Optimizing BMP Placement at Watershed-Scale Using *SUSTAIN*

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ABSTRACT

Watershed and stormwater managers need modeling tools to evaluate alternative plans for environmental quality restoration and protection needs in urban and developing areas. A watershed-scale decision-support system, based on cost optimization, provides an essential tool to support government and local watershed planning agencies as they coordinate watershed-scale investments to achieve needed improvements in water quality. Efforts have been under way by the U.S. Environmental Protection Agency (EPA) since 2003 for the development of a decision-support system for placement of BMPs at strategic locations in urban watersheds. The system is called the **S**ystem for **U**rban **S**tormwater **T**reatment and **A**nalysis **IN**tegration (*SUSTAIN*). This tool is designed to be used by experienced watershed and stormwater practitioners to develop, evaluate, and select optimal BMP combinations for various watershed scales based on cost and effectiveness.

One dominant technical requirement for *SUSTAIN* is the ability to evaluate management practices at multiple scales, ranging from local to watershed applications. The site or local scale evaluation involves simulations of individual BMPs and analyses of the impact of various combinations of practices and treatment trains on local water quantity and quality. On a larger scale watershed, there may be hundreds or thousands of individual management practices that are implemented to achieve a desired cumulative benefit. The required simulations and cost comparisons of these distributed BMP options place significant challenges on the computational accuracy and simulation time for system modeling. *SUSTAIN* incorporates an innovative tiered approach that allows for cost-effectiveness evaluation of both individual and multiple nested watersheds to address the needs of both regional and local scale applications. This paper describes the procedures of the tiered optimization/analysis approaches in *SUSTAIN* for evaluating the cost-effectiveness of BMPs on a regional scale. Selected examples are provided to demonstrate the tiered optimization approach and to illustrate the implications of model simulation time and complexity on the solution of optimization questions.

KEYWORDS

Stormwater management, decision support, watershed scale, best management practices, optimization, tiered approach.

INTRODUCTION

EPA initiated a research project in 2003 to develop a decision-support system based on sound science and engineering, for selection and placement of BMPs/LIDs at strategic locations in urban watersheds. The BMP/LID assessment tools would help develop, evaluate, select, and place BMP options based on cost and effectiveness. Called the **S**ystem for **U**rban **S**tormwater **T**reatment and **A**nalysis **IN**tegration (*SUSTAIN*), it provides a means for objective analysis of management alternatives among multiple interacting and competing factors. The desired outcome from the system application is a thorough, practical, and informative assessment of BMP/LID placement options considering the significant water quantity and quality factors in urban watersheds and associated restoration or mitigation costs.

SUSTAIN is intended to support local and county government engineers/planners, federal/state regulatory reviewers, private consulting engineers, concerned citizens, stakeholders, and academicians in the development of watershed-based management plans. The users are expected to have a fundamental understanding of watershed and BMP modeling processes.

SUSTAIN is being developed in phases because of its comprehensive scope and budgetary constraints. The Phase 1 work was completed in 2005 and the Phase 2 work is currently underway and scheduled to be completed in early 2009. *SUSTAIN* has seven key components: framework manager, ArcGIS interface, watershed module, BMP module, optimization module, post-processor, and Microsoft Access database. They are integrated under a common ArcGIS platform. In Phase 1, a conceptual framework design was developed and major components were programmed and preliminarily tested. The systematic development of the framework through a critical review of modeling needs, current and emerging data management technology, and available watershed and BMP models has been previously presented (Lai *et al.* 2003, Lai *et al.* 2004, Riverson *et al.* 2004, Lai, *et al.* 2005, Lai *et al.* 2006, and Lai *et al*. 2007). The systematic design process ensures that *SUSTAIN* provides a platform that satisfies the needs of environmental managers with technical sophistication consistent with current and emerging technology. The Phase 1 work adopted the then existing BMP module and parts of the optimization module in the Prince George's County BMP evaluation model (Prince George's County 2001). The ongoing Phase 2 work expands the capabilities and functionalities of the system. Key enhancements include a pre-processor to facilitate selection of placement sites, more tightly integrated and flexible post-processors, expanded cost estimating functions, and additional BMP types and improved BMP simulation processes. In addition, the optimization module is significantly expanded to incorporate an additional solution technique, i.e. Non-dominated Sorting Genetic Algorithm II (NSGAII), and provide a means to perform a multi-tier evaluation of individual watersheds, and of multiple, nested watersheds.

