Evaluating an Approach for Cost-Benefit Analysis of Project Alternatives

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July 31, 2009

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ABSTRACT

A variety of alternative restoration and stormwater management options are typically available to project designers in the Lake Tahoe Basin for achieving pollutant load reductions. Each combination of alternative project features tend to yield different pollutant reduction efficiencies at different implementation costs. To date it has been difficult to develop an understanding of the relationship between alternative design options and their anticipated pollutant load reductions, along with an evaluation of cost estimates for these options. The purpose of this study was to examine the utility of a matrix evaluation approach initially developed by the Nevada Department of Transportation (NDOT) for investigating cost-benefit relationships available from alternative BMP implementations on highway environmental improvement projects in the Tahoe Basin. This matrix approach was then examined in relation to the Pollutant Load Reduction Model (PLRM), currently in development as a tool for the Tahoe Total Maximum Daily Load (TMDL) program. Toward that objective the EPA Storm Water Management Model, which is the underlying model for the PLRM, was applied on a demonstration basis to a rainfall-runoff event in the north Tahoe state line drainage and resulting output was linked to an alternatives evaluation matrix, based on the NDOT prototype. Results from that demonstration showed that developing and linking an alternatives cost-benefit analysis module to the PLRM is feasible and would provide significant benefits for environmental improvement projects in the Tahoe Basin, along with better load reduction estimates compared to the spreadsheet approach initially developed for the highway projects.

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ACRONYMS AND ABBREVIATIONS

BMP	Best Management Practices
CWA	Clean Water Act
EAMP	Evaluation of Alternatives Matrix Process
EIP	Environmental Improvement Program (or a project of that program)
LRWQCB	Lahontan Regional Water Quality Control Board
NDEP	Nevada Division of Environmental Protection
NDOT	Nevada Department of Transportation
ONRW	Outstanding Natural Resource Water
PLRM	Pollutant Load Reduction Model
RSWMP	[Tahoe] Regional Stormwater Monitoring Program
RUSLE	Revised Universal Soil Loss Equation
SR	State Route (Highway)
SWMM	Stormwater Management Model
SWQIC	Stormwater Quality Improvement Committee
SWRCB	[California] State Water Resources Control Board
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Sediment
TRPA	Tahoe Regional Planning Agency
USEPA	United States Environmental Protection Agency

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INTRODUCTION

Standard engineering practices in stormwater management attempt to mitigate hydrologic risk while also achieving appropriate pollutant reduction targets within project budget limits. Evaluating alternative design options in terms of both pollutant reduction and project costs has been problematic for stormwater projects in the Tahoe Basin, where alternatives development and their evaluation is a required element of the design process. This study examines a preliminary matrix approach developed by the Nevada Department of Transportation (NDOT) that could facilitate a more objective evaluation on the relative merits of alternative design options from the perspective of both implementation costs and water quality improvements. It then considers how this approach could be implemented within the context of other tools currently in development for Tahoe Basin stormwater management.

Background

Lake Tahoe is designated as an Outstanding National Resource Water (ONRW) under the USEPA Water Quality Standards Program and the Clean Water Act. It is also listed as a CWA 303(d) impaired water body by the Nevada Division of Environmental Protection and the California Lahontan Regional Water Quality Control Board. This has triggered development of the Tahoe Environmental Improvement Program (EIP) and a Total Maximum Daily Load (TMDL) pollution control plan, both of which seek to control pollutant loadings to the lake (TRPA, 2008; SWRCB and NDEP, 2008).

The alternative design options approach is based upon guidance from the Tahoe Basin Stormwater Quality Improvement Committee (SQWIC) regarding Formulation and Evaluation of Alternatives (FEA) for water quality improvement projects (EDAW et al., 2008). A variety of alternative restoration and management options are typically available to project designers for achieving pollutant load reductions, where each combination of features may yield different reduction efficiencies at different implementation costs. To date, the Tahoe-specific BMP performance and cost-benefit data generally have not been available for pollutants of concern at Lake Tahoe, so it has been difficult to develop an understanding of BMP selection options and design effects on pollutant load reductions. Given this situation, it has been difficult to develop reliable, generally accepted design criteria and tools that would optimize load reductions while maintaining cost controls.

The NDOT approach discussed in this document applied an Evaluation of Alternatives Matrix Process (EAMP) to inform selection of an appropriate design option (see Appendix A), where numerous alternatives and their water quality benefits were evaluated by a semi-quantitative analysis of different combinations of both source control and treatment BMPs within the project area. This approach was developed for and applied on NDOT’s SR-207 EIP projects. The end result was a chart highlighting total cost for each alternative in relation to the overall project benefit derived from specific source control measures and treatment practices implemented with each alternative. Using this information, the technical team then determined which alternative(s) best met the project goals and objectives while providing maximum water quality benefit at the lowest cost.

After using this matrix approach for evaluation of alternatives on their SR-207 highway projects, NDOT petitioned the Tahoe Science Consortium to review the EAMP and determine whether it would be suitable for more general use in the Tahoe Basin. At that time it was thought the matrix could be modified to be applicable generically to other EIP projects, and so the intent of the present study was to evaluate that potential and then to make any necessary recommendations or changes to the existing matrix that would result in a generally applicable alternatives evaluation process.

During the course of this review, however, it was determined that while the NDOT EAMP provides a solid conceptual approach that facilitates alternatives evaluation and selection, it would be impractical to extend that approach to a generic set of worksheets suitable for EIP projects around the Tahoe Basin. Instead, our recommendation was to integrate an alternatives evaluation with the Pollutant Load Reduction Model, currently in development as a Tahoe TMDL tool. The linkage required for that approach was demonstrated by application of an evaluation matrix, similar to the NDOT EAMP, to model output from an urban drainage in north Tahoe. The principal benefit from this recommended approach would be consistency with pollutant loading estimates derived from TMDL tools, as well as the general acceptance and continued investment in those tools by Tahoe Basin resource management agencies and the scientific community.

Focus of the Study

The main goal of this study was to evaluate the NDOT matrix approach and to facilitate further refinement of a process for quantitative evaluation of project design alternatives in BMP and source control options at the sub-basin to watershed scale.

This was initiated with a review of the NDOT EAMP, followed by a presentation to the SWQIC on how that matrix was structured and implemented, along with an explanation of critical knowledge gaps and application limits. These observations to the SWQIC focused on the inherent limitations of a spreadsheet approach in developing realistic pollutant loading estimates. Although the spreadsheet approach could be extended to a more generic application, that effort would be extensive and of limited utility. Therefore, it was recommended that continued refinement of the matrix alternatives evaluation approach should be pursued in the context of its integration with the Pollutant Load Reduction Model (PLRM), instead of simply reworking the NDOT EAMP spreadsheets.

Since the PLRM was still in development and unavailable for general use at that time, the SWQIC endorsed our recommendation for demonstrating that suitable linkages could be established between an alternatives evaluation matrix and output from the EPA Storm Water Management Model (SWMM), which is the underlying engine for the PLRM. The SWMM was applied to an urbanized drainage at the north Tahoe state line that included highway runoff, and where event monitoring data were available for model initialization. An alternatives matrix, similar to the NDOT EAMP, was then used to evaluate model output from a subset of design alternatives developed within the drainage for the purposes of this demonstration.

The following content in this document presents a summary description of the NDOT EAMP (Wood Rogers, 2007), as it was determined to function after our review of its application on the SR-207 EIP projects. It then briefly describes the EPA SWMM and our application of that model to the north Tahoe state line drainage. In the subsequent results and discussion section we provide an assessment (as presented to SWQIC) on the relative merits and limitations of the NDOT EAMP, along with findings from the combined SWMM and matrix application to the north Tahoe drainage, which clearly showed that a matrix evaluation approach could be linked to stormwater modeling output. Finally, suggestions for incorporating a matrix evaluation process into future versions of the PLRM are provided, along with a discussion of additional factors that would make this approach more generally useful to the Tahoe Basin design and implementation community.

METHODS

Description of Alternatives Evaluation Matrix Design and Operation

The EAMP was developed by NDOT as a method for selecting among design options on their State Route (SR) 207 EIP projects in south Lake Tahoe, an area which extends approximately three miles up Kingsbury Grade to Daggett Pass from its junction with US Highway 50. Total cost for project design and construction was estimated at $8,000,000. A detailed description of this project and the methods used to develop an alternatives evaluation matrix are presented in Wood Rogers (2007). The alternatives discussed in that document provided NDOT with a quantitative basis for developing a cost-benefit assessment that explored implementation costs versus water quality benefits (primarily from sediment removal).

The matrix analysis undertaken by NDOT for alternatives evaluation on their SR-207 projects, as described in Wood Rogers (2007), was based upon a multiple spreadsheet approach constructed with three main components, consisting of a sediment production section, a source control section, and a treatment section. The project area was first divided into five highway segments (a commercial road segment, and road segments 1 through 4). Then annual soil loss rates were calculated using the Revised Universal Soil Loss Equation (RUSLE) for each slope, roadside channel and shoulder within each highway segment. The sum of loadings from each of these sources for all highway segments provided an estimate of the total annual sediment loading from the project area under existing conditions (Table 1), not including the application of traction material.

Three different overall project strategies (alternatives) were then developed, reflecting source control implementation that was increasingly aggressive from Strategy 1 through Strategy 3 (including curb and gutter installations, storm drains, channel linings, slope treatments, shoulder paving, and retaining walls). Soil loss rates were again calculated with RUSLE for the conditions that would prevail with implementation of each source control strategy (Table 1). These calculations formed the basis for estimating total sediment load reductions from the different source control measures.

Also added to the sediment calculation section of the matrix was the amount of sand typically applied to each road segment for traction during the winter months. These values represented the average from several years of abrasives application minus the average amount recovered each year during road sweeping operations. By these calculations, road abrasives were the largest source of sediment within the project area, exceeding the total RUSLE-calculated sediment delivery from all other sources by a factor of almost seven (Wood Rogers, 2007).

Furthermore, based on soil types in the area and assuming limited breakdown of road abrasives, the total sediment delivery was partitioned into a coarse-grain particle size class and a fine-grain particle size class by assuming that sediment delivery distribution on average consisted of 85% coarse and 15% fine particles. A specific grain size was not defined for distinction between coarse and fine particles.

The treatment section of the matrix was based upon the amount of sediment and roadway abrasives that proposed BMPs could capture and retain. Each BMP type (drop inlet, sediment can, channel/swale, vegetation buffer, infiltration basin) was assigned a characteristic sediment capture capacity that could be subtracted from the total annual sediment loading estimates calculated from RUSLE (Table 2).

Then various combinations of source control strategies and treatment practices were applied to each highway segment, reflecting the degree of source control and the quantities of treatment features used. Twenty-five of these combination alternatives were considered in the SR-207 matrix (Wood Rogers, 2007). Estimates for coarse and fine particle trapping efficiencies (Table 3) were based upon NDOT experience with field operations, engineering judgment, and some limited results from research reporting.

Cumulative load reductions and costs were calculated in two worksheets, one that itemized source control options and another that itemized treatment options (Appendix A). Load reduction estimates came from the sediment calculation sections of these spreadsheets, as described above. In contrast, the cost of each treatment or source control option was individually estimated and then entered into corresponding sections of each spreadsheet. Treatment and source control sediment reductions and implementation costs were estimated for each strategy along each road segment. The summation of all road segment sediment loads and costs then determined total load reductions and the total installation costs for each alternative. Preferred alternatives were those that provided sufficient benefit, in terms of percentage sediment load reduction, at acceptable cost.

By using this approach the project designer could develop many combinations of source control and treatment options, and then see the relationship between estimated sediment reductions and cumulative costs. The benefit of this process to a project designer is the ability to work within the spreadsheets to create multiple alternatives and then fine-tune the treatment options for the most cost-effective and efficient treatment system. This assumes, of course, that loading calculations and reduction estimates are accurate.

The main advantages and limitations of this approach are discussed later in this document, but our primary recommendation—following review of the NDOT SR-207 EAMP—was that the alternatives cost-benefit assessment should be developed as a component or module of the PLRM rather than as a series of independent spreadsheets. The potential for direct linkage between load modeling and alternatives cost-benefit evaluation, as done with the NDOT EAMP, was subsequently demonstrated with SWMM (the same hydraulic and pollutant transport engine used in the PLRM).

Table 1. Estimated sediment production (using RUSLE) from channels, shoulders, and slopes of each road segment under existing conditions and with application of source control measures according to each of the three main NDOT strategies. Also shown is the average annual road sand applied for traction during winter months that was not recovered by subsequent road sweeping (modified from Wood Rogers, 2007).

Sediment Production Summary (cubic feet per year)

	Channels	Shoulders	Slopes	Total	Road Sand	Total
			Existing			
Commercial	0	3	16	19	1121	1139
Segment 1	2	26	137	165	496	660
Segment 2	50	8	213	271	1244	1515
Segment 3	27	21	116	164	620	783
Segment 4	77	26	94	197	2074	2271
Total	**155**	**83**	**576**	**815**	**5554**	**6369**
			Alternative 1			
Commercial	0	0	6	6	1121	1127
Segment 1	2	0	48	50	496	546
Segment 2	28	0	147	175	1244	1419
Segment 3	12	0	109	120	620	740
Segment 4	43	0	65	108	2074	2181
Total	**85**	**0**	**375**	**460**	**5554**	**6014**
			Alternative 2			
Commercial	0	0	4	4	1121	1124
Segment 1	3	0	21	24	496	520
Segment 2	20	0	80	100	1244	1344
Segment 3	7	0	43	50	620	670
Segment 4	22	0	28	51	2074	2124
Total	**51**	**0**	**176**	**228**	**5554**	**5782**
			Alternative 3			
Commercial	0	0	3	3	1121	1124
Segment 1	2	0	19	22	496	518
Segment 2	6	0	56	63	1244	1307
Segment 3	14	0	47	60	620	680
Segment 4	27	0	24	51	2074	2125
Total	**50**	**0**	**149**	**199**	**5554**	**5753**

- **Existing Conditions:** no new source control measures or runoff treatments on any highway segments.
- **Strategy 1:** minimal source control (some channel stabilization, shoulder pavement, minimal slope treatment).
- **Strategy 2:** moderate source control (articulated block channel lining, paved swales, shoulder pavement, some storm drains, moderate slope treatment, refaced timber walls).
- **Strategy 3:** major source control (articulated block channels, shoulder pavement, extensive storm drains, curb and gutter, aggressive slope treatment, rockery walls).

Table 2. Treatment BMP sediment removal amounts estimated (see example calculation below) for each highway segment applied in different combinations with base implementation of the three main NDOT EAMP source control strategies. Note that number of infiltration basins did not change between strategies (modified from Wood Rogers, 2007).

