1999) presented a GA-based method for the optimization of urban storm sewer design. Otero et al. (1995) applied GA to determining minimum stormwater detention storage volume and optimal operating rules for managing freshwater runoff. Yeh and Labadie (1997) presented a multiobjective GA to generating nondominated solutions for system cost and detention effect for a watershed-level detention system.

Scatter search is another meta-heuristic search technique that has been explored and used in optimizing complex systems (Glover et al. 2000a), and has attracted more attention in recent years. Scatter search shares some commonalties with GAs, although it also has a number of quite distinct features. Both scatter search and GA are ''population based'' approaches, and both incorporate the idea of combining existing elements. On the other hand, GA approaches are predicated on the idea of choosing parents randomly to produce offspring, and further introduce randomization to determine which components of the parents should be combined. By contrast, the scatter search approach does not emphasize randomization, particularly in the sense of being indifferent to choices among alternatives. Instead, the approach is designed to incorporate strategic responses, both deterministic and probabilistic, that account for evaluation history. Scatter search focuses on generating relevant outcomes without losing the ability to produce diverse solutions, as a result of the way the generation process is implemented (Laguna and Marti 2002).

Because of the aforementioned feature of scatter search, for optimization problems that need a computationally expensive evaluator, it is expected that scatter search can find the near-optimal solution in a more efficient way, and therefore serves as a better optimization engine. Scatter Search has been applied to optimization problems of complex systems (Glover et al. 2000a). However, scatter search is not as widely used in the literature as GAs when applied to the stormwater management field. The only published example of applying scatter search in the water resources field was one that addresses the classic optimization problem—New York City water supply tunnel (NYCWST) design (Laguna 1998). In this study, the commercially available software: *OptQuest* was used to solve the NYCWST problem, and it is reported that the *OptQuest* model consistently finds the best solution known within 10,000 calls to the function evaluator, and compares well with the 18,053 function evaluations that the genetic algorithm employed to find the same solution, as presented by Lippai and Heaney (1996).

Optimization Model

Premises

Potential BMP sites are assumed to be preselected based on an inventory of NPS critical pollution source areas and other factors such as land availability, geographical conditions, and site-specific legal, jurisdictional considerations. As a general rule, if feasible, potential BMP sites considered ''critical'' (e.g., areas with high unit area NPS pollution loadings) should first be selected before noncritical areas for BMP implementation. This selection process allows the elimination of any obviously infeasible solutions and provides a good starting point for the optimization process. Preferably, the selected potential sites should cover a range of spatial scales, i.e. on-site, subregional, and regional (Fig. 1), in order to preserve the highest possibility for obtaining the most cost-effective BMP placement scheme at the watershed scale (Zhen and Yu 2001).

Generic Problem Formulation

Based on the preselected potential sites, the optimization problem can then be formulated as follows. For each preselected location i,

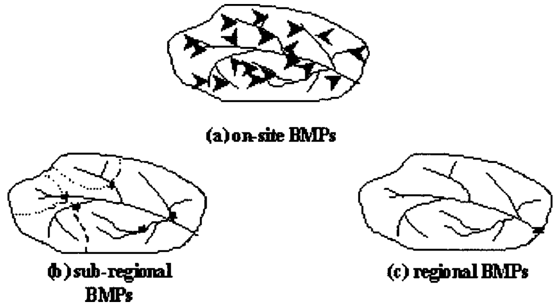

Fig. 1. Schematic diagram showing spatial arrangement of best management practices at: (a) on-site, (b) subregional, and (c) regional levels

the decision variable vector ($\mathbf{BMP}_i$) for location i represents the existence and configuration of the BMP. As the existence of a detention pond can only be represented or described by a discrete variable, the optimization of stormwater control systems naturally falls into the category of a combinatorial or a discrete problem.

Mathematically, a generic BMP placement optimization model can be expressed as:
Objective:

$$\text{Minimize} \sum_{i=1}^{n} C(\mathbf{d}_i) \tag{1}$$

Subject to:

$$L_k \leq \mathrm{L\,max}_k \quad (k=1,\ldots,m) \tag{2}$$

$$\mathbf{d}_i \in S_i \quad (i=1,\ldots,n) \tag{3}$$

where $C(\mathbf{d}_i)$ = average annual cost, including construction and maintenance cost; $\mathbf{d}_i$ = decision variables vector for pre-selected location $i=1,\ldots,n$; n = total number of potential BMP site; L_k = "long-term" average annual pollutant load at a reference point $k=1,\ldots,m$ with the implementation of BMPs; m = total number of reference point; $\mathrm{L\,max}_k$ = maximum average annual pollutant load allowed for the reference point k; and S_i = feasible range of BMPs at location i.

