Quality Assurance Project Plan

Control of Toxic Chemicals in Puget Sound Phase 3: *SUSTAIN* Modeling for Controlling Toxic Chemicals in Small Streams

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Phase 3: *SUSTAIN* Modeling for Controlling Toxic Chemicals in Small Streams

June 2012

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EAP: Environmental Assessment Program
SWMM: Stormwater Management Model
SUSTAIN: System for Urban Stormwater Treatment and Analysis Integration
BMP: Best management practices

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Abstract

The Washington State Department of Ecology (Ecology) is partnering with Herrera Environmental Consultants (Herrera) to test the newly-developed System for Urban Stormwater Treatment and Analysis Integration (*SUSTAIN*) model for identifying the most cost effective combination of best management practices (BMP) for reducing pollutants in stormwater runoff. This study is part of Phase 3 in a series of studies aimed at characterizing toxic chemical loading in the Puget Sound watershed, and identifying management strategies for reducing these loads. The ultimate goal of this study is to document the strengths and weaknesses of the *SUSTAIN* model for use by local jurisdictions in managing stormwater runoff. This quality assurance project plan (QAPP) discusses the project background and outlines the technical approach that will be used for this modeling.

SUSTAIN was developed by Tetra Tech Inc. for the Environmental Protection Agency (EPA). The *SUSTAIN* model runs in ArcGIS and is a system for modeling runoff and pollutant loads, routing them through physical models of BMPs, and optimizing treatment costs. This study applies the *SUSTAIN* model to a small (316.5 hectare) commercial/industrial catchment in the City of Federal Way. Water quality data collected by Phase 1 jurisdictions in the Puget Sound region pursuant to requirements of the Municipal Stormwater Permit will be used as a model input for estimating pollutant export from the catchment with stormwater runoff. Flow and water quality data collected at the outlet of the catchment in connection with the Phase 3 study of toxic loading in surface runoff to Puget Sound (Herrera 2011a) will also be used to calibrate the catchment's hydrology and water quality model. To overcome the limitations of the default national-level BMP costs database that comes with *SUSTAIN*, a database of BMP costs based on local project information will be developed for input to *SUSTAIN*.

Introduction

The Washington Department of Ecology (Ecology) is collaborating with the Puget Sound Partnership and other state and federal agencies to conduct scientific studies on toxic chemicals discharged to Puget Sound from surface runoff. In connection with Phase 3 of this effort, Herrera Environmental Consultants (Herrera) is partnering with Ecology and the City of Federal Way to develop a case study for assessing the capabilities and limitations of the newly-developed Urban Stormwater Treatment and Analysis Integration (*SUSTAIN*) model. This document is the Quality Assurance Project Plan (QAPP) for the modeling effort. This QAPP describes that technical approach that will be used in the development of this model including the input data, model configuration, and calibration procedures. It is organized to present information under the following major headings:

- **Background –** Explanation of why the project is needed.
- **Project Description –** Brief project summary and description of project goals and objectives.
- **Organization and Schedule –** Key personnel that are involved in the study and the schedule for completing major milestones.
- **Modeling Approach –** Overview of the technical approach that will be used for this study including a description of the selected study basin, target water quality parameters and stormwater best management practices (BMPs), and a summary of the general modeling framework and the BMP optimization approach.
- **SWMM Model Development –** Detailed description of the approach that will be used to develop and calibrate the Stormwater Management Model (SWMM) for the study; output from this model will be used for *SUSTAIN* model development.
- ***SUSTAIN* Model Development –** Detailed description of the approach that will be used to develop and calibrate the *SUSTAIN* model for the study.
- ***SUSTAIN* Model Optimization –** Modeling methods used to evaluate the most cost-effective suite of BMPs for reducing concentrations and loads of toxic chemicals in stormwater runoff from the study basin.

Background

Beginning in 2006, Ecology has been conducting studies to quantify the amount of toxic chemicals in the Puget Sound ecosystem and identify the primary sources. Each successive study (Phase) improved upon the estimates of previous studies by including additional potential contaminant sources (i.e., land uses), or by increasing the number of parameters analyzed, or the sensitivity of analysis methods. Phase 1 and Phase 2 studies relied on existing data from literature sources. These two phases identified surface runoff as the primary source of toxic chemicals to Puget Sound relative to wastewater treatment plants, groundwater, spills, combined sewer overflows, and atmospheric deposition. A Phase 3 study of toxic chemicals in surface runoff was subsequently implemented to improve upon the Phase 1 and 2 loading estimates and to advance understanding of the timing and sources of contaminant loading in the Puget Sound ecosystem by collecting and analyzing new local data on:

- Concentrations of toxic chemicals in 16 streams receiving surface runoff during storm events and periods between storms (baseflow)
- Concentrations of toxic chemicals associated with four specific land-use types (i.e., commercial/industrial, residential, agricultural, and forest/field/other [forest])
- Relative contributions of toxic chemicals in surface runoff (based on loadings) from the four major land-uses identified above

Results from the Phase 3 study (Herrera 2011a) confirmed several land use- and event-based patterns in the concentration data and load estimates:

- The detection frequency for each of the chemical classes was generally higher for samples collected during storm events than those collected in baseflow conditions. Likewise, the magnitude of concentrations for each chemical class was higher during storm events.
- Contaminants were generally detected more frequently and at higher concentrations in the commercial/industrial basins compared to the other land uses.
- Agricultural and residential stormwater also contained higher concentrations of many toxic chemicals than stormwater from forested lands.
- The fall storm generally had the highest incidence of oil and grease, lube oil total petroleum hydrocarbons, triclopyr, and other contaminants.
- At the Puget Sound scale, relative loads for most parameters were proportional to the relative areas covered by each land use.

Building on these findings, Ecology is now implementing this additional Phase 3 study as part of an overall strategy to identify effective management options and tools for reducing toxic chemicals in surface runoff. The *SUSTAIN* model has specifically been identified as a potential tool that could be used by local jurisdictions to identify the most cost-effective suite of best management practices (BMPs) for reducing concentrations and loads of toxic chemicals in stormwater runoff.

At present, there are a limited number of *SUSTAIN* modeling applications that have been completed or are ongoing. For example, Tetra Tech completed a stormwater management plan alternatives analysis for three communities affected by the Lower Charles River Phosphorus Total Maximum Daily Load (Tetra Tech 2009). In connection with this project, Tetra Tech used BMPDSS, a precursor to *SUSTAIN*, to develop estimates of optimized BMP implementation costs. Shoemaker et al. (2009) describes the *SUSTAIN* simulation modules and system components and then presents two hypothetical case studies as a proof-of-concept and a template for model application. Finally, Shoemaker et al. (2012) presents results from two case studies where the *SUSTAIN* was used to evaluate actual management strategies in Kansas City, MO and Louisville, KY. Those two case studies also outline key analytical components and provide a template for *SUSTAIN* problem formulation.

In the Puget Sound region, King County is currently partnering with the University of Washington to develop a *SUSTAIN* model for a study area that includes the Green / Duwamish River and central Puget Sound watersheds in WRIA 9, excluding the area upstream of the Howard Hanson Dam and the City of Seattle (King County 2011). This model will be used to generate a cost estimate and prioritization plan for systematically implementing stormwater BMPs and LID techniques in previously developed areas of WRIA 9. In-stream flow and water quality goals will be developed, and the combination of retrofits needed will be optimized to meet the in-stream goals at minimum cost. Planning level cost estimates for the Puget Sound basin will also be developed via extrapolation. This work will ultimately support planning efforts for implementing stormwater retrofits in developed areas pursuant to the Action Agenda for Puget Sound.