VALIDATION OF OPTIMIZATION TECHNIQUES

Phase 2 activities expanded the existing optimization module, which relied on the scatter search technique, to include a second solution technique, NSGAII. Scatter Search is a meta-heuristic search technique that has been explored and used in optimizing complex systems (Glover *et al*. 2003, Laguna *et al*. 2002, Zhen *et al* 2004). NSGAII is an advanced genetic algorithm that is based on Pareto dominance, and using non-domination and distribution instead of fitness value to score individuals (Deb *et al*. 2000). To validate the performance of the two search techniques, they were tested against a known solution. The objectives were twofold: (1) to evaluate the ability of Scatter Search to pick a known best solution for a single BMP given multiple pollutant performance functions and multiple pollutant load reduction objective criteria, and (2) to evaluate the ability of NSGAII to generate a cost-effectiveness trade-off curve for a known linear solution for a single BMP.

For the known best solution, a hypothetical BMP was constructed that reduced both sediment and total nitrogen loads. The properties of this BMP were specified to yield a sediment removal effectiveness that was exactly double its nitrogen removal effectiveness. The trade-off curves were divided into ten equally-spaced intervals. The objective functions for the optimization tests were to minimize the cost of achieving 20%, 40%, and 90% pollutant removal for both sediment and nitrogen (for a total of six hypothetical scenarios, labeled A through F). The scenario objective functions and results are:

A. Minimize the cost to achieve a 20% sediment and 10% nitrogen removal. There is a minimum cost solution which achieves both of these criteria.
B. Minimize the cost to achieve a 20% sediment and 20% nitrogen removal. Nitrogen is the limiting pollutant, which increases optimal cost from Scenario A.
C. Minimize the cost to achieve a 40% sediment and 20% nitrogen removal. There is a minimum cost solution which achieves both of these criteria.
D. Minimize the cost to achieve a 40% sediment and 40% nitrogen removal. Nitrogen is the limiting pollutant, which increases optimal cost from Scenario C.
E. Minimize the cost to achieve a 90% sediment and 40% nitrogen removal. There is a minimum cost solution which achieves both of these criteria.
F. Minimize the cost to achieve a 90% sediment and 90% nitrogen removal. There is no possible solution that can achieve both of these criteria.

The scenario results are presented in Figure 1, where the green circles represent both the known solution and the solution selected by the optimizer.

The second component of the analysis was to evaluate the ability of NSGAII to find and create the linear nitrogen and sediment removal trade-off curves. Figure 2 shows the NSGAII solution plotted against the known linear solutions. Both the scatter search and NSGAII optimization techniques were able to solve a known linear solution with 100% efficiency (in terms of accuracy). In addition, the optimization techniques were both able to select an optimum solution given multiple control objectives for controlling sediment and nitrogen simultaneously. Finally, the NSGAII technique was able to predict a known linear trade-off curve.