Treatment Features					Sediment Removal (cubic feet)					
	DI's (#)	Sed Cans (#)	Veg Buffers (LF)	Channels (LF)		DI's	Sed Cans	Veg Buffers	Channels	Infiltration Basins
Strategy 1					Strategy 1					
Commercial	13	0	0	0	Commercial	193	0	0	0	0
Segment 1	6	0	1343	663	Segment 1	89	0	190	29	0
Segment 2	2	2	1138	1774	Segment 2	30	98	161	78	302
Segment 3	4	3	2148	1872	Segment 3	60	147	304	83	602
Segment 4	3	5	192	3570	Segment 4	45	246	27	158	1318
Strategy 2					Strategy 2					
Commercial	13	0	0	0	Commercial	193	0	0	0	0
Segment 1	8	1	0	539	Segment 1	119	49	0	24	0
Segment 2	6	1	0	1689	Segment 2	89	49	0	75	302
Segment 3	9	3	0	1735	Segment 3	134	147	0	77	602
Segment 4	5	6	0	3848	Segment 4	74	295	0	170	1318
Strategy 3					Strategy 3					
Commercial	13	0	0	0	Commercial	193	0	0	0	0
Segment 1	10	0	0	621	Segment 1	149	0	0	27	0
Segment 2	11	0	0	1475	Segment 2	164	0	0	65	302
Segment 3	8	1	0	1543	Segment 3	119	49	0	68	602
Segment 4	15	1	0	4889	Segment 4	223	49	0	216	1318

Annual Sediment Capture Volumes
Drop inlet: 35 cubic feet.
Double sediment can: 96.3 cubic feet.
Vegetative buffers: length of buffer (ft) * 10 ft (avg. buffer width) * 1/4 inch (est. depth of sediment intercepted/yr).
Channel/swales lined with pervious material: length of channel (ft) * 5 ft (avg. channel width) * 1/8 inch (est. depth of sediment captured/yr).
Infiltration basin: avg. sediment load from upstream watershed in proportion to percent of 20-year 1-hour rainfall runoff infiltrated by basin.

An example calculation for sediment removal by treatment practices shown in Strategy 1 for the commercial segment is: 13 (number of DIs) * 35 ft^3 (capacity of one DI) * 0.5 (coarse sediment trapping efficiency shown in Table 3) * 0.85 (proportion of coarse particles in sediment delivery) = 193.38 ft^3 (amount of coarse sediment removed). Similar calculations were conducted for each BMP type and each pollutant. The sum of these sediment removals for each project segment thus provided an estimate of total removal by each strategy.

Table 3. Trapping efficiencies presented in the NDOT alternatives matrix (Wood Rogers, 2007).

BMP	Trapping Efficiency (Percent) Coarse Sediment	Fine Sediment
Paving /Shotcrete	100	100
Slope Riprap	90	50
Slope Revegetation	50	5
Drop Inlet	50	0
Double Barrel Sediment Cans	60	20
Channel Protection from storm drain installation	100	100
Curb/Gutter/Dike as protection and not conveyance	100	100
Infiltration Basin	100	60
Vegetative Buffer	80	30
Stabilize channel with articulated block	100	100
Stabilize channel	100	100

Description of EPA Stormwater Management Model: SWMM 5.0

The EPA Storm Water Management Model (SWMM) is a dynamic single-event to long-term (continuous) rainfall-runoff simulation model that was first developed in 1971. Since its development it has been updated several times (Huber and Dickinson, 1992). The current version, SWMM 5.0, provides a graphical user interface that facilitates study area delineation, data entry, and viewing of model output in a variety of formats (Rossman, 2009). The Storm Water Management Model was developed specifically to assess runoff and degradation of water quality from urbanized areas and to assess the effectiveness of mitigation strategies.

SWMM is designed to apply rainfall from a time-series file (or from user specified criteria) onto a number of subcatchments and then route the resulting runoff through a series of channels, pipes, storage/treatment devices, pumps, and flow regulators. While the SWMM model is fairly easy to use, it has the capability to model complex systems, including calculations for pollutant buildup and wash off from subcatchments, evaporation from open water surfaces, rainfall interception with depression storage, time-varying rainfall, snow accumulation and melting, rainfall infiltration within the unsaturated zone, groundwater recharge and discharge, and nonlinear reservoir routing of overland flow. Detailed descriptions of the model and its application can be found at http://www.epa.gov/ednnrmrl/models/swmm/.

Most importantly, in terms of this discussion, the EPA SWMM is the underlying engine for the PLRM at Tahoe. Thus, many of the model routines and calibrations can be linked directly to a substantial effort that has been invested in developing the Tahoe TMDL and its associated tools, including the PLRM. For that reason the following demonstration of potential linkage between a dynamic stormwater runoff model and the cost-benefit alternatives evaluation process was conducted with SWMM.

Site Selection and Drainage Characteristics

Unfortunately, the SR-207 NDOT project area in south Tahoe was not ideal for an initial demonstration of linkage between an alternatives evaluation matrix and a stormwater model like the EPA SWMM or the Tahoe PLRM. Although some stormwater runoff monitoring had been conducted within the project area, available data were sparse and the requisite high-resolution precipitation records were not available for that drainage. Ultimately, a drainage that straddles the Nevada-California state line in north Lake Tahoe (Figure 1) was selected for this demonstration.

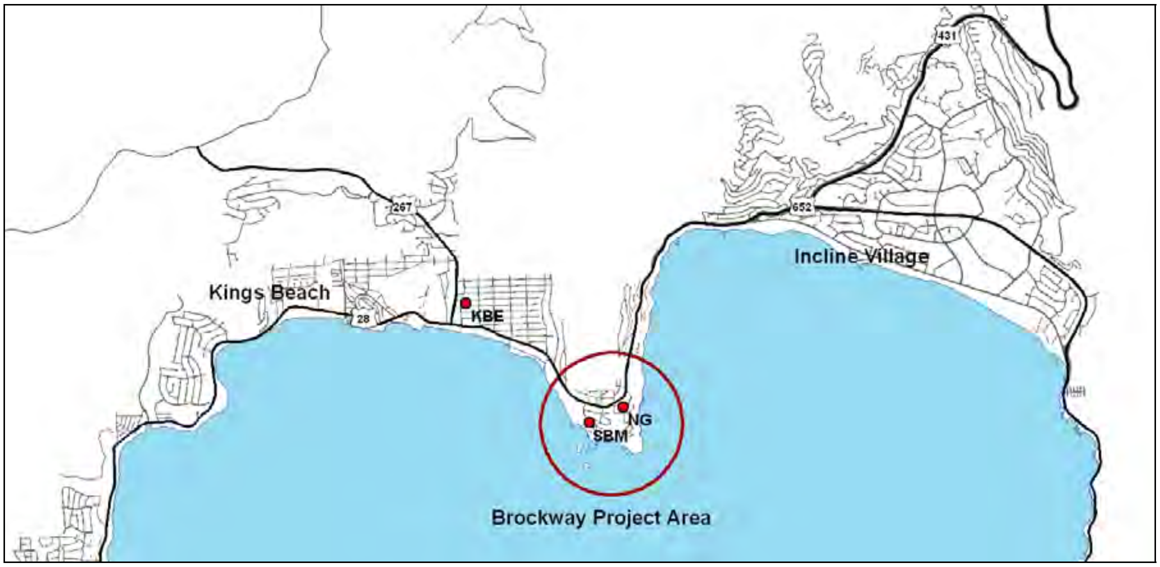

Figure 1. Location of Brockway project area within the Tahoe Basin showing locations of nearby meteorological stations (NG, SBM, KBE).

There were three main reasons for selecting the Brockway drainage site in north Tahoe. First, this drainage contains multiple land uses, including runoff from commercial, highway and residential areas, so it is relatively representative of the type of area that is usually considered for EIP erosion control and mitigation projects in the Tahoe Basin. Second, high quality runoff monitoring and precipitation data were readily available from ongoing studies within this area (Heyvaert et al., 2008), which would serve well in model initialization and testing. Third, there are several erosion control projects currently in development or implementation for this drainage, so the modeling effort could provide use beyond the scope of this limited demonstration.

The topography of the Brockway drainage slopes in a southerly direction such that stormwater flows that originate along SR-28 and its commercial corridor at the Nevada–California state line are directed through moderately sloped residential areas before discharging into Lake Tahoe.

Data used to initialize the EPA SWMM in this demonstration were collected from two instrumented stormwater monitoring stations within the drainage area. The Biltmore (BM) site is located on the north shoulder of SR-28, just west of Stateline Road, and it largely represents runoff flows from Nevada into California. The Speedboat (SB) site, located on Speedboat Avenue near Dip Street, measures runoff in transit from the BM station to Lake Tahoe, along with contributions from the surrounding residential areas. Each monitoring station was equipped with monitoring flumes, accompanied by Sigma 900MAX portable samplers and Sigma 950 data loggers. Flow rates were automatically calculated every five minutes and samples were generally taken at constant volume intervals during runoff events.

Precipitation data were collected from the Nugget (NG) meteorological station, which is located within the drainage and includes a heated tipping bucket for continuous rainfall measurements during both rain and snowfall events. Data from the NG station were logged at ten-minute intervals.

Distribution of land use types were calculated for each subdrainage delivering runoff to one of the two monitoring stations (Table 4). Residential SFP is defined as the permeable area on parcels classified as single family residential, while residential SFI is impermeable area on single-family residential parcels. Residential MFP is the permeable area on parcels classified as multi-family residential, while residential MFI is impermeable area on multi-family residential parcels. CICU pervious is permeable area on parcels classified as commercial, industrial, communications, and utilities, while CICU impervious is impermeable area on CICU land use parcels. Primary roads comprise highways and principal routes (like SR-28), while secondary roads consist of residential streets or equivalent. Vegetated (unimpacted) areas are the undeveloped parcels with natural or secondary vegetative cover that are not used for recreational purposes.

Table 4. GIS calculated land use areas for Brockway subcatchments.

Brockway Drainage Areas		Percent Coverage by Landscape Classification									Drainage Area
ID	BKWY Subbasins	Residential_SFP	Residential_SFI	Residential_MFP	Residential_MFI	CICU-Pervious	CICU-Impervious	Roads_Primary	Roads_Secondary	Veg_Unimpacted	(acres)
BM	Biltmore	1	0	0	0	12	49	5	21	12	8.6
SB	Speedboat	39	10	2	0	4	5	4	11	26	29.2
BM+SB	Biltmore and Speedboat	30	8	2	0	5	15	4	13	22	37.8

SFP: single family pervious
SFI: single family impervious
MFP: multifamily pervious
MFI: multifamily impervious
CICU: commercial, industrial, communications, utilities

The BM site receives runoff directly from the commercial-highway corridor of SR-28, with additional runoff from parking lots around the Biltmore Casino and adjacent areas. This subdrainage is approximately 8.6 acres, 75% of which comprises impervious surfaces.

The SB station receives all runoff that passes through the BM station, plus additional runoff from the more westerly sections of SR-28 and surrounding residential streets. This stormwater is conveyed from SR-28 via culverts and rock-lined channels through residential land use areas. The SB monitoring station receives its runoff from 37.8 acres (including the BM drainage area), of which 40% comprise impervious surfaces.

Model Setup and Calibrations

The model representation of the Brockway project area is shown in Figure 2. It was set up with two subcatchments (Biltmore and Speedboat), two junctions (J1 and J2), two conduits (C1 and C2), and one outfall (O1). The Biltmore subcatchment consists of the 8.6 acres that lie north of SR-28. Much of this subcatchment contains the Biltmore Casino, its associated parking areas and surrounding paved roads. All runoff from this subcatchment is routed to junction J1, which is the location of a Palmer-Bowlus flume that monitors runoff from the subcatchment. The Speedboat subcatchment is 29.2 acres consisting predominately of residential land use. Runoff for the Speedboat subcatchment is routed to junction J2, which is the location of the second flume. The two junctions at J1 and J2 are connected by a conduit (C1), which is in reality a rock-lined channel. Modeled discharge at J2, therefore, represents the combined runoff and outfall (O1) from both of these two subcatchments. One element of this approach was that conduit C2 could not be modeled as a loosing channel, where infiltration occurs (representing a potential model limitation that might be resolved by using more advanced methods in SWMM).

Precipitation data for this modeling exercise was measured at the NG meteorological station (noted on Figure 2 as the red dot south of the Biltmore subcatchment), and it was uniformly applied to both subcatchments for the modeled event.

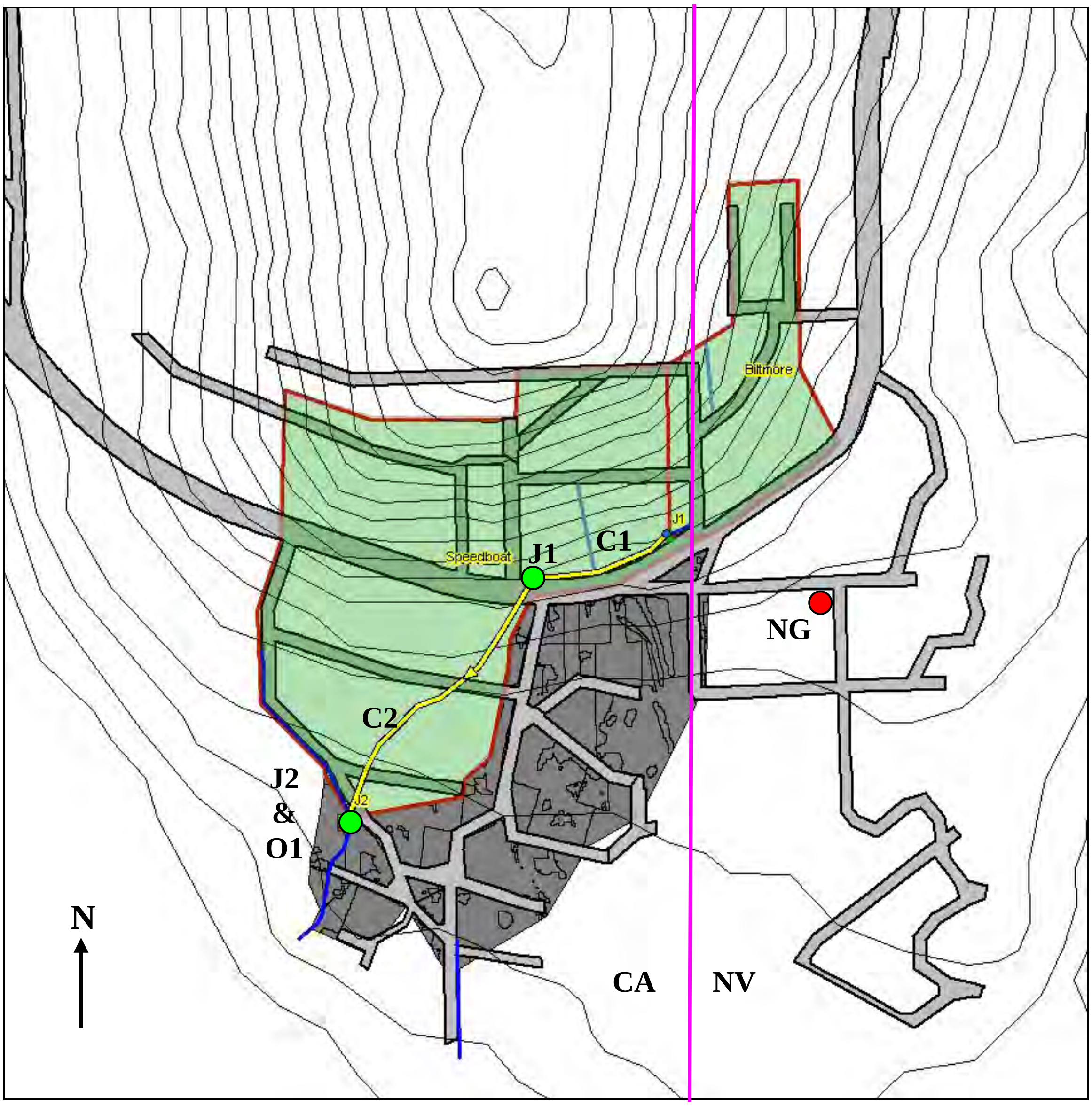

Figure 2. Model representation of study area showing the California-Nevada state line and site/model features: C1, C2, J1, J2, O1, NG.

