The Use of WinSLAMM to Evaluate Combinations of Source Area and Outfall Controls Using Continuous, Long-term Rainfall Records

Robert Pitt[1] and John Voorhees[2]

[1]Cudworth Professor of Urban Water Systems, Department of Civil, Construction, and Environmental Engineering, The University of Alabama, P.O. Box 870205, Tuscaloosa, AL 35487 USA, PH:(205)348-2684, Fax: (205) 348-0783, e-mail: rpitt@eng.ua.edu
[2]Senior Water Resources Engineer, EarthTech, Inc., Madison, WI

Abstract

There are a wide range of controls that have been used to reduce stormwater pollutant and flow discharges. These include, with a few examples: development practices (reducing the amount of pavement and roof areas; directing runoff from these areas to pervious areas instead of directly connecting them to the drainage system); public works practices (street and catchbasin cleaning; the use of grass swales instead of concrete curbs and gutters); sedimentation controls (source area hydrodynamic separators; outfall wet detention ponds); filtration and infiltration practices (bioretention parking lot islands; rain gardens; percolation ponds; media filters); runoff rate and energy controls (runoff volume controls; dry detention facilities); water reuse (rain barrels and cisterns to capture site runoff for irrigation or other non-potable uses); etc. Obviously, there are many controls that can be used to minimize stormwater problems for both new development and when retrofitting controls in existing areas. A comprehensive stormwater quality model should be capable of predicting the benefits of many of these controls under a variety of conditions.

Introduction

This paper will illustrate several applications of WinSLAMM, specifically showing how it can be used to consider combinations of development characteristics, source area controls, and outfall controls when evaluating stormwater management programs.

Decision analysis techniques may be used as an important guide in selecting an urban runoff control program. Decision analysis is a systematic procedure that enables one to study the trade-offs among multiple and usually conflicting program objectives. An alternative procedure is to separately determine the programs necessary to meet each objective and to use the least costly program that satisfies all the identified critical objectives. This is an acceptable procedure some of the time, but it may not result in the most cost-effective program, especially when multiple objectives need to be considered. Decision analysis considers the partial fulfillment of all the objectives. It translates these into their relative worth to the decision-maker or other interested parties. This paper describes the types of output information calculated by WinSLAMM, the Source Loading and Management Model, and how it can be used in decision analysis procedures of varying complexities. Prior descriptions of WinSLAMM have been presented in this conference series and in other publications (Pitt 1986; 1997;

1999; Pitt and Voorhees 2002 for example). The model web site (http://www.winslamm.com/) also contains further model descriptions and references.

There is a great deal of information calculated by WinSLAMM during an analysis for a site and stormwater management alternative. In most cases, just a few of the values presented on the main summary screen are sufficient for quick comparisons. These include the overall percent runoff and particulate solids reductions, the final Rv and runoff volume, and the resulting particulate solids yields and concentrations. Recent enhancements to WinSLAMM also now enable the costs and the expected habitat conditions of the receiving waters to be compared, in addition to flow-duration information. Cost data were summarized from several studies, including those by APWA 1992, Brown and Schueler 1997, Frank 1989, Heaney, *et al*. 2002, Muthukrishnan, *et al*. 2006, Sample, *et al.* 2003, SEWRPC 1991, Wiegand, *et al*. 1986, and Wossink and Hunt 2003.

The batch processor option of WinSLAMM is frequently used to automatically examine all the land use and stormwater control options for a relatively large area, such as for city-wide analysis, especially when used in conjunction with GIS data.

Figure 1 is a screen shot of the main batch processor screen that is used to select the standard land use files for a specific area being examined, along with the areas, and soils. This screen is also used to select a set of *.dat files that can be run in batch mode to compare multiple stormwater controls for the same site, as described later. In that configuration, the first *.dat file listed is the “base” condition that is compared to the other files.

