



Multi-objective Optimization of Watershed Management Plans: Bartlett Brook Case Study

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There are waters in 14 subwatersheds in the Vermont portion of the Lake Champlain Basin that are listed as "impaired" primarily due to urban stormwater runoff.



http://www.ci.burlington.vt.us/stormwater/



http://www.lcbp.org/

The VT ANR has targeted these as priority sites for treatment, to reduce sediment and contaminant load to Lake Champlain.

In order to control storm-water runoff, so-called Best Management Practices (BMPs), such as detention ponds and rain gardens, can be installed to reduce storm flash and remove pollutants, although often at a significant cost.

Detention Ponds:

Larger, Impervious Cheaper per area treated, Minimum size restrictions, Less well-suited to residential areas





http://www.mychamplain.net/programs/fish-and-flowers-rain-gardens

Rain Gardens: Smaller, Infiltrating, More expensive, Prettier, Preferable for residential areas

http://www.uvm.edu/~ran/ranenglesby/

Problem:

How to determine the appropriate number, types, placement, and sizing of BMPs in impaired watersheds?

Multiple Objectives:

- 1) Minimize sediment and contaminant load
- 2) Minimize costs of BMPs
- 3) Make the design robust to climate change





Constraints:

The proposed plans must be feasibly accommodated by the geography and land-use patterns

We Propose a Complex Systems Approach:

Multi-scale, multi-pass, multi-objective evolutionary algorithm
Present watershed decision-makers with a family of potential solutions, evenly spaced along the non-dominated Pareto front, so they can best weigh alternatives and competing objectives.



http://www2.q-city.com/shelbayreports/bartlett/part2bartlett.pdf

Bartlett Brook is a gently-sloping 2.85 km² mixed-use watershed, which contains three housing developments, a commercial district along Route 7, two farms.

We built a hydrologic model in HSPF, decomposing the watershed into 14 subwatersheds.

For each subwatershed, we pre-computed optimal (feasible) BMP configurations and associated costs, for treating anywhere from 0% to 100% of the maximum treatable area in each subwatershed, based on geophysical (e.g., slope, open area) and other characteristics (e.g., preference for rain gardens in residential areas) of each subwatershed.





The potential solutions to be evolved are thus simplified to realvalued vectors with each element in the range [0,1]. Each element is associated with a distinct pre-computed cost curve associated BMP design. <u>subwatershed:</u> 1 2 3 4 5 6 7

Once such a watershedlevel solution has been selected for implementation, watershed managers and developers can select the specific locations of detention ponds and rain gardens within each subwatershed, based on practical and political considerations.



This multi-scale decomposition greatly reduces the search space to feasible solutions and speeds the evolution.

Since evolutionary algorithms are population based, they are wellsuited to solving multi-objective functions, where there is no single 'best' solution.

Instead, we seek a set of solutions that are "Pareto Optimal", i.e., non-dominated.

e.g., A is better than B in objective 1, but B is better than A in objective 2



Ideally, we would like solutions uniformly spaced along the Pareto front, in order to best weigh alternatives.

Solutions evolved with Differential Evolution (DE): Storn and Price, 1997 (better for real-valued vectors than standard GA or ES)



Basically, DE adds the weighted difference between two population vectors to a third vector. This makes the scheme completely self-organizing, automatically moving from "exploration" to "exploitation".

The current state-of-the-art method for improving spread along the non-dominated front (used in NSGA-II) calculates "crowding distances" between 2 nearest neighbor solutions, and then discards those with lowest crowding distances.



Objective 1

Unfortunately, for pairs of close points (shaded), *both* will be removed when ideally, to achieve the most uniform coverage along the front, only one of the pair should be removed.

New proposed Uniform Spacing (US) crowding metric



This function is maximized when *shortest* = *longest* in all objectives, so pruning lowest values, then recalculating, maximizes the uniformity of spacing of remaining solutions.

To assess uniformity of spread in multiple dimensions, we take the standard deviation of all Euclidean distances in the minimum spanning tree (MST) between solutions.

		NSGA-II crowding		US crowding		
Benchmark	Objectives	Mean	Standard Deviation	Mean	Standard Deviation	P-value (US < NSGA-II)
ZDT1	2	6.646e-03	5.643e-04	2.521e-03	1.985e-04	4.388e-09
ZDT2	2	6.697e-03	9.196e-04	2.498e-03	2.175e-04	2.439e-08
ZDT3	2	7.994e-03	9.570e-04	3.818e-03	3.215e-04	7.213e-08
ZDT4	2	5.963e-03	6.476e-04	2.034e-03	2.300e-04	8.733e-09
ZDT6	2	4.776e-03	3.904e-04	1.868e-03	1.442e-04	2.792e-09
DTLZ1	3	9.153e-03	5.702e-04	9.081e-03	2.367e-04	3.430e-01
DTLZ2	3	2.182e-02	9.186e-04	2.203e-02	6.450e-04	2.434e-01
DTLZ4	3	2.234e-02	8.450e-04	2.118e-02	4.967e-04	2.833e-03

Results on 7 multi-objective benchmark problems confirmed that US crowding method yields better spacing than the NSGA-II crowding method.

Simulating sediment transport is computationally costly, so we searched for a rapidly computable hydrologic surrogate to use as a surrogate objective to minimize for the bulk of the evolution.



Through a rigorous study of 28 potential hydrologic metrics, we discovered that log(standard deviation of flow) was highly correlated with log(sediment load); this was validated on 9 watersheds.

After using the computationally efficient sediment surrogate objective function (standard deviation of flow) to evolve the initial Pareto front, we then switch to the actual sediment load objective to fine tune the front.

Precipitation events are expected to become more intense in the NE due to global climate change (NECIA, 2006.)

To assess the robustness of solutions along the Pareto front to anticipated changes, we assessed change in sediment load between:

•2008 measured rainfall pattern

 synthetic precipitation pattern generated with the same annual rainfall total but with more intense rain events distributed over 1-day storms every 7 days
Non-dominated solutions were pruned

We assessed 3 possible multi-pass orders for when to introduce these refinements into the evolution:



Order 3 was the winner: best solutions, best spread, fastest; (using the more intense precipitation pattern first makes sense)



Order 3 (black plusses) was able to achieve the same quality of solutions as when using the more computationally costly sediment load objective for the entire evolution throughout the evolution (solid green line) Under the more intense precipitation patter, sediment load increases by a factor of around 1.47 for the highest cost solutions, but this increases to a factor of about 1.57 for the lowest-cost solutions.



High-cost solutions not only reduce sediment the most, but are also likely to be more robust to climate change; this should be taken into account when selecting which solution to implement.

Summary of proposed method for Multi-objective Optimization of Watershed Management Plans

Multi-scale decomposition

✓ Constrains evolutionary search space to feasible solutions

- •Multi-objective differential evolution
- Uniform spacing crowding method
- •Multi-pass minimizes:
 - ✓ 1st: cost and sediment surrogate
 - $\checkmark 2^{nd}$: cost and sediment
 - \checkmark 3rd: cost and sediment increase due to climate change
- Applied to Bartlett Brook Watershed

→ Resulting family of potential management plans provides decisionmakers with the information needed to appropriately assess the trade-offs between competing objectives when selecting which solution to implement.