CASE STUDY FOR APPLYING *SUSTAIN* TO A SMALL WATERSHED IN THE PUGET LOWLAND

Prepared for

Department of Ecology State of Washington

February 2013

Department of Ecology Publication No. 13-03-009

Prepared by

Herrera Environmental Consultants, Inc.

Publication and Contact Information

This report is available on the Department of Ecology's website at
https://fortress.wa.gov/ecy/publications/SummaryPages/1303009.html

Data for this project are available at Ecology's Environmental Information Management (EIM) website www.ecy.wa.gov/eim/index.htm. Search User Study ID, PSTox001.

The Activity Tracker Code for this study is 10-199.

The Water Resource Inventory Area (WRIA) for the study area is 9.

For more information contact:

Publications Coordinator
Environmental Assessment Program
P.O. Box 47600, Olympia, WA 98504-7600
Phone: (360) 407-6764

Washington State Department of Ecology - www.ecy.wa.gov/

o	Headquarters, Olympia	(360) 407-6000
o	Northwest Regional Office, Bellevue	(425) 649-7000
o	Southwest Regional Office, Olympia	(360) 407-6300
o	Central Regional Office, Yakima	(509) 575-2490
o	Eastern Regional Office, Spokane	(509) 329-3400

CASE STUDY FOR APPLYING *SUSTAIN* TO A SMALL WATERSHED IN THE PUGET LOWLAND

Prepared for

DEPARTMENT OF ECOLOGY
State of Washington

P.O. Box 47600
Olympia, Washington 98504-7600

Prepared by
Herrera Environmental Consultants, Inc.
2200 Sixth Avenue, Suite 1100
Seattle, Washington 98121
Telephone: 206/441-9080

This page is purposely left blank

CONTENTS

Acknowledgements vii
Introduction 1
Background 3
Modeling Approach 5
Study Basin Selection 5
Study Water Quality Parameter Selection 6
Best Management Practice Selection 6
Modeling Framework 9
Management Targets 11
Existing Conditions Model Development 13
SWMM Model Development 13
Input Data 13
Calibration Data 21
Computational Time Step 22
Hydrograph Development 22
Pollutograph Development 22
SUSTAIN Model Development 24
Land Module 24
Conveyance Module 25
BMP Module 25
Future Condition BMP Scenario Development 29
BMP Selection 29
BMP Design and Sizing 29
BMP Optimization Scenarios 29
BMP Scenarios 29
Basin Area Feasibly Treated 35
Scenario A 35
Scenario B 38
BMP Treatment Calibration 38
BMP Cost Data 43
Bioretention Cost Scaling 44
SUSTAIN Model Optimization 47
Assessment Points 47
Management Target 47
Dissolved Copper, Dissolved Zinc, and Chrysene 47
Total Suspended Solids, Total Copper, and Total Zinc 48
Decision Variables 48

SUSTAIN Model Results 49
Model Runtime Considerations 49
NSGA-II 51
Solution Convergence 51
Scenario A 51
Total Copper and Total Zinc Optimization 59
Scenario B 59
Scenario Comparison 61
Scatter Search 67
Acute Water Quality Standards Optimization 67
Chronic Water Quality Standards 67
Chrysene Removal 72
Sensitivity Analysis 72
Ancillary Flow Control Benefits 72
SUSTAIN Model Evaluation 75
User Experience 76
Limitations of *SUSTAIN* 78
SUSTAIN Model Recommendations 81
References 85

Appendix A Herrera SWMM Model Conveyance Network Inputs
Appendix B Stage-Discharge Curves for Regional Facility Outlet Control
Appendix C. Results from Repeat *SUSTAIN* to Derive Pollutant Decay Rates for Modeling Existing Conditions in *SUSTAIN*
Appendix D Assumptions for Percent Removal Targets to be Applied to BMPs for Modeling Future Conditions in *SUSTAIN*
Appendix E Results from Repeat *SUSTAIN* to Derive Pollutant Decay Rates for Modeling Future Conditions in *SUSTAIN*
Appendix F NSGA-II Optimization for Total Copper and Total Zinc
Appendix G Acronyms and Abbreviations

TABLES

Table 1. Land Use Breakdown for Basin CBB. 5

Table 2. Land Use Breakdown for Basin CBB. 6

Table 3. Summary of Subcatchment Input Parameters. 15

Table 4. CH2M Hill Values for Pervious Minimum and Maximum Infiltration Rate by Hydrologic Soil Group. 19

Table 5. Horton Pervious Minimum and Maximum Infiltration Rates by Subcatchment. 19

Table 6. Summary of Wetland Geometries. 20

Table 7. Summary of Regional Detention Pond Geometries. 21

Table 8. 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). 24

Table 9. Summary of *SUSTAIN* Wetland and Regional Detention Pond Geometries. 26

Table 10. Computation of Decay Rates for Modeling Wetlands and Regional Detention Ponds Under Existing Conditions in *SUSTAIN*. 27

Table 11. BMPs Selected for the Study. 30

Table 12. BMP Design and Sizing. 31

Table 13. BMP Optimization Approach. 34

Table 14. Technical and Participation Factors by Property Type. 35

Table 15. Scenario A Aggregate BMP Land Use Distribution. 36

Table 16. Scenario A Optimization Decision Variables. 39

Table 17. Scenario B Aggregate BMP Land Use Distribution. 40

Table 18. Scenario B Optimization Decision Variables. 42

Table 19. Target Pollutant Percent Removals for BMPs in *SUSTAIN*. 42

Table 20. Wet Pond and Wetland Pollutant Decay Rates for Modeling Future Condition BMP Scenarios in *SUSTAIN*. 43

Table 21. Summary of BMP Costs Used for This Study. 45

Table 22. Number of Possible Combinations in Scenario A and B Search Space. 52

Table 23. Summary of Flow Benefits. 74

FIGURES

Figure 1. Basin Boundaries and Land Use in Basin CBB. 7
Figure 2. SWMM and *SUSTAIN* Model Development and Calibration Process. 10
Figure 3. BMP Performance Optimization Process. 12
Figure 4. Land Cover Changes in Basin CBB from 1990 to 2011. 14
Figure 5. Wetland, Regional Detention Ponds, and Routing Network Explicitly Modeled in the Herrera SWMM Model for Basin CBB. 17
Figure 6. Plots of Observed and Modeled Flow for Representative Storms. 23
Figure 7. Assumed Bioretention Facility Geometry for Cost Scaling. 46
Figure 8. Scenario A NSGA-II Optimization Results. 50
Figure 9. Scenario A NSGA-II Convergence. 53
Figure 10. Scenario B NSGA-II Convergence. 54
Figure 11. Scenario A Cost-Effectiveness Curve for TSS Removal. 55
Figure 12. Scenario A Cost Distribution by BMP for TSS Removal. 55
Figure 13. Scenario A Rainfall and Runoff Response for a TSS-Optimized Solution. 56
Figure 14. Scenario A TSS Performance Summary. 57
Figure 15. Scenario B Cost-Effectiveness Curve for TSS Removal. 60
Figure 16. Scenario B Cost Distribution by BMP for TSS Removal. 61
Figure 17. Scenario B Rainfall and Runoff Response for a TSS-Optimized Solution. 62
Figure 18. Scenario B TSS Performance Summary. 63
Figure 19. Comparison of TSS-Optimized NSGA-II Solutions for Scenario A and B. 64
Figure 20. Comparison of Total Copper (TCu) Optimized NSGA-II Solutions for Scenario A and B. 65
Figure 21. Comparison of Total Zinc (TZn) Optimized NSGA-II Solutions for Scenario A and B. 66
Figure 22. Scatter Search Solutions of Dissolved Copper (DCu) Concentrations for Scenario A and B, Optimized for Acute Water Quality Standards. 68
Figure 23. Scatter Search Solutions of Dissolved Zinc (DZn) Concentrations for Scenario A and B, Optimized for Acute Water Quality Standards. 69
Figure 24. Scatter Search Solutions of Dissolved Copper (DCu) Concentrations for Scenario A and B, Optimized for Chronic Water Quality Standards. 70

Figure 25. Scatter Search Solutions of Dissolved Zinc (DZn) Concentrations for Scenario A and B, Optimized for Chronic Water Quality Standards. 71

Figure 26. Scenario A Cost-Effectiveness Curve for TSS Removal Assuming 100 Percent Increase in Regional Facility Costs. 73

Figure 27. Scenario A Cost Distribution by BMP for TSS Removal Assuming 100 Percent Increase in Regional Facility Costs. 73

This page is purposely left blank

ACKNOWLEDGEMENTS

The authors of this report thank the following people for their contribution to this study:

- Washington State Department of Ecology
  - Mindy Roberts, Project Manager
  - Ed O'Brien
- US Environmental Protection Agency
  - Dino Marshalonis
- Tetra Tech, Inc.
  - Alvi Khalid
  - Ryan Murphy
  - John Riverson
  - Jenny Zhen
- City of Federal Way
  - William Appleton
  - Fei Tang
- King County
  - Jeff Burkey
  - Curtis DeGasperi
- Herrera Environmental Consultants, Inc.
  - John Lenth, Project Manager
  - Rebecca Dugopolski
  - Meghan Feller
  - Alice Lancaster
  - Peter Steinberg
  - Anneliese Sytsma

This page is purposely left blank

INTRODUCTION

The Washington State Department of Ecology (Ecology) partnered with Herrera Inc. to test the newly developed System for Urban Stormwater Treatment and Analysis Integration (*SUSTAIN*) model. 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 primary purpose of the study was to explore the capabilities and limitations of *SUSTAIN* as a prioritization tool for considering stormwater management strategies in an urban basin. This report is not intended to represent an optimal plan to address stormwater contamination and should not be cited as a complete assessment of the costs or water quality benefits that Ecology endorses.

SUSTAIN was developed by Tetra Tech Inc. for the US Environmental Protection Agency (USEPA) as a decision support system, designed to facilitate the selection and placement of stormwater best management practices (BMPs) to minimize the costs associated with meeting user specified objectives (e.g., flow control, pollutant load reduction).

Working with Ecology and the City of Federal Way, Herrera developed a *SUSTAIN* model for a small (305-hectare) commercial/industrial basin in the City of Federal Way. Water quality data collected by Phase 1 jurisdictions in the Puget Sound region pursuant to requirements of the National Pollutant Discharge Elimination System (NPDES) Municipal Stormwater Permit have been used as a model input for estimating pollutant export from the basin with stormwater runoff. Flow and water quality data collected at the outlet of the study basin in connection with the Phase 3 study of toxic chemicals in surface runoff to Puget Sound (Herrera 2011) were also used to calibrate the basin's hydrology and water quality model.

Once baseline conditions within the basin were established, a series of BMP scenarios were modeled and evaluated using *SUSTAIN*'s optimization routine for a series of management goals. All modeled BMP scenarios are based on development and design standards adopted by the City of Federal Way (King County 2009; PSAT 2005). To improve upon the default national-level BMP costs database built into *SUSTAIN*, a database of BMP costs based on local project information was developed (Herrera 2012).

This report summarizes the technical approach used to develop the *SUSTAIN* model and provides a discussion of the results of the case study optimization routines. Additionally, this report documents *SUSTAIN's* current strengths and weaknesses, as observed in this exercise, and provides a context for use by local jurisdictions as a stormwater runoff management tool.