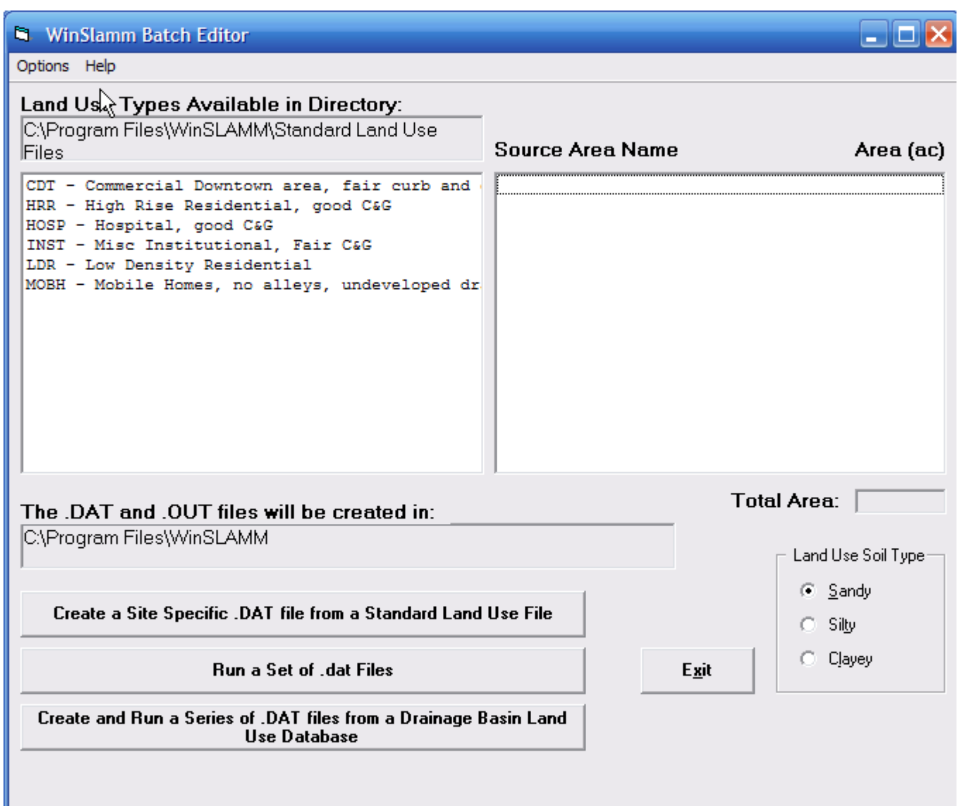

Figure 1. WinSLAMM batch editor setup screen.

Recent enhancements to WinSLAMM allow the batch processor to be used to enable comparisons of different stormwater control programs for a single site. As noted above, there are many stormwater factors calculated for each analysis, and a stormwater manager may have difficulty comparing the different alternatives. Table 1 is a csv output file (only showing a few of the calculated factors, as an example), comparing five alternative stormwater management programs to a base condition for a single 65 ac mixed land use catchment area, that was calculated with the WinSLAMM batch processor. The different stormwater management programs considered in this example include: grass swales (G), wet detention ponds (W), and two levels of porous pavement (P), plus a combination of grass swales and a smaller wet detention pond. WinSLAMM can evaluate many other alternative controls, and combinations, but this is only shown as a short example of the output table.

Table 1. Preliminary Output Table Comparing Different Stormwater Control Options for Study Area

File Name	Runoff Volume (cf)	Partic. Solids Yield (lbs)	Sub Basin Capital Cost	Sub Basin Land Cost	Sub Basin Maint. Cost	Sub Basin Total Annualized Cost	Sub Basin Total Present Value Cost	Percent Part. Solids Reduc.	Cost per lb Sediment Reduced per Year
Cost Example - Base Case No Controls	5246545	37413	0	0	0	0	0	0%	base
Cost Example - G	3136146	22341	119109	0	9100	18658	232515	40%	$ 1.24
Cost Example - P 20 percent	4425257	30761	681686	0	3422	58122	724332	18%	$ 8.74
Cost Example - P 50 percent	3193328	20784	1704215	0	8555	145306	1810829	44%	$ 8.74
Cost Example - W	5204862	7496	366536	300000	7125	60609	755328	80%	$ 2.03
Cost Example - W G	2840801	6825	360849	170000	14109	56706	706683	82%	$ 1.85

This table doesn't show the example base costs associated with a conventional storm drainage system, so the costs shown above would need to be further adjusted. If at least 80% particulate solids was needed (a typical goal for some programs, including those in Massachusetts and Wisconsin), then only the last two options meet this goal. The last option, the use of grass swales plus a smaller wet detention pond, is the least costly of these two options. This option also has the benefit of significant runoff volume reductions, compared to the base condition.

The above approach illustrates a relatively straight-forward approach in selecting the "best" stormwater control program for this site. However, it may be desirable to also consider other attributes associated with the different options. The following discussion is based on material originally presented by Pitt (1979) and is a hypothetical example application of a decision analysis procedure that considers conflicting and multiple objectives applied to selecting a street cleaning program as part of a stormwater management plan.

Example Application with Extended Data Output

The above example was prepared some time ago when stormwater modeling techniques were still in their infancy, and environmental regulations, especially for stormwater, were not well developed. It is now possible, such as with the recent enhancements made to WinSLAMM, to more completely evaluate different stormwater management programs that consider a wide variety of conflicting objectives. The following short hypothetical example illustrates a procedure, based on the above discussions.

Attribute Levels Associated With Different Stormwater Management Programs. WinSLAMM generates a great deal of information when stormwater management options are evaluated, as previously described. New revisions to the batch processor option in the model make it possible to summarize many of the important attributes in a simple spreadsheet format. The site and corresponding stormwater management options for this example are described below.