Project Description

This project involves the development of a case study for using the newly-developed *SUSTAIN* model to evaluate toxic chemical loading reduction strategies in the Puget Sound region. From the information that is currently available on the *SUSTAIN* model, it appears to be a promising tool for local jurisdictions in the Puget Sound region that are planning toxic chemical control strategies for surface runoff. However, before encouraging widespread adoption of the *SUSTAIN* model, it is necessary to test the model's capabilities and limitations.

Working with Ecology and the City of Federal Way, Herrera will development a *SUSTAIN* model for one of the 16 drainage basins that was monitored for the Phase 3 study of toxic loading in surface runoff to Puget Sound. To the extent possible, this will be a "real world" application of the model with the modeled BMPs scenarios selected based on development and design standards that have been adopted by the City of Federal Way (King County 2009; PSAT 2005). Results from this modeling will be summarized in a project report. As part of the report's review and publication, Ecology and Herrera will also host a half-day workshop to present "lessons learned" on the *SUSTAIN* model from this case study.

One known limitation of the *SUSTAIN* model for its application in the Puget Sound region is that the default BMP cost database that is built into the model only includes data from national sources. With this limitation in mind, a parallel effort related to this study will be the development a regional BMP cost database that can be used for *SUSTAIN* modeling applications in the Puget Sound region and as a stand-alone source of cost information for other regions of the country.

Organization and Schedule

Ecology will provide technical oversight for this study, quality assurance review, and report review. Herrera will be the study lead and oversee the development of this QAPP. The City of Federal Way is a partner in this study and will be providing direct input on the BMP scenarios that will be modeled through this effort. Key staff members from each of these entities are shown in Table 1 with their roles. The schedule for completing key project deliverables is shown in Table 2.

Table 1. Organization of project staff and responsibilities.

Staff	Title	Responsibilities
Mindy Roberts Washington Department of Ecology (360) 407-6804	Department of Ecology project manager	Develops and oversees all project-related activities. Provides technical guidance and oversight to aid model development and subsequent refinement. Reviews and approves the QAPP.
Will Appleton City of Federal Way Public Works Department (253) 835-2750	City of Federal Way project coordinator	Point of contact for the City of Federal Way input on model development.
John Lenth Herrera Environmental Consultants (206) 441-9080	Contractor project manager	Oversees all technical work related to the project. Coordinates all activities of the contractor project team. Tracks progress on deliverables relative to the project schedule and budget.
Alice Lancaster Herrera Environmental Consultants (206) 441-9080	Modeling lead	Oversees all technical work related to modeling for the project.
Meghan Feller Herrera Environmental Consultants (206) 441-9080	SWMM modeling lead	Oversees all technical work related to SWMM modeling for the project.
Peter Steinberg Herrera Environmental Consultants (206) 441-9080	*SUSTAIN* modeling lead	Oversees all technical work related to *SUSTAIN* modeling for the project.
Rebecca Dugopolski Herrera Environmental Consultants (206) 441-9080	BMP cost database lead	Oversees compilation and review of BMP cost data for the BMP cost database.
Jennifer Schmidt Herrera Environmental Consultants (206) 441-9080	GIS and database lead	Provides GIS and database support for the project.

BMP: Best Management Practice
GIS: Geographic Information System
SWMM: Stormwater Management Model
SUSTAIN: Urban Stormwater Treatment and Analysis Integration
QAPP: Quality Assurance Project Plan

Table 2. Schedule for completing modeling work and reports.

Deliverable	Draft to Ecology	Draft to External Review	Final to Ecology
Quality Assurance Project Plan	11/11/2011	12/16/2011	4/20/2012
BMP Costs Database with Cover Memo	11/09/2011	11/18/2011	12/02/2011
SUSTAIN application inputs and output files			6/30/2012
Report summarizing the *SUSTAIN* model calibration and application	6/30/2012	8/15/2012	9/30/2012
Workshop overview of *SUSTAIN* application			(coincident with external review)

BMP: Best Management Practice

SUSTAIN: Urban Stormwater Treatment and Analysis Integration

Modeling Approach

This section provides an overview of the technical approach for identifying the most cost-effective suite of BMPs for achieving target management goals in the study basin. It includes a description of the rationales for study basin, water quality parameters, and treatment BMP selection. A subsequent subsection describes the overall framework for the hydrologic, hydraulic and water quality modeling. Finally, the specific management goals that will be evaluated using the *SUSTAIN* model are identified.

Study Basin Selection

A *SUSTAIN* model will be developed for one of the 16 drainage basins monitored under the Phase 3 study of toxic loading in surface runoff to Puget Sound. The selected basin is a mixed land use basin (CBB) with a large portion of commercial/industrial land use in the Puyallup River watershed (Figure 1). This 316.5-hectare basin is located in Federal Way, Washington, and includes a majority of the downtown core of the City of Federal Way from just west of Pacific Highway S to I-5 stretching from S 312th St. to S 343rd St. Commercial/industrial land use represents 46.8 percent of the land area in the basin. The remaining area is predominantly residential (44.5 percent) with a small portion of forest land use (8.7 percent) (see Table 3). The drainage basin discharges to an unnamed tributary to West Hylebos Creek.

Table 3. Land use breakdown for commercial/industrial basin CBB.

Land Use	Study Basin Area (hectares)	Study Basin % of Total Area
Residential	140.9	44.5%
Forest	27.5	8.7%
Commercial/Industrial	148.1	46.8%
Total	**316.5**	

Although residential land use represents a majority of the developed land use in the region and contributes a relatively high percentage of the total load of toxic chemicals to Puget Sound, a commercial/industrial basin was selected for modeling in this study since streams draining this land use exhibited the highest concentrations of organic pollutants and metals compared to the other land uses. Therefore, identifying effective management actions for commercial/industrial areas is expected to be a high priority in efforts to reduce toxic loading to Puget Sound.

Basin CBB was specifically selected over the other three commercial/industrial basins that were sampled for the Phase 3 study of toxics loading in surface runoff because it generally had the highest quality flow data based on reviews quality assurance data (e.g., rating curve standardized root mean square and sensor calibration checks). High quality flow data is required for model calibration efforts in this study. Furthermore, samples collected from basin CBB for the Phase 3 study of toxic loading in surface runoff had relatively high concentrations of the water quality parameters that will be targeted for modeling in this study (see discussion in the section below).

Finally, staff from the City of Federal Way were also interested in supporting this study and are providing relevant GIS data, guidance on BMP selection, and reports and electronic files from previous modeling efforts in the selected basin.

Study Water Quality Parameter Selection

This study will evaluate optimum BMP configurations in basin CBB for reducing concentrations and loads of total suspended solids, total and dissolved copper, total and dissolved zinc, and chrysene. As noted above, these parameters were detected frequently in samples collected from basin CBB and are common stormwater pollutants for which water quality treatment BMPs are being applied in the region.