Stormwater BMPs are applied to serve a variety of purposes. For this project, *SUSTAIN* was applied to several parameters monitored in the Phase 3 study of toxic chemicals in surface runoff to Puget Sound (Herrera 2011) to explore BMP treatment capabilities for parameters that are currently well characterized, such as metals in particulate form, but also for parameters for which little information exists, such as chrysene. However, this project was exploratory in nature and intended to identify important information gaps that strongly influence the *SUSTAIN* modeling outcome.

The results of this analysis should not be used to characterize stormwater costs to achieve compliance with a particular standard because the project purpose did not include identifying an optimal management solution for the basin studied.

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: 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 2011) confirmed several land-use-based 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, 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 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, and none have addressed toxics. 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 2007). 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. 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.

SUSTAIN was also used to support development of the Los Angeles County Watershed Management Modeling System as documented in Tetra Tech (2011). Another case study was completed for Albuquerque, New Mexico in conjunction with the USEPA Office of Research and Development and USEPA Region 6, and is pending formal publication. Finally, Tetra Tech recently published a journal article documenting the methods for building a watershed-scale stormwater BMP optimization in *SUSTAIN* (Lee et al. 2012).

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[1] 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 low impact development (LID) techniques in previously developed areas of WRIA 9. In-stream flow and water quality goals will be developed, and the combination of stormwater management 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.

The applications of *SUSTAIN* to a basin in Federal Way, Washington for this case study and the King County project are for different purposes by design to explore the model's capabilities and limitations. Future *SUSTAIN* users should review results from both projects and modify the approaches to suit specific needs. The selection of BMPs was driven by the specific basin needs and will vary in other regions.

[1] Water Resource Inventory Area

MODELING APPROACH

This section provides an overview of the technical approach used to identify the most cost-effective suite of BMPs for achieving target management goals in the study basin. The first three subsections present 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 evaluated using the *SUSTAIN* model are identified.

Study Basin Selection

A *SUSTAIN* model was developed for basin CBB, one of the 16 drainage basins monitored under the Phase 3 study of toxic loading in surface runoff to Puget Sound. Basin CBB is a mixed land use basin with a large portion of commercial/industrial land use in the Puyallup River watershed (Figure 1). This 754-acre (305-hectare) basin is located in Federal Way, Washington, and includes a majority of the downtown core of the City of Federal Way just west of Interstate-5 stretching from S 312th Street to S 343rd Street. Commercial/industrial land use represents 46.5 percent of the land area in the basin. The remaining area is predominantly residential (41.6 percent) with a small portion of forest land use (11.9 percent) (see Table 1). The study basin drains in a southerly direction to an unnamed tributary that discharges to West Hylebos Creek.

Table 1. Land Use Breakdown for Basin CBB.

Land Use	Study Basin	
	Area (acres)	% of Total Area
Residential	313.6	41.6%
Forest	89.5	11.9%
Commercial/Industrial	350.6	46.5%
Total	753.7	

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 because, of the basins assessed in the Phase 3 study of toxics loading in surface runoff, 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 quality assurance reviews of the data (e.g., rating curve standardized root mean square and sensor calibration checks). High quality flow data was 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 have been targeted for modeling in this study (see discussion in the section below). Finally, staff from the City of Federal Way were interested in supporting this study and provided 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 evaluated optimum BMP configurations in basin CBB for reducing concentrations and loads of total suspended solids (TSS), 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. TSS as well as particulate metals are generally well managed with traditional stormwater BMPs. However, dissolved metals require enhanced BMPs with limited information on removal efficiencies. Furthermore, very few studies have evaluated the behavior of chrysene in stormwater BMPs. Therefore, this suite of parameters represents a range of behaviors as well as knowledge to test the capabilities of *SUSTAIN*.

Best Management Practice Selection

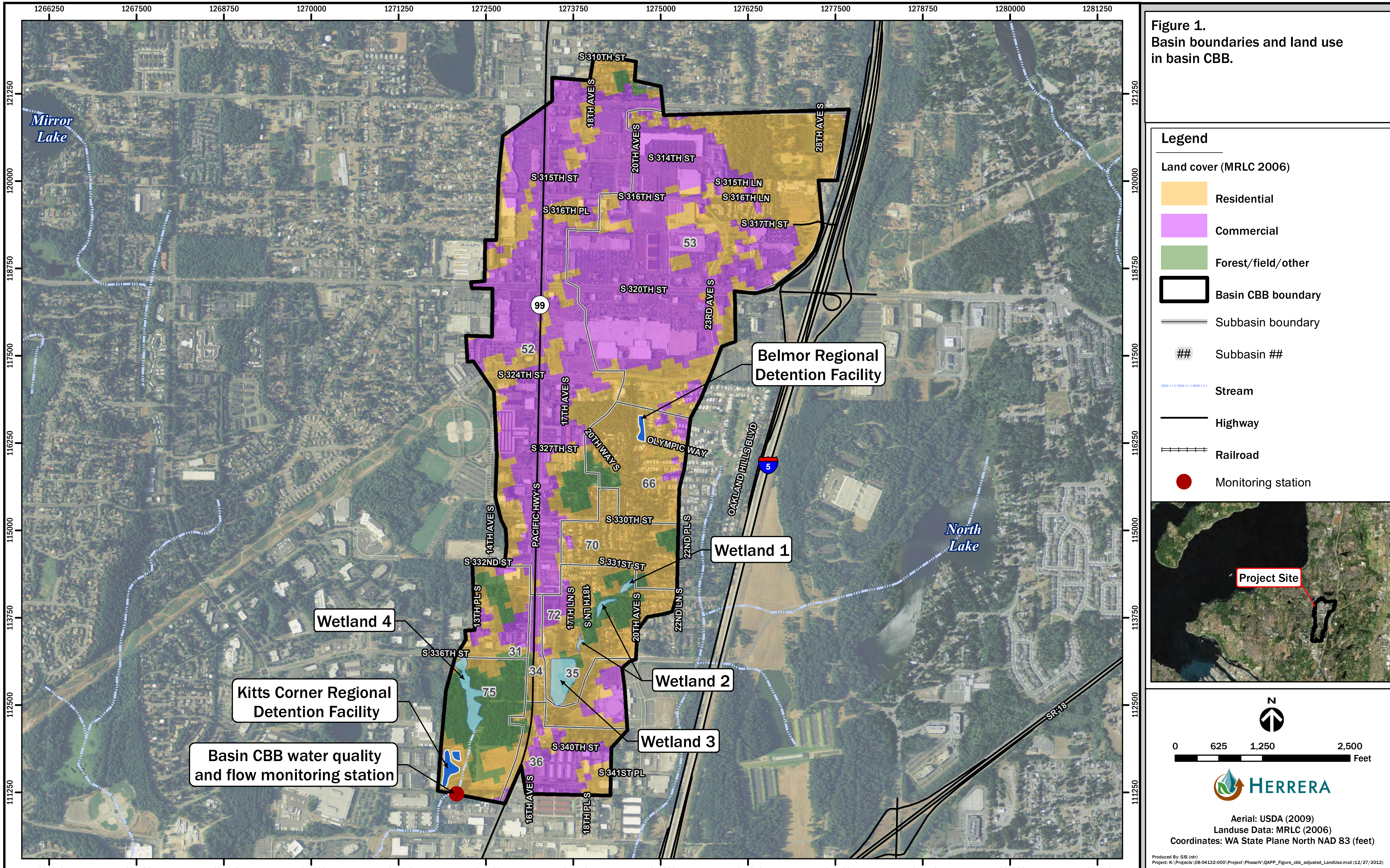
The intent of this effort was to develop a case study for the *SUSTAIN* model based on a "real world" application. To that end, City of Federal Way and Herrera staff met on December 5, 2011, to discuss the selection and applications of BMPs for this modeling effort based on the City's stormwater management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

Table 2. Land Use Breakdown for Basin CBB.

BMP	Application	Scenario [a]		Description
		A	B	
Distributed Facilities				
Bioretention	Right-of-Way	X	X	Roadside bioretention swales
Bioretention	Parcels		X	Bioretention on public and private parcels
Permeable Pavement	Parcels		X	Porous asphalt parking lots on public and private parcels
Centralized Facilities				
Constructed Wetland	Regional	X	X	Supplement existing regional detention pond
Wet Pond	Regional	X	X	Expand existing regional detention pond

[a] "X" denotes scenario(s) where each BMP was applied.

Figure 1.
Basin boundaries and land use in basin CBB.



This page is purposely left blank

Both of the regional retrofit options evaluated in *SUSTAIN* involve improvements to the Kitts Corner Regional Detention Facility, a large regional detention pond near the outlet of the basin. One option involves an expansion of the existing wet pond and the other includes installation of a new pre-treatment facility (i.e., constructed wetland) upstream of the Kitts Corner detention facility. Inclusion of these regional BMP facilities was considered important for comparison to the distributed stormwater BMPs (bioretention and permeable pavement) evaluated as part of this modeling effort.

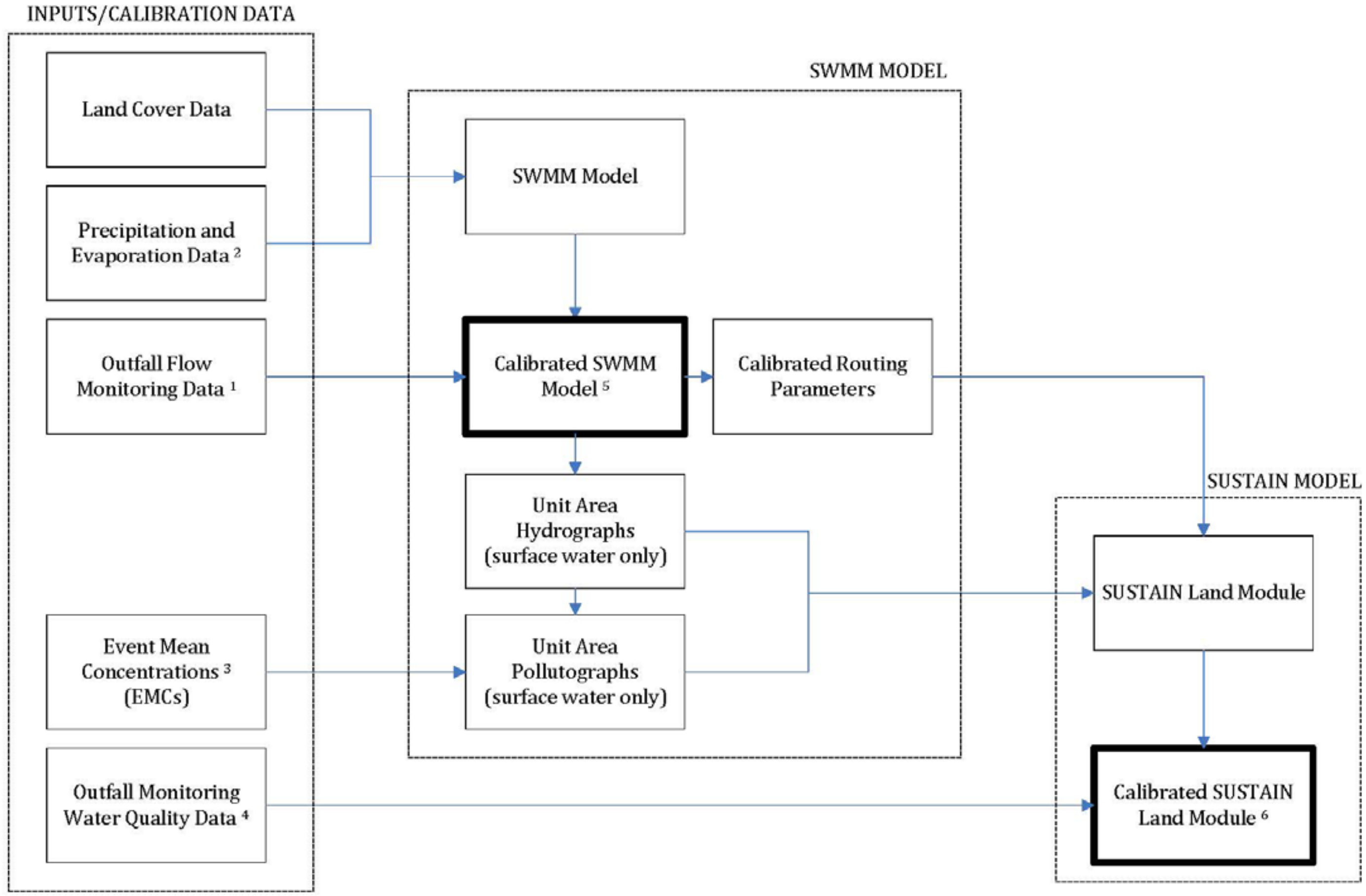
Cisterns, rain barrels, and green roofs were excluded for this modeling effort because they do not provide a high level of water quality treatment and are more applicable to private property retrofits. Vegetated filterstrips were also excluded because the module for this BMP is not yet fully functional 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 Surface Water Management Model (SWMM) was developed to simulate hydrographs for the study basin, and these hydrographs were subsequently imported into the *SUSTAIN* model. This section describes the linkages between the SWMM and *SUSTAIN* models and provides a step-by-step process of the modeling methodology.