Model Components

There are several features available in SWMM that can be used to model the hydrology of complex systems, including subcatchment delineation, land use areas, conveyance lines and junctions, precipitation events, infiltration processes, and pollutant specifications. An aquifer module can be used if groundwater plays a significant role in the observed hydrograph, and a snow pack module allows the model to operate as if accumulated snow is present on the ground, where snow pack would adsorb precipitation and delay runoff as well as release water during melt cycles.

In the case of this demonstration, for showing potential linkage between cost-benefit analysis and the PLRM, we did not use the aquifer or snow pack modules. Also, the PLRM takes a slightly different approach that uses characteristic event concentrations (CEC), instead of pollutant buildup and wash off functions. Indeed, the PLRM contains several features and refinements in overall approach that were not included in this demonstration, since they were not yet available at the time of this work. Therefore, our discussion of this SWMM application for demonstration of potential linkage with a cost-benefit analysis on project alternatives should not be construed as a representation of how the PLRM functions.

Most importantly, this demonstration is not presented as a validated model, rather it has been fit to available monitoring data from a single event at a particular site so that the model output could serve as input data to the matrix for cost-benefit analysis.

Water Quality

For this simulation we modeled total nitrogen (TN), total phosphorus (TP), and total suspended sediment (TSS) as the pollutants of concern (the PLRM also considers soluble nutrients and sediment size fractions). Pollutant buildup and wash off functions were controlled in land use portions of the model by user-selected mathematical functions that describe how the pollutants accumulate over time and how they are removed by street sweeping practices, runoff, and BMPs.

In the demonstration model (Appendix B) we described three land uses: commercial, residential, and treated. The treated land type was used to describe a BMP consisting of residential road shoulder stabilization, which did not buildup or wash off any pollutants. In our model we utilized a saturation function to describe pollutant buildup on the residential and commercial land uses. The saturation function builds up pollutant at a rate that declines over time until a saturation value is reached. Each of the pollutants used the same equation to define buildup but different coefficients. Pollutant wash off was described by an exponential function proportional to the product of runoff volume and to the amount of pollutant remaining on the subcatchments. Again different coefficients were used for each pollutant.

When the model is set up for a project area the user determines how much of each land use should be assigned to each subcatchment. For simplicity in this model we only applied three land use categories: commercial, residential, and treated. The Biltmore subcatchment was assigned 90% commercial and 10% residential land use, which includes area roadways, while the Speedboat subcatchment was assigned 100% residential, also including roadways. During several of the modeled alternative runs, the Speedboat subcatchment was changed to 95% residential and 5% treated land use to simulate road shoulder treatment, such as graveled shoulders with drainage swales.

Runoff Event Selection

A specific precipitation event was selected to demonstrate the application of this modeling approach to the alternatives evaluation process. The event had to match several criteria. First, it had to be free of snow or snow pack to simplify the modeling exercise. Second, it had to be a precipitation event with reasonable quality discharge data at both the Biltmore and the Speedboat sites. Third, the matching water quality data had to be of sufficient quality to allow good model calibration. The event chosen to demonstrate this approach was a fall rainstorm that occurred on October 29, 2007, represented by dry antecedant conditions with no rainfall during the previous nine days. Again, it is worth emphasizing that the purpose of this exercise was not to formally test application of SWMM, but to produce reasonable output data for the purpose of demonstrating its potential linkage with an alternatives evaluation process in cost-benefit analysis.

The October 29th event was a relatively small rainstorm that delivered total precipitation of 0.23 inches. This event dropped 0.11 inches of rain between midnight and 3:00 a.m. on October 29, 2007, then let up for several hours, and resumed around 3:00 p.m. Most of the runoff did not occur until the second half of the storm, beginning at both sites shortly after 3:00 p.m. Peak flows at the Biltmore (BM) and Speedboat (SB) sites were 0.77 and 0.88 cfs, respectively, resulting from 0.08 inches of rain falling onto the watershed over a 20-minute period, with a peak precipitation intensity of 0.05 inches in ten minutes. Total runoff volumes measured at the Biltmore (1,175 cf) and Speedboat (1,206 cf) sites were modest, compared to typical events in the area, although peak flows were relatively high (Heyvaert et al., 2008). During this event five discrete samples were collected at BM and six were collected at SB, which were then used to create three flow-weighted composites from each site for subsequent analysis of nutrients and suspended sediment.

RESULTS AND DISCUSSION

Erosion control and restoration project designers in the Tahoe Basin typically develop and evaluate a set of proposed alternatives during the process of selecting their preferred design for implementation. As discussed previously, when NDOT became interested in considering the relative cost-benefit relationships between several project alternatives for water quality improvements on SR-207, they set up a project matrix to facilitate objective comparison and evaluation of their design alternatives. Although tailored specifically to the SR-207 highway project, NDOT considered this approach to be potentially applicable to wider use in the Tahoe Basin. Therefore, they requested the TSC to review the concept as represented in their SR-207 matrix and provide an assessment of its relative merits and limitations. The following summarizes our findings based on the review of that approach and its potential for application on a wider basis in the Tahoe Basin.

Review of NDOT Alternatives Evaluation Matrix Process

Files provided from the SR-207 project consisted of a set of extensive interlinked spreadsheets that represented location-specific hydrologic properties, sediment loading estimates, load reduction calculations for alternative designs, and a cost-benefit summary for comparison of alternatives. Considerable time was spent in review of available project documents to elucidate critical assumptions inherent to the spreadsheet calculations and to understand interdependencies between worksheet elements ultimately leading to the cost-benefit summary matrix.

A set of findings from that assessment are summarized below, and were presented to the Tahoe Stormwater Quality Improvement Committee (SWQIC) at their meeting on December 17, 2008. Beneficial aspects of the matrix approach were discussed at that meeting, along with some important limitations and evident knowledge gaps. Then a series of next steps were recommended to the committee for their approval.

Principal benefits derived from the application of an EAMP approach are that it:

- provides a method to explore different combinations of source control actions and treatment options in project design;
- yields a standardized application of efficiency metrics for the different treatment BMPs and source control measures;
- develops a cost-benefit evaluation of the various project alternatives;
- promotes a consistent approach in alternatives evaluation and selection;
- provides a scale of application that targets unit BMPs at the project level.

Given the preliminary nature of this approach and its development for a specific NDOT project, there understandably were several important limitations to the approach. It is worth emphasizing, however, that the intent of NDOT in requesting this review was not to suggest that the tool was immediately applicable for wider scale use, but that the general approach had merit, which should be explored for potential development and application on a broader basis in the Tahoe Basin.

A list of some specific limitations identified with the SR-207 EAMP are presented below, followed by a brief discussion relevant toward extending that approach for Tahoe EIP projects in general.

- RUSLE is generally not considered ideal for estimating sediment yields from erosion control projects in the Tahoe Basin;
- Only limited treatment options are currently built into EAMP;
- Many calculations are conducted outside of EAMP;
- Complexity increases with cost-benefit analysis for each pollutant added;
- It would be difficult to align EAMP results with mechanistic stormwater runoff and pollutant loading models (like SWMM or the PLRM);
- The process does not integrate directly with a spatially-based (GIS) representation of pollutant sources and BMP locations;
- Branching conveyance networks typical of most EIP projects would be much more complex to evaluate than the linear segmented approach used on SR-207;
- The EAMP does not exist in a template format that would work for other projects.
- Cost estimates considered installation expenditures for each treatment and source control option, but longer-term maintenance costs would be more difficult to represent and could alter cost-benefit calculations.

The Universal Soil Loss Equation (USLE: Wischmeier and Smith, 1978) was originally developed for conservation planning within agricultural settings. Over the years it has been modified to improve results (RUSLE1: Renard et al. 2001) and to extend its application (RUSLE2: Foster et al. 2003). While both RUSLE1 and RUSLE2 have added some process-based functions, where empirical data and relationships were inadequate, neither of these are considered simulation models. In contrast, the EPA Stormwater Management Model (SWMM) and the USDA Water Erosion Prediction Project (WEPP) model are examples of dynamic simulation models. Given the constraints inherent from the agricultural heritage of soil loss equations in RUSLE, the dynamic simulation models are generally seen as providing more flexibility and a better representation of features typically encountered in erosion control projects at the Tahoe Basin, including urban runoff conditions and treatment BMPs.

The treatment options built into NDOT's SR-207 EAMP reflect to some extent the limitations associated with a soil loss equation approach. For example, most standard urban treatment BMPs are not represented in RUSLE, beyond installation of sediment basins, vegetation cover and barrier strips. While it may possible to build some features of other BMP types into the EAMP, this additional effort would be unnecessary with the alternative dynamic simulation models for urban erosion and runoff.

Furthermore, many of the EAMP calculations are already conducted outside of the matrix, which adds to the operator time required for matrix setup and initialization. The NDOT matrix used a 20-yr, 1-hr design storm to determine water yield from cut-and-fill slopes, road shoulders and road surfaces. Sediment yield was estimated using the revised universal soil loss equation (RUSLE) and road sand application rates. All of these calculations were conducted independently from the matrix, and then results were manually entered to serve as a starting point for subsequent matrix operations in cost-benefit analysis.

The NDOT matrix considered sediment as the only pollutant of concern, with division into coarse- and fine-grained fractions based on an assumption of 85% total sediment produced as coarse grained and the remaining 15% as fine grained. This is a somewhat arbitrary determination and the approach does not lend itself to variable distributions dependent upon landscape factors and site conditions. To include these factors would rapidly make the spreadsheet approach unwieldy. For similar reasons other pollutants of concern were not included, such as total and dissolved phosphorous, and total and dissolved nitrogen. Furthermore, soil loss equations are not designed to account for nutrient losses, although these are often associated with sediment transport. To account for additional pollutants in the matrix would extend beyond the capabilities of RUSLE, would substantially increase the complexity of the spreadsheets, and would increase the amount of operator time required to run alternative scenarios in the cost-benefit analysis. In contrast the PLRM is designed to calculate pollutant and size-fractionated sediment loadings for variable conditions associated with different land use types and treatment practices. It would be virtually impossible to accurately replicate these functions with a spreadsheet approach.

Reduction of sediment loads by the various source control and treatment options within the NDOT SR-207 matrix were determined by trapping efficiencies. These trapping efficiencies were used in the EAMP as factors or multipliers in spreadsheet calculations for determining sediment reduction. The percent reductions applied for each type of treatment or source control method were based upon experience with field operation and engineering judgment, with some limited research on literature values. This one size fits all approach does not lend itself to consideration of the diverse treatment efficiencies that would be expected with different landscape factors, site conditions and design characteristics. Ultimately, the optimal approach is represented by the Tahoe TMDL management tools currently under development, which will include functions that address the variability in these types of site-specific characteristics relevant to pollutant generation, transport and capture.

Equally important, while this matrix was useful to NDOT in the design of their environmental improvement project for SR-207, the EAMP is not a tool that would be directly applicable to other EIP projects. Although the approach could be used on other projects, essentially all of the work presented in the EAMP would have to be reproduced for a new project location. This represents a significant user burden and an important inefficiency that would have to be addressed in any future applications of the alternatives assessment approach. Our main conclusion was that while the matrix approach served its purpose for the SR-207 project, there were many refinements that would be necessary to make it a useful tool for other design groups in the Tahoe Basin.

The primary recommendation to SWQIC was that this alternatives evaluation process should ultimately integrate with the PLRM, a tool currently being developed in support of the Tahoe TMDL. It is envisioned that elements of the EAMP could be included in a future version of the PLRM as a module or application that directly provides cost-benefit functionality.

The underlying engine of the PLRM is the EPA Stormwater Management Model (SWMM), tailored and calibrated for characteristics unique to the Tahoe Basin. Since a working version of the PLRM was not available at the time of our recommendation to SWQIC, we proposed that during the interim its potential integration with the matrix evaluation approach could be demonstrated by application of SWMM 5.0 to a typical Tahoe Basin catchment.

Event Runoff Simulations

The event chosen to demonstrate potential integration of modeling output with the alternatives evaluation matrix was a 0.23 inch rainstorm on October 29, 2007. Figure 3 shows the time-series plot of precipitation measured during that event, which served as rainfall input for the model simulation. Although SWMM output for runoff flows during the event did not exactly match measured flows, the results were considered adequate for purposes of this demonstration.

Modeled discharge was lower at the Biltmore (J1) site than observed (Figure 4), but showed reasonable agreement at the Speedboat (J2) site (Figure 5). This discrepancy was likely due to the rock-lined channel that was modeled as a conduit feature connecting the two monitoring sites (since there are no model components that directly simulate channel infiltration). Model parameters were used to fit observed discharge to modeled discharge, which created some discrepancies in timing and flow between the modeled and measured values. Given sufficient time and resources to fine-tune the model and catchment conditions with parameters like surface depression storage, percent volume routed from impervious to pervious areas, and percent slope, it is likely that output would conform more closely to the observed values, but this was deemed unnecessary for the demonstration.

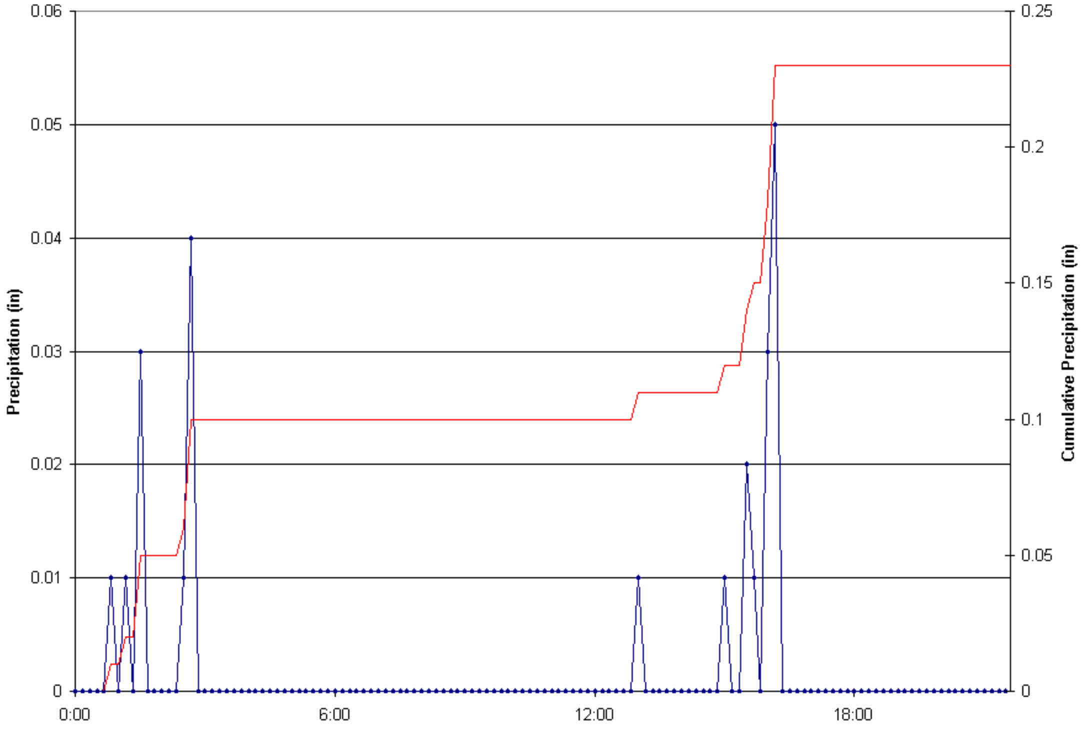

Figure 3. Precipitation and cumulative precipitation measured at the Nugget Site for the modeling period.