Descriptions of Site and Alternative Stormwater Controls
This example site is a new industrial park in northern Alabama. The portion of the site considered below is about 98 acres in area, comprised of about 33.8 acres of industrial land, 60.2 acres of open space land, and 4.6 acres surrounding sinkholes. There are 13 industrial lots in this subarea, each about 2.6 acres in area. The following list shows the estimated total surface covers for these 98 acres:

- Roofs: 18.4 acres
- Paved parking: 2.3 acres
- Streets (1.27 curb-miles): 3.1 acres
- Small landscaped areas (B, or sandy-loam soils, but assumed silty soils due to compaction): 10.0 acres
- Large undeveloped area (B or sandy-loam soils, but assumed silty soils due to compaction): 60.2 acres
- Isolated areas (sinkholes): 4.6 acres

The stormwater control options examined in this subarea included the following:
Conventional storm drainage system elements:
The base conditions (associated with the “Base Conditions, No Controls” option) have conventional curb and gutters with concrete storm drainage pipes, and the roofs and paved parking areas are directly connected to the storm drainage system. The main components of the conventional drainage system for base conditions are assumed to be comprised of: 5,200 ft of 18 inch and 3,360 ft of 36 inch storm drainage pipe, plus 39 on-site and 45 public street inlets. The estimated costs for these conventional storm drainage elements are from RS Means (2006) and are \$19 per ft for 18 inch and \$72 per ft for 36-inch reinforced concrete pipe. Excavation and backfilling costs add \$6/yd^3. The inlets are \$3,000 each. The on-site drainage elements are needed whenever the site biofilter-swale option is not being used:

5,200 ft of 18 inch concrete pipe (buried in a 5 ft deep trench) at \$25/ft = \$130,000
39 inlets = \$117,000

Total on-site drainage costs: $247,000 (1996 costs) x 1.2 = $296,400 (2005 costs, based on ENR index). In addition, it is assumed that annual maintenance costs for these drainage elements will be 1% of the total capital costs for each year = $2,960/yr (2005 costs)

The roadside drainage elements are needed whenever the regional swale option is not being used:

3,360 ft of 36 inch concrete pipe (buried in an 8 ft deep trench) at $80/ft = $268,800
25 inlets = $75,000

Total roadside drainage costs: $343,800 (1996 costs) x 1.2 = $412,560 (2005 costs, based on ENR index). In addition, it is assumed that annual maintenance costs for these drainage elements will be 1% of the total capital costs for each year = $4,130/yr (2005 costs)
These initial costs need to be converted to annualized costs. The following is based on the procedures outlined by Narayanan and Pitt (2005) and is the same procedure used in WinSLAMM for calculating the costs of the stormwater controls.

Annual on-site drainage costs:
Interest rate on debt capital = 5%
Project financing period = 20 years
Capital cost of project = $296,400 (2005)
Annual maintenance cost = $2,960/year (2005)

Annual value of present amount = $\frac{i(1+i)^N}{(1+i)^N - 1}$

Annual value of present amount (or) annual value multiplier = $\frac{0.05(1+0.05)^{20}}{(1+0.05)^{20} - 1}$ = 0.0806

Annualized value of all costs = Annualized value of (total capital cost of project) + annual maintenance and operation cost.

= 0.0806 * ($296,400) + $2,960 = $26,850 per year

Annual roadside drainage costs:
Interest rate on debt capital = 5%
Project financing period = 20 years
Capital cost of project = $412,560 (2005)
Annual maintenance cost = $4,130/year (2005)

Annualized value of all costs = Annualized value of (total capital cost of project) + annual maintenance and operation cost.

= 0.0806 * ($412,560) + $4,130 = $37,380 per year

On-site biofilter swales:

These small drainage swales, included in options 3, 6, and 8, collect the on-site water from the roofs and paved areas and direct it to the large natural swales. These have the following general characteristics: 200 ft long, with 10 ft bottom widths, 3 to 1 (H to V) side slopes (or less), and 2 inches per hour infiltration rates. One of these will be used at each of the 13 sites on the site. These swales will end at the back property lines with level spreaders (broad crested weirs) to create sheetflow towards the large drainage swale.

When modeling the site biofilters, the following dimensions were used:

Top area: 4400 ft^2
Bottom area: 2000 ft^2
Depth: 2 ft
Seepage rate: 2 in/hr
Peak to average flow ratio: 3.8
Typical width for cost purposes: 10 ft
Number of biofilters: 13 (one per site)
All roofs and all paved parking/storage areas drained to the biofilters

The level spreader located at the end of the biofilter was modeled assuming a broad-crested weir having a crest length of 12 ft , a crest width of 10 ft, and the height from the datum to bottom of opening was 1 ft. Table 2 shows the evaporation rates used for this example analyses.