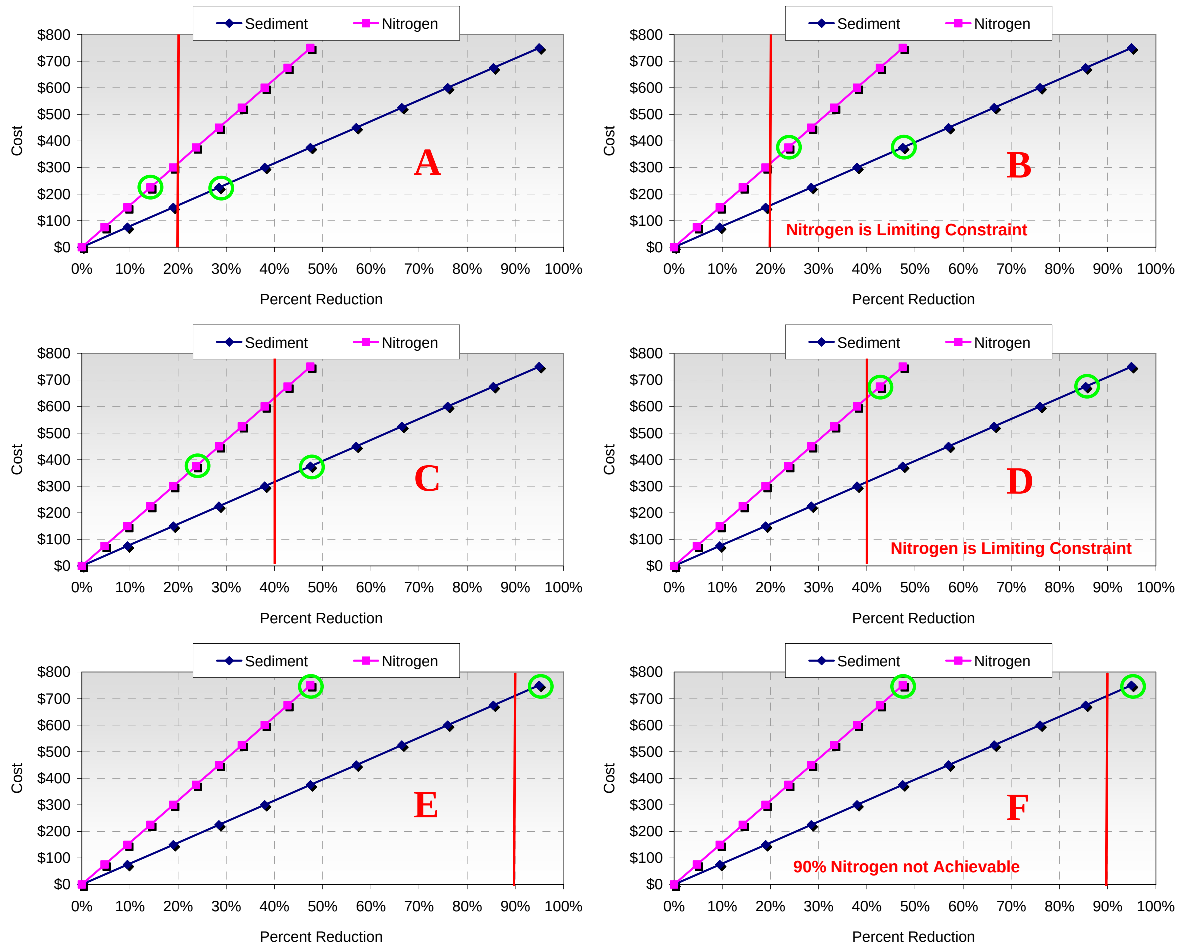

Figure 1 – Scatter search evaluation scenario results.

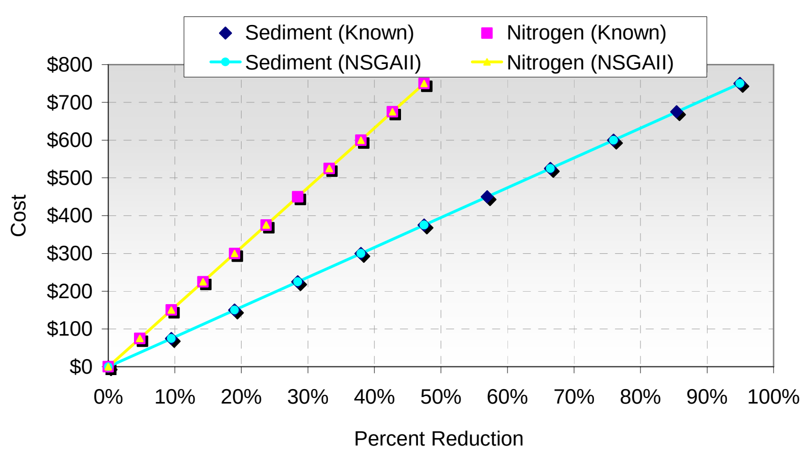

Figure 2 – NSGAII evaluation scenario results.

COMPUTATIONAL EFFICIENCY CONSIDERATION

Computation time can be of concern for complex optimization runs. As a result, initial tests for simulating various numbers of simulation units (BMP, conduit, or BMP/conduit combination) were conducted. The objectives of the tests were to evaluate the computational performance of the following conditions:

- Different numbers of the same BMP unit and multiple simulation periods
- Different numbers of the same conduit unit and multiple simulation periods
- Different combinations of BMPs and conduits and multiple simulation periods.

The test examples were prepared for 1, 10, and 50 units (BMPs, conduits, or BMP/conduit combinations) to be simulated for duration options of 1, 5, and 10 years. The simulation time step 5 minutes was used. The computer configuration used for the tests was a 1.6 GHz CPU, 768 MB RAM, and Windows XP operating system.

The preliminary results (Figure 3) show that the run time increases almost linearly with the increase of the number of simulation units (i.e., BMP, conduit, or BMP/conduit combination). The run time also increases linearly with the increase of simulation period.