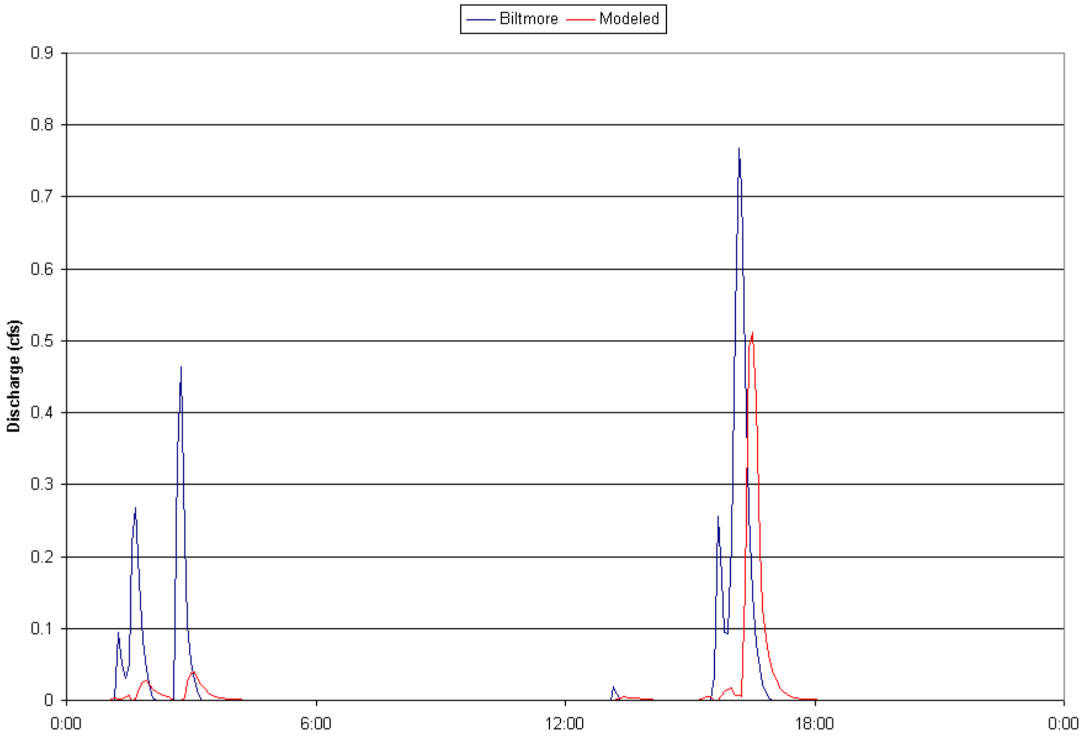

Figure 4. Measured and modeled discharge at J1 in the Biltmore subcatchment

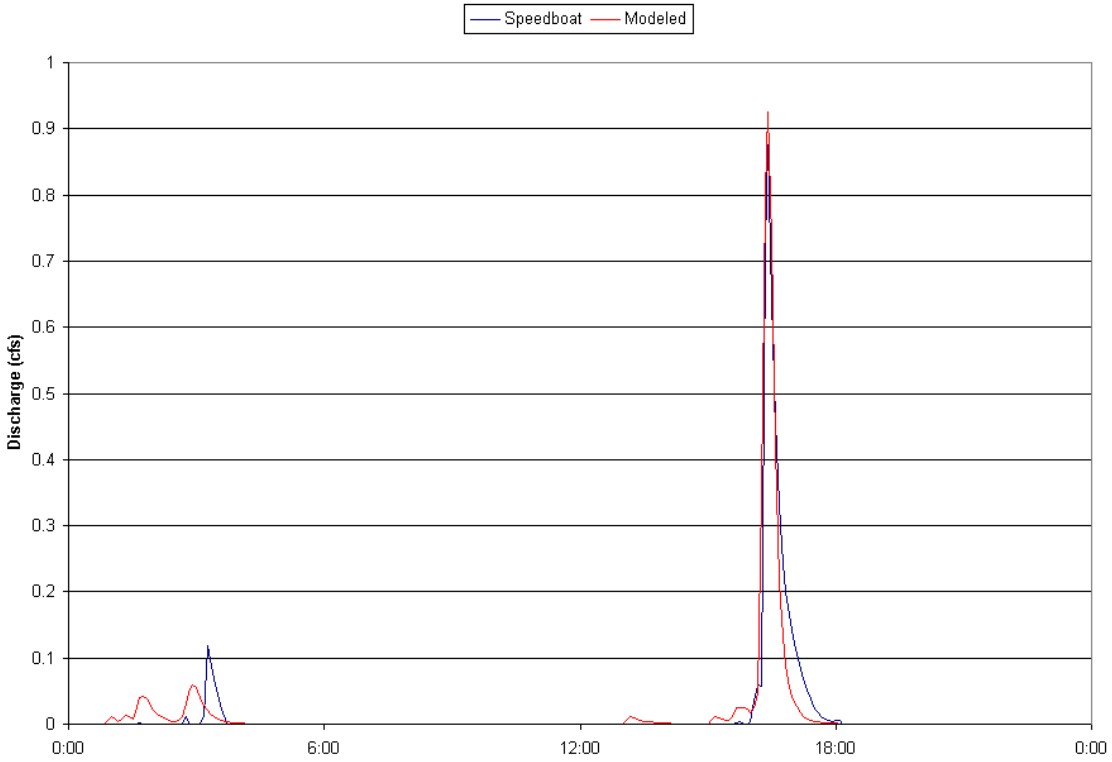

Figure 5. Measured and modeled discharge at J2 in the Speedboat sub catchment

Once modeled and observed hydrographs were in approximate agreement, as shown in Figures 4 and 5, the pollutant buildup and wash off functions were added. With ten days of antecedent dry conditions set in the model options, pollutant buildup functions were not as important as the wash off functions, since modeled land surfaces were already saturated with respect to pollutants. Figures 6 through 11 show modeled pollutant runoff concentrations during the precipitation event along with the measured concentrations in samples from both Speedboat and Biltmore sites. Unfortunately, no samples were collected during the first part of this event at either site. However, modeled concentrations during the second part of this event matched measured concentrations of samples at Speedboat very well, while timing and magnitude of concentrations modeled at Biltmore slightly lagged the measured values, similar to differences seen in the event hydrograph.

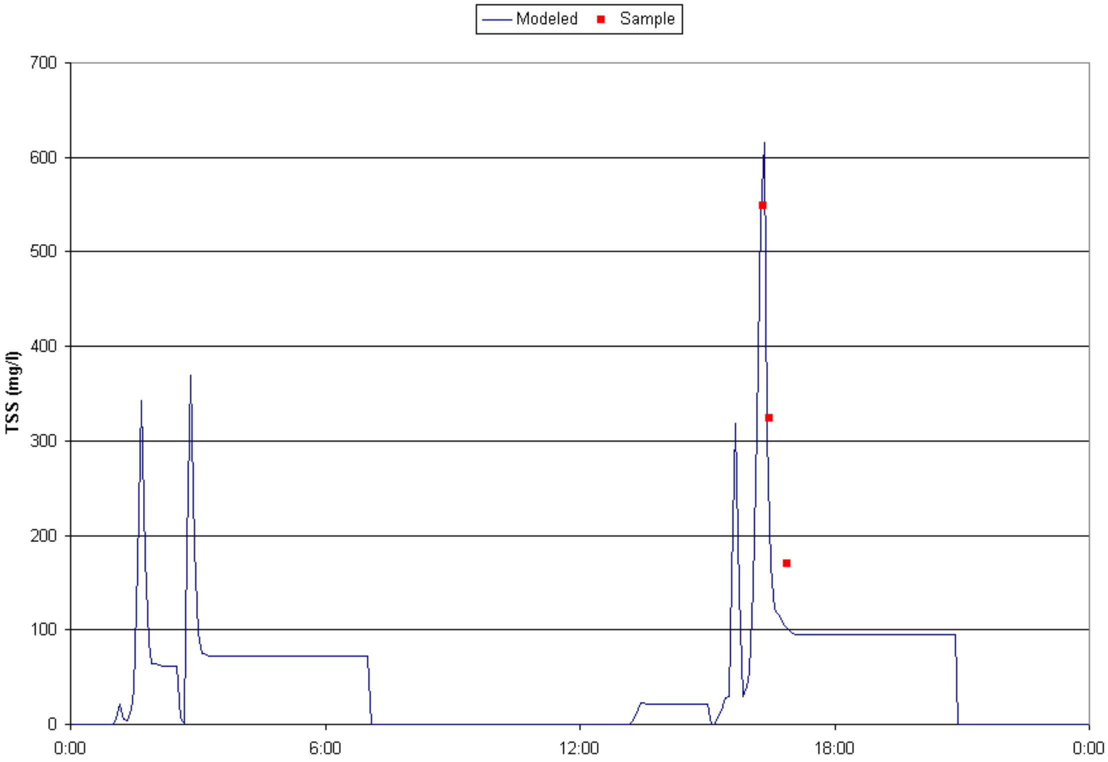

Figure 6. Modeled and measured TSS concentrations at J2 in the Speedboat subcatchment.

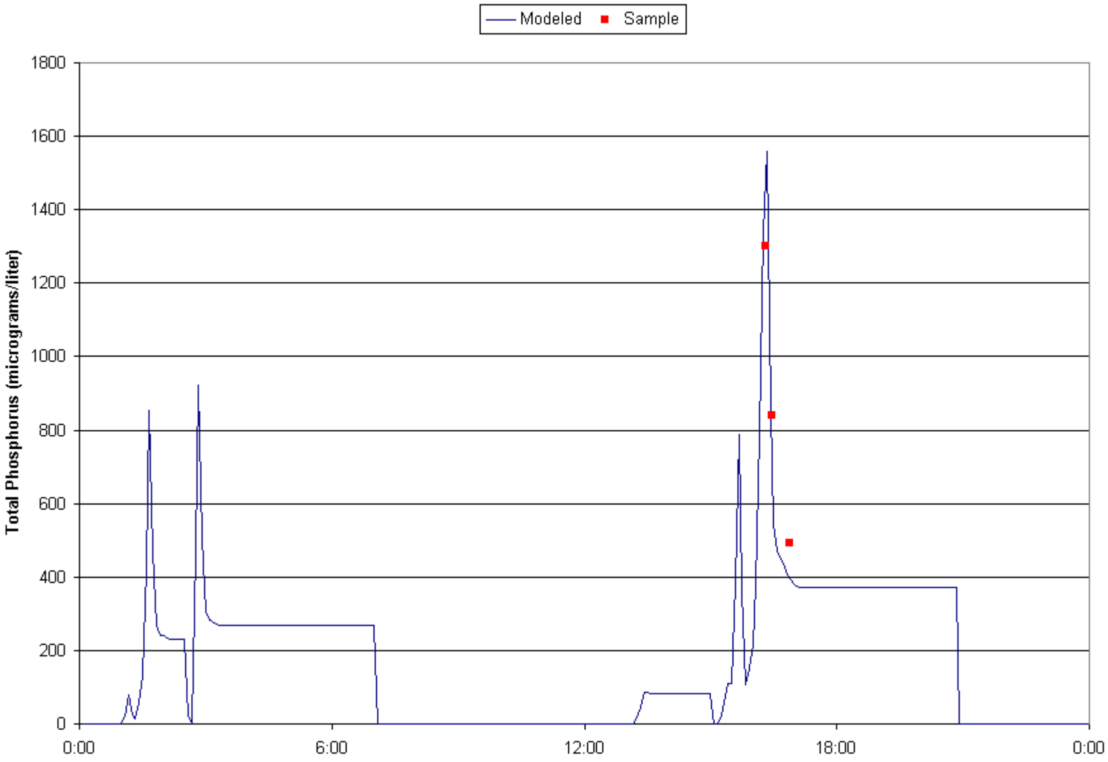

Figure 7. Modeled and measured phosphorous concentrations at J2 in the Speedboat subcatchment.

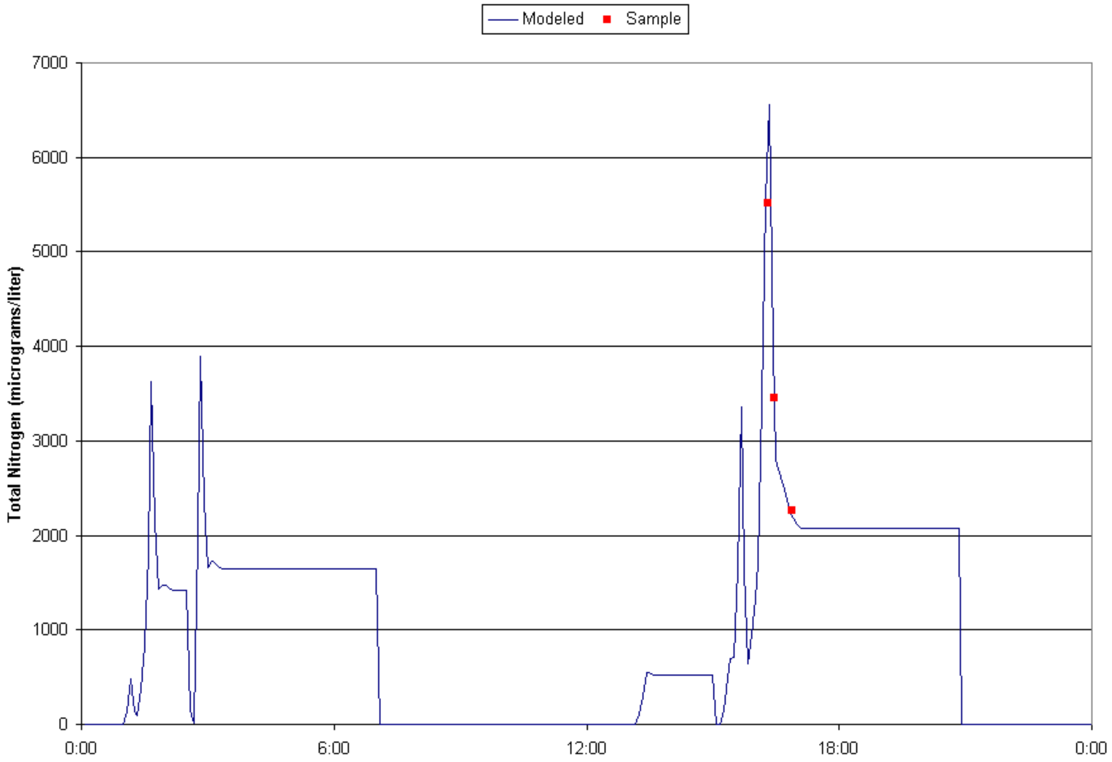

Figure 8. Modeled and measured nitrogen concentrations at J2 in the Speedboat subcatchment.