Table 2. Example Monthly Average Evaporate Rates (in/day)

January	0.01
February	0.03
March	0.06
April	0.08
May	0.12
June	0.25
July	0.25
August	0.15
September	0.08
October	0.06
November	0.03
December	0.01

Large regional drainage swale:

Options 2, 5, 6, 7, and 8 include a natural drainage swale in this subarea that will collect the sheetflows from the bioretention swales from each site and direct the excess water to the ponds. This swale is about 1700 feet long, on about a 2.6% slope, and is 50 ft wide. It has 3 to 1 (H to V) side slopes, or less, and 1 inch per hour infiltration rates. The bottom of the swale will be deep vibratory cultivated during proper moisture conditions to increase the infiltration rate, if compacted. This swale also has limestone check dams every 100 ft to add alkalinity to the water and to encourage infiltration. The vegetation in the drainage will be native grasses having deep roots and be mowed to a height of about

6 inches, or higher. Any cut grass will be left in place to act as a mulch that will help preserve infiltration rates. The swale will also have a natural buffer on each side at least 50 ft wide.

When modeling this large regional swale, the model used a swale density of 29 ft/ac with 57acres served by the swales, resulting in a total swale length of 1653 ft. The drainage system was described as 58% grass swales and 42% undeveloped roadside in order to obtain the 57 acres of swale drained area. The infiltration rate in the swale was 1 in/hr. The swale bottom width was 50 ft, with 3H:1V side slopes. The longitudinal slope was 0.026 ft/ft, and the Manning's n roughness coefficient was 0.024. For the cost analysis, the typical swale depth was assumed to be 1 ft.

Wet detention pond:

Options 1, 4, 5, 6, 7 and 8 include a wet detention pond located across the main road next to the southern property boundary. The regional swale will direct excess water into the pond far from the discharge point. The pond is a wet pond having the approximate dimensions and depths shown in Table 3.

Table 3. Wet Detention Pond Size and Elevation Characteristics

Pond Elevation (ft)	Pond Area (acres)
1	0.15
2	0.25
3	0.5
4	0.75
5	1.0 (normal pool elevation, and invert elevation of 30o v-notch weir)
6	1.5
7	2
8	2.5 (invert elevation of flood flow broad-crested weir). Normal maximum elevation during one and two year rains.
9	3.0 (approximate maximum pond elevation, or as determined based on flood flow analysis). Additional storage and emergency spillway may be needed to accommodate flows in excess of the design flood flow.

The pond storage between 5 and 9 feet is about 8 acre-ft. If additional storage is needed for flood control, either the pond can be enlarged, or an additional dry pond can be located immediately north of the road crossing of the drainageway upstream of the wet pond.

The normal pool elevation of the pond is at 5 ft, about 4 ft below the ground elevation, with an overall pond excavation of 9 ft. The pond is created by a combination of excavation and a downstream embankment. Accessible forebays are located near each of the flow entrance locations to encourage pre-settling of larger sediment in restricted areas. A safety ledge 6 to 12 inches underwater also extends out 3 to 10 ft around the pond perimeter. This ledge is planted with a thick stand of emerging vegetation to restrict access to deep water. The edge of the pond along the water is also planted with appropriate vegetation to also act as a barrier. Perimeter plantings also discourage nuisance geese populations. A boardwalk extends through this perimeter vegetation at selected locations for access for demonstration purposes. This boardwalk is also connected with the path system through the industrial park that connects other points of interest for recreational use by site workers.

When modeling the pond, the following was also used: The "medium" particle size file was used, corresponding to a median particle size of about 20 µm, with 90% of the particles (by mass) less than 250 µm in diameter. The emergency spillway was a 50 ft long broad crested weir, having a 3 ft width, with one foot of freeboard. The same evaporation rates used for the biofilters were also used for the ponds.

Predicted Performance of Stormwater Control Options

Table 4 below summarizes the calculated stormwater discharges for different site options. WinSLAMM, version 9.1, was used along with a typical Huntsville rain year (1976). This year had 102 recorded rains ranging from 0.01 to 3.70 inches in depth. The total rain recorded was 53.4 inches and the average rain depth was 0.52 inches.

Table 4. Attributes of Several Different Stormwater Management Programs

Stormwater Treatment Option	Part. Phos Yield (lbs/yr)	Volum. Runoff Coeff. (Rv) (est. bio. cond.)	% of time flow >1 cfs	% of time flow >10 cfs	SS conc. (mg/L)	Part. P conc. (mg/L)	Zn conc. (µg/L)
Base, No Controls	174	0.29 (poor)	4.5	0.3	204	0.50	359
Option 1 Pond	25	0.29 (poor)	4	0.05	30	0.073	128
Option 2 Reg. Swale	79	0.15 (fair)	2	0.1	178	0.43	390
Option 3 Site Biofilter	172	0.14 (fair)	2	0.2	408	1.0	696
Option 4 Small pond	41	0.29 (poor)	4	0.2	48	0.12	151
Option 5 Pond and reg. swale	10	0.15 (fair)	2	0	23	0.057	203
Option 6 Pond, swale, biofilter	5.5	0.06 (good)	0.5	0	29	0.073	386
Option 7 Small pond and swale	17	0.15 (fair)	2	0.05	39	0.095	220
Option 8 Small pond, swale and biofilter	10	0.07 (good)	0.8	0	53	0.13	390

Table 4. Attributes of Several Different Stormwater Management Programs (continued)