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

1. Built SWMM model to simulate runoff and routing for study basin.
2. Calibrated 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 July 2010).
3. Using the calibrated SWMM model, developed unit-area surface water hydrographs (not including stream baseflow) to characterize runoff from each subcatchment by land use (commercial, residential, or forest) and land cover (pervious or impervious) for the 1-year calibration period.
4. Developed unit-area pollutographs for the calibration period by applying event mean concentrations (EMCs) from each land use to the unit-area hydrographs (not including stream baseflow).
5. Built *SUSTAIN* land and conveyance module using unit-area hydrographs, pollutographs, and calibrated routing parameters from the SWMM model for the 1-year calibration period.
6. Confirmed flow calibration was maintained by comparing runoff files from calibrated SWMM model to those from *SUSTAIN.*
7. Calibrated *SUSTAIN* existing detention facility and wetland 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: wetland infiltration rate.
6. Calibrate surface water flow water quality concentrations. Target calibration parameters: decay rates in detention facilities and wetlands.

Figure 2. SWMM and *SUSTAIN* Model Development and Calibration Process.

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

1. Repeated steps 3 and 4 from list above to develop hydrographs and pollutographs for a 30-year period of record
2. Input long-term hydrographs and pollutographs into the calibrated *SUSTAIN* model
3. Built *SUSTAIN* BMP module and integrated with land and conveyance modules
4. Used 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 water quality management targets were selected for evaluating the cost effectiveness of different BMP scenarios in basin CBB using the *SUSTAIN* optimization module:

- Meet Washington 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
- Maximize TSS, total copper, and total zinc load reductions for a range of costs (assessed via cost-effectiveness curve)

There was also interest in evaluating the ancillary flow control benefits provided by the BMP scenarios optimized for the water quality management targets listed above. When initially identifying criteria for evaluation of flow control benefits, the hope was to evaluate a long-term precipitation series (i.e., the 158-year extended series) and compare the recurrence interval statistics for the 2-, 10-, 25-, and 50-year flows for the three scenarios: existing conditions, BMP Scenario A, and BMP Scenario B. However, the *SUSTAIN* model repeatedly crashed while running this long-term simulation period; therefore, the simulation period was shortened to 7 years for the existing conditions simulation (the maximum allowed before the model would terminate the simulation) and further shortened to 2 years for optimization scenarios due to runtime limitations. Because the *SUSTAIN* optimization runs were limited to a 2-year simulation period, flow statistics (e.g., recurrence interval flows) could not be evaluated. Therefore, the assessment of ancillary flow control benefits was based on the total runoff volume and maximum peak flow value for the 2-year time series.

More generally, the model crashes while simulating existing conditions, and the optimization scenarios are likely related to the number of basins and time series per basin in the *SUSTAIN* model developed for this case study. Because *SUSTAIN* attempts to read the entirety of each time series into memory prior to running the simulation, the length of simulation period the model will run (without crashing) is likely a function of the complexity of the basin hydrologic representation (i.e., total number of unit-area hydrographs modeled). This and other runtime considerations are further discussed in the *SUSTAIN* Model Results section.

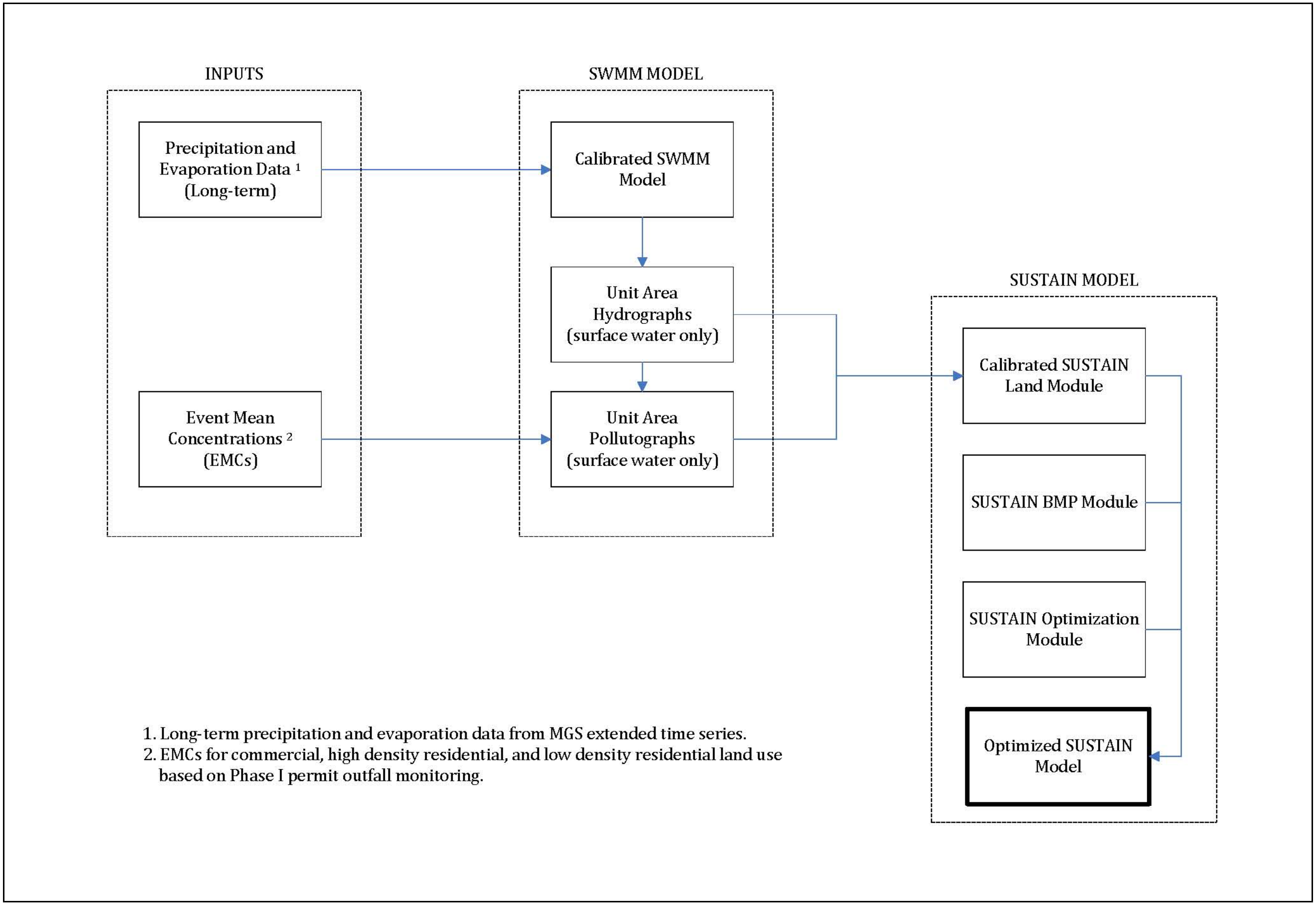


Figure 3. BMP Performance Optimization Process.

EXISTING CONDITIONS MODEL DEVELOPMENT

SWMM Model Development

SWMM (USEPA, Version 5.0.022) was 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. 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 used to develop the SWMM runoff and routing components are provided below.

Input Data

A brief discussion of the input data used for SWMM model development is provided below. Elements include:

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

The SWMM model for this project (Herrera SWMM model) was developed based on a previously developed SWMM model (1994 SWMM model) documented in a report by CH2M Hill (CH2M Hill 1994). The model was updated with Federal Way GIS data and Federal Way record drawings documenting modifications to the basin and drainage network since the 1994 SWMM model development. Changes in land cover within the study area over the nearly 20-year period since original model development were assessed using aerial imagery from 1990 and 2011 (see Figure 4). For the purposes of this effort, the minimal development that has occurred in the basin since 1994 SWMM model development was deemed negligible, thus all original land cover inputs from the 1994 SWMM model (i.e., subcatchment width and slope, imperviousness, surface roughness) were used.