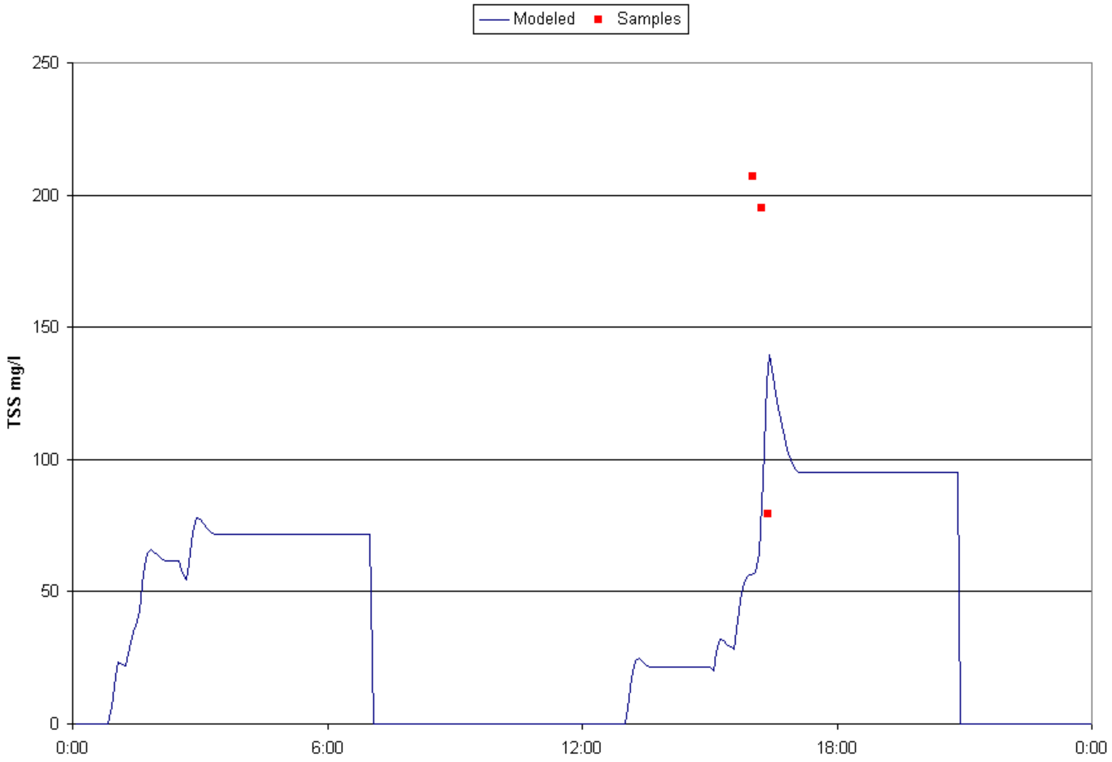

Figure 9. Modeled and measured TSS concentrations at J1 in the Biltmore subcatchment.

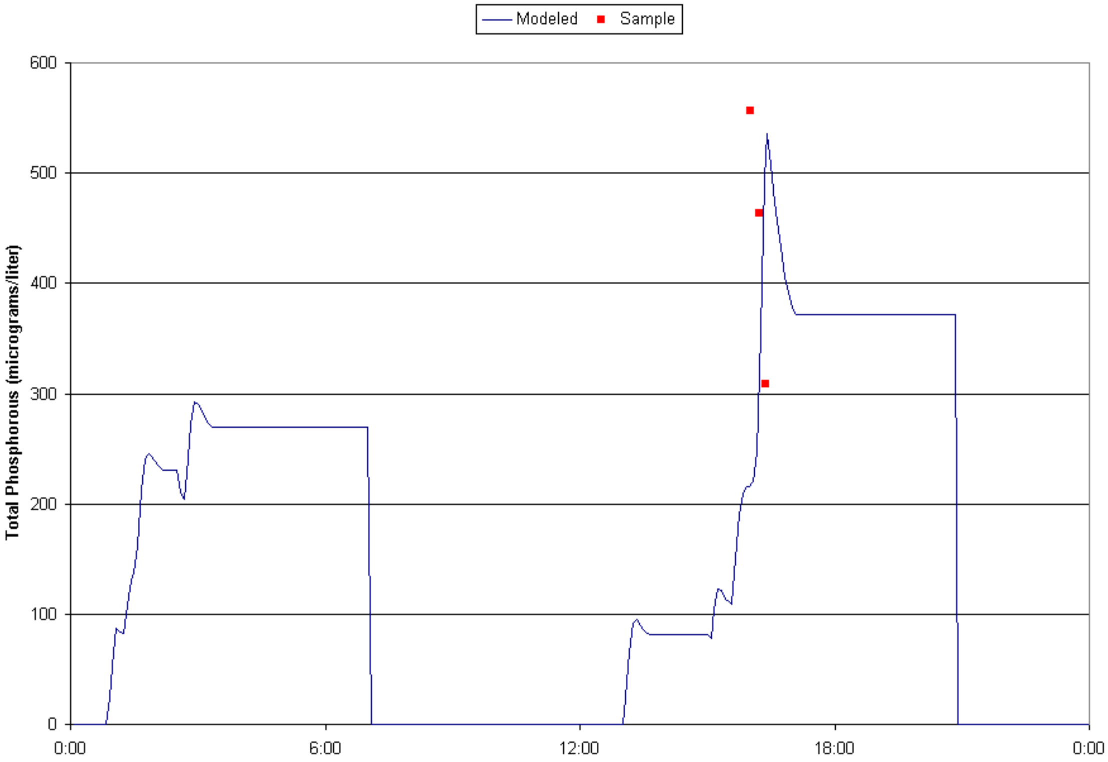

Figure 10. Modeled and measured phosphorous concentrations at J1 in the Biltmore subcatchment.

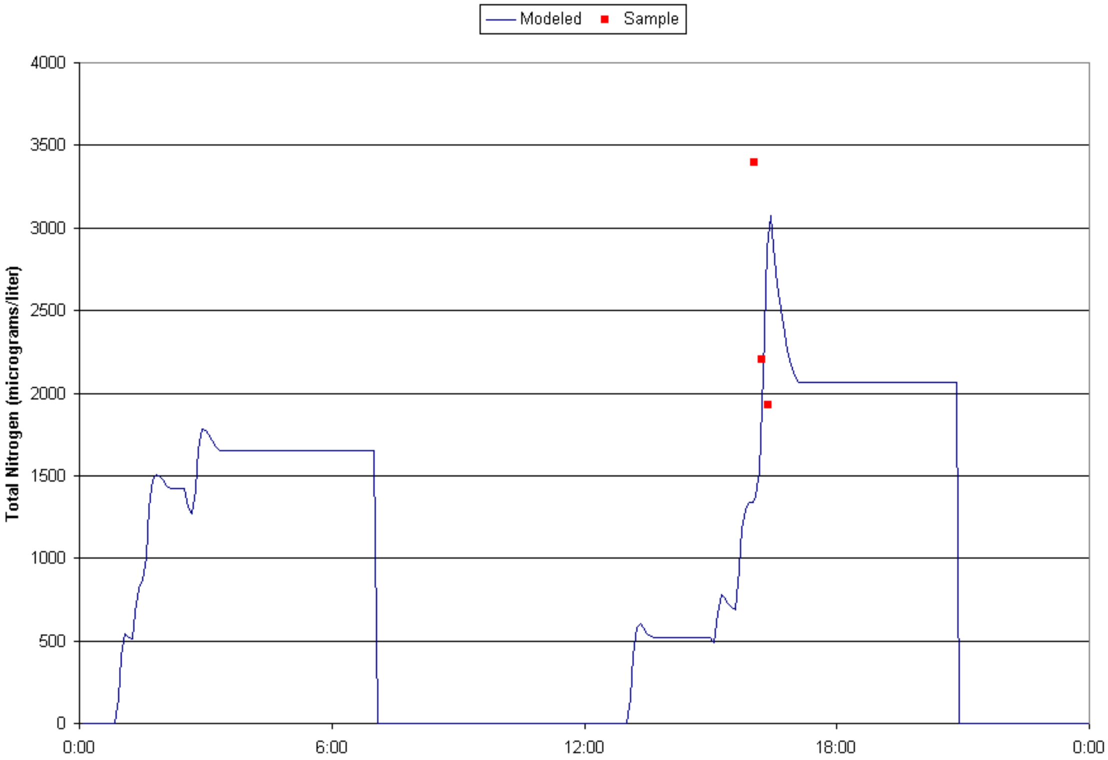

Figure 11. Modeled and measured nitrogen concentrations at J1 in the Biltmore subcatchment.

Alternative Design Simulations

Once the model was reasonably calibrated to existing field conditions for both discharge and pollutant concentrations, nine additional model runs were conducted employing different BMPs and subcatchment source control improvements. These BMPs or subcatchment improvements were analogous to the different combination alternatives used within the NDOT matrix.

The alternatives used for the SWMM runs included:

1) Existing conditions (calibrated initial model run).
2) A change in land use for the Speedboat subcatchment from 100% residential to 95% residential and 5% treated. This is analogous to road shoulder treatment in the residential area, such as enhanced road runoff infiltration.
3) Sediment cans installed at junctions J1 and J2.
4) Combining the treatments of model runs (alternatives) 2 and 3.
5) The existing conditions with the addition of a retention pond at the outfall of the system (O1).
6) Existing conditions with the size of the retention pond doubled at the outfall.
7) Removing 0.4 acres of parking lot at the Biltmore site thus reducing impervious area from 95% to 90%.
8) The same treatment as model run (alternative) 7 but routing an additional 10% of runoff from the impervious parking lot to the newly created pervious area.
9) The same treatment described in model run (alternative) 8 plus the installation of sediment cans at junctions J1 and J2, plus the small retention pond at the outflow of the system.
10) The same treatment described in model run (alternative) 9 with the size of the retention pond doubled at the outflow of the system.

Model outputs were compared from each alternative model run to determine the relative benefits from these source control and treatment options.

Modeled Alternatives Evaluation

There are many output values for runoff quantity and quality variables that can be used to determine effectiveness of the various modeled alternatives (Appendix B). With respect to runoff quantity the model produces output values relevant to hydraulic design, such as infiltration losses, evaporation losses, surface storage, surface runoff, external outflow, maximum link velocity and groundwater inflow. For runoff quality some of the more useful output values include pollutant surface buildup, BMP pollutant removal, surface wash off of pollutants, external outflow of pollutants, and the mass of pollutants reacted.

For demonstration of potential SWMM linkage to an alternatives evaluation matrix or module we chose to use the following model outputs for comparing results: surface buildup and wash off of the three main pollutants (TN, TP, TSS); external stormwater outflow; discharge of the three pollutants; and mass of each pollutants reacted (retained by BMPs). Table 5 shows these results from the model runs for project alternatives 1–10, as described above. The values presented are percent reductions for pollutant and stormwater outflow as compared to model alternative #1, which represents results from existing (initial) conditions. Bold values in Table 5 represent the mass of each pollutant retained by project BMPs (sediment traps or detention ponds). Accurate values for BMP implementation costs were not critical here, as we are only representing a methodology for alternatives evaluation linked to SWMM output. Therefore, the costs shown in Table 5 were estimates derived from the unit costs represented in the NDOT matrix for SR-207.

Figures 12 to 14 are bar charts representing the benefits of the various alternative project designs, represented by model runs 2–10 (discussed above), compared to alternative #1, which was the no action (existing conditions) model. Figure 12 shows how much of each pollutant would be captured by the BMPs represented in each model alternative, while Figure 13 shows how much of each pollutant would be reduced from building up on subcatchment surfaces, and Figure 14 show how much of each pollutant would be suppressed from washing off the subcatchment surfaces. These charts represent examples of the type of output that could be generated by future versions of the PLRM that would include a cost-benefit module. The sum of pollutant amounts captured by BMPs and reduced from buildup and washoff are ultimately represented as total reductions in outflow loads (Figure 15).

Figure 15 shows the cost-benefit analysis, similar to the chart produced by the NDOT EAMP (Appendix A). The model alternatives in this figure represent aggregate percentage reduction for each pollutant at final outflow from the project area, compared to the no-change alternative (#1). Clearly, alternatives 5 and 6 would provide superior benefit relative to their cost. Note, however, that there was no weighting of pollutant reduction benefits. Instead the results represent aggregate percent reduction in terms of load for each pollutant. That is why it is possible, for example, to show a 160% benefit (the sum of each percent reduction for multiple pollutants). In subsequent versions of this approach it may be feasible to produce standardized relationships representing the relative importance of load reductions for each pollutant, with final results normalized to a maximum value of 100%, facilitating interpretation of net benefit among alternatives.

Table 5. Comparison of results from the design alternatives (model alternative #) for pollutant buildup, wash off and mass reacted (retained in BMPs). Values shown represent benefit compared to model alternative #1, which was the existing conditions (no action) alternative. Values shown in **bold font** represent the mass (in pounds) retained by the structural BMPs (sediment traps and detention ponds). Values shown in non-bold font represent the percent reductions achieved by each alternative.