Stormwater Treatment Option	Annual Total SW Treat. Cost ($/yr)	Annual Addit. Drain. System Cost ($/yr)	Total Annual Cost ($/yr)	Land Needs for SW mgt (acres)	Runoff Volume (cf/yr)	Part. Solids Yield (lbs/yr)	Reduc. in SS Yield (%)
Base, No Controls	0	64,230	64,230	0	5,600,000	71,375	n/a
Option 1 Pond	19,134	64,230	83,364	4.5	5,507,000	10,192	86
Option 2 Reg. Swale	3,158	26,850	30,008	0	2,926,000	32,231	55
Option 3 Site Biofilter	32,330	37,380	69,710	0	2,705,000	68,890	1
Option 4 Small pond	10,209	64,230	74,439	2.3	5,557,000	19,552	73
Option 5 Pond and reg. swale	22,292	26,850	49,142	4.5	2,844,000	4,133	94
Option 6 Pond, swale, biofilter	54,622	0	54,622	4.5	1,203,000	2,183	97
Option 7 Small pond and swale	13,367	26,850	40,217	2.3	2,887,000	6,937	90
Option 8 Small pond, swale and biofilter	45,698	0	45,698	2.3	1,253,000	4,125	94

Utility Functions for, and Tradeoffs between, the Different Attributes

The utility functions and tradeoffs between the different attributes are highly dependent on the local goals and regulations that need to be addressed in a stormwater management program. The following discussion describes several alternative goals for a hypothetical situation, and how the attributes for each option can be evaluated.

Single Absolute Goal/Limit. In some cases, a watershed analysis may have been completed that recognizes the critical pollutants, and set removal goals. This may be especially relevant for areas attempting to address retrofitting stormwater controls in areas already developed. For new development, some areas may require an 80% reduction in suspended solids, compared to traditional development. If this was the case, the utility functions for particulate solids would be easily defined as being zero for outcomes that do not meet the reduction goal, and one for outcomes that do meet the reduction goal. The ranking of the options would simply be based on examining only those options that meet this simple goal, possibly by cost of implementation. In the above example, the options are shown on Table 5.

Table 5. Suspended Solids Reduction Goals and Costs (bold and italic values meet numeric criterion)

Stormwater Treatment Option	Total Annual Cost ($/yr)	Reduction in SS Yield (%)	Meet 80% particulate solids reduction goal?	Rank based on annual cost
Option 1 Pond	83,364	86	Yes	5
Option 2 Regional Swale	30,008	55	No	n/a
Option 3 Site Biofilter	69,710	1	No	n/a
Option 4 Half-sized pond	74,439	73	No	n/a
Option 5 Pond and reg. swale	49,142	94	Yes	3
Option 6 Pond, reg. swale and biofilter	54,622	97	Yes	4
Option 7 Small pond and reg. swale	40,217	90	Yes	1
Option 8 Small pond, reg. swale and biofilter	45,698	94	Yes	2

Therefore, the use of a small pond in conjunction with a regional swale would be the least expensive option that meets the reduction goal of 80% particulate solids removal. The most costly option that meets the particulate solids removal goal is the use of a pond with a conventional storm drainage system, at about twice the expected annual cost. In this example, no other attributes of the different stormwater management options are considered. This solution simply meets the single goal at the least cost. In fact, this option exceeds the goal. It would therefore be worthwhile to examine slightly smaller ponds that will more closely meet the single target, with some additional cost savings for the pond construction. This example would also apply for any other situation where there is a single goal that must be met.

Several Absolute Goals/Limits. When more than one absolute goal is required to be met, the analysis becomes only slightly more complex. It is still relatively simple with absolute goals; the first step is to filter out the options that do not meet all of the required goals. This situation may occur when water quality numeric standards must be met. As an example, assume that the effluent concentration limits shown on Table 6 must be met. The attribute table only shows the flow-weighted concentrations. If standards need to be met for all rains with a specific recurrence probability, then those concentrations can be summarized from the probability distributions of outfall concentrations that WinSLAMM can calculate.

Again, simple filtering enables the suitable options to be identified, and these can be ranked based on their annual cost to identify the least costly option that meets the applicable numeric standards (option 7 again is the least costly option that meets all of these three goals).

Table 6. Options and Specific Criteria (bold and italic values meet numeric criteria)

	Total Annual Cost ($/yr)	SS conc. (mg/L)	Part. P conc. (mg/L)	Zn conc. (µg/L)	Meets all Numeric Standards?	Rank Based on Annual Cost
Applicable Numeric Limit:		<50 mg/L	<0.2 mg/L	<400 µg/L		
Option 1-Pond	83,364	*30*	*0.073*	*128*	Yes	6
Option 2 Regional Swale	30,008	178	0.43	*390*	No	n/a
Option 3 Site Biofilter	69,710	408	1.0	696	No	n/a
Option 4 Half-sized pond	74,439	*48*	*0.12*	*151*	Yes	5
Option 5 Pond and reg. swale	49,142	*23*	*0.057*	*203*	Yes	3
Option 6 Pond, reg. swale and biofilter	54,622	*29*	*0.073*	*386*	Yes	4
Option 7 Small pond and reg. swale	40,217	*39*	*0.095*	*220*	Yes	1
Option 8 Small pond, reg. swale and biofilter	45,698	53	*0.13*	*390*	Yes	2