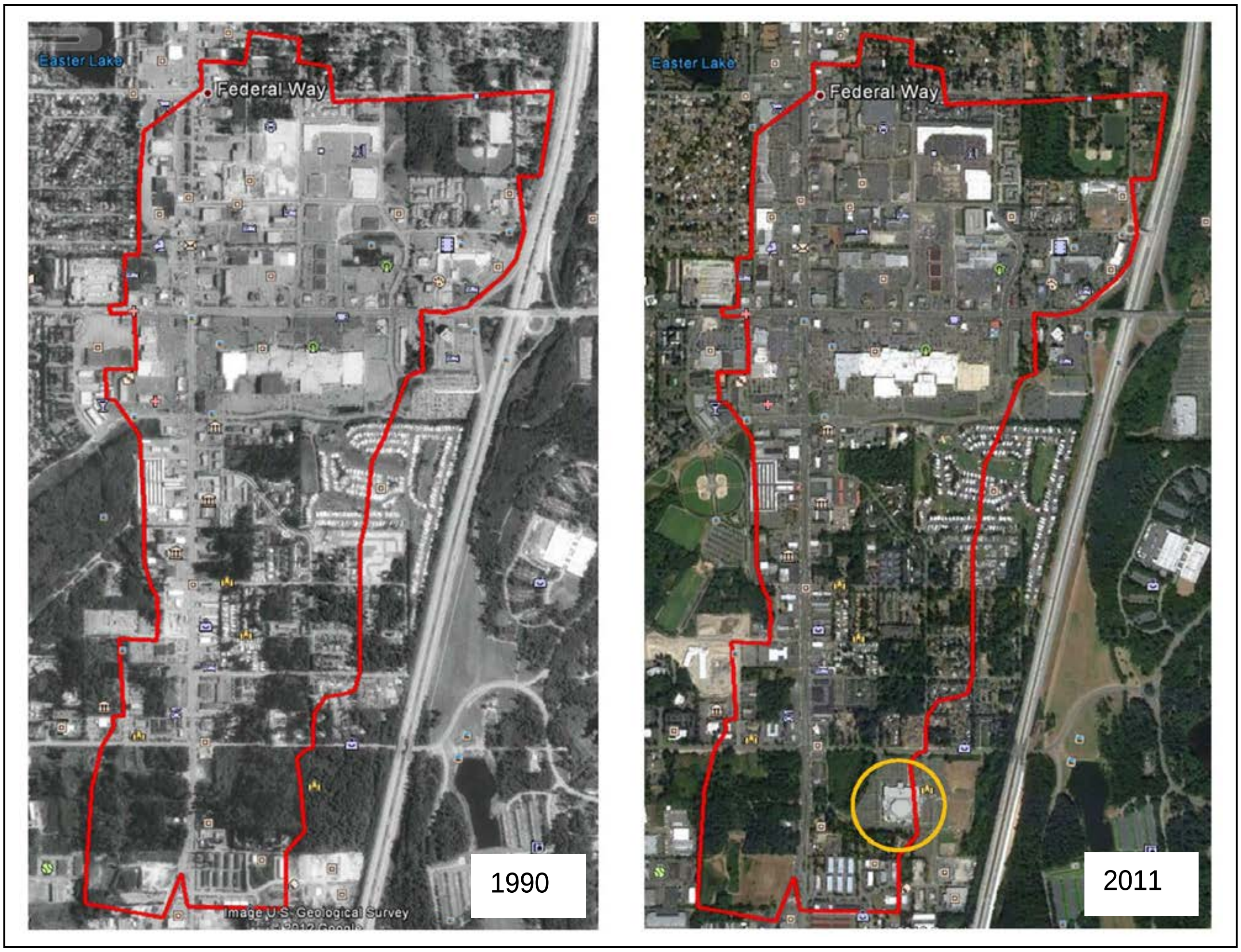


Figure 4. Land Cover Changes in Basin CBB from 1990 to 2011.

Precipitation and Evaporation Data

Two distinct precipitation and evaporation data sets were used in this analysis; the first was used to calibrate the Herrera SWMM model, and the second was used to develop unit-area hydrographs and pollutographs for use in *SUSTAIN* to evaluate BMP performance.

Model Calibration

Precipitation and evaporation data from the King County Lake Dolloff Precipitation Monitoring Station 41v was used to calibrate the Herrera SWMM model for the Phase 3 monitoring period (August 2009 to July 2010). The mean annual precipitation at the gage, based on record data from 1989 to 2011, is 40.2 inches. The total (annual) precipitation for the calibration period (August 2009 to July 2010) is 47.2 inches. Study basin mean annual precipitation, based on PRISM data from 1971 to 2000, is slightly higher than the average annual precipitation at the gage, totaling 42.8 inches.

Hydrograph/Pollutograph Development

A truncated version of the extended precipitation and evaporation time series, developed by MGS Engineering Consultants, Inc. (MGS 2002), was applied to the calibrated Herrera SWMM model to develop unit-area hydrographs and pollutographs. MGS developed the extended, 158-year series by combining and rescaling hourly records from Seattle Washington, Vancouver British Columbia, and Salem Oregon to replicate the storm characteristics representative of the Puget Sound lowlands. For this study, the MGS extended time series for a mean annual precipitation depth of 44 inches for the east Puget Sound region was selected to represent precipitation and evaporation in the study basin. The first 30 years of this 158-year extended precipitation and evaporation series was used to develop unit-area hydrographs and pollutographs for import to *SUSTAIN* to evaluate BMP performance. Note that, as explained in the *SUSTAIN* Model Development section, the time series was further truncated for subsequent *SUSTAIN* simulations due to model instability issues and runtime limitations.

Drainage Area

The 754-acre (305-hectare) study basin was subdivided into a series of smaller subcatchments, connected via an explicitly represented conveyance network (Figure 5). This network routes flows to the monitoring location at the bottom of the study basin. Routing within subcatchments was accounted for in the unit-area hydrographs, but not explicitly represented in the model. Subcatchment delineation follows Federal Way's existing drainage basin network, resulting in 10 subcatchments ranging in size from approximately 8 to 250 acres (Table 3).

Table 3. Summary of Subcatchment Input Parameters.

Subcatchment ID [a]	Area (acre)	Width (feet)	Slope (%)	Percent Impervious	Manning's n		Depression Storage (in)	
					Impervious	Pervious	Impervious	Pervious
53	251.05	3409	3.2	69.03	0.014	0.164	0.1	0.2
52	239.13	1301	2.5	72	0.014	0.194	0.1	0.2
31	25.25	810	6.05	52.37	0.014	0.319	0.1	0.2
75	49.18	1017	4.4	21.62	0.014	0.3305	0.1	0.2
36	33.29	1049	3.8	54.9	0.014	0.297	0.1	0.2
35	17.50	680	4.6	28.5	0.014	0.3633	0.1	0.2
34	7.91	186	4.3	44.6	0.014	0.278	0.1	0.2
72	52.05	1466	4.7	39.23	0.014	0.305	0.1	0.2
70	31.55	1696	5.48	44.75	0.014	0.28167	0.1	0.2
66	44.83	1469	5.3	49.2	0.014	0.1913	0.1	0.2

[a] See Figure 5 for geographic location of subcatchments.

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 used the subcatchment widths and slopes from the original model (Table 3).

Imperviousness

The subcatchment imperviousness estimates (i.e., percent of the subcatchment composed of impervious surface) from the 1994 SWMM model were used for this study (Table 3).

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 and impervious surfaces. Because there has been very little development in the basin since the 1994 SWMM model was developed, Manning's n values from the original model were used for this study, including a value of 0.014 for impervious areas and an area-weighted value for pervious areas (Table 3).

A typical Manning's n value for pervious land cover is 0.25, with higher values applied to heavily vegetated areas. To better represent variability in pervious Manning's n values, the 1994 modeling effort characterized lawn/landscape and forested areas independently using a Manning's n for lawn/landscape and forest of 0.13 and 0.4, respectively. An area-weighted average Manning's n was used to represent pervious land cover, 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

These typical depression storage values were applied to each subcatchment in the Herrera SWMM model (Table 3).

Soil Infiltration

Infiltration of rainfall on the pervious areas of a subcatchment into the unsaturated upper soil zone was 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. This study used all of these parameters developed for the 1994 SWMM model. As summarized in Table 4, CH2M Hill identified typical values for maximum and minimum infiltration rates by hydrologic soil group in their report for the 1994 SWMM model (CH2M Hill 1994).

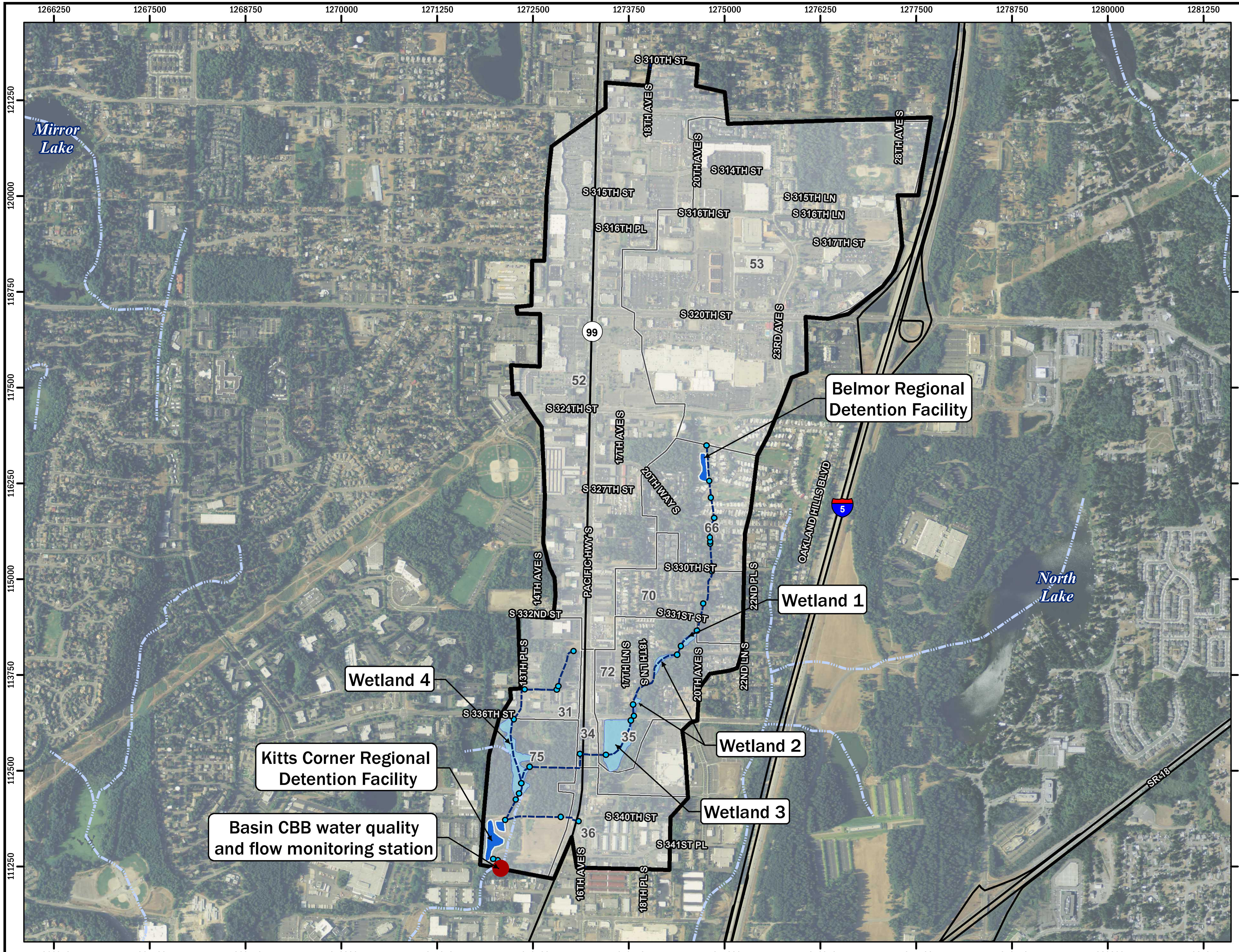


Figure 5.
Wetland, regional detention ponds, and routing network explicitly modeled in the Herrera SWMM model for basin CBB.

Legend

- Basin CBB boundary
- ## Subbasin ##
- Modeled pipe network
- Junction
- Stream
- Highway
- Railroad
- Monitoring station

N

0 625 1,250 2,500 Feet

HERRERA

Aerial: USDA (2009)
Landuse Data: MRLC (2006)
Coordinates: WA State Plane North NAD 83 (feet)

Produced By: GIS (rdr)
Project: K:\Projects\08-04132-000\Project\PhaseIV\QAPP_Figure_cbb_adjusted_Wetland_RoutingNetwork.mxd (12/4/2012)

This page is purposely left blank

Table 4. CH2M Hill Values for Pervious Minimum and Maximum Infiltration Rate by Hydrologic Soil Group.		
Hydrologic Soil Group	Minimum Infiltration Rate (based on average of typical range) (in/hr)	Maximum Infiltration Rate (in/hr)
A	0.375	4.0
B	0.225	3.0
C	0.1	2.0
D	0.025	1.0

in/hr – inches per hour

Based on the values presented in Table 4, CH2M Hill calculated an area-weighted average minimum and maximum infiltration rate, representing the typical infiltration rate of each subcatchment. Table 5 provides a summary of inputs by subcatchment used in the Herrera SWMM model.