In this work, selected decision variables are the detention-time for a user-specified design storm and the depth of a pond. Detention time is discretized between zero and a maximum value at a constant increment. A zero valued detention time indicates that the pond does not exist.

The cost function calculates the "long-term" average annual cost of BMPs, including both initial construction cost and annual operation and maintenance (O&M) cost over the planning time period. The construction cost is distributed evenly over each year of the project life of a BMP in order to amortize the cost.

In the water quality constraint, the right-hand-side of Eq. (2), $\mathrm{L\,max}_k$, is determined by the user based on existing regulations such as local runoff control ordinances or other watershed pollution control regulations such as a TMDL allocation, or on values suggested by previous studies regarding the watershed in question. The left-hand-side of Eq. (2), (L_k), or the annual pollutant loads at a designated checkpoint, indicates the pollutant removal effectiveness of the potential BMP implementation. It is computed by a watershed model that has the capability of incorporating the "long-term" continuous simulation of the performance of stormwater ponds placed in the watershed. In this study, a distributed watershed model AnnAGNPS was employed to simulate the pollutant load generation and transport in the watershed. Continuous simulation of the detention pond pollutant removal process was performed by the impoundment routine embedded in AnnAGNPS.

It should be noted that the objective function (cost function) and the water quality constraint are discrete and nonlinear, and the tractable mathematical formulations and their derivatives are difficult to define. In order to solve such a complex problem and to find the optimal or near optimal solution, a meta-heuristic optimization technique—scatter search, is selected and applied.

Optimization Algorithm—Scatter Search

Scatter Search, from the standpoint of meta-heuristic classification, may be viewed as an evolutionary (or also called population based) algorithm that constructs solutions by combining others. One of the main aspects of scatter search is the manner in which it combines solutions, and undertakes to exploit these combinations. Scatter search operates on a set of solutions, the reference set, by combining these solutions to create new ones. The reference set is updated based on rules regarding the solution quality and diversity. The way scatter search combines solutions and updates the set of reference solutions used for combination sets this methodology apart from other population-based approaches. Unlike a "population" in genetic algorithms, the reference set of solutions in scatter search tends to be small. This is needed because the combination process in scatter search considers at least all pairs of solutions in the reference set. Typically, the reference set has 20 or less solutions. In general, if the reference set consists of **b** solutions, the procedure examines approximately $(3\mathbf{b}-7)\times(\mathbf{b}/2)$ combinations of four different types (Glover et al. 2000a).

The principles of the scatter search methodology are summarized as follows (Glover and Laguna 2000b). Useful information about the form (or location) of optimal solutions is typically contained in a suitably diverse collection of elite solutions. When solutions are combined as a strategy for exploiting such information, it is important to provide mechanisms capable of constructing combinations that extrapolate beyond the regions spanned by the solutions considered. Similarly, it is also important to incorporate heuristic processes to map combined solutions into new solutions. The purpose of these combination mechanisms is to incorporate both diversity and quality. Taking account of multiple solutions simultaneously, as a foundation for creating combinations, enhances the opportunity to exploit information contained in the union of elite solutions.

As a search strategy, scatter search has shown the capability to yield promising outcomes for solving combinatorial and nonlinear optimization problems (Glover et al. 2000a). Although convergence to global or even local optimum is not guaranteed, scatter search performs the heuristic search process in an effective and efficient way, requiring relatively fewer calls to the evaluation function to find the near optimal solution. This is significantly advantageous for complex systems, which need considerable amounts of computer run time to evaluate one alternative solution. The problem of stormwater control system design is usually formulated as a discrete integer nonlinear optimization problem, which can be effectively solved by the scatter search algorithm.

Optimization Framework

A seamless optimization framework integrating the system evaluator and the optimizer was developed to solve the above-formulated problem. The structure of the optimization framework