Best Management Practice Selection

The intent of this effort is to develop a case study for the *SUSTAIN* model based on a "real world" application. To that end, City of Federal Way and Herrera staff met on December 5, 2011, to discuss the selection and applications of BMPs for this modeling effort based on the City's stormwater management goals and current stormwater manuals (King County 2009; PSAT 2005). At the meeting, it was determined that two retrofit scenarios will be evaluated: Scenario 1 will limit retrofit options to publicly-owned roadside (right-of-way) applications and regional facilities, while Scenario 2 will include private property retrofits in addition to roadside and regional facilities. Based on the discussion at this meeting, the following BMPs in *SUSTAIN* will be considered in this modeling effort:

- Bioretention – roadsides (Scenario 1 and 2) and public and private parcels (Scenario 2)
- Permeable Pavement – public and private parking lots (Scenario 2)
- Constructed Wetland – supplement existing regional pond (Scenario 1 and 2)
- Wet Pond – expand existing regional pond (Scenario 1 and 2)

There are several existing regional detention facilities in the basin. At least two of these facilities, including one near the outlet of the basin (Kitts Corner/S 336th St. Regional Stormwater Detention Facility) and one south of South 324th Street in the basin (Belmor Regional Storage Facility) will be explicitly modeled. The regional retrofit options considered will include expansion of the Kitts Corner wet pond and installing a new pre-treatment facility such as a constructed wetland upstream of the Kitts Corner detention facility. These alternatives will be evaluated based on potentially available land and will include an estimated cost for obtaining this land. Inclusion of these regional BMP facilities was considered important for comparison to the distributed stormwater BMPs (bioretention and permeable pavement) that will be evaluated as part of this modeling effort.

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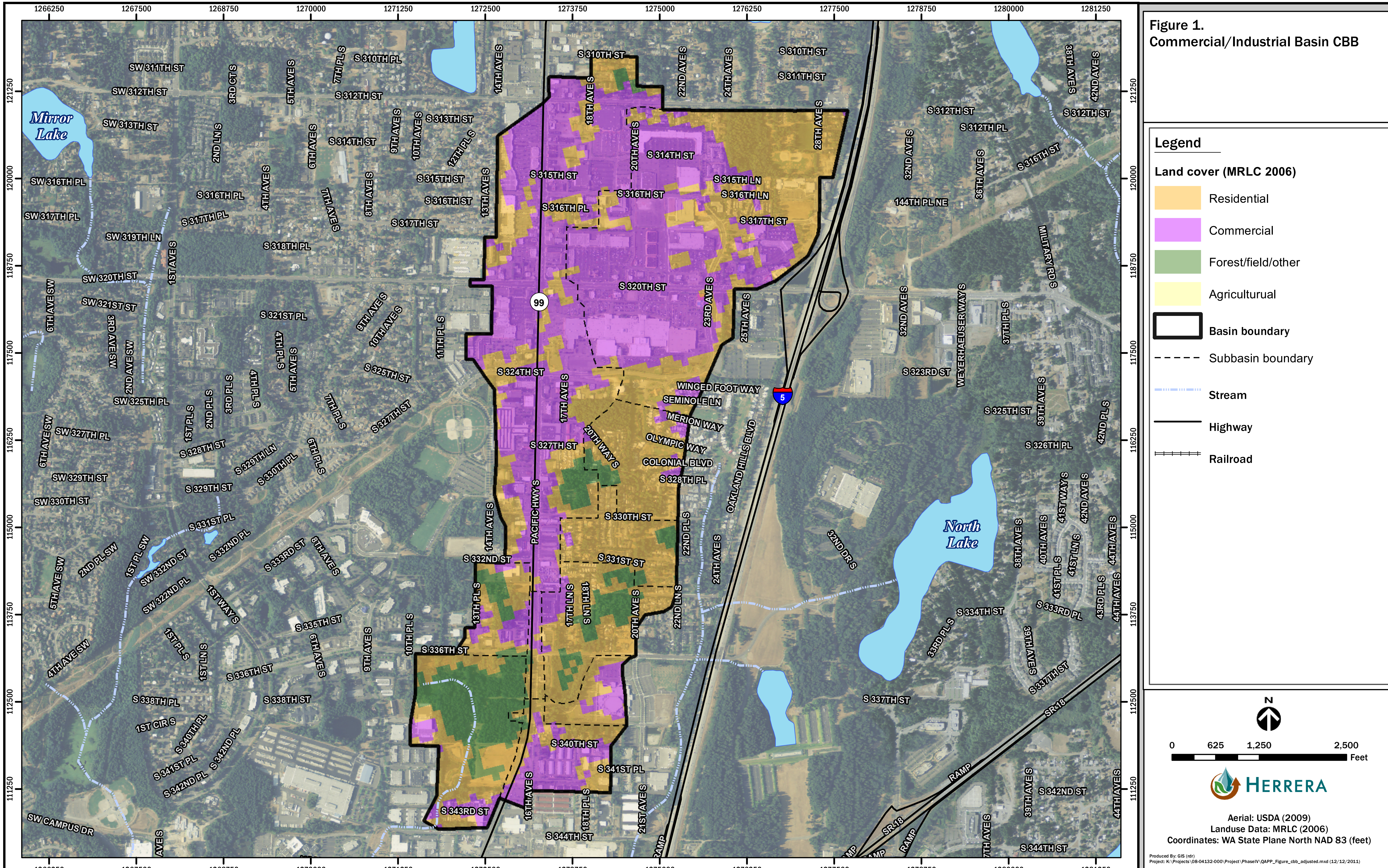

Figure 1.
Commercial/Industrial Basin CBB

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The rationale for excluding additional BMPs from this modeling effort is provided below:

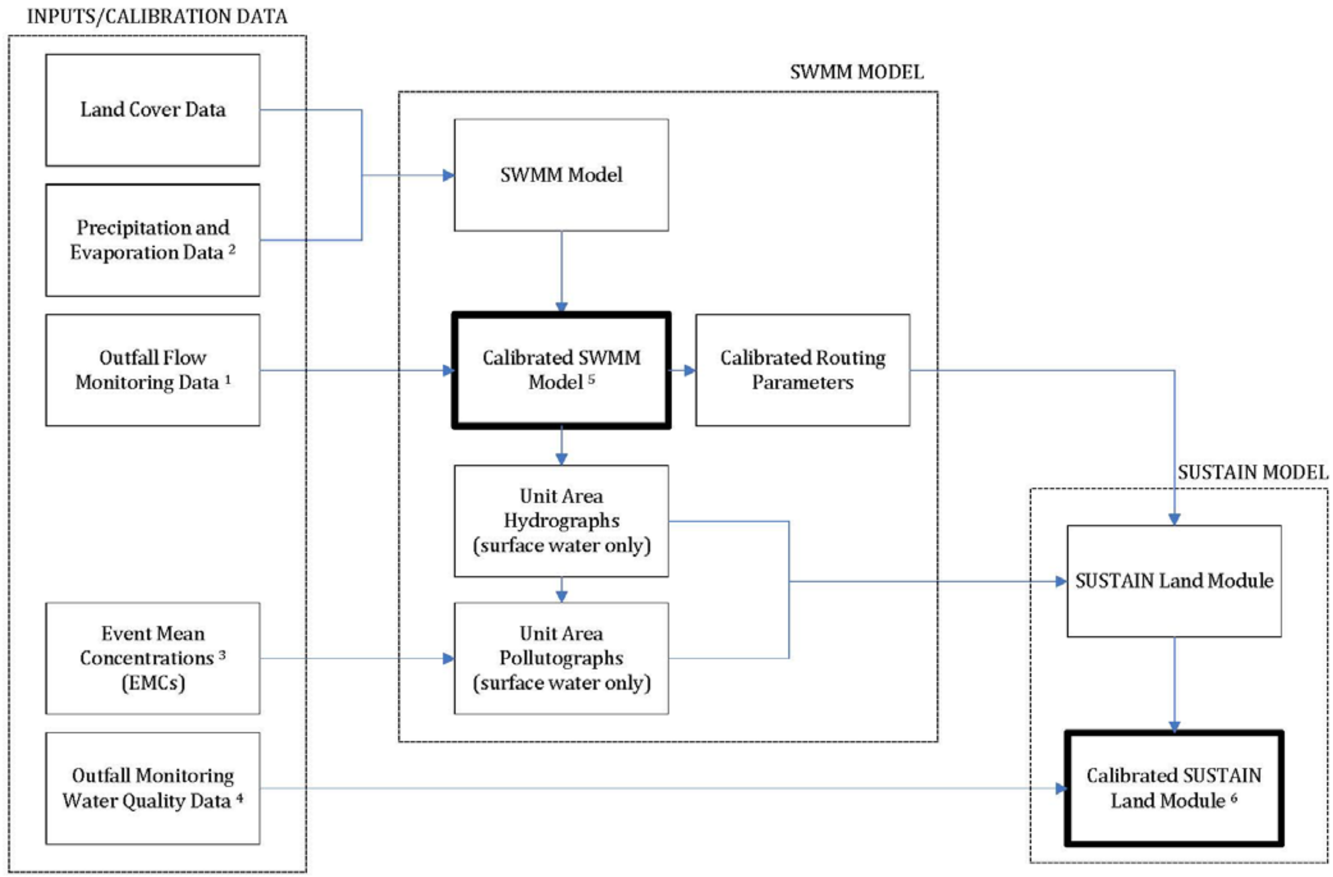
- Cisterns, rain barrels, and green roofs were excluded for this modeling effort because they do not provide a high level of water quality treatment and are more applicable to private property retrofits.
- Vegetated filterstrips were excluded because the module for this BMP is not yet fully functional in *SUSTAIN*.