Table 5. Horton Pervious Minimum and Maximum Infiltration Rates by Subcatchment.				
Subcatchment ID	Minimum Infiltration Rate (in/hr)	Maximum Infiltration Rate (in/hr)	Decay Constant (1/hour)	Drying Time (days)
53	0.04	1.26	4.14	7
52	0.0307	1.11	4.14	7
31	0.0385	1.17	4.14	7
75	0.202	2.78	4.14	7
36	0.077	1.73	4.14	7
35	0.0833	1.83	4.14	7
34	0.106	1.86	4.14	7
72	0.05211	1.439	4.14	7
70	0.036156	1.1514	4.14	7
66	0.0258	1.011	4.14	7

in/hr – inches per hour

Routing Data

The SWMM routing module uses continuous surface runoff data generated by the land module as input to simulate hydraulic conditions in open ditches and closed conduits. The study basin conveyance network is composed of both piped storm drainage and open ditch conveyance. Both networks were modeled based on inputs from the previously developed SWMM model updated with Federal Way GIS data and Federal Way record drawings documenting modifications to the basin and drainage network since original SWMM model development. Conveyance was simulated using Kinematic wave routing. Appendix A provides a summary of the conveyance network inputs including the geometry, roughness, lengths, and cross-sectional shapes of conduits, weirs, and orifices, respectively.

Detention and Wetland Facilities

The SWMM model allows the user to explicitly model detention or other storage facilities within a drainage network. Basin CBB contains a series of interconnected natural wetlands, two regional detention ponds, and several smaller detention ponds and vaults distributed across the basin. For the purposes of developing the Herrera SWMM model, four of the wetlands and the two larger regional detention ponds (Figure 5) were modeled explicitly in SWMM (i.e., facilities governed by stage-storage curves, multi-stage outlet structures) per the City of Federal Way GIS data, aerial imagery, and record drawings.

To incorporate the four wetlands into the Herrera SWMM model, the surface area of wetlands was calculated based on the GIS data. Average wetland depth across this surface area was assumed to be approximately 6 inches. In all cases, the wetland outlet was assumed to be the nearest downstream pipe or culvert. Table 6 provides a summary of the wetland input data.

Table 6. Summary of Wetland Geometries.

Wetland ID	Surface Area (sf)	Invert Elevation (ft)	Outlet	Outlet Elevation (ft)
1	19,624	340.02	(2) 42" orifice	340.52
2	32,347	330.03	48" orifice	330.53
3	190,777	324.3	48" orifice	324.8
4	158,182	281.2	60" orifice	281.7

sf– square feet; ft - feet

The two regional detention ponds, Kitts Corner Regional Detention Facility (constructed in 1997) and Belmor Regional Detention Facility (constructed in 1998) (see Figure 5), were modeled based on record drawings provided by the City of Federal Way, including approximation of a stage-storage table and reconstruction of outlet control structures. Table 7 provides a summary of the stage-storage tables and outlet control structures used in the model.

In addition to the wetlands and regional detention ponds, there are a number of smaller detention facilities in the basin. Subcatchment 53 (Figure 5) contains the majority of the additional detention ponds and storage vaults on record (including five facilities explicitly modeled in the 1994 SWMM model). For this study, these storage facilities were represented as an aggregate storage vault to represent the cumulative effect of distributed storage in the northwesterly quadrant of the basin. This aggregate detention facility was modeled as a single, 55,714 square foot storage vault, controlled by five, 0.58-foot diameter orifices (one for each of the individual facilities represented in aggregate). This approach simplified the routing network for use in *SUSTAIN* while maintaining the hydrologic integrity of the drainage system.

Table 7. Summary of Regional Detention Pond Geometries.						
Pond Storage [a]			Pond Outlet [b]			
Stage (ft)	Surface Area (sf)	Elevation (ft)	Type	Length/Width (ft)	Height (ft)	Inlet Offset (ft)
Kitts Corner Regional Detention Facility						
2	21,330	273	Weir (V-Notch)	4.5	2.25	1.5
2.5	123,253	275.5	Weir (Transverse)	25	1.72	10
13	162,863	286	Weir –Spillway (Transverse)	90	2	11.5
Belmor Regional Detention Facility						
0	139	384	Orifice (Closed Rect.)	2	2	3.08
1	4,302	385	Orifice (Closed Rect.)	2.5	2.5	7.08
2	11,494	386	Weir (Transverse)	8	2	12.13
15	43,637	399	Weir –Spillway (Transverse)	30	1.5	13.1

sf– square feet; ft - feet

[a] Pond storage has been estimated based on record drawings provided by the City of Federal Way. The stage-storage values provided in this table are approximations, assumed to be accurate enough for the study goals, but do not necessarily apply for other hydrologic or hydraulic analyses.

[b] Some of the pond outlet structures have been simplified for ease of modeling. The effect of these simplifications on this study is expected to be minimal.

Calibration Data

Streamflow generated in the Herrera SWMM model was calibrated to one year of measured streamflow data collected for the Phase 3 study of toxics in surface runoff at the bottom of the study basin (Figure 5). Precipitation and evaporation data from the Lake Dolloff station was used as explained above. The model was calibrated to match the timing, magnitude, and total volume of the field-observed streamflow data.

The Herrera SWMM model was initially run with the input parameters defined above, but without representing the existing wetlands. In these initial model runs, the bias of the model was about -0.3 cubic feet per second (cfs) (i.e., model was overpredicting runoff at the outlet of the basin by 0.3 cfs), and the correlation between model and observed data was about 0.92 in linear space. For reference, the average flow rate measured at the bottom of the study basin over the 1-year calibration period was approximately 1.74 cfs.

The existing wetlands were subsequently added to the SWMM model as explained in the section above. The model was then calibrated to match the timing, magnitude, and total volume of the field-observed streamflow data by varying loss parameters (specifically Green-Ampt infiltration rate) in the wetlands to get a zero mean bias in predicted flow at the outlet of the basin. The resulting infiltration rate is approximately 0.07 inches per hour. This reduced the bias to 0.009 cfs, and the Pearson (or linear) correlation was maintained at 0.93. Several plots of observed and modeled flows at the outlet of the basin are included in Figure 6.

Computational Time Step

SWMM model runoff and routing were evaluated at a 5-minute computational time step to maintain numerical stability within the kinematic wave routing approximations. Results were reported on a 15-minute increment.

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 includes commercial/industrial, high-density residential, and low-density residential land use, composed of impervious, lawn/landscape, and forested land cover types.

For each subcatchment and land use type, unit-area hydrographs were developed for impervious and lumped pervious land cover. To develop these hydrographs, the calibrated SWMM model was used to build two additional, independent SWMM models. These independent models maintained 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 represent two hypothetical basin conditions: 100 percent impervious subcatchments and 100 percent pervious subcatchments. The runoff hydrographs generated for each subcatchment was divided by the total subcatchment area to develop a set of pervious and impervious unit-area hydrographs to serve as inputs to the *SUSTAIN* model.

Unit-area hydrographs were developed for two precipitation and evaporation time series. The first set of unit-area hydrographs were developed for the 1-year calibration period (August 2009 to July 2010). These hydrographs (and corresponding pollutographs) were used to calibrate existing wetland and regional detention facility decay rates for pollutant loading within *SUSTAIN*. A second set of unit-area hydrographs was developed using the 30-year truncated MGS precipitation time series. These unit hydrographs were used to calibrate decay rates for BMPs used in condition scenarios and served as the basis for analysis of BMP scenario performance and cost effectiveness in *SUSTAIN*.

Pollutograph Development

To develop pollutographs for the *SUSTAIN* model, the hydrographs developed in SWMM were multiplied by representative pollutant EMCs that were derived from monitoring performed by Phase 1 jurisdictions in the Puget Sound region pursuant to NPDES Municipal Stormwater Permit requirements. To develop pollutographs for the *SUSTAIN* model, EMCs from the Phase 1 jurisdictions for commercial, high-density residential, or low-density residential land use (Table 8) were applied to the corresponding land use hydrograph for each subcatchment to generate pollutographs. Once these pollutographs were loaded into *SUSTAIN*, decay rates

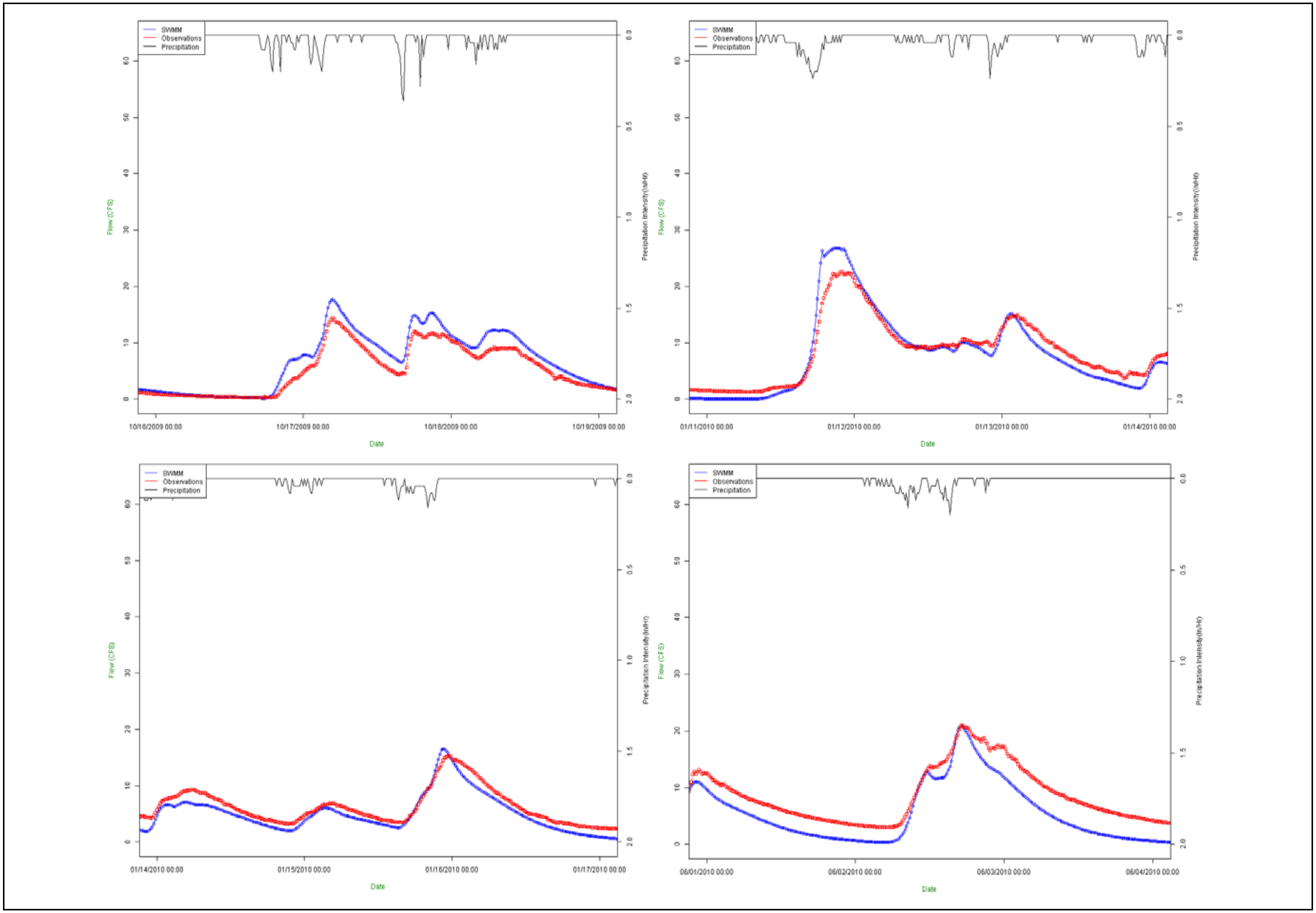


Figure 6. Plots of Observed and Modeled Flow for Representative Storms.

for existing wetlands and regional detention ponds in basin CBB (see discussion above) were calibrated so that modeled concentrations matched concentrations measured at the outlet of the basin during the Phase 1 study of toxic loading to Puget Sound (see more detailed discussion below).