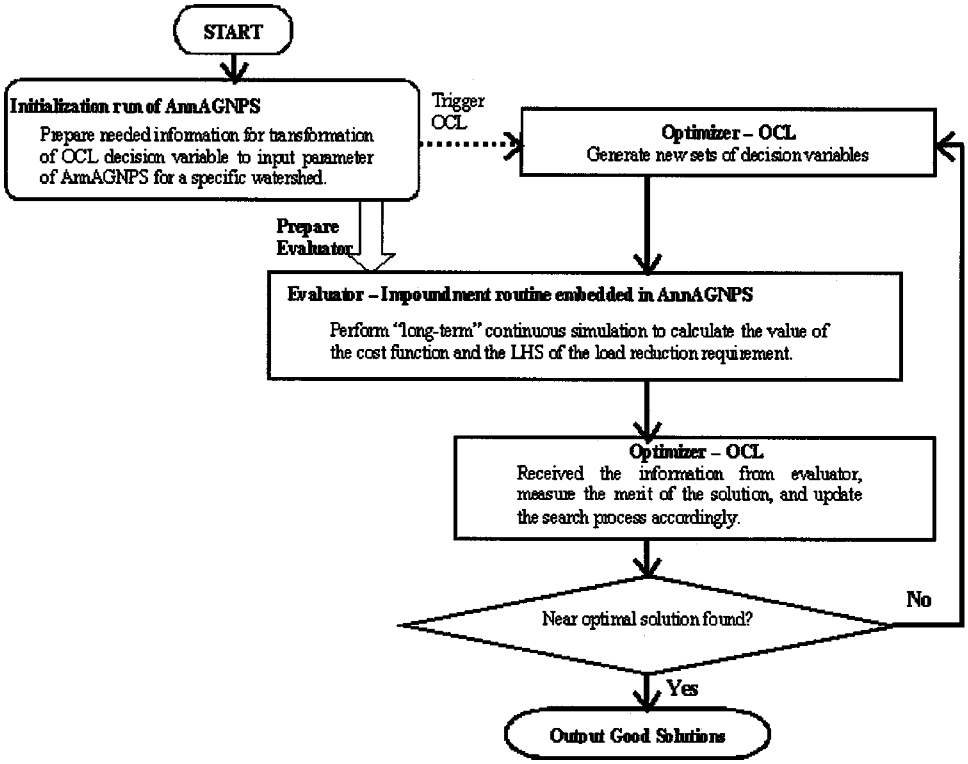

Fig. 2. Conceptual design of optimization framework

is illustrated in Fig. 2, which consists of three functional components: (1) initialization run of AnnAGNPS, (2) system evaluator, and (3) optimizer.

Initialization Run of AnnAGNPS

The purpose of the initialization run of AnnAGNPS is to generate the design runoff volume for a user-specified design storm at each pre-selected BMP site in the test watershed. The runoff volume is required in order to transform the decision variables, which are the detention time for a designated design storm and the pond depth, into the required input parameters for running the impoundment subroutine of AnnAGNPS.

System Evaluator

The mission of the system evaluator is to measure the merits of the decision vector, or solution, generated by the optimizer and to provide feedback information to the optimizer. The system evaluator consists of two components: a BMP performance evaluator to assess water quantity and quality control effectiveness, and a BMP cost function to calculate the total expected cost for various planned stormwater control options. The AnnAGNPS model with the embedded impoundment routine is employed as the BMP performance evaluator.

Watershed Simulation Model—AnnAGNPS. The AnnAGNPS model, developed by U.S. Department of Agriculture (USDA), Agricultural Research Service, and Natural Resources Conservation Service scientists and engineers, is a batch process, distributed parameter, continuous-simulation surface runoff computer model for estimating nonpoint source pollutant loads (AGNPS 2001). The model simulates surface runoff, and generation and transport of sediment, nutrients, and pesticides. Pollutant loadings are generated from land areas, which are treated as cells or subwatersheds, and routed through stream channel systems on a continuous daily basis. The constituents (runoff and pollutants) originated within a cell are either deposited in the stream channel system or transported out of the watershed. Pollutants can be identified at their sources and tracked as they move through the stream system. This leads to the distinctive feature of the source accounting function of AnnAGNPS. Annual AGNPS generates output information on the contribution of runoff and pollutant loading from each cell to any user-selected location. This information is used to identify critical areas, which contribute significant amount of pollutant, sediment or nutrients, to any designated location, for instance, the watershed outlet.

Impoundment Simulation Routine. The original impoundment routine (noted as IR1) in AnnAGNPS was based on the "surface loading" concept with the assumption of ideal performance for the pond. Sediment resuspension was not considered in this case. According to the "surface loading" concept, it can be derived that, for the same pond storage volume, the lower the depth and the larger the surface area, the greater the pollutant removal efficiency.

The original impoundment routine cannot simulate sediment accumulation and resuspension processes, which are believed to have a significant impact on stormwater pond performance. As such, an improved version of the impoundment module (noted as IR2) was developed, which takes into account the sediment accumulation and resuspension process (Zhen 2002). The sediment accumulation effect is simulated by modifying the pond geometric parameter according to the amount of sediment trapped in the pond. For sediment resuspension, a simplified zero-dimensional formulation relating the magnitude of sediment resuspension to the inflow rate was developed. With application of IR-2 in the optimization model, the pond depth is treated as a decision variable, ranging from 2 to 3.5 m.