Modeling Framework

Under the current *SUSTAIN* model structure, subcatchment hydrology must be simulated externally when using *SUSTAIN's* aggregate BMP approach (see description in *SUSTAIN* Model Development section). For this project, an external SWMM model will be developed to simulate hydrographs for the study basin. These hydrographs will subsequently be imported into the *SUSTAIN* model. This section describes the linkages between the two models and provides a step-by-step process of the modeling approach.

The general steps for model development and calibration are listed below and illustrated in Figure 2.

1. Build SWMM model to simulate runoff and routing for study basin.
2. Calibrate SWMM model runoff volume and timing to flow monitoring data collected at station CBB (Figure 1) for Phase 3 study for the calibration period (August 2009 to September 2010).
3. Using calibrated SWMM model, develop unit area surface water hydrographs (not including stream baseflow) to characterize runoff from each subcatchment by land use and land cover for the calibration period.
4. Develop unit area pollutographs for the calibration period by applying event mean concentrations (EMCs) from each land use to the hydrographs.
5. Build *SUSTAIN* land and conveyance modules using unit area hydrographs, pollutographs, and calibrated routing parameters from SWMM model for the calibration period.
6. Compare runoff files from calibrated SWMM model to those from *SUSTAIN* to confirm that the flow calibration has been maintained.
7. Calibrate *SUSTAIN* conveyance module and detention facility decay functions using water quality data measured at station CBB (Figure 1) for the Phase 3 study of toxics loading in surface runoff to Puget Sound.



1. Flow monitoring data at station CBB from Phase 3 study of toxics loading to Puget Sound (August 2009 to July 2010).
2. Precipitation and evaporation data from local monitoring station for period of Phase 3 monitoring (August 2009 to July 2010).
3. EMCs for commercial, high density residential, and low density residential land use based on Phase I permit outfall monitoring.
4. Water quality data (measured concentrations and pollutant load estimates) at station CBB (Figure 1) from Phase 3 study of toxics loading to Puget Sound (August 2009 to July 2010).
5. Calibrate to flow monitoring data. Target calibration parameters: land cover characteristics and routing elements.
6. Calibrate surface water flow water quality concentrations. Target calibration parameters: decay rate in detention facility and routing elements.

Figure 2. *SUSTAIN* model calibration process.

The steps for the evaluation of BMP scenario performance and optimization are listed below and illustrated in Figure 3.

1. Repeat steps 3 and 4 from list above to develop hydrographs and pollutographs for a longer period of record. If model runtime is not limiting, a 30-year time series will be used. If model runtime is limiting, a shorter duration representative time series will be selected for modeling.

2. Input long-term hydrographs and pollutographs into the calibrated *SUSTAIN* model.

3. Build *SUSTAIN* BMP module and integrate with land and conveyance modules.

4. Use calibrated *SUSTAIN* model to optimize placement of water quality treatment BMPs across basin based on performance and cost.

Management Targets

Based on discussions between City of Federal Way and Herrera staff at the December 5, 2011 meeting referenced above, the following management targets were identified for evaluating the cost effectiveness of different BMP scenarios using the *SUSTAIN* optimization module:

- Identify the most cost effective BMP configuration in basin CBB to meet State acute and chronic water quality standards for both dissolved copper and zinc, and national recommended water quality standard for chrysene to protect human health.

- Construct a cost-effectiveness curve that relates different BMP configurations to TSS load reductions in basin CBB.

- The optimized model for each water quality management target will also be evaluated for ancillary flow control benefits including runoff volume and peak flow reduction. For example, total runoff volume for the simulation period and selected peak flow values will be evaluated for both the existing condition (i.e., without BMPs) and the optimized condition (i.e., with BMPs). If it is possible to use a long-term precipitation time series (i.e., the 158-year extended series), the 2-, 10-, 25-, and 50-year recurrence interval flows will be calculated and compared. If a shorter time series is used, the peak runoff rates from selected storm events will be compared.