Table 8. 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 2011 personal communication
WY: Water Year
ug/L: micrograms per liter; mg/L: milligrams per liter

SUSTAIN Model Development

SUSTAIN version 1.2 (June 2012) was used to simulate pollutant transport and removal throughout the study basin. The model is designed to select and place BMPs to determine the most cost-effective strategies for achieving target water quality or flow control objectives. The model framework is a series of components, all accessible via *SUSTAIN*'s Framework Manager (an ArcGIS extension). These components include a BMP siting tool; land module; conveyance module; BMP module; BMP cost database; post processor; and optimization module.

The *SUSTAIN* land simulation, conveyance, and BMP modules are described in more detail, including the input data used for model development, in the following subsections.

Land Module

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

Hydrology Component

Runoff hydrographs were generated in the externally calibrated Herrera SWMM model for basin CBB as described in the SWMM Model Development section. Unit-area hydrographs for impervious and pervious land cover type were then imported into *SUSTAIN* for each subcatchment in basin CBB.

Water Quality Component

Pollutographs were generated using unit-area hydrographs and EMCs for commercial, high-density, and low-density residential land uses that were based on data compiled by Phase 1 jurisdictions in the Puget Sound region pursuant to NPDES Municipal Stormwater Permit requirements (see SWMM Model Development section). These pollutographs were then imported into *SUSTAIN* for each subcatchment in basin CBB.

Conveyance Module

The conveyance module routes hydrographs and pollutographs from the land and BMP modules, through the model drainage network (e.g., conduits, open channels). 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) were directly applied to the *SUSTAIN* conveyance routine.

BMP Module

The BMP module in *SUSTAIN* was used to represent the existing detention facilities and natural wetlands in the study basin. The intent was to include these facilities as they were represented in the Herrera SWMM model (see the SWMM Model Development section); however, the BMP module in *SUSTAIN* relies on generally simplified facility geometries and outlet controls, thus necessitating several additional assumptions to represent the BMPs in *SUSTAIN*. This section describes these additional assumptions.

Facility Geometry

For this modeling effort, the existing wetlands and the aggregated storage in the northeast quadrant of the basin were represented as conceptualized detention facilities with vertical side walls in both the Herrera SWMM model and *SUSTAIN*. These facilities were conceptualized in the model because the distributed storage was being aggregated into an “equivalent” facility and there is a lack of information on the actual geometry of the existing wetlands.

Alternatively, the geometries of the existing regional detention ponds in the Herrera SWMM model were represented using stage-storage curves to provide a more accurate representation of the true facility storage volumes. This detailed representation is not possible in *SUSTAIN*’s current BMP module. Instead, the two regional detention ponds are represented using the same approach that was applied for the wetlands (vertical facility side walls with geometries described by a surface area and depth only).

Table 9 contains both wetland and regional detention pond geometry input parameters.

Outlet Control Structures

Outlet control structures in *SUSTAIN* can only be represented as a single circular orifice and a single weir. As a result, culvert outlet control structures regulating flow from the existing wetlands (modeled explicitly in the Herrera SWMM model) were modeled assuming a weir width equal to the culvert diameter and set at a height of 6 inches above the assumed wetland bottom (the assumed average wetland depth across the facility surface area). See Table 9 for outlet representation.

Table 9. Summary of *SUSTAIN* Wetland and Regional Detention Pond Geometries.

BMP ID	Length (ft)	Width (ft)	Surface Area (sf)	Outlet	Outlet Height (ft)
Wetland 1	140	140	19,600	3.5' wide weir	0.5
Wetland 2	180	180	32,400	4' wide weir	0.5
Wetland 3	436	436	190,096	4' wide weir	0.5
Wetland 4	397	397	157,609	5' wide weir	0.5
Kitts Corner	351	351	123,201	Pump Curve	
Belmor	107	107	11,449	Pump Curve	
Aggregate Vault	236	236	55,696	Pump Curve	

sf– square feet; ft – feet

In addition, the compound outlet structures of the existing regional detention ponds cannot be explicitly modeled in *SUSTAIN*. Instead, a storage-discharge function was developed outside of the model and input into *SUSTAIN* using the BMP module pump curve function. These curves represented outflows from the Kitts Corner, Belmor, and aggregate vault facilities. These storage-discharge curves are provided in Appendix B.

Finally, outflow from the Belmor Regional Detention Facility is partially controlled by an adjustable sluice gate that changes the storage capacity of the facility seasonally to better accommodate flow control demands in the basin. *SUSTAIN*, unlike SWMM, is not capable of capturing this function of the wet pond; therefore, seasonal outlet control was neglected by fixing the sluice gate position to maximize storage volume in the facility.

Decay Rates

Decay rates for existing wetlands, regional detention ponds, and aggregated storage in the northeast quadrant of basin CBB were calibrated so that modeled concentrations at the bottom of the basin matched concentrations measured at the outlet of the basin during the Phase 1 study of toxic loading to Puget Sound. Pollutant routing through BMPs in *SUSTAIN* can be simulated as a completely mixed system or as continuously stirred tank reactors (CSTRs) in series. CSTRs in series is the preferred method for simulating first-order pollutant removal processes (e.g., settling, decay) that occur in ponds, wetlands, and other similar BMPs; therefore, this method was used to simulate pollutant routing in the existing wetlands and regional detention ponds for this effort. The method requires the number of reactors in series to be selected to represent the shape of the BMP; pollutant removal within the BMP is then estimated based through simple first-order decay. To derive appropriate numbers of reactors and first-order decay rates for each of the target pollutants in this study, the following steps were performed:

1. The *SUSTAIN* model was run with no pollutant decay provided within the existing wetlands and regional detention ponds. Flow weighted average concentrations for

each pollutant were then computed from these simulations at the outlet of basin CBB (Table 10).

2. The concentrations from Step 1 were compared to flow weighted average concentrations from samples collected at the outlet of basin CBB (Table 10) during the Phase 3 study of toxics chemicals in surface runoff to Puget Sound (Herrera 2011).

3. Target percentage reductions for each pollutant were then derived based on the comparisons in Step 2 (Table 10).

4. Repeated *SUSTAIN* model runs were performed using the time series from the 1-year calibration period (August 2009 to July 2010) to compute concentration reductions for TSS with the existing wetlands and regional detention ponds in basin CBB given different decay rates and number of CSTRs. Decay rates (in units of 1/hour) in these model runs were set at 0, 0.02, 0.05, 0.1, 0.2, 0.3, 0.4, and 0.5. These resultant relationships between decay rates and pollutant reduction are summarized in Appendix C.

5. The relationships developed in Step 4 were used to estimate decay rates for TSS and the other pollutants based on target percent reductions from Step 3. The resultant decay rates are summarized in Table 10 assuming three and five CSTRs for the detention ponds and wetlands, respectively. These decay rates were used in all subsequent *SUSTAIN* modeling to represent the treatment provide by these existing features.

Table 10. Computation of Decay Rates for Modeling Wetlands and Regional Detention Ponds Under Existing Conditions in *SUSTAIN*.

Pollutant	Flow Weighted Average from *SUSTAIN* [a] (mg/L)	Flow Weighted Average from Sampling [b] (mg/L)	Target Pollutant Reduction (%)	Decay Rate for Detention Ponds [c] (1/hour)	Decay Rate for Wetlands [d] (1/hour)
TSS	64.3	9.96	85	0.2090	0.2151
Total Copper	0.0211	0.0036	83	0.1943	0.1973
Dissolved Copper	0.0083	0.0023	73	0.1188	0.1237
Total Zinc	0.0985	0.0334	66	0.0877	0.0902
Dissolved Zinc	0.0469	0.0280	40	0.0289	0.0305
Chrysene	0.000094	0.000034	64	0.0815	0.0842

mg/L – milligrams per liter

[a] Flow weighted average concentrations from *SUSTAIN* model with no pollutant decay provided within the existing wetlands and regional detention ponds.

[b] Flow weighted average concentrations from samples collected at the outlet of basin CBB during the Phase 3 study of toxics chemicals in surface runoff to Puget Sound (Herrera 2011).

[c] Decay rates reflect pollutant removal with 3 CSTRs (see Appendix C).

[d] Decay rates reflect pollutant removal with 5 CSTRs (see Appendix C).

When interpreting the decay rates derived through the steps above, it should be noted that the dissolved metals tend to be highly unstable in water and will vary with changes in hardness or sediment concentration. In contrast, total metals concentrations are generally more conservative in transport than dissolved. *SUSTAIN* cannot model the hypothetical condition where hardness and TSS levels are such that dissolved metals concentrations increase as a result of desorption from TSS. That being said, the current model representation assumes that fate and transport of dissolved metals follows first-order decay. In other words, it is assumed that dissolved concentrations will vary proportional to total concentrations.

FUTURE CONDITION BMP SCENARIO DEVELOPMENT

This section describes the methods that were used to incorporate future condition BMP scenarios into the *SUSTAIN* model. It is organized to present the following information related to this task:

- **BMPs Selected:** The distributed LID and regional BMPs selected for retrofit scenarios and the rationale for their selection
- **BMP Design and Sizing:** The assumptions made for BMP design and sizing
- **Basin Area Feasibly Treated:** How the basin areas suitable for LID BMP retrofit were estimated
- **BMP Optimization Scenarios:** A summary of the BMPs and the decision variables selected for two treatment retrofit scenarios
- **BMP Costs:** A summary of the construction, design, and maintenance costs assumed for each BMP

BMP Selection

The LID and regional water quality treatment BMPs selected for *SUSTAIN* model optimization are summarized in Table 11. They include two LID BMPs (bioretention with underdrains and porous asphalt) and two regional BMPs (wet ponds and treatment wetlands). Originally the project scope also included grassy swales and infiltration trenches for application along roadsides. To simplify the analysis, only one BMP (bioretention) was selected for use in the right-of-way and swales, and infiltration trenches were eliminated.

BMP Design and Sizing

The assumptions for BMP design and sizing 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 guidance in these manuals, in combination with professional judgment from past modeling efforts, was used to develop a list of BMP input assumptions that are summarized in Table 12. This table includes a description of each treatment BMP, design configuration (e.g., materials, infiltration rates), and BMP inputs to *SUSTAIN*.