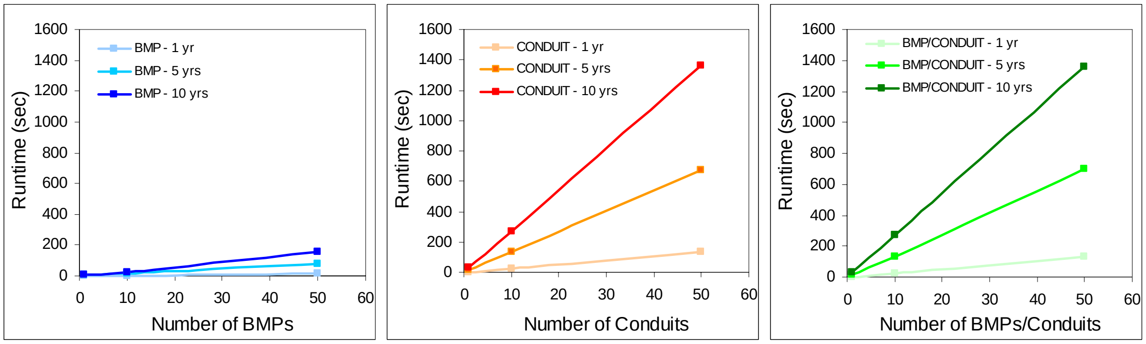

Figure 3 – Runtime comparison of various number of simulation units (BMP, conduit, or BMP/conduit combination) and of various simulation periods.

The initial results (Figure 4) also reveal that conduit simulation consumes much longer run times (approximately 9 times) than the BMP simulation, mainly because it requires solving the coupled continuity equation and Manning's equation for conduit flow routing.

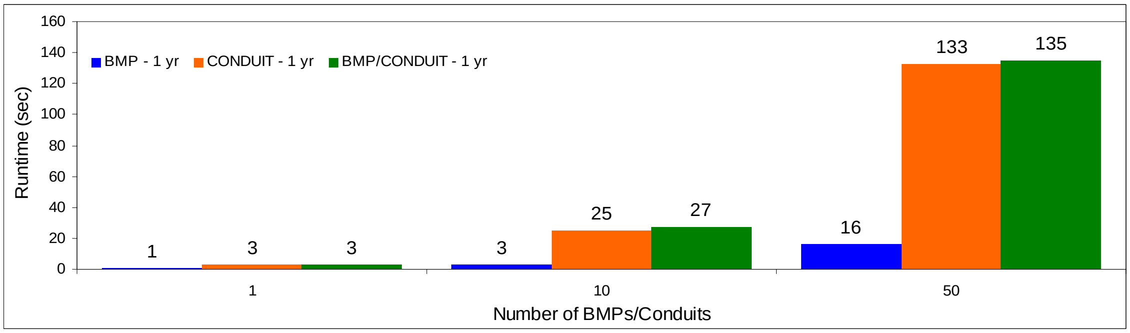

Figure 4 – Runtime comparison of various simulation units (BMP, conduit, or BMP/conduit combination) for a 1-y simulation period.

To reduce the computational burden, it is desirable to simplify the routing simulation during optimization runs. Additional research will be needed to develop ways to balance the computational efficiency and accurate hydraulic routing in conduits.

TIERED OPTIMIZATION APPROACH

A relatively large watershed can usually be subdivided into several smaller sub-watersheds. For each sub-watershed, users select an appropriate suite of feasible BMP options (types, configurations, and costs) at strategic locations. *SUSTAIN* generates time series rainfall-runoff data from BMP drainage areas and routes them through BMPs, in parallel or in series, and predicts quantity and quality at selected locations. *SUSTAIN* produces output for deriving optimal cost-effectiveness curves that relate flow or pollutant load reductions with costs as shown in Figure 5. Each point on the cost-effectiveness curve represents an optimal combination of BMPs that will collectively remove the targeted amount of pollutant load at the least cost.