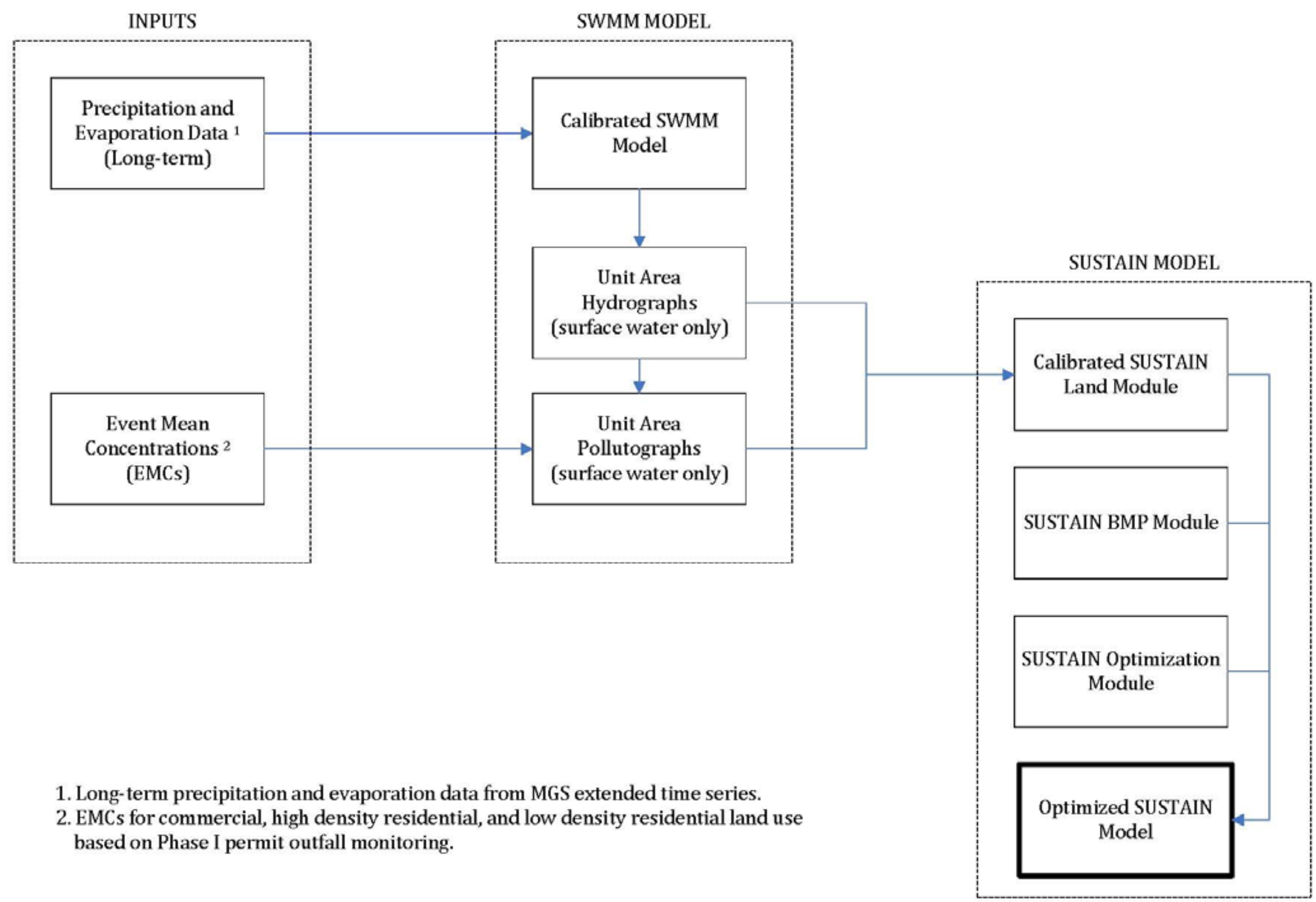


Figure 3. BMP performance optimization process.

SWMM Model Development

USEPA Storm Water Management Model (SWMM) Version 5.0.022 will be used to simulate the hydrology and hydraulic routing for the study basin. SWMM is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of subcatchment areas on which rain falls and runoff is generated. The routing component of SWMM transports this runoff through a conveyance system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period. The input and calibration data for the runoff and routing model components are provided below.

Input Data

The following input data are required for the SWMM model; a brief discussion of each element follows:

- Precipitation and evaporation data
- Drainage area
- Subcatchment width (shape factor) and slope
- Imperviousness
- Surface roughness
- Depression storage
- Soil infiltration parameters
- Routing data

The model will be developed using inputs from a previously developed SWMM model (documented in a report by CH2M Hill [1994]), Federal Way GIS data, and Federal Way record drawings documenting modifications to the basin and drainage network since original SWMM model development. Changes in land use within the study area over the nearly twenty year period since original model development were assessed using aerial imagery from 1990 and 2011. To represent the current basin conditions and calibrate the model, inputs may be refined based on the approaches described below.

Precipitation and Evaporation Data

Two distinct precipitation and evaporation data sets will be used in this analysis; the first will be used to calibrate the SWMM model, the second to evaluate BMP performance over a longer duration. Precipitation and evaporation data from the King County Lake Dolloff Precipitation Monitoring Station 41v will be used for calibration of the SWMM model. The mean annual precipitation at the gage, based on record data from 1989 to 2011, is 40.2 inches. Study basin mean annual precipitation, based on PRISM data from 1971 to 2000, is slightly higher, totaling 42.8 inches. The City of Federal Way may also have rain data collected closer to the study basin, at Federal Way City Hall, and, if so, these data will be checked for quality and possibly used to assist calibration of timing and storage of runoff.

Once the SWMM model has been calibrated, a truncated version of the extended precipitation and evaporation time series, developed by MGS Engineering Consultants, Inc. (MGS 2002), will be used to evaluate BMP performance. The extended, 158-year series were developed by combining hourly records from high-quality precipitation measurement stations including records from Seattle Washington, Vancouver British Columbia, and Salem Oregon. These series were combined and rescaled to replicate the storm characteristics representative of the Puget Sound lowlands. The study basin (Figure 1) is located in the eastern Puget Sound lowlands and receives an average of 42.8 inches of precipitation annually. To develop a long-term precipitation and evaporation series for the site, the MGS extended time series for mean annual precipitation depths of 40 and 44 inches will be interpolated. This extended series will be truncated to a 30-year timeframe to reduce runtime in *SUSTAIN*.

Drainage Area

The 316.5-hectare (782.1-acre) study basin (Figure 1) will be subdivided into a series of smaller subcatchments, connected via an explicitly represented conveyance network. This network will route flows from each subcatchment to the monitoring location at the bottom of the study basin. Routing within subcatchments will be neglected in the model.

Subcatchment delineation will follow Federal Way's existing drainage basin network, resulting in ten subcatchments ranging in size from approximately 8 to 250 acres. The existing drainage basin boundaries result in subcatchments with relatively low heterogeneity in land use type. Because of this, and for ease of model development, each subcatchment will be assigned a single land use type (e.g., commercial/industrial, low-density residential, high-density residential) based on prevailing land use designation.

Subcatchment Width and Slope

Subcatchment width is defined as the subcatchment area divided by the overland flow path length. Because there has been very little development in the basin since the 1994 SWMM model was developed, this effort will use the subcatchment widths and slopes from the original model.

Imperviousness

Subcatchment imperviousness (i.e., percent of the subcatchment composed of impervious surface) will be assigned based on estimates from the original SWMM model. A GIS analysis of land cover type within each subcatchment will also be conducted based on the Multi-Resolution Land Characterization (MRLC) 2006 National Land Cover Database (NLCD) (Fry et al. 2011) to ensure that these estimates are representative of current basin conditions.

Surface Roughness

Manning's n values are used by the runoff module for the routing of overland flows. Separate roughness coefficients are applied to pervious versus impervious surfaces. Typical values are as follows:

- *Impervious:* 0.015 (dimensionless)

- *Pervious:* 0.250 (dimensionless) or higher in heavily vegetated areas

Manning's n values will be assigned based on estimates from the original SWMM model. A GIS analysis of land cover type within each subcatchment will also be conducted based on land cover delineations from the 2006 NLCD (Fry et al. 2011) to ensure that surface roughness estimates are representative of current basin conditions. To better represent variability in pervious Manning's n values, lawn/landscape and forested areas will be characterized independently. These values will be represented as an area-weighted average Manning's n, variable by subcatchment.

Depression Storage

Depression storage (ds) refers to the storage depth associated with surface depressions that are filled prior to runoff. The potential depression storage is related to the surface roughness coefficient; thus, separate values are required for pervious and impervious surfaces. Typical values are as follows:

- *Impervious*: ds = 0.1 inch
- *Pervious*: ds = 0.2 inch

Depression storage values will be assigned based on a GIS analysis of land cover type within each subcatchment. Evaluation will include land cover delineations based on the 2006 NLCD (Fry et al. 2011). To better represent variability in pervious surface depression storage, lawn/landscape and forested areas will be characterized independently. These values will be represented in the model as an area-weighted average depression storage value, variable by subcatchment.

Soil Infiltration

Infiltration of rainfall on the pervious areas of a subcatchment into the unsaturated upper soil zone will be simulated using the Horton infiltration method. This method assumes that soil infiltration capacity decays exponentially with time, from an initial, maximum infiltration rate to a final, constant rate. The input parameters required are the initial and final infiltration rates and a decay constant. Each of these parameters will be based on values from the original SWMM model.