BMP Optimization Scenarios

BMP Scenarios

The *SUSTAIN* model will be used to optimize application of treatment BMPs in the study basin. Two modeling scenarios (Scenario A and B) were evaluated for this study.

Table 11. BMPs Selected for the Study.

BMP Type	BMP	General Application within Basin	Rationale for Selection
LID BMP	Bioretention with Underdrain	Distributed in each subcatchment. Applied to right-of-way, public parcels, and private parcel land uses.	Because we are optimizing the model for water quality benefit, it makes sense to optimize the BMP design for water quality benefit (i.e., bioretention with underdrains can provide the same treatment with a smaller size and lower cost relative to systems that rely on native infiltration). This approach simplifies the analysis because performance will not vary with soil type.
	Porous Asphalt	Distributed in each subcatchment Applied to public and private parcel land uses (parking lots only).	Retrofitting right-of-way areas, particularly roadways, with permeable pavement is typically less feasible than retrofitting these areas with bioretention facilities. Therefore, permeable pavement is not applied to the right-of-way for this study. While permeable pavement could be applied to sidewalks, these surfaces are not considered pollution generating. Therefore, permeable pavement application is limited to parking lot and driveway settings on public and private parcels. Given this application, porous asphalt was selected. For permeable pavement installed in areas primarily comprised of till soils, it is assumed for this study that the till soil would meet Ecology's soil treatment requirements (e.g., cation exchange capacity, organic content) and provide treatment for infiltrated water. For permeable pavement installed in areas primarily comprised of outwash soils, it is assumed that a sand treatment layer will be incorporated to provide treatment before infiltration to native soils.
Regional BMP	Wet Pond	Located at bottom of basin treating runoff from all subcatchments.	City may consider expansion of the existing Kitts Corner wet pond.
	Wetland	Located at bottom of basin treating runoff from all subcatchments.	City may consider installing pre-treatment upstream of the Kitts Corner wet pond such as a constructed wetland.

Table 12. BMP Design and Sizing.

	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 is included for installations over outwash soil.	Treatment wetland	Basic wet pond
BMP Cross-Section				
	Bioretention soil: Depth = 1.5 feet Porosity = 0.4 Infiltration rate = 3 in/hr Aggregate Underdrain Bedding: Depth and porosity designed to ensure unrestricted flow through underdrain	Porous Asphalt: 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: (Outwash soils only) Depth = 4 inches Porosity = 0.3 All Courses: Infiltration Rate = 10 in/hr (not limiting)	NA	NA
Underlying Soil Infiltration Rate	NA (underdrain controlled)	Till = 0.15 in/hr Outwash = 1.5 in/hr	0 in/hr	0 in/hr

Table 12 (continued). BMP Design and Sizing.				
	Bioretention	**Permeable Pavement**	**Constructed Wetland**	**Wet Pond**
BMP Sizing Basis				
Drainage Area	1,000 sf	Permeable asphalt area is 1,000 sf with no contributing drainage area	1 acre	1 acre
Sizing Method	Bioretention area sized to infiltrate 91 percent of the runoff file (sized in *SUSTAIN*). *SUSTAIN* does not account for side slopes, so the costs per area for this BMP may need to be adjusted to account for a larger footprint.	Aggregate storage layer thickness required to infiltrate 91 percent of the runoff file (sized in *SUSTAIN*) is significantly less than the thickness required for structural loading requirements.	Water quality treatment volume estimated as 4,810 cubic feet (MGSFlood). Presettling and wetland cell areas and dimensions calculated per Ecology guidance.	Water quality treatment volume estimated as 4,810 cubic feet (MGSFlood). First and second cell areas and dimensions calculated per Ecology guidance.
Other Assumptions		Storage in wearing course, choker course, and treatment layer neglected	Note: guidance allows wetland volume to be less than water quality volume.	
Preliminary Size	4.1 feet x 4.1 feet 6 inches of surface ponding 1.5 feet bioretention soil Vertical side slopes	9 inches of aggregate storage layer sufficient for both till and outwash soils (thickness based on assumed structural loading requirements).	Presettling Cell Area: 720 sf Depth: 6 feet Side Slopes: 2:1 Wetland Cell Area: 1315 sf Depth: 1.5 feet Side Slopes: 2:1	First Cell Area: 720 sf Depth: 6 feet Side Slopes: 2:1 Second Cell Area: 1315 sf Depth: 6 feet Side Slopes: 2:1
BMP Representation in *SUSTAIN*				
SUSTAIN BMP Type	Bioretention	Till: Porous Pavement Outwash: Infiltration Trench [a]	Wet Pond	Wet Pond

Table 12 (continued). BMP Design and Sizing.

	Bioretention	Permeable Pavement	Constructed Wetland	Wet Pond
BMP Representation	4.1 feet x 4.1 feet 6 inches of surface ponding 1.5 feet bioretention soil (0.4 porosity) Underdrain flow uncontrolled	9 inches of aggregate (0.3 porosity)	Represented as simple representative storage reservoir Area: 45 feet x 45 feet Represented as several CSTRs Average depth: 1.6 feet Overflow set at average ponding depth (sized so unrestrictive)	Represented as simple representative storage reservoir Area: 45 feet x 45 feet Represented as several CSTRs Average depth: 2.4 feet Overflow set at average ponding depth (sized so unrestrictive)

[a] Aggregate BMP template in *SUSTAIN* only allows for one application of each BMP type. However, the BMP templates in *SUSTAIN* are interchangeable (e.g., the "bioretention" template may be used to represent another BMP such as permeable pavement, if necessary). This study relies on this workaround to represent permeable pavement on both till and outwash soils.

in/hr = inches per hour

NA = not applicable

sf = square feet

CSTR = continuous stirred tank reactor

- **Scenario A:** Optimize mix of bioretention to treat runoff from the right-of-way and regional treatment systems at the bottom of the basin (constructed wetland and wet pond) to meet water quality management targets
- **Scenario B:** Optimize Scenario A BMPs plus a mix of bioretention or porous asphalt to treat runoff from public/private parcels to meet water quality management targets

This study used the aggregate BMP approach to represent distributed bioretention and permeable pavement facilities and to route runoff from a fraction of a given subcatchment to each BMP type for treatment. In the current version of *SUSTAIN*, the aggregate BMP template allows for only one application of each BMP type (e.g., the user can define just one bioretention configuration per aggregate BMP). This study relied on the inherent interchangeability of BMP templates as a workaround for representing two permeable pavement configurations: one on outwash and one on till soils. In addition, only one aggregate BMP type can be applied to each unit area in a subcatchment. In other words, even if both BMP types are feasible for a given area, the user must specify only one of the BMPs. This is a fundamental limitation of the model with no current workaround. Because two BMP types are used under Scenario B for this study, bioretention and porous asphalt are each applied to up to half of the public and private parcel areas for which treatment is feasible. Scenarios are further detailed in Table 13. Note that a baseline assumption is that porous pavement would be applied to parking lots and driveways areas only.

Table 13. BMP Optimization Approach.

	Bioretention	Permeable Pavement	Constructed Wetland	Wet Pond
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	Area of BMP at bottom of basin	Area of BMP at bottom of basin
Optimization Scenario A				
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 B				
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 and driveway areas only)		
Private Parcels				

Basin Area Feasibly Treated

Not all areas of the basin are suitable for LID retrofit. To address this issue, the area of each subcatchment for which bioretention and permeable pavement are feasible was estimated by applying a "Technical Factor" to account for technical engineering constraints and a "Participation Factor" to account for anticipated participation in retrofit programs (Table 14).

Table 14. Technical and Participation Factors by Property Type.

Property Type	Bioretention with Underdrains		Porous Asphalt	
	Technical Factor (%)	Participation Factor (%)	Technical Factor (%)	Participation Factor (%)
Private	50	20	50	20
Public	50	80	50	80
Right-of-Way	50	100	NA	NA

NA - not applicable (optimization scenarios do not include permeable pavement in the right-of-way)

The "Technical Factor" represents the percent of the subcatchment area that is likely technically feasible for LID retrofit. Considerations include: infiltration restrictions (e.g., high groundwater, steep slopes), existing site improvements and infrastructure, available space, and positive drainage for parcel-scale facility overflows to a safe discharge point. Because it is not in the scope of this project to complete a feasibility assessment for the study basin, a typical technical factor of 50 percent was estimated, based on studies of similar basins and professional judgment. This factor was applied to all property types.

The "Participation Factor" represents the percent of the subcatchment area that is likely socially feasible for LID retrofit. A participation factor of 20, 80, and 100 percent was applied to private parcels, public parcels, and right-of-way areas, respectively, based on best professional judgment.

For each scenario, the impervious area in each subcatchment that could feasibly be treated by LID retrofit BMPs was estimated as:

Maximum Area Treated = Total Area x "Technical Factor" x "Participation Factor"

As an example, the "Maximum Area Treated" by bioretention facilities on private parcels = Subcatchment Area x 50% x 20% = Subcatchment Area x 10%. Therefore, the technical factor together with the participation factor significantly decreased the portion of the subcatchment considered treatable. A more detailed assessment would be needed to provide site-specific factors; however, this type of assessment was beyond the scope of this project.

Scenario A

The areas feasibly treated by distributed LID BMPs for Scenario A are summarized in Table 15. This table is formatted to correspond to *SUSTAIN* input requirements. Note that areas not routed to a BMP are routed to the "outlet" and leave the subcatchment untreated.

Table 15. Scenario A Aggregate BMP Land Use Distribution.

	Impervious Basin Area					Pervious Basin Area				
		Maximum Percent Area Routed to BMP					Maximum Percent Area Routed to BMP			
	Total Impervious Area (acre)	Bioretention (%)	Permeable Pavement on Outwash (%)	Permeable Pavement on Till (%)	Outlet (%)	Total Pervious Area (acre)	Bioretention (%)	Permeable Pavement on Outwash (%)	Permeable Pavement on Till (%)	Outlet (%)
BMP ID		**1**	**2**	**3**	**0**		**1**	**2**	**3**	**0**
Subcatchment	**31**									
Commercial	7.1	4	0	0	96	1	0	0	0	100
Residential	7.7	13	0	0	87	5.1	0	0	0	100
Forest	1.3	7	0	0	93	3.7	0	0	0	100
Subcatchment	**34**									
Commercial	3.5	39	0	0	61	0	--	--	--	--
Residential	3.4	33	0	0	67	0.8	0	0	0	100
Forest	0	16	0	0	84	0.1	0	0	0	100
Subcatchment	**35**									
Commercial	0	--	--	--	--	0	--	--	--	--
Residential	0.3	24	0	0	76	1.1	0	0	0	100
Forest	13.9	1	0	0	99	2.2	0	0	0	100
Subcatchment	**36**									
Commercial	14.1	10	0	0	90	2.2	0	0	0	100
Residential	7.8	22	0	0	78	6.2	0	0	0	100
Forest	0.2	14	0	0	86	2.8	0	0	0	100
Subcatchment	**52**									
Commercial	159.2	9	0	0	91	9	0	0	0	100
Residential	41.9	7	0	0	93	23.3	0	0	0	100
Forest	1.8	0	0	0	100	5.2	0	0	0	100