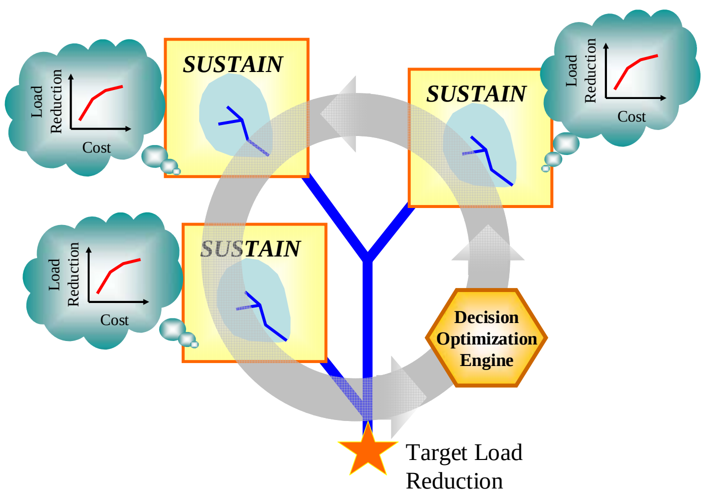

Figure 5 – Tiered application of *SUSTAIN* for developing cost-effectiveness curves.

One dominant technical requirement for *SUSTAIN* is the ability to place management practices at multiple scales. This is because placement of BMPs at different spatial levels, i.e., on-site, sub-regional, and regional, affects the overall cost-effectiveness of the stormwater control system (Zhen et al., 2004). Management plans often need to evaluate the cumulative benefit of management practices at multiple scales on downstream water quality in rivers, lakes, or estuaries. Detailed simulation can be performed at the site scale or small watershed scale to evaluate the impacts of various combinations of practices and treatment trains on localized water quantity and quality. For evaluation and placement at a larger scale watershed, there can be hundreds or thousands of individual management practices that comprise the aggregated treatment. To manage the complexity of larger scale applications, *SUSTAIN* uses a tiered evaluation approach shown in Figure 5 that allows for evaluation of both individual watersheds and multiple nested watersheds.

As the first step of the tiered optimization analysis, cost-effectiveness curves for each sub-watershed tier (tier-1) are generated by performing continuous multiple optimization runs at incremental flow/pollutant reduction targets. The second step of the tiered optimization analysis is to construct the search domain for watershed tier (tier-2) optimization using the tier-1 results. The search domain contains the discrete solutions on the tier-1 cost-effectiveness curves at various assessment points i and j. Figure 6 illustrates the search domain construction process.

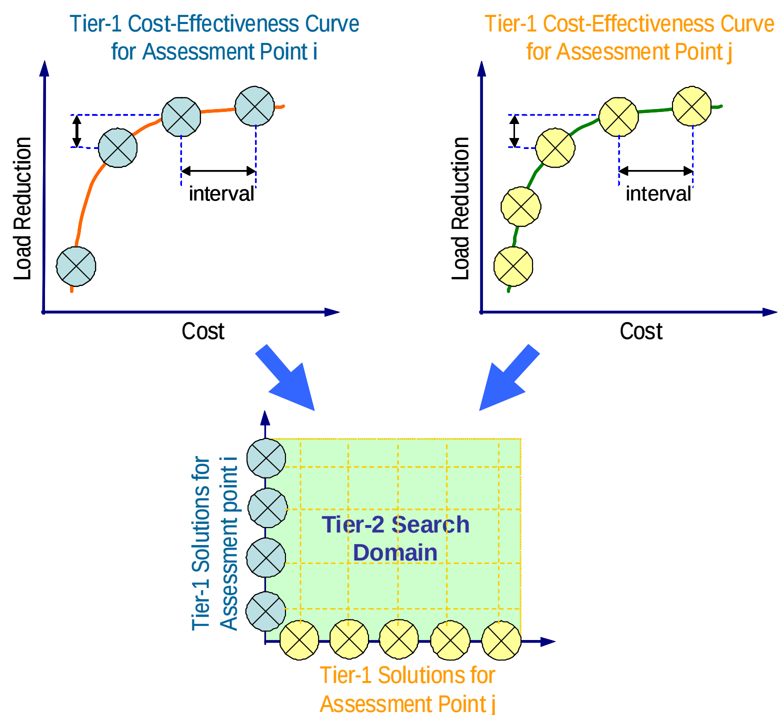

Figure 6 - Construction of the tier-2 search domain using tier-1 results.

The third step is to perform the tier-2 optimization on the search domain constructed in the second step. The optimization engine can strategically sample within the search domain. The goodness-of-fit of each sample is measured, stored, and analyzed to guide the next search direction. Figure 7 illustrates the simulation process that generates the results used for measuring the goodness-of-fit of each iteration run. The simulated time series output for each set of tier-1 solutions (assessed at smaller scale✭**)** are stored and used every time when the solution is sampled. Similarly, the watershed area that is not covered by the tier-1 assessment points will be represented by a pre-simulated time series or real time simulation in the tier-2 search process (assessed at larger scale ✭**)**. For every iteration run, the transport module is applied to perform a real-time simulation using the time series for the sampled tier-1 solutions and the watershed areas that are not covered by tier-1 assessment points. The tiered approach can be applied to a large watershed that contains several sub-watersheds or to a small watershed that requires the development of a detailed management plan, e.g., at a parcel or a street block level.