Table 1. Selected Construction and Annual Maintenance Cost Functions for Stormwater Ponds

Best management practice	Construction cost		Annual maintenance cost
	Cost ($)	V_s unit	Construction cost (%)
Dry ponds	$C=7.47V_s^{0.78}$	ft^3	<1
Wet ponds	$C=18.5V_s^{0.70}$	ft^3	3–6

Note: Source: USEPA (1999).

Inherently, without considering sediment accumulation and resuspension, the original impoundment routine tends to overestimate sediment trap efficiency over a long-term period, especially for periods with high intensity storm events and after the sediment accumulation depth reaches a significant level. To examine the sensitivity of the optimization results to the effect of sediment accumulation and resuspension, both impoundment routines, IR1 and IR2, were applied, and the optimization results compared.

Cost Functions. Cost estimation is an essential part of a cost-effectiveness evaluation of stormwater control systems in real-world applications. In this study, the concept of the annual life-cycle cost is employed to formulate the cost functions. The life-cycle costs of a stormwater control facility include the initial capital costs and the present value of the annual O&M costs that incurred over time, less the present value of the salvage value at the end of the service life. The annual life-cycle cost is the annual construction cost, which is calculated as the initial capital cost divided by the length of service life, plus the annual O&M cost, and less the annual salvage value. In the cost formulations, the present value was not computed due to the consideration of currently low interest rates, and also because all BMP placement alternatives are compared on the same basis. Neglecting the present value does not significantly affect the optimization results. In addition, land cost was not included in the cost estimation because it varies dramatically from location to location. However, it should be noted that land costs could represent a significant portion of the total initial cost, particularly in highly developed urban areas. Therefore, it could possibly influence the optimization results.

The initial capital cost, namely construction cost associated with a stormwater pond, is usually calculated as a function of the pond storage volume (V), and annual O&M costs is often estimated as a percentage of the construction cost (Table 1). Regarding service life, stormwater ponds are considered as long-term facilities. The USEPA (1993) estimated a service life of 50 years for both dry and wet stormwater ponds. In this study, the length of an extended dry pond service life was assumed to be 50 years, and the salvage value assumed to be zero.

Based on the above information and assumptions, a cost function was formulated to estimate the annual life-cycle cost, which included the construction and the O&M costs for extended dry ponds. The construction cost function for dry pond presented in Table 1 was employed. The maintenance cost was estimated dynamically based on the amount of sediment accumulated in the pond over time. The USEPA (1999) reported that maintenance activities for detention ponds typically would include removal of accumulated sediment, repair of control structure, as well as repair of embankment and side slopes. Among the above activities, removal of sediment is important for keeping the pond operating efficiently over period of time. No specific information on repair cost for the control structure, embankment, and side slopes was found. Considering the fact that the scale of sediment removal work is usually significantly greater than the other repairs, and that the annual maintenance cost is less than 1% of the initial construction cost, it was assumed that the annual repair cost (C_{rep}) is 0.2% of the construction cost.

The annual average cost for accumulated sediment removal (C_{sed}) for a dry pond was determined based on the assumptions as follows: (1) the accumulated sediment needs to be removed when it occupies 1/4 of the original storage volume ($V_{\text{sed}}=V/4$), and (2) the average annual cost for sediment removal (C_{sed}) is calculated as $(7.47V_{\text{sed}}^{0.78})/N_{\text{sed}}$, where V_{sed} = accumulated sediment volume when sediment is cleaned out, which is assumed to be 1/4 of V; and N_{sed} = number of years when the removal of sediment is needed.

The one-time sediment removal cost is calculated by using the dry pond construction cost function $(7.47V_{\text{sed}}^{0.78})$, since both of the activities mainly involve soil excavation, and this method is validated using local data (Zhen 2002). Finally, the total annual life cycle cost function is formulated as

$$\begin{aligned}\text{Cost} &= \text{construction cost} + C_{\text{rep}} + C_{\text{sed}} \\ &= (7.47V^{0.78})/50 + (7.47V^{0.78}) \times 0.2\% \\ &\quad + (7.47V_{\text{sed}}^{0.78})/N_{\text{sed}} \\ &= 0.022 \times (7.47V^{0.78}) \\ &\quad + (7.47V_{\text{sed}}^{0.78})/N_{\text{sed}}\end{aligned} \tag{4}$$