Combinations of Goals/Limits

Things get more complicated as the goals become more involved. In these situations, a more formal decision analysis approach may be worthwhile, possibly as described previously following Keeney and Raiffa (1976) methods. The goals may be separated into different classes:

1) Specific criteria or limits that must be met. As in the above examples, it is possible to simply filter out (remove) the options that do not meet all of the absolutely required criteria. If the options remaining are too few, or otherwise not very satisfying, it is definitely possible to continue to explore additional options. The above examples only considered combinations of 3 types of stormwater control devices, for example. There are many others that can also be explored. If the options that meet the absolute criteria look interesting and encouraging, it is possible to continue onto the next steps. Options 1, 5, 6, 7, and 8 are the five remaining options, after the specific criteria listed above are met.

2) Goals that are not absolute. In this case, utility curves and tradeoffs can be developed for the remaining attributes. The above example includes attributes of several different types:

- costs
- land requirements

- runoff volume (volumes, habitat responses, and rates)
- particulate solids (reductions, yields and concentrations)
- particulate phosphorus (concentrations)
- total zinc (concentrations)

In this example, the particulate solids reductions, suspended solids concentrations, particulate phosphorus concentrations, and total zinc concentrations are assumed to have absolute criteria, and only those options that meet them will be further considered. This leaves the attributes, shown in Table 7, that need tradeoffs and utility curves. The rankings and trade-offs shown on Table 7 were selected for the attributes based on their assumed importance for this project site. These trade-offs could be expected to vary for different decision makers and other interested parties. Separate analyses can therefore be conducted for each different set of trade-offs, resulting in slightly different, but hopefully similar, rankings of the options. As note above, these trade-offs can be mathematically determined, basically by determining the expected improvements in each attribute for a specific increase in expenditures, and then by solving the set of simultaneous equations. They can also be rather arbitrarily selected, as in this example, simply by assigning the rankings and values to each attribute so the resultant trade-off values are summed to equal 1.0.

The utility curve values for these attributes are shown below. For the flow rates and volumetric runoff coefficients, site conditions and local receiving waters enabled groupings of the attribute values into categories having specific utility values. The best categories were intended to protect the receiving water aquatic habitat by minimizing sediment scour and stream enlargement, while the poorest categories would be associated with conventional development practices that frequently are associated with severe receiving water problems. The flow rate groupings are very specific to the site, based on local hydrology and hydrologic calculations, while the Rv groupings may be more generally applicable. The other utility curves (for cost, phosphorus yield, land needs, and particulate solids yields) are simple straight line relationships, with the best attribute values obtained for the different options assigned a value of 1.0, and the worst attribute values obtained assigned a value of 0.0. Intermediate values are simply interpolated between these extreme values.

Table 7. Ranges of Attributes for Pre-Screened Options

Attribute	Range of attribute value for acceptable options	Attribute ranks for selection (after absolute goals are met)	Trade-offs between remaining attributes
Total annual cost ($/year)	$40,217 to 83,364	2	0.20
Land needs (acres)	2.3 to 4.5 acres	5	0.08
Rv	0.06 to 0.29	1	0.30
% of time flow >1 cfs	0.5 to 4 %	7	0.05
% of time flow >10 cfs	0 to 0.05 %	3	0.18
Particulate solids yield (lbs/yr)	2,183 to 10,192 lbs/yr	6	0.07
Part. Phosphorus yield (lbs/yr)	5.5 to 25 lbs/yr	4	0.12
			Sum = 1.0

• Volumetric runoff coefficient (Rv) as an indicator of habitat quality and aquatic biology stress:

Attribute value	Expected Habitat Condition	Utility value
<0.1	Good	1.0
0.1 to 0.25	Fair	0.75
0.26 to 0.50	Poor	0.25
0.51 to 1.0		0

• Total annual cost: straight line, with $83,364 = 0 and $40,217 = 1.0.

• % of time flow >10 cfs:

% of time flow >10 cfs	Utility value
<0.05	1.0
0.05 - 1	0.75
1.1 – 2.5	0.25
>2.5	0

• Part. Phosphorus yield (lbs/yr): straight line, with 25 lbs/yr = 0 and 5.5 lbs/yr = 1.0

• Land needs (acres): straight line, with 4.5 acres = 0 and 2.3 acres = 1.0

• Particulate solids yield (lbs/yr): straight line, with 10,192 lbs/yr = 0 and 2,183 lbs/yr = 1.0

• % of time flow >1 cfs:

% of time flow >1 cfs	**Utility value**
<1	1.0
1 – 3	0.75
3.1 – 10	0.25
>10	0

Calculation of Utilities and Ranking of Alternative Stormwater Management Programs

Most of the particulate solids originate from the non-developed areas, so the site biofilters have minimal benefits on reducing particulate solids discharges. Also, the site biofilters infiltrate water having much lower particulate concentrations compared to the undeveloped areas, so the concentrations actually increase. The regional swale and detention ponds treat all of the site water, so they have a much larger benefit on the particulate solids.