Model Alternative (#)	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
TSS surface buildup	8.42	0.00	8.42	0.00	0.00	1.89	1.89	1.89	1.89
TSS surface washoff	9.32	0.00	9.32	0.00	0.00	1.97	12.85	12.85	12.85
TP surface buildup	8.53	0.00	8.53	0.00	0.00	0.78	0.78	0.78	0.78
TP surface washoff	7.69	0.00	7.69	0.00	0.00	1.92	17.31	17.31	17.31
TN surface buildup	7.00	0.00	7.00	0.00	0.00	2.33	2.33	2.33	2.33
TN surface washoff	7.03	0.00	7.03	0.00	0.00	3.13	19.14	19.14	19.14
External outflow Q (MG)	0.00	0.00	0.00	0.00	0.00	0.00	18.18	18.18	18.18
TSS outflow	7.30	27.44	32.56	58.17	73.55	1.19	7.58	60.34	68.70
TSS Mass Reacted (lb)	**0.00**	**6.77**	**6.22**	**10.93**	**15.92**	**0.00**	**0.00**	**10.37**	**12.61**
TP outflow	5.80	14.49	20.29	28.99	42.03	1.45	10.14	40.58	46.38
TP Mass Reacted (lb)	**0.00**	**0.01**	**0.01**	**0.02**	**0.03**	**0.00**	**0.00**	**0.02**	**0.02**
TN outflow	5.96	14.73	19.75	27.59	40.75	1.88	12.54	41.69	46.71
TN Mass Reacted (lb)	**0.00**	**0.05**	**0.04**	**0.07**	**0.12**	**0.00**	**0.00**	**0.07**	**0.09**
Cost	$200,000	$12,200	$212,200	$9,000	$13,500	$75,000	$100,000	$121,200	$125,700

Bold values are pounds of pollutant reduced
non bolded values are % reduction

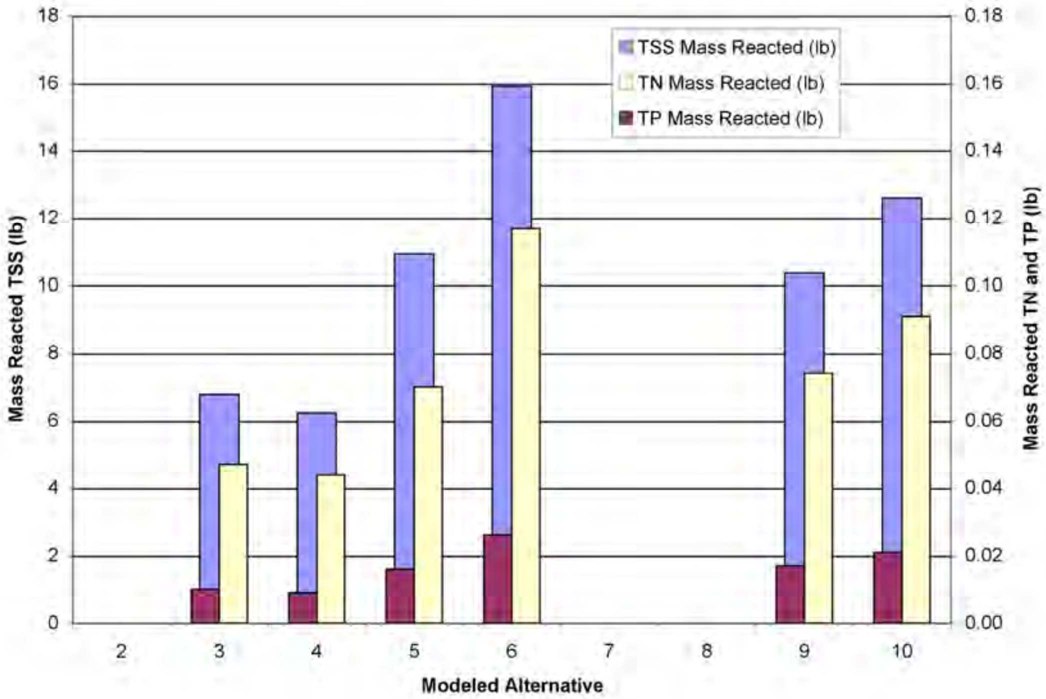

Figure 12. Stacked bar chart showing model estimates for the mass of each pollutant that would be captured by BMPs (mass reacted) with each alternative design.

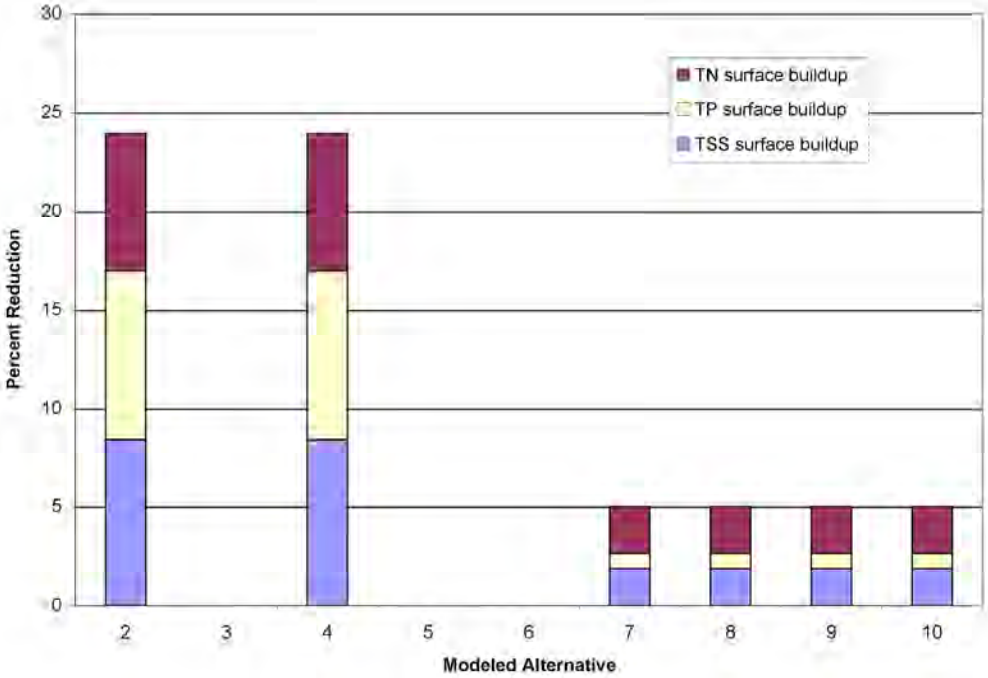

Figure 13. Stacked bar chart showing model estimates for reductions in pollutant buildup on subcatchment surfaces with each alternative design.

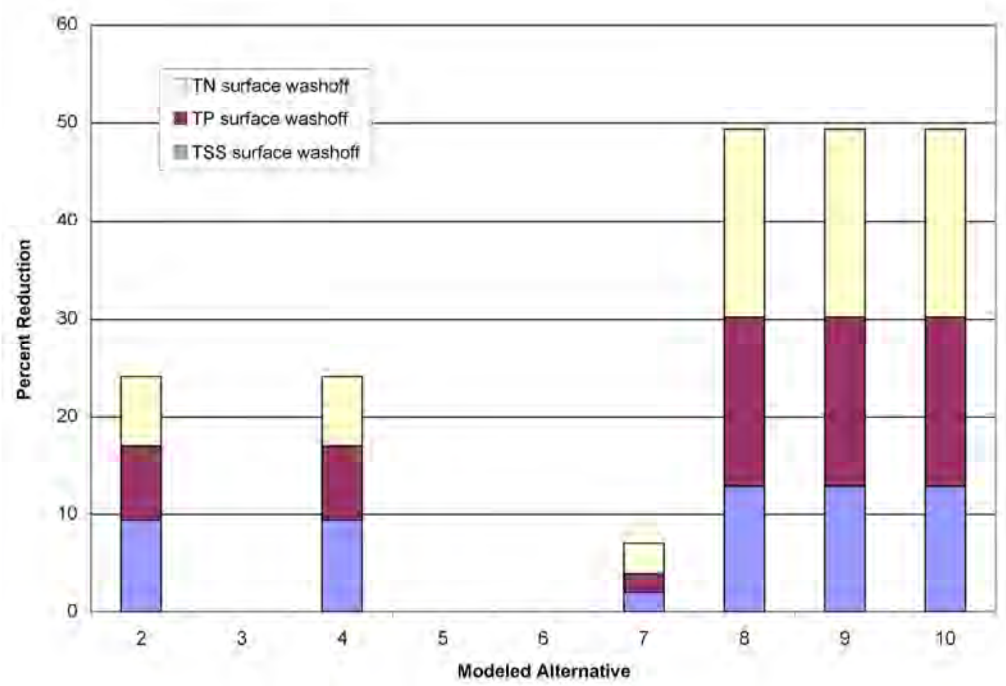

Figure 14. Stacked bar chart showing model estimates for reductions in pollutant wash off from subcatchment surfaces with each alternative design.

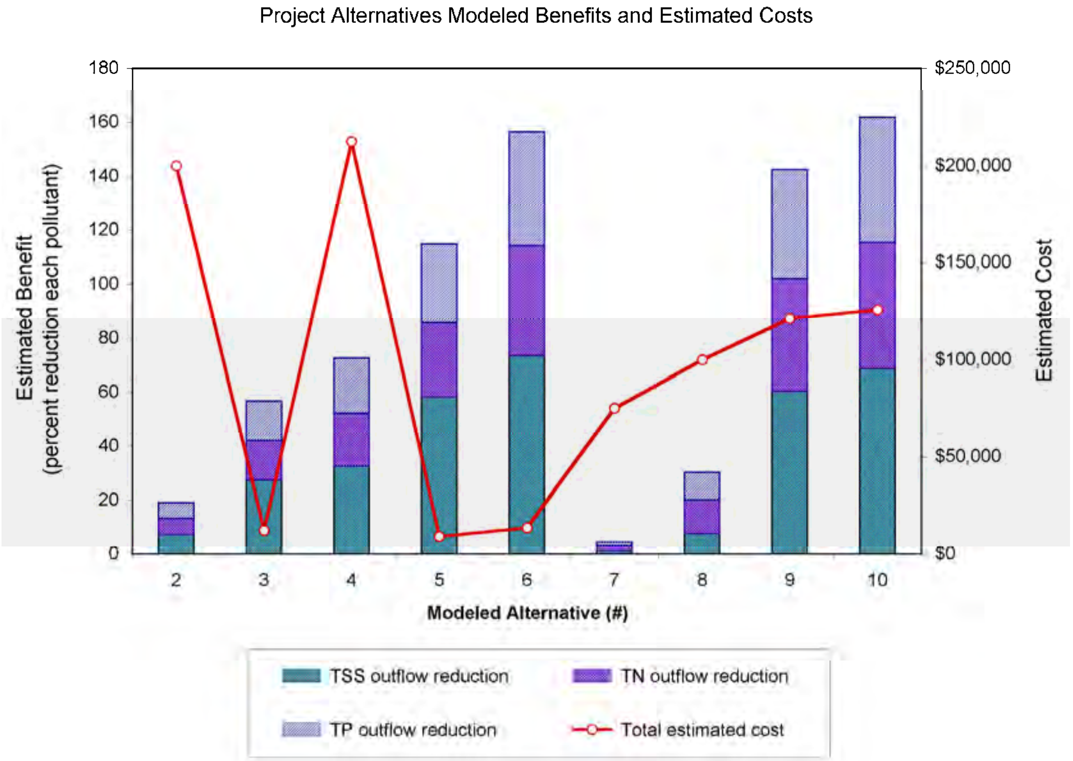

Figure 15. Cost-benefit assessment of design alternatives showing aggregate percentage reduction for each pollutant at final outflow from the project area, compared to the no-change alternative (#1).

CONCLUSIONS

While the NDOT EAMP worked well for the SR-207 highway projects, it was specific to that project area. If another design group in the Tahoe Basin wanted to use this approach on different projects they would have to construct a new EAMP each time to represent the local features specific to that project site. It seemed unlikely that a generalized worksheet matrix could be produced that would easily serve as a template for other EIP projects and also provide realistic pollutant loading and reduction estimates.

Based on the NDOT experience with their EAMP, however, it was recognized that some sort of framework for development and evaluation of design alternatives would be very useful in helping to facilitate and standardize the alternative selection process on a wider basis. Therefore, our primary recommendation following review of the NDOT SR-207 EAMP was that the alternatives evaluation process and cost-benefit analysis should be developed as direct components or modules of the PLRM. In consultation with the PLRM development team (personal communication, Brent Wolfe, Fall 2008), this recommendation was made during the SWQIC presentation (Heyvaert et al. 2008).

The upcoming release of PLRM Version 1 will provide an alternatives analysis tool with pollutant loading estimates for different design options within a project area. Although this first version of the PLRM does not include a cost-benefit comparison component or module, there will be an opportunity and a process established to formally request such refinements and additional features in subsequent versions.

One significant advantage of integrating cost-benefit analysis for project alternatives evaluation in a future version of the PLRM is that it would provide a standardized platform for representing the diverse conditions associated with site-specific hydrology, hydraulics, erosion and pollutant transport, as well as for source control and treatment options throughout the Tahoe Basin. All these parameters would be established as part of the PLRM and accepted through scientific consensus, based on the best available research and monitoring data. Since the underlying database for the PLRM provides Tahoe-specific input data, it is applicable across a wide range of Tahoe conditions, and its application is supported by a steadily increasing body of targeted research. Furthermore, as one of the primary load estimation tools for the Tahoe TMDL, the PLRM will continue to be supported by an iterative process of continual improvement in its calibrations and validation.

The potential for successful integration of an alternatives cost-benefit evaluation process as part of the PLRM was demonstrated by application of the EPA SWMM to an urban catchment along a state highway corridor and its drainage in north Lake Tahoe. The SWMM was initialized with values from monitoring data and run for a typical rainstorm event. It produced runoff hydrographs and pollutant concentrations that were a reasonable match to monitoring data. The drainage model was then fitted with a series of alternative treatment and source control options, which were tested for their net pollutant reductions and cost comparisons. These SWMM output data were linked to an evaluation matrix that demonstrated the cost-benefit relationships between project alternatives (as done with the NDOT EAMP), representing an approach that could be automated as a separate module or application in future versions of the PLRM.

One point of concern from the project design and implementation community has been that calculating pollutant loading and pollutant load reductions will require another layer of effort in project development, since the implementation community must still conduct drainage design for flood control and public safety. While pollutant loading models such as the PLRM are not intended to be used to size facilities and conveyances for flood protection, the PLRM development team has streamlined many features of that model with the intention of simplifying the alternatives development process, and thus provide a significant time savings relative to current efforts for estimating pollutant load reductions from different design options.

The PLRM is expected to be released for preliminary use within the same period as this report is issued. We strongly recommend continued support for the PLRM and suggest that a formal request be made to create the module(s) necessary to support automated routines for calculating the cost-benefit relationships among design alternatives. The PLRM development team anticipates working with members of the SWQIC and a project advisory committee (PAC) to consider any relevant features and functions that should be prioritized for subsequent development in the PLRM. Our testing of potential linkage between a cost-benefit matrix and the SWMM (as surrogate for PLRM) has suggested several additional features that could be considered for future versions of the PLRM. These are listed below for reference only, in no particular order of priority.

- ArcGIS capability could be included. One of the primary benefits of the approach we took for this demonstration of PLRM and EAMP integration was the ability to create drainage, conveyance and treatment elements in a spatially-based format that worked directly with SWMM 5. Although this was done in PC SWMM, it appears possible to create a version of the PLRM that runs ArcGIS as an extension. Visual representation would greatly facilitate accurate spatial distribution and manipulation of project features and the development of alternatives. Furthermore, a wealth of data exists in ArcGIS (soil characteristics, land use, impervious coverage) or will be created, and these could then be imported directly to project design. Also, file conversion is common between ArcGIS and many other formats, such as AutoCAD.
- Performance estimates for treatment BMPs and source controls should be updated periodically to represent currently accepted Tahoe TMDL pollutant reduction estimates, based on best available data from studies conducted in the Tahoe Basin and peer-reviewed by the Lake Tahoe scientific community, potentially through an organization such as the Tahoe Regional Stormwater Monitoring Program (RSWMP). Resulting pollutant reductions will be determined for all priority pollutants based on standard design attributes or perhaps in some cases user specified design features.
- Include treatment BMP and source control cost matrix. This module would detail the costs associated with different practices applied to a particular erosion control or water quality improvement project. A default set of values representing typical installation expenses could be included. However, because these cost estimates

would vary between jurisdiction and would depend upon various project conditions and site constraints, this module should have the option to be edited by the end user.