Optimizer—OptQuest Callable Library

A commercially available program *OptQuest Callable Library* (OCL) was adopted as the optimizer to perform the optimization search process. The OCL is a general-purpose optimizer that employs the scatter search framework to obtain high quality solutions for optimization problems defined in complex settings (Laguna 1998). The OCL consists of a set of 23 functions (OptTek Systems, Inc. 2001), among which the "parameter setting" function group may be used to construct a suitable search strategy for a specific problem. Another important OCL feature is the dynamic requirement handling method. Like other meta-heuristics, scatter search does not explicitly incorporate requirements (nonlinear constraints) into the formulation; instead they are handled by using penalty functions. In OCL, a dynamic penalty function is adopted to penalize the requirement violation corresponding to the degree of the violation, as well as the violation history. For example, requirement-infeasible solutions are penalized more heavily when no requirement-feasible solution has been found during the search than when one is already available (Laguna and Marti 2002).

Hypothetical Case Study

The optimization scheme developed herein was applied to solve a hypothetical case. The study area is a 1,172-ha watershed. The dominant land uses of the hypothetical watershed are grazed pasture and forest. The study area is covered by one single loamy texture soil type. The statistics of the precipitation data are: annual average precipitation = 1,084 mm (42.7 in.); rainfall depth of the 1-year, 24-h storm = 56 mm (2.2 in.), and rainfall depth of the 10-year, 24-h storm = 122 mm (4.8 in.). The temporal rainfall distribution is the Soil Conservation Service Type-II distribution. AnnAGNPS was used to simulate the watershed hydrology and NPS pollutant loading generation, and to provide results for the

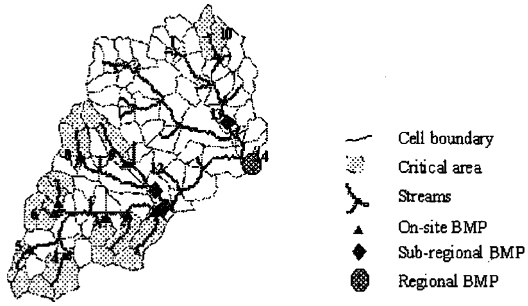

Fig. 3. Study area: critical areas and potential best management practices locations

identification of the critical areas. The study area was delineated into 155 cells with an average cell size of 7.56 ha. Each cell was assumed to be homogeneous in terms of soil type and land cover. The geographic information system tool package—AnnAGNPS Input Data Preparation Model (AIDPM) (Darden et al. 2001) was used to calculate the drainage area; average land slope; average elevation; overland flow length and slope; shallow concentrated flow length and slope; concentrated flow length and slope; and the length slope factor for each cell. The reach length and reach slope were also generated by applying AIDPM. Three years of synthetic climate data were used in the watershed hydrology and water quality simulations. Suspended sediment was selected as the concerned pollutant.

Selection of Potential Best Management Practices Locations

Based on the watershed simulation results, ten subwatersheds were identified as critical areas (shown in Fig. 3), which have unit area sediment loads ranging from 0.542 to 0.994 t/ha/year and are greater than the average value of 0.379 t/ha/year for the entire watershed. Logically, ''critical areas'' should be the priority areas for installing NPS control practices or BMPs. Therefore, ten potential on-site (Nos. 1–10) BMP sites were selected to control the critical areas. In addition to the ten on-site locations, three subregional sites (Nos. 11–13), and one regional (No. 14) site were selected to serve as alternative BMP sites (see Fig. 3).

Optimization Model Formulation

In the hypothetical case study, dry extended detention ponds were assumed as the selected BMP type at all the potential sites. The detention time for a user specified design storm (a 1-year, 24-h storm in this case) and the average pond depth are the two parameters that were optimized by the optimization model as the decision variables. These two parameters are considered to be the most important design parameters that contribute to the performance of a detention pond (Zhen 2002). Other less important independent design features were either estimated based on the current knowledge of pond design practices (Stahre and Urbonas 1990; Schueler and Claytor 2000) or assumed for the sake of simplicity. The pond length to width ratio was taken to be 3:1. A bed slope of 0.015 was used. The pond sidewalls were assumed to be vertical. For the hypothetical watershed, suspended solid (SS) was the target pollutant, and the evaluation reference location was the watershed outlet. The optimization formulation for this case is described mathematically as

$$\text{minimize} \sum_{i=1}^{14} C_p(T_{di}, H_i) \tag{5}$$

subject to

$$\frac{\text{SS load at outlet w/BMPs}}{\text{SS load at outlet w/o BMPs}} \leqslant \text{ADF} \tag{6}$$