Tables 8 and 9 show the calculated utility factors for each option, along with the sums of the factors and the overall ranking of the options. Option 8, the small pond with the regional swale and the on-site biofilter swale was ranked significantly ahead of the other options. Options 5 (large pond and regional swale) and 7 (small pond and regional swale) ranked next and were basically tied. Option 1, the large pond alone, ranked far below the other options.

Table 8. Utility and Tradeoffs for Different Options

Stormwater Control Option	Volumetric Runoff Coefficient (Rv)	Rv utility	% of time flow >1 cfs	Mod flow utility	% of time flow >10 cfs	High flow utility
Tradeoff Value	0.30	0.30	0.05	0.05	0.18	0.18
Option 1 Pond	0.29	0.25	4	0.25	0.05	0.75
Option 5 Pond and reg. swale	0.15	0.75	2	0.75	0	1.0
Option 6 Pond, reg. swale and biofilter	0.06	1.0	0.5	1.0	0	1.0
Option 7 Small pond and reg. swale	0.15	0.75	2	0.75	0.05	0.75
Option 8 Small pond, reg. swale and biofilter	0.07	1.0	0.8	1.0	0	1.0

Table 8. Utility and Tradeoffs for Different Options (continued)

Stormwater Control Option	Total Annual Cost ($/yr)	Cost utility	Land Needs for SW mgt (acres)	Land utility	Part. Solids Yield (lbs/yr)	Part. Solids utility	Part. Phos. Yield (lbs/yr)	Phos. utility
Tradeoff Value	0.20	0.20	0.08	0.08	0.07	0.07	0.12	0.12
Option 1 Pond	83,364	0	4.5	0	10,192	0	25	0
Option 5 Pond and reg. swale	49,142	0.79	4.5	0	4,133	0.76	10	0.77
Option 6 Pond, reg. swale and biofilter	54,622	0.67	4.5	0	2,183	1.0	5.5	1.0
Option 7 Small pond and reg. swale	40,217	1	2.3	1	6,937	0.41	17	0.41
Option 8 Small pond, reg. swale and biofilter	45,698	0.87	2.3	1	4,125	0.76	10	0.77

The factors are calculated by multiplying the utilities by the trade-off values. As an example, for Option 5, the cost trade-off was 0.20 (same for all options) and the cost utility was 0.79, the calculated cost factor for Option 5 is therefore 0.20 X 0.79 = 0.158. The sum of factors is the sum of all factors for all attributes. The ranks are based on the sum of factors, with the largest sum of factors being 1. Table 9 shows that Option 8, having the small pond, the regional swale, and the on-site biofilters, is the clear choice, using these trade-offs and utility curves. Option 6, the same set of controls, except that a large pond is used, is the second best choice, while Options 5 and 7 are very close and Option 1 (just a large pond alone) is a clear poor performer, compared to the other options.

Table 9. Calculations of Ranks for Different Stormwater Management Options

Stormwater Control Option	Cost utility	Cost factor	Land utility	Land factor	Part. utility	Part. factor	Phos. utility	Phos factor
Tradeoff Value	0.20		0.08		0.07		0.12	
Option 1 Pond	0	0	0	0	0	0	0	0
Option 5 Pond and reg. swale	0.79	0.158	0	0	0.76	0.053	0.77	0.092
Option 6 Pond, reg. swale and biofilter	0.67	0.134	0	0	1.0	0.07	1.0	0.12
Option 7 Small pond and reg. swale	1	0.20	1	0.08	0.41	0.029	0.41	0.049
Option 8 Small pond, reg. swale and biofilter	0.87	0.174	1	0.08	0.76	0.053	0.77	0.092

Table 9. Calculations of Ranks for Different Stormwater Management Options (continued)

Stormwater Control Option	Rv utility	Rv factor	Mod flow utility	Mod flow factor	High flow utility	High flow factor	Sum of factors	Over-all Rank
Tradeoff Value	0.30		0.05		0.18			
Option 1 Pond	0.25	0.075	0.25	0.0125	0.75	0.135	0.2225	5
Option 5 Pond and reg. swale	0.75	0.225	0.75	0.0375	1.0	0.18	0.7455	4
Option 6 Pond, reg. swale and biofilter	1.0	0.30	1.0	0.05	1.0	0.18	0.8540	2
Option 7 Small pond and reg. swale	0.75	0.225	0.75	0.0375	0.75	0.135	0.7555	3
Option 8 Small pond, reg. swale and biofilter	1.0	0.30	1.0	0.05	1.0	0.18	0.9290	1