- Annual maintenance costs should be represented. While implementation costs are of primary importance considering the options available in project design, it may be essential to also represent maintenance costs when making decisions about which alternative to implement. Some BMPs may have a low initial cost, but over time maintenance costs could result in a less than ideal alternative. Most treatment practices and source control measures require some regular maintenance to sustain optimal effectiveness, so representation of these life-cycle cost estimates would improve the cost-benefit analysis.
- Automated routines for testing cost-benefit results of design alternatives. This could be done in batch mode or iteratively at user command to analyze results as different source control or treatment options are inserted into a project area. Immediate feedback on the likely costs and benefits resulting with alternatives could facilitate the exploration of design alternatives.
- Graphical representation of the cost-benefit analysis. The NDOT SR-207 EAMP provided a chart from the cost-benefit analysis for sediment yield reduction by different project alternatives. This was a useful approach for evaluating the relative merit and obligations associated with various alternatives. A more sophisticated representation will be needed when dealing with a cost-benefit analysis of the multiple pollutants represented in the PLRM.
- In the process of incorporating a cost-benefit analysis as part of the Tahoe PLRM there should be close communication between the project engineering design community, TMDL scientists and the PLRM development team to ensure that critical needs are addressed. This includes developing a process of periodically updating the PLRM with new information as it becomes available for better loading estimates and cost analysis.

To enhance functionality of the PLRM will require an investment to support continued development. However, a robust, full-featured implementation of the alternatives evaluation process and cost-benefit analysis integrated as part of the PLRM would yield a very useful standardized tool applicable to diverse water quality improvement projects around the Tahoe Basin. Properly developed it would enhance the design process, facilitate selection of preferred alternative(s), and substantially reduce the user efforts associated with meeting regulatory requirements. It would also ensure more consistent basin-wide tracking and estimation of the pollutant reductions resulting from EIP project implementation.

ACKNOWLEDGEMENTS

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APPENDIX A: Nevada Department of Transportation Evaluation of Alternatives Matrix Process for Determining Project Preferred Alternatives.

(As provided to the Tahoe science consortium for evaluation of their EAMP process.)

Nevada Department of Transportation Evaluation of Alternatives Matrix Process for Determining Project Preferred Alternative

The Nevada Department of Transportation (NDOT) is in the final phase of its Tahoe Basin Environmental Improvement Program (EIP). As part of the program, NDOT is developing the Lake Tahoe Phase III Master Plan document that will serve as the blue print for erosion control and water quality projects along portions of SR-431 (Mt Rose Highway), SR-207 (Kingsbury Grade), US 50 and SR-28.

NDOT is following guidelines developed by the Tahoe Basin Stormwater Quality Improvement Committee (SQWIC) requiring the Formulation and Evaluation of Alternatives (FEA) for each EIP project. To aid in the selection of a final alternative, NDOT has developed the Evaluation of Alternatives Matrix Process (EAMP). The process evaluates numerous alternatives and related water quality benefits by analyzing different combinations of both source and treatment control BMPs within the project area. The end result is a chart highlighting each alternative's cumulative cost in conjunction with related source and treatment control benefit, overall project benefit treatment and cost. With this information, TAC members can then readily determine which alternative meets project goals and objectives while providing the maximum water quality benefit at the lowest cost.

Development of a project EAMP is as follows:

1. Sediment production for each project is estimated using the Revised Universal Soil Loss Equation (or other appropriate sediment yield model) and NDOT road sand application rates.
    a. Sediment yield is estimated for cut/fill slopes, ditches, roadway shoulders etc.
    b. Total project sediment yield is then subdivided into an estimated percentage of course and fine sediment based on the predominant soil type within project limits. For NDOT Tahoe basin roadways 85 and 15% was the estimated breakout of course and fine sediment.
2. Project strategies for reducing sediment yield are identified. Depending on site conditions, different strategies might include varying level of treatment for cut slopes, construction of infiltration/detention basins, sump drop inlets, water quality vaults, curb and gutter, stormdrain systems, etc.
    a. Alternatives for each strategy are developed using combinations of appropriate BMPs to accomplish project goals.
    b. Selected BMPs include both source control and treatment control options
3. Sediment reduction is estimated by multiplying each BMP type by a trapping efficiency factor (see BMP Trapping Efficiency table below) according to the

estimated efficiency of individual BMPs for removing course and fine sediment. Trapping efficiency estimates are based on limited research, field operations and engineering judgment.

4. The percent of total sediment captured for each alternative is then compared to the estimated total cost to achieve overall sediment reduction. The preferred alternative is readily identifiable in the resulting graph.

The following is an example analysis of an estimated sediment capture benefit for both source and treatment control options along a fictitious project segment:

Project A produces 1000 ft^3 /yr of sediment. The project 20-yr 1-hr runoff volume for segment one is 150 ft^3. An alternative for segment one includes slope treatment, installation of five drop inlets and construction of one 100 ft^3 infiltration basin receiving an annual sediment load of 75 ft^3.

<u>Source Control Benefit Calculation:</u> Slope treatment reduces the sediment yield by 85 ft^3 and 15 ft^3 of course and fine sediment respectively. The proposed slope treatment is 60% slope riprap and 40% slope revegetation. Using the Trapping Efficiency table below, the source control capture benefit is as follows:

$\frac{85}{1000} * (0.6 * 0.90 + 0.40 * 0.50) = 6.3\%$ for course sediment and

$\frac{15}{1000} * (0.60 * 0.50 + 0.40 * 0.05) = 0.48\%$ for fine sediment.

<u>Treatment Control Benefit Calculation:</u> The total sediment capacity of the five drop inlets is 200 ft^3. If The estimated treatment control capture benefit, assuming 200 ft^3 reaches the drop inlets, would be:

$\frac{200}{1000} * 0.50 * 0.85 = 8.5\%$ for course sediment and $\frac{200}{1000} * 0.0 * 0.15 = 0\%$ for fine sediment.

Capture benefit result for the infiltration basin is $\frac{100}{150} * \frac{75}{1000} * 0.85 * 1.0 = 4.3\%$ for course sediment and $\frac{100}{150} * \frac{75}{1000} * 0.15 * 0.60 = 0.45\%$ for fine sediment.

BMP	**Trapping Efficiency (Percent)**	
	Coarse Sediment	Fine Sediment
Paving /Shotcrete	100	100
Slope Riprap	90	50
Slope Revegetation	50	5
Drop Inlet	50	0
Double Barrel Sediment Cans	60	20
Channel Protection from storm drain installation	100	100
Curb/Gutter/Dike as protection and not conveyance	100	100
Infiltration Basin	100	60
Vegetative Buffer	80	30
Stabilize channel with articulated block	100	100
Stabilize channel	100	100

Chart 1 illustrates the final result of alternatives developed for SR-207. Bars show the estimated sediment capture benefit in percent. Individual alternative costs are shown with the x-line and available project funding is the horizontal bar. Alternatives 14, 24 and the hybrid alternative appear to maximize the overall water quality benefit for available funding dollars. These warrant further consideration prior to final selection.

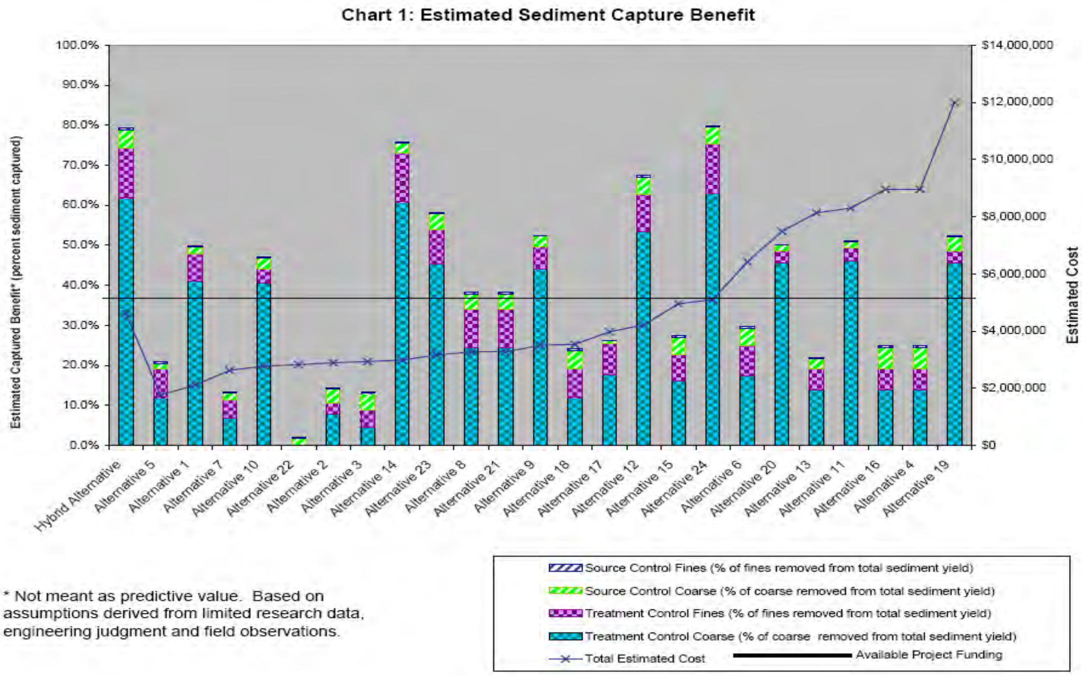

Chart 1: Estimated Sediment Capture Benefit

* Not meant as predictive value. Based on assumptions derived from limited research data, engineering judgment and field observations.

APPENDIX B: SWMM Calibration and Output Files for Ten Alternative Model Runs on the North Tahoe State Line Drainage as Part of this Study. The model was applied as a demonstration of potential linkage between the PLRM and a cost-benefit analysis for alternatives evaluation. It is not intended as a fully calibrated SWMM representation of the drainage, nor does it represent application of PLRM in any form.

Options	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Flow units	CFS	CFS	CFS	CFS	CFS	CFS	CFS	CFS	CFS	CFS
Infiltration method	Horton	Horton	Horton	Horton	Horton	Horton	Horton	Horton	Horton	Horton
Flow routing method	Kinematic wave	Kinematic wave	Kinematic wave	Kinematic wave	Kinematic wave	Kinematic wave	Kinematic wave	Kinematic wave	Kinematic wave	Kinematic wave
Link offsets defined by	Elevation	Elevation	Elevation	Elevation	Elevation	Elevation	Elevation	Elevation	Elevation	Elevation
Allow ponding	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Skip steady periods	No	No	No	No	No	No	No	No	No	No
Ignore rainfall/runoff	No	No	No	No	No	No	No	No	No	No
Inertial dampening	Partial	Partial	Partial	Partial	Partial	Partial	Partial	Partial	Partial	Partial
Define supercritical flow by	Both	Both	Both	Both	Both	Both	Both	Both	Both	Both
Force main equation	H-W	H-W	H-W	H-W	H-W	H-W	H-W	H-W	H-W	H-W
Variable time step	On	On	On	On	On	On	On	On	On	On
Adjustment factor (%)	75	75	75	75	75	75	75	75	75	75
Conduit lengthening (s)	0	0	0	0	0	0	0	0	0	0
Minimum surface area (ft^2)	0	0	0	0	0	0	0	0	0	0
Starting date	Oct-28-2007 12:00:00 AM	Oct-28-2007 12:00:00 AM	Oct-28-2007 12:00:00 AM	Oct-28-2007 12:00:00 AM	Oct-28-2007 12:00:00 AM	Oct-28-2007 12:00:00 AM	Oct-28-2007 12:00:00 AM	Oct-28-2007 12:00:00 AM	Oct-28-2007 12:00:00 AM	Oct-28-2007 12:00:00 AM
Ending date	Oct-29-2007 12:00:00 AM	Oct-29-2007 12:00:00 AM	Oct-29-2007 12:00:00 AM	Oct-29-2007 12:00:00 AM	Oct-29-2007 12:00:00 AM	Oct-29-2007 12:00:00 AM	Oct-29-2007 12:00:00 AM	Oct-29-2007 12:00:00 AM	Oct-29-2007 12:00:00 AM	Oct-29-2007 12:00:00 AM
Duration of simulation (hours)	24	24	24	24	24	24	24	24	24	24
Antecedent dry days (days)	10	10	10	10	10	10	10	10	10	10
Rain interval (h:mm)	0:10	0:10	0:10	0:10	0:10	0:10	0:10	0:10	0:10	0:10
Report time step (h:mm:ss)	0:05:00	0:05:00	0:05:00	0:05:00	0:05:00	0:05:00	0:05:00	0:05:00	0:05:00	0:05:00
Wet time step (h:mm:ss)	0:15:00	0:15:00	0:15:00	0:15:00	0:15:00	0:15:00	0:15:00	0:15:00	0:15:00	0:15:00

Dry time step (h:mm:ss)	1:00:00	1:00:00	1:00:00	1:00:00	1:00:00	1:00:00	1:00:00	1:00:00	1:00:00	1:00:00
Routing time step (s)	30	30	30	30	30	30	30	30	30	30
Minimum time step used (s)	30	30	30	30	30	30	30	30	30	30
Average time step used (s)	30	30	30	30	30	30	30	30	30	30

Model inventory

	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Raingages	1	1	1	1	1	1	1	1	1	1
Subcatchments	2	2	2	2	2	2	2	2	2	2
Aquifers	0	0	0	0	0	0	0	0	0	0
Snowpacks	0	0	0	0	0	0	0	0	0	0
RDII hydrographs	0	0	0	0	0	0	0	0	0	0
Junction nodes	2	2	2	2	2	2	2	2	2	2
Outfall nodes	1	1	1	1	1	1	1	1	1	1
Flow divider nodes	0	0	0	0	0	0	0	0	0	0
Storage unit nodes	1	1	1	1	1	1	1	1	1	1
Conduit links	3	3	3	3	3	3	3	3	3	3
Pump links	0	0	0	0	0	0	0	0	0	0
Orifice links	0	0	0	0	0	0	0	0	0	0
Weir links	0	0	0	0	0	0	0	0	0	0
Outlet links	0	0	0	0	0	0	0	0	0	0
Treatment units	3	3	3	3	3	3	3	3	3	3
Pollutants	3	3	3	3	3	3	3	3	3	3
Land uses	3	3	3	3	3	3	3	3	3	3
Control rules	0	0	0	0	0	0	0	0	0	0

Uncertainty (number of uncertain parameters)

	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Raingages	0	0	0	0	0	0	0	0	0	0
Subcatchments	31	33	31	33	31	31	31	31	31	31
Aquifers	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Snowpacks	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
RDII hydrographs	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Junction nodes	2	2	2	2	2	2	2	2	2	2
Outfall nodes	1	1	1	1	1	1	1	1	1	1
Flow divider nodes	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Storage unit nodes	3	3	3	3	3	3	3	3	3	3
Conduit links	21	21	21	21	21	21	21	21	21	21
Pump links	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Orifice links	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Weir links	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Outlet links	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Transect	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Pollutants	2	2	2	2	2	2	2	2	2	2
Land uses	27	27	27	27	27	27	27	27	27	27
Total	87	89	87	89	87	87	87	87	87	87

Inflows

	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Time series inflows	0	0	0	0	0	0	0	0	0	0
Dry weather inflows	0	0	0	0	0	0	0	0	0	0
Groundwater inflows	0	0	0	0	0	0	0	0	0	0
RDII inflows	0	0	0	0	0	0	0	0	0	0