where T_{di} = design storm detention time of the pond at location i ($i=1,\ldots,14$); H_i = depth of the pond at location i ($i=1,\ldots,14$); C_p = cost function to calculate the total cost of the pond, including construction and maintenance costs; and ADF = allowed discharge fraction of the existing load. In the optimization model, the decision variables (i.e., design storm detention time and pond depth for the 14 potential ponds) are represented by an array of 28 elements, which can be illustrated as $(T_{d1}, T_{d2}, \ldots, T_{d14}, H_1, H_2, \ldots, H_{14})$.

For the 10 on-site ponds ($i=1...10$), the decision variable-design storm detention time (T_{di}) ranged from 0 to 72 h with a 24-h increment. For the three subregional ponds ($i=11,12,13$), Td_i ranged between 0 and 48 h, with a 3-h increment. For the regional pond ($i=14$), T_{di} ranged between 0 and 12 h, with a 1-h increment. The reason for using different increments of T_{di} is because, for ponds at different spatial levels, the effect of the same increments of designed detention time on the system cost as well as the pollutant load reduction are dramatically different due to significant differences of the drainage area at different spatial levels. In order to reduce the gap caused by decision variables of ponds at a higher spatial level, and not to sacrifice the search efficiency at the same time, finer increments were used for ponds at the higher spatial level. The depth of the ponds ranged between 2.0 and 3.5 m with a 0.5-m increment.

Optimization Results

The optimization framework was then applied to the hypothetical case to determine the near optimal placement and configurations of stormwater ponds under certain water quality constraints, which were indicated by the ADF of the existing sediment load. From a series of runs under various ADF values, it was observed that the search process rapidly converges to near optimal solutions (since scatter search is a heuristic method, the optimum is not guaranteed) and usually within 10,000 iterations for the case study presented. The average computation time is about 18 h on a Pentium 866-MHz microprocessor with 128 MB random access memory (RAM) and PC133 MHz SDRAM. Figs. 4(a and b) show the search process and convergence under water quality constraint of an ADF of 0.65. Fig. 4(a) presents the costs of all feasible solutions, including the near optimal solutions, identified by the searching process. Among all the feasible solutions in Fig. 4(a), many of them provide excessive treatment than required, resulting in higher costs. In Fig. 4(b), only the feasible solutions that just meet the constraint of ADF = 0.65 were presented. One can observe in Fig. 4(b) that different solutions, though providing the same sediment removal efficiencies, require dramatically different costs, ranging from approximately $45,000 to $18,216, the latter being the optimal or near optimal cost. This observation illustrated the significant cost-saving potential by using optimization techniques. Fig. 5 shows the costs of the near optimal solutions found for various ADFs, and Fig. 6 depicts the optimal stormwater pond placements, i.e., the optimal design detention time T_d relative to upper limit T_d^*, for various ADF values. The design detention time T_d of each potential pond was normalized by the upper bound value T_d^* to give a better picture showing the se-

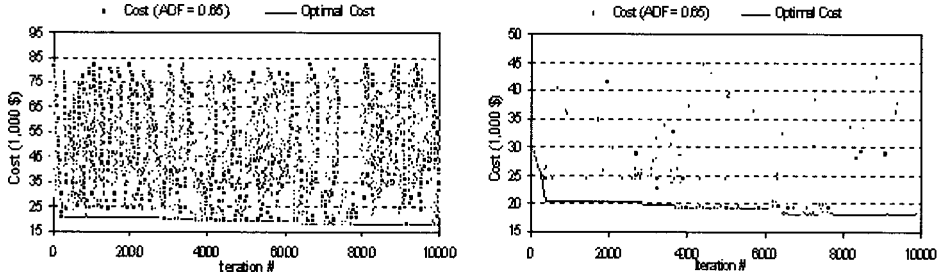

Fig. 4. Searching process and convergence of optimal or near optimal cost (allowable discharge fraction = 0.65)

quence of preference of each pond rather than presenting the values of the design detention time themselves. As described before, $T_d^* = 72$ for on-site ponds ($i = 1,2,3, \ldots, 10$), $T_d^* = 48$ for subregional ponds ($i = 11,12,13$), and $T_d^* = 12$ for the regional pond ($i = 14$).