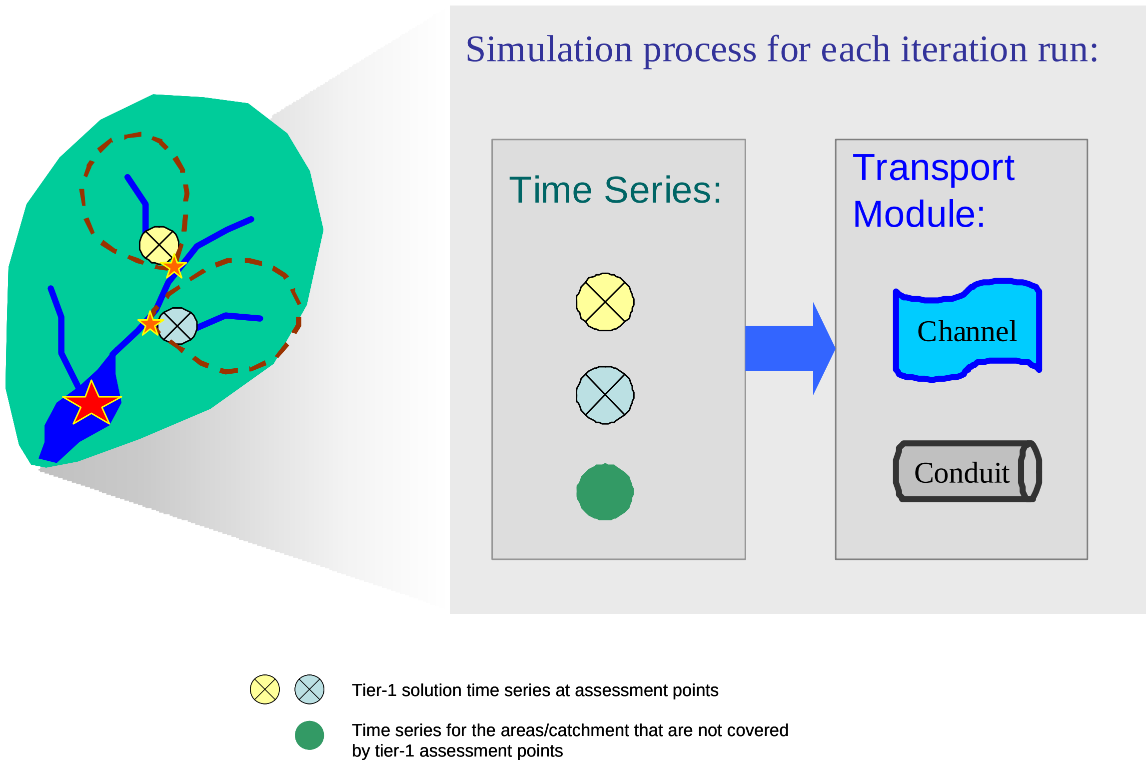

Figure 7 - Simulation process for each iteration run.

A hypothetical exercise is carried out to further demonstrate the tiered optimization approach. The objective of this optimization search is to find the solutions with minimum cost while achieving the desired total phosphorous (TP) load reduction at the specified assessment points. The hypothetical watershed consists of one infiltration facility and one detention pond in series located upstream in the watershed, and two tier-1 subwatersheds (subwatershed A and B). The two tier-1 subwatersheds are identical, and each has three sets of infiltration facility/detention ponds in series. Subwatershed A directly drains to the watershed outlet, while subwatershed B is located further upstream, and drains to the watershed outlet through a conduit. The schematic in Figure 8 depicts the watershed layout.