Conclusions

The decision analysis approach outlined in this paper has the flexibility of allowing for variable levels of analytical depth, depending on the problem requirements. The preliminary level of defining the problem explicitly in terms of attributes often serves to make the most preferred alternatives clear. The next level of analysis might consist of a first-cut assessment and ranking as described in this example. Several different utility function curve types were assumed and an additive model was employed. Spreadsheet calculations with such a model are easily performed, making it possible to conduct several decision analysis evaluations using different trade-offs, representing different viewpoints. It is possible there will be a small set of options that everyone agrees are the best choices. Also, this procedure documents the process for later discussion and review. Sensitivity analyses can also be conducted to identify the most significant factors that affect the decisions. The deepest level of analysis can utilize all the analytical information one collects, such as probabilistic forecasts for each of the alternatives and the preferences of experts over the range of individual attributes. Monte Carlo options available in WinSLAMM can also be used that consider the uncertainties in the calculated attributes for each option.

In summary, decision analysis has several important advantages. It is very explicit in specifying trade-offs, objectives, alternatives, and sensitivity of changes to the results. It is theoretically sound in its treatment of trade-offs and uncertainty. Other methods ignore uncertainty and often rank attributes in importance without regard to their ranges in the problem. It can be implemented flexibly with varying degrees of analytical depth, depending on the requirements of the problem.

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References

American Public Works Association (APWA). 1992. *A Study of Nationwide Costs to Implement Municipal Storm Water Best Management Practices*. Southern California Chapter. Water Resource Committee.

Brown, W. and T. Schueler. 1997. *The Economics of Storm Water BMPs in the Mid-Atlantic Region*. Center for Watershed Protection. Ellicott City, MD.

Frank, J. 1989. *The Costs of Alternative Development Patterns: A Review of the Literature*. Urban Land Institute. Washington, DC.

Heaney, James P.; David Sample and Leonard Wright. 2002. *Costs of Urban Stormwater Control*. EPA Contract No. 68-C7-0011. National Risk Management Research Laboratory Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

Keeney, R.L. and H. Raiffa. 1976. *Decision Analysis with Multiple Conflicting Objectives*. John Wiley & Sons. New York.

Means, R.S. *RS Means Building Construction Cost Data* (64th Annual Edition). Reed Publications. 2006.

McGraw Hill *Construction. Engineering News Record*. ENR.com.

Muthukrishnan, Swarna; Bethany Madge, Ari Selvakumar, Richard Field and Daniel Sullivan. 2006. *The Use of Best Management Practices (BMPs) in Urban Watersheds*. National Risk Management Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio. ISBN No. 1-932078-46-0.

Narayanan, A. and R. Pitt. (2005). *Costs of Urban Stormwater Control Practices*. Stormwater Management Authority of Jefferson County, AL

Pitt, R. *Demonstration of Nonpoint Pollution Abatement Through Improved Street Cleaning Practices*, EPA-600/2-79-161, U.S. Environmental Protection Agency, Cincinnati, Ohio. 270 pgs. 1979.

Pitt, R. "The incorporation of urban runoff controls in the Wisconsin Priority Watershed Program." In: *Advanced Topics in Urban Runoff Research*, (Edited by B. Urbonas and L.A. Roesner). Engineering Foundation and ASCE, New York. pp. 290-313. 1986.

Pitt, R. "Unique features of the Source Loading and Management Model (SLAMM)." In: *Advances in Modeling the Management of Stormwater Impacts*, Volume 6. (Edited by W. James). Computational Hydraulics International, Guelph, Ontario and Lewis Publishers/CRC Press. pp. 13 – 37. 1997.

Pitt, R. "Small storm hydrology and why it is important for the design of stormwater control practices." In: *Advances in Modeling the Management of Stormwater Impacts*, Volume 7. (Edited by W. James). Computational Hydraulics International, Guelph, Ontario and Lewis Publishers/CRC Press. 1999.

Pitt, R. and J. Voorhees. "SLAMM, the Source Loading and Management Model." In: *Wet-Weather Flow in the Urban Watershed* (Edited by Richard Field and Daniel Sullivan). CRC Press, Boca Raton. pp 103 – 139. 2002.

Sample, D.J., J.P.Heaney, L.T.Wright, C.Y.Fan, F.H.Lai, and R.Field. 2003. "Cost of best management practices and associated land for urban stormwater control." *Journal of Water Resources Planning and Management*, Vol. 129, No.1, pp. 59-68

Southeastern Wisconsin Regional Planning Commission (SEWRPC). 1991. *Costs of Urban Nonpoint Source Water Pollution Control Measure*. Waukesha, WI.

Wiegand, C., T. Schueler, W.Chittenden and D.Jellick. 1986. "Cost of urban runoff quality controls." pp 366-380. In: *Urban Runoff Quality*. Engineering Foundation Conference. ASCE, Henniker, NH. June 23-27.

Wossink, Ada, and Bill Hunt. 2003. *An Evaluation of Cost and Benefits of Structural Stormwater Best Management Practices in North Carolina*, North Carolina State University.