Fig. 5 shows the tradeoff relationship (Pareto frontier curve) between cost and water quality goal or the ADF. It can be observed that the tradeoff curve has a steeper slope at the lower and of the ADF. This means the sensitivity of the cost to the ADF is higher for the higher water quality goal (lower ADF). In other words, the same amount of ADF variation at the lower ADF values causes a greater cost variation. For example, increasing ADF from 0.3 to 0.35 reduces the cost by about $11,000, while increasing ADF from 0.7 to 0.75 only reduces it by $3,500. In Fig. 6, it appears that the optimal solution tends to prefer ponds at the higher spatial level to meet required water quality goals. In other words, when the water quality requirement increases (ADF decreases), ponds are selected in a preference sequence of regional, subregional, and on site. The results generated by the optimization model are consistent with what is expected considering the economy of scale.

Impact of Considering Sediment Resuspension on Optimization Results

As an essential component of the evaluator in the optimization framework, the impoundment routine estimates the sediment removal effectiveness of detention ponds. It is anticipated that sediment resuspension affects significantly the performance of stormwater ponds. In order to examine the impact of considering sediment accumulation and resuspension on optimization results, the optimal solutions generated with and without considering sediment resuspension, by using IR-2 and IR-1 respectively, were compared.

When IR-1 (i.e., not considering accumulation and resuspension) is applied, according to the "surface loading" concept, it can be derived that, for the same pond storage volume, the lower the depth and the larger the surface area, the greater the removal efficiency. Experiment results using the hypothetical case described above showed that the optimal pond depth tended to converge to the lower bound (2 m) when IR-1 was used. Whereas IR-2 simulates the sediment accumulation and resuspension effect on pond performance, it therefore has the capability of recognizing an optimal depth that takes into account the negative effect of a shallow depth on sediment trap efficiency due to resuspension. It is anticipated when sediment resuspension becomes more pronounced as inflow rate or/and sediment accumulation depth increase, a deeper pond depth would be more preferable. For example, as shown in Fig. 7, by increasing the resuspension coefficient from $K_r = 1.0 \times 10^{-5}$ to $K_r = 1.0 \times 10^{-4}$, and from $K_r = 2.0 \times 10^{-5}$ to 2.0×10^{-4} (kg/m^3) for clay and silt, respectively, to represent a higher sediment resuspension rate, the optimal solutions for ADF = 0.45 changed dramatically. Not only were more ponds and longer detention times required in the optimal solution, but also the optimal depth of the regional pond (No. 14) was increased to 3.5 m. It illustrated that a deeper pond depth is preferred as the sediment resuspension effect becomes more pronounced.

Fig. 8 shows the optimal or near optimal solution of stormwater pond system at various ADFs, which were obtained as the impoundment routine IR-I (without considering the sediment resuspension effect) was employed. As depicted similarly in Fig. 6, ponds are preferably selected in the sequence of regional, subregional, and onsite to obtain the optimal costs, similar to what is observed in Fig. 8. Comparing the optimal solutions shown in Fig. 6, which were generated by using IR-2 with considering

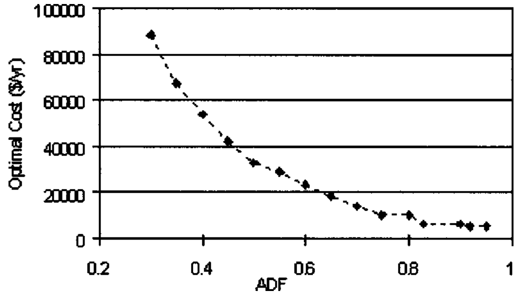

Fig. 5. Optimal cost for various allowable discharge fraction of existing sediment load (using IR-2)

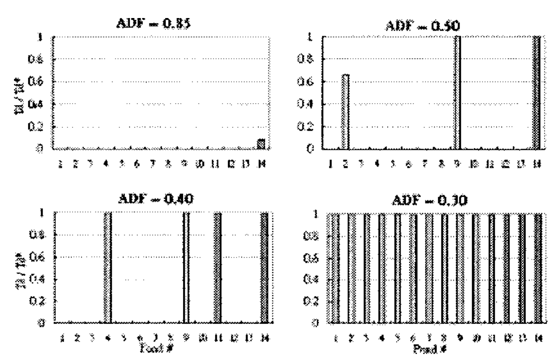

Fig. 6. Optimal stormwater pond placements, i.e., design detention time relative to upper limit, for various allowable discharge fraction values, using IR-2