Routing Data

The SWMM routing module uses continuous surface runoff data generated by the runoff module as input to simulate hydraulic conditions in open ditches or closed conduit. The study basin conveyance network is primarily composed of a piped storm drainage network with minimal open ditch conveyance. The piped network will be modeled based on inputs from the previously developed SWMM model, Federal Way GIS data, and Federal Way record drawings documenting modifications to the basin and drainage network since original SWMM model development. The open ditch network will be characterized based on aerial imagery, a digital elevation model, and the existing piped conveyance network.

Detention Facilities

The SWMM model allows the user to explicitly model detention or other storage facilities within a given drainage network. The study basin (CBB) contains two regional detention ponds and several smaller detention ponds and vaults distributed across the basin. For the purposes of this modeling effort, the two larger regional detention ponds will be modeled explicitly in SWMM (i.e., facilities governed by stage-storage curves, multi-stage outlet structures) per the City of Federal Way record drawings. The remaining, smaller detention facilities will be aggregated on a subcatchment basis and modeled as additional depression storage in the subcatchment. If this method does not sufficiently explain the variability in the modeled and observed hydrographs, in particular the timing and recession of peak flows, these smaller detention facilities will be explicitly modeled as storage units in SWMM, located at the outlet of the corresponding subcatchment. These approaches will simplify the modeling effort while still maintaining the hydrologic integrity of the drainage system.

Calibration Data

Streamflow generated in the model will be calibrated to measured streamflow data collected for the Phase 3 study of toxics in surface runoff at the bottom of the study basin (Figure 1). Precipitation and evaporation data from the Lake Dolloff station will be used for calibration for the period of available monitoring data as explained above. The model will be calibrated to match the timing, magnitude, and total volume of the field-observed streamflow data by varying loss and conveyance input parameters.

To simplify the calibration routine, a subset of model inputs will be used as calibration parameters for the SWMM model. The Tier 1 calibration parameters, outlined in Table 4, will be used to calibrate the model. In the event these parameters do not sufficiently explain variability in the runoff series from the Phase 3 study of toxics in surface runoff, the Tier 2 parameters will be considered for calibration.

Each parameter will be assigned a default value (based on inputs from the original SWMM model, GIS analysis and/or literature review) and variable bounds (based on the expected range of results and the estimated degree of uncertainty in the calibration parameter). Each parameter will be allowed to vary within the defined bounds in an effort to optimize the model. Goodness of fit will be determined based on three metrics: peak flow rate, peak flow timing, and total volume. The accuracy of the model calibration will be quantified based on the calculated root mean square error for the modeled and the observed flows.

Table 4. SWMM calibration parameters.

Variable	Units	Description
Hydrologic		
Tier 1		
Dstore-Imperv	in	Depth of depression storage on impervious area
Dstore-Perv	in	Depth of depression storage on pervious area
N-Imperv	[unitless]	Manning's n for impervious area in subcatchment
N-Perv	[unitless]	Manning's n for pervious area in subcatchment
Tier 2		
% Slope	%	Average surface slope of subcatchment
% Zero-Imperv	%	Percent of impervious area with no depression storage
Hydraulic		
Tier 1		
Roughness	[unitless]	Manning's n for conduit/channel
Bottom Width	ft	Channel bottom width
Max. Depth	ft	Conduit/channel maximum flow depth
Tier 2		
Length	ft	Conduit/channel length
Sideslopes	H:V	Channel sideslopes
Invert El.	ft	Inlet and outlet invert elevation (conduit/channel slope)

Computational Timestep Considerations

SWMM model runoff will be evaluated at an hourly computational timestep. Routing within the model will be evaluated at a finer timestep to maintain numerical stability within the kinematic wave routing approximations. Five to 15 minute computational timesteps are typically sufficient for this type of analysis. In the event model continuity error is excessively high (e.g., greater than approximately 10 percent), computational time steps for surface runoff, flow routing, or both, may be reduced.

Hydrograph Development

The *SUSTAIN* land module requires unit area runoff hydrograph inputs to represent externally simulated basin hydrology. These hydrographs can be developed to represent a variety of physiographic basin properties (e.g., topography, soil type, land use). The study basin is characterized as commercial/industrial, high-density residential, and low-density residential land use; composed of impervious, lawn/landscape, and forested land cover types. For each subcatchment, unit area hydrographs will be developed for impervious and lumped pervious land cover only. Since the main objective of the project is to evaluate pollutant reduction strategies and the resolution of available water quality data is limited to land use designated EMCs, it is likely not necessary to develop independent hydrographs for lawn/landscape and forest areas.

The calibrated SWMM model will be used to develop two additional independent models for the generation of pervious and impervious unit area hydrographs. These independent models will maintain the spatial (e.g., basin area, slope, and width) and hydraulic (e.g., channel geometry, slope, and roughness) integrity of the original SWMM model, but will represent two hypothetical basin conditions: 100 percent impervious subcatchments and 100 percent pervious subcatchments. The runoff hydrographs generated for each subcatchment will be divided by the total subcatchment area to develop a set of pervious and impervious unit area hydrographs to be input into the *SUSTAIN* model.

The first series of unit area hydrographs will be developed for the calibration period of record (August 2009 to September 2010). These hydrographs (and corresponding pollutographs) will be used to calibrate in-stream and detention facility decay rates for pollutant loading within *SUSTAIN*. A second series of unit area hydrographs will be developed using the 30-year truncated MGS precipitation time series. These unit hydrographs will serve as the basis for analysis of BMP scenario performance and cost effectiveness in *SUSTAIN*.

To evaluate how well the simplified unit area hydrograph approach represents CBB hydrology, pervious and impervious unit area hydrographs for the calibration period will be scaled and compared to the original (mixed land cover) SWMM model hydrographs. Pervious and impervious unit area hydrographs will be multiplied by the corresponding land cover areas for each subcatchment. The resulting hydrographs will be summed over the calibration period to develop total runoff hydrographs for each subcatchment and compared to the original calibrated SWMM model to estimate error introduced.

Pollutograph Development

To develop pollutographs for the *SUSTAIN* model, the hydrographs developed using SWMM will be multiplied by representative pollutant EMCs. EMCs will be derived from monitoring performed by Phase 1 jurisdictions in the Puget Sound region pursuant NPDES Municipal Stormwater Permit requirements. Because it is difficult to separate and monitor runoff from various land cover types in a developed (mixed use) setting, the Phase I NPDES monitoring study results provide pollutant concentrations for typical landuse mixes (e.g., low-density residential). For the study basin, each subcatchment will be assigned a land use designation according to the development thresholds adopted by King County in their Phase 1 Municipal Permit QAPP (King County 2010). Thresholds are summarized in Table 5. Based on this land use designation, corresponding EMCs (i.e., commercial, high-density residential, or low-density residential EMCs as defined in Table 6) will be applied to runoff for all landcover types within each subcatchment (i.e., impervious, lawn/landscape and forest/field).

Table 5. Land use category characteristics.

Land Use Category	Characteristics
High-Density Residential	Four dwelling units per acre or greater
Low-Density Residential	One dwelling unit per 1 to 5 acres
Commercial	Includes multi-family residential

Table 6. Initial compilation of event-mean concentrations for commercial, low-density residential and high-density residential land uses from monitoring conducted by Phase 1 Municipal Stormwater Permittees (WY2009-2010).

Parameter	Units	Commercial	High-density Residential	Low-density Residential
TSS	mg/L	75.4	50.99	18.98
Total Copper	ug/L	28.42	10.06	3.08
Dissolved Copper	ug/L	11.06	4.1	2.26
Total Zinc	ug/L	124.45	61.49	23.1
Dissolved Zinc	ug/L	57.04	32.21	18.83
Chrysene	ug/L	0.12	0.04	0.12

Source: Roberts, personal communication, December 8, 2011.