For the tier-1 optimization, the decision variables are the sizes of the infiltration and detention ponds. The outcome of the tier-1 optimization is the near optimal solutions along the trade-off curve for each tier-1 subwatershed (the red and green diamonds shown in Figure 9). Each near optimal solution is one combination of decision variables. For the tier-2 optimization, the decision variables include the tier-1 near optimal solutions for each subwatershed and the sizes of the BMPs located upstream. The tier-2 optimization search generates the most cost-effective solutions, which are combinations of the tier-1 near-optimal solutions and the BMP sizes at tier-2 level. The blue squares in Figure 9 show the cost and TP load reduction of the tier-2 optimization solutions. Figure 10 shows the decision variable values (normalized by the maximum value) for each near-optimal solution along the tier-2 cost-effectiveness trade-off curve. For example, at the 18 % tier-2 TP load reduction target, the second tier-1 near-optimal solution with 20 %

reduction for both subwatershed A and B are selected, while the upstream infiltration facility and detention pond are not chosen. As the tier-2 TP load reduction target increases, the tier-2 near-optimal solutions tend to allocate more TP load reduction on subwatershed A, which directly drains to the watershed outlet. Also the upstream pond and infiltration facility are selected only at higher target values, and a pond is preferred over an infiltration facility.

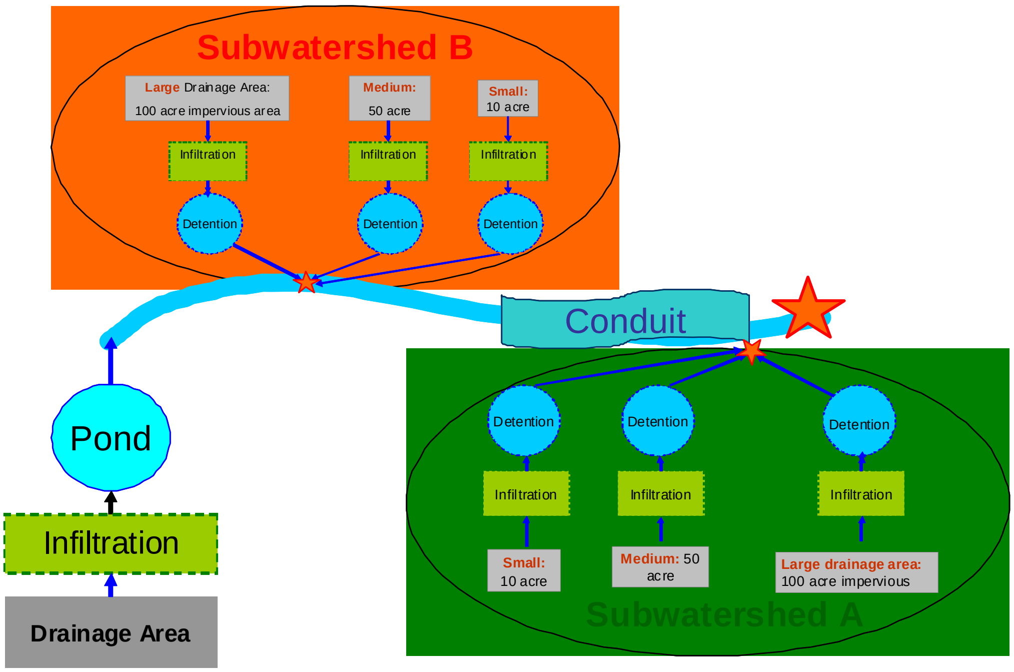

Figure 8 - Tiered watershed schematic.