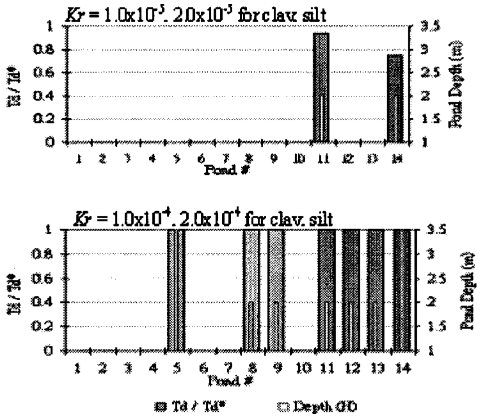

Fig. 7. Optimal solutions found using different values of Kr in impoundment routine IR-2 (for allowable discharge fraction = 0.45)

resuspension effect, and those shown in Fig. 8 using IR-1, for the same ADF, longer design detention time and/or more ponds are required when using IR-2. Also, the lower the ADF, the more pronounced the differences are. This is because the smaller size sediment particles, such as clay, are more difficult to remove and more likely to resuspend. At lower ADFs, smaller size sediment particles take a greater portion of the total sediment removed, therefore the sediment resuspension effect has greater impact on the optimization results. This finding suggests that, without considering the sediment resuspension effect, the control system would likely be underdesigned, especially when the sediment removal requirement is high, for which a greater amount of finer particles needs to be trapped.

Summary and Conclusions

An optimization framework coupling with a watershed simulation model (AnnAGNPS) and an optimization model (scatter search) was successfully developed. The significance of the optimization framework developed lies with its capability of efficiently identifying the optimal stormwater pond implementation plan based on long-term evaluation in the context of a watershed. The scatter search optimization tool was proven to be a superior optimization algorithm for computing time-intensive complex systems. The optimization scheme was used to develop the tradeoff (Pareto frontier) curve of the optimal stormwater pond system cost for various water quality goals. In general, the sensitivity of the system cost to changes in water quality goals is more significant when the water quality requirements are higher. Additionally, by analyzing the optimal pond design strategies for a hypothetical case, it was observed that when the water quality goal becomes higher, ponds are selected, in order of preference, according to the sequence of regional, subregional, and on site, as long as spaces are available for pond construction at all the potential sites. This finding challenged the current "on-site," performance-based approach for stormwater treatment system design, and demonstrated the superiority and cost saving potential of the holistic watershed approach.

This study also investigated how the optimization results are affected by different impoundment routines with and without considering sediment resuspension. In general, the results indicated that without considering the sediment resuspension effect, the control system would likely be underdesigned; especially when the water quality requirement is high, which means a larger amount of finer particles needs to be removed. More importantly, the distinction of considering sediment resuspension in the impoundment routine lies in that it potentially lends the optimization framework the capability of identifying an optimal pond depth, which would balance the preference for smaller depth because of the "surface loading" theory and the preference for larger depth due to the resuspension effect. Yet, it is also recognized that the full extent of the sediment resuspension effect on the optimal design configuration might be influenced by many case specific factors such as sediment accumulation depth, storm intensity, and resuspension coefficients (K_r), etc., and therefore can only be examined and discussed on a case-by-case basis.

The optimization framework developed herein provides a platform and tool to help users examine and analyze the treatment efficiencies of a spectrum of stormwater control alternatives, understand the factors affecting the performance of stormwater BMPs, and more importantly facilitate a robust and cost-effective design of stormwater treatment systems.

On the technological side, the results herein have illustrated the importance of including the sediment accumulation and resuspension effect into the BMP implementation strategies. Best management practices performance is significantly affected by the amount of sediment accumulation. Since, in general, BMPs such as ponds are not serviced or cleaned out frequently, a conservative strategy may be the inclusion of expected loss of pond storage volume and depth due to sedimentation when designing a detention pond, as indicated by the optimal solutions when sediment accumulation and resuspension were taken into account.

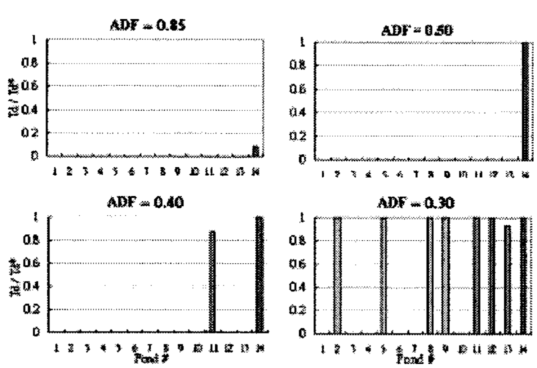

Fig. 8. Optimal stormwater pond placements as normalized detention time, i.e., design detention time relative to its upper limit, for various allowable discharge fraction values, using IR-1

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