µg/L: micrograms per liter; mg/L: milligrams per liter

While it is possible to simulate pollutographs in SWMM, this option was not selected because of a lack of calibration data for buildup and washoff in the study basin. Having only several concentration data points at the mouth of the basin, it is not possible to calibrate the buildup and washoff, and detention facility and in-stream decay rates, simultaneously. The other factor limiting the applicability of buildup and washoff equations is the fact that Municipal Stormwater Permit monitoring data are event mean concentrations.

Once pollutographs are loaded into *SUSTAIN*, pollutant concentration data at the mouth of the basin will be used to calibrate *SUSTAIN*'s detention facility and in-stream decay rates.

SUSTAIN Model Development

SUSTAIN version 1.0 will be used to simulate pollutant transport and removal throughout the study basin. The model will also support the selection and placement of BMPs to determine the most cost effective strategies for achieving target water quality objectives. The model is composed of a series of framework components, all accessible via *SUSTAIN*'s Framework Manager (an ArcGIS extension). These components include a BMP siting tool; a watershed runoff module, a routing module; a BMP simulation module; a BMP cost database; a post-processor; and an optimization module.

Separate subsection below describe the *SUSTAIN* modules in more detail including the data required for implementation and calibration in this study. Runtime considerations related to model are also summarized in a separate subsection.

Land Simulation Module

The *SUSTAIN* land module represents basin hydrology and water quality. For this study, rainfall-runoff response and pollutant loading will not be explicitly modeled in *SUSTAIN*; rather the model will rely on externally developed hydrographs and pollutographs to characterize the land module.

Hydrology Component

Runoff hydrographs will be generated in an externally calibrated SWMM model of the study basin as described in the section above. Unit area hydrographs for impervious and pervious land cover type will be imported into *SUSTAIN* for each subcatchment.

Water Quality Component

Pollutographs will be generated using unit area hydrographs and EMCs for commercial, high-density, and low-density residential land uses. These will be imported into *SUSTAIN* for each subcatchment in the study basin (see SWMM Model Development section).

Conveyance Module

The conveyance module routes hydrographs and pollutographs from the land and BMP modules, through the model drainage routing network (e.g., conduits, open channels). Kinematic wave routing will be used for this study.

Flow and pollutant routing in *SUSTAIN* are simulated using algorithms from SWMM (version 5). Therefore, the routing parameters calibrated in SWMM (conduit/channel dimensions, longitudinal slope and roughness) can be directly applied to the *SUSTAIN* conveyance routine, so that hydrographs can be incorporated directly.

This model will be used to calibrate the pollutant decay rate in detention facilities and conveyance features (e.g., streams and channels). Decay rate parameters will be calibrated until simulated concentrations match observed concentrations from the Phase 3 study of toxics in surface runoff (Herrera 2011a). For reference, the concentrations observed at the monitoring station for the Phase 3 study (Figure 1) are provided below in Table 7. The skill of the model calibration will be quantified based on comparisons of the median concentration from the modeled time series to the median concentrations for each parameter that are reported in Table 7.

BMP Module

BMP Module information on each BMP (dimensions, substrate properties, growth index, water quality parameters, unit costs, and sediment information) must be entered in the BMP module. This section describes the input assumptions for the six BMP types that were selected for evaluation for this modeling effort.

Input Data

For each BMP, the user is required to enter the following inputs:

- BMP dimensions and substrate (soil and underdrain media) properties
- Pollutant removal
- Cost for each functional component of the BMP

These input data are described in separate subsections below.

BMP Dimensions and Substrate Properties

The assumptions for the BMP dimensions and substrate (soil and underdrain media) properties were developed based on a review of the King County Surface Water Design Manual (King County) and the LID Technical Guidance Manual for Puget Sound (PSAT 2005) which have been adopted by the City of Federal Way. The information contained in these manuals was used in combination with professional judgment from past modeling efforts to develop a list of input assumptions that are summarized in Table 8.

Table 7. Summary statistics for total suspended solids, total and dissolved zinc, total and dissolved copper, and chrysene concentrations in storm event samples collected from commercial/industrial basin CBB.

Parameter	Units	n	Percent Detected (%)	Reporting Limit Minimum	Reporting Limit Maximum	Mean	Median	Minimum	25th Percentile	75th Percentile	Maximum	Inter Quartile Range
Total Suspended Solids	mg/L	6	100%	1	4	8.17	9	3	6	10	12	4
Total Copper	ug/L	6	100%	0.1	0.1	3.99	3.71	2.74	3.15	4.72	5.9	1.57
Dissolved Copper	ug/L	6	100%	0.10	0.10	2.74	2.66	1.81	2.40	3.02	3.88	0.62
Total Zinc	ug/L	6	100%	5	5	37.4	34.3	32.3	32.4	37	54.1	4.6
Dissolved Zinc	ug/L	6	100%	1.0	1.0	33.3	31.0	25.4	26.8	37.1	48.5	10.3
Chrysene	ug/L	6	83%	0.0097	0.0100	0.0277	0.0235	0.0049	0.0081	0.0470	0.0590	0.0389

Table 8. Basic BMP assumptions for City of Federal Way *SUSTAIN* modeling.

	Bioretention	Permeable Pavement	Constructed Wetland	Wet Pond
BMP Description				
	Bioretention cell with 6 inches of surface ponding and underdrain (infiltration to native soil assumed to be negligible)	Self-mitigating porous asphalt with no run-on. A treatment layer will be included for installations over outwash soil.	Treatment wetland	Basic wet pond
BMP Material Section				
	Bioretention soil: Depth= 1.5 feet Porosity= 0.4 Aggregate Underdrain Bedding: Depth and porosity designed to ensure unrestricted flow through underdrain	Wearing Course: Depth = 4 inches Porosity= 0.3 Choker Course: Depth = 1.5 inches Porosity= 0.3 Aggregate Storage Layer: Depth = 9 inches Porosity= 0.3 Sand Treatment Layer: Depth = 4 inches Porosity= 0.3	NA	NA
Design Infiltration Rates				
Underlying Soil	NA	Till = 0.15 in/hr Outwash = 1.5 in/hr	0	0
Materials	Bioretention soil =3 in/hr	All courses = 10 in/hr (not limiting)	NA	NA
BMP Sizing Basis				
Drainage Area	1,000 sf	1,000 sf	10,000 sf	10,000 sf

	Bioretention	Permeable Pavement	Constructed Wetland	Wet Pond
Sizing Variable	Bioretention area sized to infiltrate 91 percent runoff file (sized in SUSTAIN). SUSTAIN does not account for side slopes, so the area costs for this BMP may need to be adjusted to account for a larger footprint.	Aggregate storage layer thickness sized to infiltrate at least 91 percent runoff file (sized in SUSTAIN). The layer thickness will likely be increased based on structural loading requirements.	Wetland volume sized as water quality treatment volume (Calculated using MGSFlood)	Wetland volume sized as water quality treatment volume (Calculated using MGSFlood)
Other Assumptions	SUSTAIN	Storage in wearing course and treatment layer neglected		
BMP Optimization Approach				
BMP Type	Aggregate (Distributed)	Aggregate (Distributed)	Regional	Regional
Decision Variable	Number of BMP units per subcatchment	Number of BMP units per subcatchment	Number of BMP units at bottom of basin [a]	Number of BMP units at bottom of basin [a]
Optimization Scenario 1				
Right-of-Way	Applied in all right-of-way subcatchment areas deemed feasible for retrofit	Not applied	Applied as a regional facility	Applied as a regional facility
Public Parcels	Not applied			
Private Parcels				
Optimization Scenario 2				
Right-of-Way	Applied in all right-of-way subcatchment areas deemed feasible for retrofit	Not applied	Applied as a regional facility	Applied as a regional facility
Public Parcels	Applied in 50% parcel subcatchment areas deemed feasible for retrofit	Applied in 50% parcel subcatchment areas deemed feasible for retrofit (assumed parking lots only)		
Private Parcels				

BMP = best management practice in/hr = inches per hour NA = not applicable sf = square feet

a. The number of BMPs rather than the areas of the BMP will be varied for optimization to properly represent the function of the facility overflow control structure.