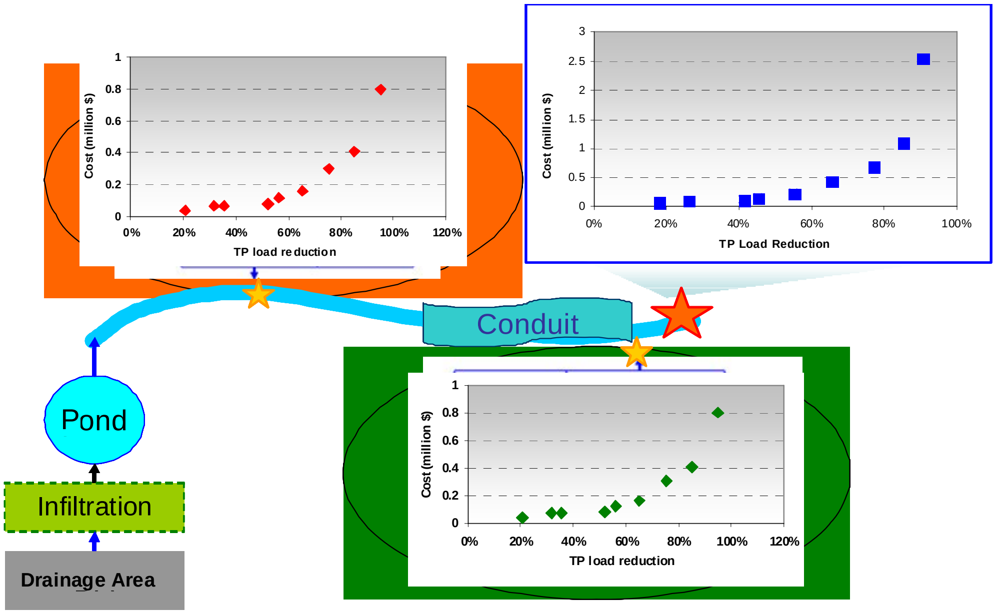

Figure 9 - Tier-1 and Tier-2 optimization results.

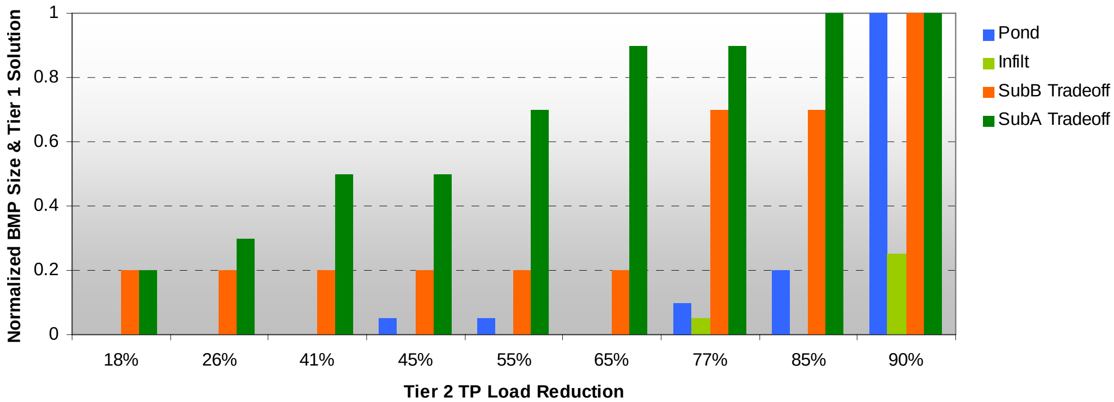

Figure 10. Tier-2 optimization solutions.

One advantage of the tiered optimization approach is that it significantly improves search efficiency. Taking the hypothetical case described above as an example, the total number of solutions for each tier-1 subwatershed is 5^6 (5 is the number of possible sizes for each BMP, and there are 6 potential BMPs in each subwatershed), and the number of solutions for the tier-2 run is 10^2 x 5^2 (10 tier-1 near optimal solutions for both subwatersheds, and 5 possible sizes for the two upstream BMPs), so the exhaustive number of solutions using the tiered approach is $5^6 + 5^6 + 10^2 \times 5^2 = 33{,}750$. In comparison, for the same case, if conducting a single optimization run, the exhaustive number of solutions would be $5^{14} =$ 6,102,515,625 (5 is the number of possible sizes for each BMP, and there are 14 potential BMPs in the entire watershed), which is approximately 180,000 times more than that of the tiered approach. Given that the conduit simulation is computationally expensive, reducing the number of runs that involve conduit routing becomes extremely desirable. In addition, the tiered optimization allows users to place assessment points and have explicit control at up-stream locations.

CONCLUSIONS

The two search techniques (i.e. Scatter Search and NSGAII) currently implemented within the SUSTAIN framework were tested using a linear problem with known optimal solutions. The results show that both optimization techniques were able to identify the known optimal solutions, and the optimization techniques were both able to select an optimum solution given multiple control objectives. The computation efficiency test results reveal that conduit simulation requires much longer run times (approximately 9 times) than a BMP simulation. For a large watershed-scale application, in which many conduits/reaches are involved, the computational burden of conduit simulation will become daunting. Therefore, it is desirable to simplify the routing simulation during optimization runs, and also reduce the number of iteration runs during the optimization search process.

The tiered optimization implemented in *SUSTAIN* not only provides a more efficient and manageable means for large scale applications, but also allows users to place assessment points and have explicit control at up-stream locations.

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DISCLAIMER

Any opinions expressed in this paper are those of the author(s) and do not, necessarily, reflect the official positions and policies of the EPA. Any mention of products or trade names does not constitute recommendation for use by the EPA.

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