Subcatchment attribute ranges

	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Max. width (ft)	4566.458	4566.458	4566.458	4566.458	4566.458	4566.458	4566.458	4566.458	4566.458	4566.458
Min. width (ft)	1685.6066	1685.6066	1685.6066	1685.6066	1685.6066	1685.6066	1685.6066	1685.6066	1685.6066	1685.6066
Max. area (ac)	29.43	29.43	29.43	29.43	29.43	29.43	29.43	29.43	29.43	29.43
Min. area (ac)	8.56	8.56	8.56	8.56	8.56	8.56	8.56	8.56	8.56	8.56
Total area (ac)	37.99	37.99	37.99	37.99	37.99	37.99	37.99	37.99	37.99	37.99
Max. length of overland flow (ft)	280.7364	280.7364	280.7364	280.7364	280.7364	280.7364	280.7364	280.7364	280.7364	280.7364
Min. length of overland flow (ft)	221.2103	221.2103	221.2103	221.2103	221.2103	221.2103	221.2103	221.2103	221.2103	221.2103
Max. slope (%)	20	20	20	20	20	20	20	20	20	20
Min. slope (%)	15	15	15	15	15	15	15	15	15	15
Max. imperviousness	95	95	95	95	95	95	90	90	90	90

(%)										
Min. imperviousness (%)	15	15	15	15	15	15	15	15	15	15
Max. imp. roughness	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Min. imp. roughness	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Max. perv. roughness	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Min. perv. roughness	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Max. imp. depression storage (in)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Min. imp. depression storage (in)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Max. perv. depression storage (in)	1	1	1	1	1	1	1	1	1	1
Min. perv. depression storage (in)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Node attribute ranges

	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Max. ground elev. (ft)	6388	6388	6388	6388	6388	6388	6388	6388	6388	6388
Min. ground elev. (ft)	6290	6290	6290	6290	6290	6290	6290	6290	6290	6290
Max. invert elev. (ft)	6388	6388	6388	6388	6388	6388	6388	6388	6388	6388
Min. invert elev. (ft)	6289.5	6289.5	6289.5	6289.5	6289.5	6289.5	6289.5	6289.5	6289.5	6289.5
Max. max. depth (ft)	3	3	3	3	3	3	3	3	3	3
Min. max. depth (ft)	0	0	0	0	0	0	0	0	0	0

Conduit attribute ranges

	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Max. roughness	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Min. roughness	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Max. entry loss coef.	0	0	0	0	0	0	0	0	0	0
Min. entry loss coef.	0	0	0	0	0	0	0	0	0	0
Max. exit loss coef.	0	0	0	0	0	0	0	0	0	0
Min. exit loss coef.	0	0	0	0	0	0	0	0	0	0
Max. avg. loss coef.	2	2	2	2	2	2	2	2	2	2
Min. avg. loss coef.	0	0	0	0	0	0	0	0	0	0
Max. length (ft)	1477.18	1477.18	1477.18	1477.18	1477.18	1477.18	1477.18	1477.18	1477.18	1477.18
Min. length (ft)	5.95	5.95	5.95	5.95	5.95	5.95	5.95	5.95	5.95	5.95

Total length (ft)	1505.4	1505.4	1505.4	1505.4	1505.4	1505.4	1505.4	1505.4	1505.4	1505.4
Max. slope (ft/ft)	0.5042	0.5042	0.5042	0.5042	0.5042	0.5042	0.5042	0.5042	0.5042	0.5042
Min. slope (ft/ft)	0.0663	0.0663	0.0663	0.0663	0.0663	0.0663	0.0663	0.0663	0.0663	0.0663

Conduit Inventory

	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Circular (ft)	28.22	28.22	28.22	28.22	28.22	28.22	28.22	28.22	28.22	28.22
Rect_Triangular (ft)	1477.18	1477.18	1477.18	1477.18	1477.18	1477.18	1477.18	1477.18	1477.18	1477.18

Pipe inventory

	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Max. pipe diameter (ft)	1	1	1	1	1	1	1	1	1	1
Min. pipe diameter (ft)	1	1	1	1	1	1	1	1	1	1
Total 12” pipe length (ft)	28.22	28.22	28.22	28.22	28.22	28.22	28.22	28.22	28.22	28.22
Total pipe length (ft)	28.22	28.22	28.22	28.22	28.22	28.22	28.22	28.22	28.22	28.22

Unused objects

	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Rain gages	0	0	0	0	0	0	0	0	0	0
Aquifers	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Snow packs	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Unit hydrographs	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Transects	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Control curves	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Diversion curves	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Pump curves	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Rating curves	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Shape curves	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Storage curves	0	0	0	0	0	0	0	0	0	0
Tidal curves	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Time series	1	1	1	1	1	1	1	1	1	1
Time patterns	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Runoff quantity continuity	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Initial snow cover (in)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Total precipitation (in)	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Evaporation loss (in)	0.047	0.047	0.047	0.047	0.047	0.047	0.046	0.046	0.046	0.046
Infiltration loss (in)	0.163	0.163	0.163	0.163	0.163	0.163	0.165	0.166	0.166	0.166
Surface runoff (in)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.008	0.008	0.008
Snow removed (in)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Final snow cover (in)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Final surface storage (in)	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018
Continuity error (%)	-3.538	-3.538	-3.538	-3.538	-3.538	-3.538	-3.465	-3.583	-3.583	-3.583

Runoff quality continuity: TSS	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Initial buildup (lbs)	571.665	540.436	571.665	540.436	571.665	571.665	571.665	571.665	571.665	571.665
Surface buildup (lbs)	10.424	9.546	10.424	9.546	10.424	10.424	10.227	10.227	10.227	10.227
Wet deposition (lbs)	0	0	0	0	0	0	0	0	0	0
Sweeping removal (lbs)	0	0	0	0	0	0	0	0	0	0
Infiltration loss (lbs)	0	0	0	0	0	0	0	0	0	0
BMP removal (lbs)	0	0	0	0	0	0	0	0	0	0
Surface runoff (lbs)	17.165	15.565	17.165	15.565	17.165	17.165	16.827	14.959	14.959	14.959
Remaining buildup (lbs)	525.821	498.267	525.821	498.267	525.821	525.821	526.4	526.4	526.4	526.4
Continuity error (%)	6.718	6.573	6.718	6.573	6.718	6.718	6.645	6.966	6.966	6.966

Runoff quality continuity: TP	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Initial buildup (lbs)	1.478	1.399	1.478	1.399	1.478	1.478	1.478	1.478	1.478	1.478
Surface buildup (lbs)	0.129	0.118	0.129	0.118	0.129	0.129	0.128	0.128	0.128	0.128
Wet deposition (lbs)	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Sweeping removal (lbs)	0	0	0	0	0	0	0	0	0	0
Infiltration loss (lbs)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
BMP removal (lbs)	0	0	0	0	0	0	0	0	0	0

Surface runoff (lbs)	0.052	0.048	0.052	0.048	0.052	0.052	0.051	0.043	0.043	0.043
Remaining buildup (lbs)	1.447	1.368	1.447	1.368	1.447	1.447	1.448	1.448	1.448	1.448
Continuity error (%)	6.822	6.715	6.822	6.715	6.822	6.822	6.719	7.161	7.161	7.161

Runoff quality continuity: TN	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Initial buildup (lbs)	5.821	5.508	5.821	5.508	5.821	5.821	5.821	5.821	5.821	5.821
Surface buildup (lbs)	0.729	0.678	0.729	0.678	0.729	0.729	0.712	0.712	0.712	0.712
Wet deposition (lbs)	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396
Sweeping removal (lbs)	0	0	0	0	0	0	0	0	0	0
Infiltration loss (lbs)	0.288	0.288	0.288	0.288	0.288	0.288	0.291	0.294	0.294	0.294
BMP removal (lbs)	0	0	0	0	0	0	0	0	0	0
Surface runoff (lbs)	0.256	0.238	0.256	0.238	0.256	0.256	0.248	0.207	0.207	0.207
Remaining buildup (lbs)	5.854	5.54	5.854	5.54	5.854	5.854	5.853	5.853	5.853	5.853
Continuity error (%)	7.894	7.838	7.894	7.838	7.894	7.894	7.761	8.306	8.306	8.306

Flow routing continuity	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Dry weather inflow (MG)	0	0	0	0	0	0	0	0	0	0
Wet weather inflow (MG)	0.011	0.011	0.011	0.011	0.011	0.011	0.01	0.009	0.009	0.009
Groundwater inflow (MG)	0	0	0	0	0	0	0	0	0	0
RDII inflow (MG)	0	0	0	0	0	0	0	0	0	0
External inflow (MG)	0	0	0	0	0	0	0	0	0	0
External outflow (MG)	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.009	0.009	0.009
Internal outflow (MG)	0	0	0	0	0	0	0	0	0	0
Evaporation loss (MG)	0	0	0	0	0	0	0	0	0	0
Initial stored volume (MG)	0	0	0	0	0	0	0	0	0	0
Final stored volume (MG)	0	0	0	0	0	0	0	0	0	0
Continuity error (%)	-2.869	-2.869	-2.869	-2.869	-2.869	-2.933	-2.919	-2.994	-2.994	-3.138

Quality routing continuity: TSS	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Dry weather inflow (lbs)	0	0	0	0	0	0	0	0	0	0
Wet weather inflow (lbs)	23.967	22.166	23.967	22.166	23.967	23.967	23.682	22.14	22.14	22.14
Groundwater inflow (lbs)	0	0	0	0	0	0	0	0	0	0
RDII inflow (lbs)	0	0	0	0	0	0	0	0	0	0
External inflow (lbs)	0	0	0	0	0	0	0	0	0	0
Internal flooding (lbs)	0	0	0	0	0	0	0	0	0	0
External outflow (lbs)	24.988	23.165	18.132	16.852	10.453	6.609	24.691	23.093	9.909	7.822
Mass reacted (lbs)	0	0	6.772	6.221	10.931	15.917	0	0	10.373	12.609
Initial stored mass (lbs)	0	0	0	0	0	0	0	0	0	0
Final stored mass (lbs)	0	0	0	0	0	0	0	0	0	0
Continuity error (%)	-4.258	-4.508	-3.907	-4.094	10.775	6.015	-4.259	-4.304	8.393	7.716

Quality routing continuity: TP	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Dry weather inflow (lbs)	0	0	0	0	0	0	0	0	0	0
Wet weather inflow (lbs)	0.067	0.062	0.067	0.062	0.067	0.067	0.066	0.06	0.06	0.06
Groundwater inflow (lbs)	0	0	0	0	0	0	0	0	0	0
RDII inflow (lbs)	0	0	0	0	0	0	0	0	0	0
External inflow (lbs)	0	0	0	0	0	0	0	0	0	0
Internal flooding (lbs)	0	0	0	0	0	0	0	0	0	0
External outflow (lbs)	0.069	0.065	0.059	0.055	0.049	0.04	0.068	0.062	0.041	0.037
Mass reacted (lbs)	0	0	0.01	0.009	0.016	0.026	0	0	0.017	0.021
Initial stored mass (lbs)	0	0	0	0	0	0	0	0	0	0
Final stored mass (lbs)	0	0	0	0	0	0	0	0	0	0
Continuity error (%)	-3.159	-3.339	-3.128	-3.285	3.256	1.935	-3.181	-3.321	4.158	3.695

Quality routing continuity: TN	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Dry weather inflow (lbs)	0	0	0	0	0	0	0	0	0	0
Wet weather inflow (lbs)	0.312	0.292	0.312	0.292	0.312	0.312	0.306	0.272	0.272	0.272
Groundwater inflow (lbs)	0	0	0	0	0	0	0	0	0	0
RDII inflow (lbs)	0	0	0	0	0	0	0	0	0	0
External inflow (lbs)	0	0	0	0	0	0	0	0	0	0
Internal flooding (lbs)	0	0	0	0	0	0	0	0	0	0
External outflow (lbs)	0.319	0.3	0.272	0.256	0.231	0.189	0.313	0.279	0.186	0.17
Mass reacted (lbs)	0	0	0.047	0.044	0.07	0.117	0	0	0.074	0.091
Initial stored mass (lbs)	0	0	0	0	0	0	0	0	0	0
Final stored mass (lbs)	0	0	0	0	0	0	0	0	0	0
Continuity error (%)	-2.411	-2.534	-2.49	-2.598	3.509	2.142	-2.426	-2.593	4.323	3.884

Results	Biltmore_Rain_BMP1	Biltmore_Rain_BMP2	Biltmore_Rain_BMP3	Biltmore_Rain_BMP4	Biltmore_Rain_BMP5	Biltmore_Rain_BMP6	Biltmore_Rain_BMP7	Biltmore_Rain_BMP8	Biltmore_Rain_BMP9	Biltmore_Rain_BMP10
Max. subcatchment total runoff (Mgal)	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.005
Max. subcatchment peak runoff (cfs)	0.713	0.713	0.713	0.713	0.713	0.713	0.685	0.653	0.653	0.653
Max. subcatchment runoff coefficient	0.105	0.105	0.105	0.105	0.105	0.105	0.101	0.072	0.072	0.072
Max. subcatchment total precip (in)	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Min. subcatchment total precip (in)	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Total subcatchment runoff coefficient	0.044	0.044	0.044	0.044	0.044	0.044	0.043	0.036	0.036	0.036
Max. node depth (ft)	3.55	3.55	3.55	3.55	3.55	2.14	3.35	2.11	2.11	1.42
Num. nodes surcharged	1	1	1	1	1	1	1	1	1	1
Max. node surcharge duration (hours)	0.38	0.38	0.38	0.38	0.38	0.35	0.37	0.26	0.26	0.22
Max. node height above crown (ft)	2.546	2.546	2.546	2.546	2.546	1.137	2.348	1.114	1.114	0.416
Min. node depth below rim (ft)	0	0	0	0	0	0	0	0	0	0
Num. nodes flooded	1	1	1	1	1	0	1	0	0	0
Max. node flooding duration (hours)	0.16	0.16	0.16	0.16	0.16	0	0.13	0	0	0

Max. node flood volume (Mgal)	0	0	0	0	0	0	0	0	0	0
Max. node ponded volume (acre-in)	0.01	0.01	0.01	0.01	0.01	0	0.01	0	0	0
Max. storage volume (1000 ft³)	0.198	0.198	0.198	0.198	0.198	0.219	0.184	0.093	0.093	0.112
Max. storage percent full (%)	126	126	126	126	126	64	117	59	59	33
Max. outfall flow frequency (%)	30.54	30.54	30.54	30.54	30.54	30.58	30.44	29.19	29.19	29.19
Max. outfall peak flow (cfs)	0.63	0.63	0.63	0.63	0.63	0.62	0.63	0.63	0.63	0.64
Max. outfall total volume (Mgal)	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.009	0.009	0.009
Total outfall volume (Mgal)	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.009	0.009	0.009
Max. link peak flow (cfs)	0.93	0.93	0.93	0.93	0.93	0.93	0.91	0.77	0.77	0.77
Max. link peak velocity (ft/s)	6.16	6.16	6.16	6.16	6.16	6.16	6.12	5.83	5.83	5.83
Min. link peak velocity (ft/s)	0.91	0.91	0.91	0.91	0.91	0.89	0.89	0.9	0.9	0.89
Num. conduits surcharged	1	1	1	1	1	1	1	1	1	1
Max. conduit surcharge duration (hours)	0.41	0.41	0.41	0.41	0.41	0.38	0.39	0.28	0.28	0.27
Max. conduit capacity limited duration (hours)	0.41	0.41	0.41	0.41	0.41	0.38	0.39	0.28	0.28	0.27