Pollutant Routing and Removal

Pollutant routing through BMPs in *SUSTAIN* is simulated as continuously stirred tank reactors (CSTRs) in series, with pollutant removal through simple first order decay or first order decay above a background concentration. If a BMP is designed with an underdrain system, pollutant removal for water that is discharged from the underdrain is expressed as a percent removal. While several published reports (Tetra Tech 2007, 2010) provide pollutant removal estimates for the targeted BMPs in this study these reports are limited to a select few pollutants with decay rate calculations based on small sample sizes. Due to the general absence of current monitoring data to support calculation of BMP decay rates, this study will rely on local pollutant percent removal data and data from the International Stormwater BMP database (ISBMP) to calibrate BMP decay rates in *SUSTAIN*.

The steps for the calibration of decay rates based on percent removal data are listed below.

1. Analyze local and ISBMP data to determine median percent removal estimates by pollutant and BMP type
2. Develop simplified *SUSTAIN* models of single BMPs
3. Route hydrographs and pollutographs through BMPs characterized by first order decay
4. Evaluate percent removal efficiency of each BMP for all flow below the design flow rate
5. Calibrate decay rate to match observed percent removal data from ISBMP
6. Apply the calibrated decay rates in optimization models

BMP Cost Data

The BMP cost database is a Microsoft Access database organized according to construction components (e.g., grading, backfilling, filter fabric) and includes unit costs for each component. The user can select the source locale, source, source year, unit, and number of units for each unit cost or enter a lump sum (user defined) cost. As part of this project, Herrera developed a BMP cost database for Puget Sound that includes construction and O&M costs for stormwater BMPs throughout the region.

The Puget Sound cost data were gathered through e-mail requests to Phase I and Phase II stormwater permittees; internet research on cistern and rain barrel costs; phone calls and e-mail requests to vendors with permeable pavement, cistern, and green roof products; and targeted phone calls and e-mail requests to local jurisdictions that had received Ecology grant funding or had recently constructed projects with stormwater BMP components. Additional information on the data collection effort and the results of an analysis of the cost data is included in a separate memorandum (Herrera 2011b).

The modeling performed for this project will include lump sum (user defined costs) based on the average of what was collected for the Puget Sound BMP Cost database (Table 9). These costs may be adjusted to reflect the BMP design and application assumptions for this study.

Table 9. Lump sum BMP costs from the Puget Sound BMP Cost database.

BMP Type	Unit	Construction Cost	Design Cost	O&M Cost
Bioretention	SF	$30.55	$16.08	$1.22
Permeable Pavement [a]	SF	$13.90	NA	NA
Constructed Wetland	SF	$8.49	$2.25	NA
Wet Pond	CF	$7.97	$0.61	$0.03

CF: cubic feet NA: not available SF: square feet

a. Study assumes porous asphalt.

SUSTAIN Model Optimization

The *SUSTAIN* optimization module repeatedly runs the models defined in the land, BMP, and conveyance modules to iteratively arrive at the optimized BMP scenario. The necessary inputs to the optimization module are assessment points, management target, and decision variables. Each of these inputs is described in more detail below. Modeling scenarios and runtime considerations related to the optimization module are then addressed at the end of this section.

Assessment Points

An assessment point is the location in the study basin where runoff and pollutant loading reduction will be evaluated relative to optimization goals. The assessment point for this study will be the monitoring location for commercial/industrial basin CBB from the Phase 3 study of toxics in surface runoff (Figure 1).

Management Target

In *SUSTAIN*, the user must specify a desired management target for the modeled BMP configuration. These management targets can be based on flow or water quality. For example, a management target for flow can be a desired reduction in average annual volume, peak discharge, or exceedance frequency. Similarly, management targets for water quality can be a desired reduction in average annual load or average annual concentration. Depending on the management target selected, the user has the choice of two algorithms for identifying the optimum BMP configurations: the non-dominated sorting genetic algorithm (NSGA-II) and scatter search methods. The NSGA-II method can be used to build a cost effectiveness curve (e.g., total watershed BMP costs versus watershed pollutant removal efficiency) for a single pollutant or runoff parameter. The scatter search method can be used to identify the optimum BMP configuration that minimizes the cost associated with reaching one or more user-defined targets (optimization constraints) for runoff or pollutant loading reduction.

In this study, specific management targets have been identified for each of the water quality parameters identified for this study. The sections below discuss how each management target will be assessed using *SUSTAIN*.

Dissolved Copper, Dissolved Zinc, and Chrysene

There are applicable state water quality standards for dissolved copper and zinc (WAC 173-201A) to prevent adverse effects on aquatic organisms due to acute and chronic exposure to these contaminants. There is also a national recommended water quality standard for chrysene to prevent adverse human health effects from the consumption of contaminated water and aquatic organisms (EPA 2009). In this study, dissolved copper and zinc have been identified as primary management targets whereas chrysene is considered a secondary target. Given this consideration, the scatter search algorithm in *SUSTAIN* will be used to identify the optimum BMP configuration (based on cost effectiveness) for meeting the acute and chronic water quality standards for both dissolved copper and zinc at the assessment point identified above. Chrysene concentrations will then be evaluated based on this same optimum BMP configuration to determine if the associated national recommended water quality standard will also be met at the assessment point.

In these analyses, acute water quality standards of 3.2 μg/L and 25.4 μg/L for dissolved copper and zinc, respectively, will be assumed based on the median hardness concentration (16.94 mg/L as $CaCO_3$) measured during storm events in commercial/industrial basin CBB in connection with the Phase 3 study of toxics in surface runoff. Chronic water quality standards of 2.5 μg/L and 23.2 μg/L for dissolved copper and zinc, respectively, will also be assumed based on the same hardness concentration. Finally, the national recommended water quality standard for chrysene is 0.0038 μg/L.

Total Suspended Solids, Total Copper, and Total Zinc

There are no applicable water quality standards for total suspended solids, total copper, and total zinc. Therefore, the NSGA-II algorithm in *SUSTAIN* will be used to build separate cost effectiveness curves for each parameter that relate removal efficiency to different BMP configurations.

Decision Variables

To run the optimization module in *SUSTAIN*, the user must define decision variables that will be used to explore the various possible BMP configurations. In this study, the decision variable to be varied in the optimization module will vary depending on the type of BMP. For distributed BMPs (e.g., bioretention and permeable pavement) the decision variable will be the relative number of each BMP. For regional BMPs (e.g., constructed wetlands and wet ponds), the decision variable will be the relative size of each BMP.

Modeling Scenarios

Two modeling scenarios (Scenario 1 and 2) will be evaluated for this study. Scenario 1 will compare the options of distributed bioretention BMPs in the right-of-way to an expansion of the existing regional facility (wet pond) or modification of the existing regional facility (constructed wetland). Scenario 2 will also incorporate distributed stormwater BMPs (bioretention and permeable pavement) in on private parcels. For this scenario it is assumed that permeable pavement is limited to porous asphalt applied to parking lots.

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