Table 15 (continued). Scenario A Aggregate BMP Land Use Distribution.										
	Impervious Basin Area					Pervious Basin Area				
	Total Impervious Area (acre)	Maximum Percent Area Routed to BMP				Total Pervious Area (acre)	Maximum Percent Area Routed to BMP			
		Bioretention (%)	Permeable Pavement on Outwash (%)	Permeable Pavement on Till (%)	Outlet (%)		Bioretention (%)	Permeable Pavement on Outwash (%)	Permeable Pavement on Till (%)	Outlet (%)
BMP ID		**1**	**2**	**3**	**0**		**1**	**2**	**3**	**0**
Subcatchment	**53**									
Commercial	140.3	5	0	0	95	5	0	0	0	100
Residential	54	10	0	0	90	51.7	0	0	0	100
Forest	0	--	--	--	--	0	--	--	--	--
Subcatchment	**66**									
Commercial	3.3	0	0	0	100	0.7	0	0	0	100
Residential	17	6	0	0	94	22.1	0	0	0	100
Forest	0.5	0	0	0	100	1.2	0	0	0	100
Subcatchment	**70**									
Commercial	0.5	0	0	0	100	0	--	--	--	--
Residential	11.8	7	0	0	93	11.6	0	0	0	100
Forest	2.9	0	0	0	100	4.8	0	0	0	100
Subcatchment	**72**									
Commercial	4.3	6	0	0	94	0.2	0	0	0	100
Residential	15.9	10	0	0	90	14.6	0	0	0	100
Forest	2.2	13	0	0	87	14.9	0	0	0	100
Subcatchment	**75**									
Commercial	0.1	0	0	0	100	0	--	--	--	--
Residential	0.3	0	0	0	100	16.8	0	0	0	100
Forest	0	--	--	--	--	32	0	0	0	100
Downstream ID		0	0	0			0	0	0	

Based on the areas that can feasibly be treated (Table 15), the corresponding maximum number of LID BMP units were calculated (Table 16). Because the drainage area for each bioretention cell was set at 1,000 square feet (see Table 12), the maximum number of bioretention cells was calculated as the maximum area routed to bioretention (Table 15) divided by 1,000 square feet.

The optimization module varies the number of bioretention BMPs between zero and the maximum number at a user-specified bin increment. A fixed increment of 10 was selected for bioretention BMPs under Scenario A. Before being entered into the model, the maximum numbers of BMP units were rounded down to be divisible by a BMP bin increment of 10 (Table 16).

Scenario B

The areas feasibly treated by distributed LID BMPs for Scenario B are summarized in Table 17. For this scenario, both bioretention and porous asphalt BMPs are included.

As explained for Scenario A, the corresponding maximum number of LID BMP units was calculated (Table 18). The porous asphalt BMP size was set at 1,000 square feet (see Table 12), so the maximum number of porous asphalt BMP was calculated as the maximum area "routed" to permeable pavement (Table 18) divided by 1,000 square feet.

Because Scenario B has more decision variables (e.g., more BMPs), larger BMP bin increments were used to reduce model runtimes. For a more detailed discussion, see the Model Runtime Considerations section. Instead of applying a fixed bin increment of 10 for the BMP optimization (as done for Scenario A), the BMP increment was calculated as 20 percent of the maximum number of BMPs, or a fixed increment of 10, whichever was larger. Before being entered into the model, the maximum numbers of BMP units were rounded down to be divisible by the BMP bin increment (Table 18).

BMP Treatment Calibration

As described previously, pollutant routing through BMPs in *SUSTAIN* is simulated as 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 can be expressed as a percent removal. While several published reports (Tetra Tech 2007, 2010) provide representative decay rates 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. Therefore, decay rates for this study were derived for each combination of BMP and pollutant based on percent removal targets that were identified in coordination with Ecology (O'Brien 2012 personal communication) and other data sources (Melesi et al. 2006). These percent removal targets are identified in Table 19; specific assumptions that provide the basis for these targets are summarized in Appendix D.

In *SUSTAIN*, the pollutant percent removal targets from Table 19 were directly applied to all water discharging from underdrain systems for bioretention facilities; no pollutant removal

Table 16. Scenario A Optimization Decision Variables.

Subcatchment	Maximum BMP Units Feasible			BMP Bin Increment			Maximum BMP Units Entered [a]		
	Bioretention	Permeable Pavement on Outwash	Permeable Pavement on Till	Bioretention	Permeable Pavement on Outwash	Permeable Pavement on Till	Bioretention	Permeable Pavement on Outwash	Permeable Pavement on Till
31	57	0	0	10	NA	NA	50	0	0
34	109	0	0	10	NA	NA	100	0	0
35	8	0	0	10	NA	NA	0	0	0
36	134	0	0	10	NA	NA	130	0	0
52	758	0	0	10	NA	NA	750	0	0
53	554	0	0	10	NA	NA	550	0	0
66	42	0	0	10	NA	NA	40	0	0
70	35	0	0	10	NA	NA	30	0	0
72	0	0	0	10	NA	NA	0	0	0
75	0	0	0	10	NA	NA	0	0	0

NA – not applicable

[a] Maximum BMP units rounded down to be divisible by BMP bin increment

Table 17. Scenario B Aggregate BMP Land Use Distribution.

	Impervious Basin Area					Pervious Basin Area				
	Total Impervious Area (acre)	Maximum Percent Area Routed to BMP				Total Pervious Area (acre)	Maximum Percent Area Routed to BMP			
		Bioretention (%)	Permeable Pavement on Outwash (%)	Permeable Pavement on Till (%)	Outlet (%)		Bioretention (%)	Permeable Pavement on Outwash (%)	Permeable Pavement on Till (%)	Outlet (%)
BMP ID		**1**	**2**	**3**	**0**		**1**	**2**	**3**	**0**
Subcatchment	**31**									
Commercial	7.1	8	5	0	87	1.0	0	0	0	100
Residential	7.7	17	4	0	80	5.1	0	0	0	100
Forest	1.3	11	4	0	84	3.7	0	0	0	100
Subcatchment	**34**									
Commercial	3.5	40	0	1	58	0	--	--	--	--
Residential	3.4	35	1	1	63	0.8	0	0	0	100
Forest	0	19	3	0	77	0.1	0	0	0	100
Subcatchment	**35**									
Commercial	0	--	--	--	--	0	--	--	--	--
Residential	0.3	27	3	0	70	1.1	0	0	0	100
Forest	13.9	6	0	5	89	2.2	0	0	0	100
Subcatchment	**36**									
Commercial	14.1	13	2	2	83	2.2	0	0	0	100
Residential	7.8	25	1	1	72	6.2	0	0	0	100
Forest	0.2	17	2	2	79	2.8	0	0	0	100
Subcatchment	**52**									
Commercial	159.2	13	1	3	83	9.0	0	0	0	100
Residential	41.9	11	1	3	85	23.3	0	0	0	100
Forest	1.8	5	0	5	90	5.2	0	0	0	100

Table 17 (continued). Scenario B Aggregate BMP Land Use Distribution.

		Impervious Basin Area					Pervious Basin Area				
			Maximum Percent Area Routed to BMP					Maximum Percent Area Routed to BMP			
		Total Impervious Area (acre)	Bioretention (%)	Permeable Pavement on Outwash (%)	Permeable Pavement on Till (%)	Outlet (%)	Total Pervious Area (acre)	Bioretention (%)	Permeable Pavement on Outwash (%)	Permeable Pavement on Till (%)	Outlet (%)
BMP ID			1	2	3	0		1	2	3	0
Subcatchment		53									
	Commercial	140.3	10	0	5	85	5.0	0	0	0	100
	Residential	54.0	15	0	5	80	51.7	0	0	0	100
	Forest	0	--	--	--	--	0	--	--	--	--
Subcatchment		66									
	Commercial	3.3	5	0	5	90	0.7	0	0	0	100
	Residential	17.0	10	0	4	85	22.1	0	0	0	100
	Forest	0.5	5	0	5	90	1.2	0	0	0	100
Subcatchment		70									
	Commercial	0.5	5	0	5	90	0	--	--	--	--
	Residential	11.8	11	0	4	84	11.6	0	0	0	100
	Forest	2.9	5	0	5	90	4.8	0	0	0	100
Subcatchment		72									
	Commercial	4.3	10	0	4	85	0.2	0	0	0	100
	Residential	15.9	14	0	4	82	14.6	0	0	0	100
	Forest	2.2	17	0	4	80	14.9	0	0	0	100
Subcatchment		75									
	Commercial	0.1	0	0	0	100	0.0	0	0	0	100
	Residential	0.3	0	0	0	100	16.8	0	0	0	100
	Forest	0	--	--	--	--	32.0	0	0	0	100
Downstream ID			0	0	0			0	0	0	

Table 18. Scenario B Optimization Decision Variables.

Subcatchment	Max BMP Units Feasible			BMP Bin Increment			Max BMP Units Entered [a]		
	Bioretention	Permeable Pavement on Outwash	Permeable Pavement on Till	Bioretention	Permeable Pavement on Outwash	Permeable Pavement on Till	Bioretention	Permeable Pavement on Outwash	Permeable Pavement on Till
31	85	28	0	17	10	10	85	20	0
34	112	1	2	22	10	10	110	0	0
35	37	0	29	10	10	10	30	0	20
36	167	18	14	33	10	10	165	10	10
52	1124	118	246	224	23	49	1120	115	245
53	974	15	404	194	10	80	970	10	400
66	82	0	40	16	10	10	80	0	40
70	64	0	27	12	10	10	60	0	20
72	8	1	38	10	10	10	0	0	30
75	0	0	0	10	10	10	0	0	0

[a] Maximum BMP units rounded down to be divisible by BMP bin increment

Table 19. Target Pollutant Percent Removals for BMPs in *SUSTAIN*.

Pollutant	TSS (%)	Total Copper (%)	Dissolved Copper (%)	Total Zinc (%)	Dissolved Zinc (%)	Chrysene (%)
Bioretention	70.0	56.5	40.0	70.0	70.0	34.0
Wet Pond	70.0	46.6	18.0	60.3	50.0	18.0
Permeable Pavement [a]	0.0	0.0	0.0	0.0	0.0	0.0
Wetland	70.0	46.6	18.0	60.3	50.0	18.0

[a] Percent removal for treated effluent from permeable pavement was assumed to be 0% when routed to surface water and 100% where it infiltrates to the ground.

was assumed for water bypassing these facilities at the surface. Furthermore, no pollutant removal was also assumed for effluent that is discharged from permeable pavement to surface water.

First-order decay rates were estimated for wet ponds and wetlands based on the percent removal targets in Table 19 using a process similar to the one described above for the existing wetlands and regional detention ponds in basin CBB (see Existing Conditions Model Development). In this case, a series of *SUSTAIN* models were developed that featured either a wet pond or wetland implementation sized to treat the design drainage area. Repeated model runs were then performed using the 30-year truncated MGS precipitation time series (see description above) to compute mass and concentration percent reductions for TSS with each BMP given different decay rates and number of CSTRs. The resultant relationships between decay rates and pollutant percent reduction are summarized in Appendix E for each BMP. These relationships were subsequently used to identify appropriate decay rates for each pollutant based on target percent reductions from Table 19. The resultant decay rates are summarized in Table 20 assuming three and five CSTRs for the detention ponds and wetlands, respectively. As noted previously, the current model representation assumes that fate and transport of dissolved metals follows first-order decay. In other words, it is assumed that dissolved concentrations will vary proportional to total concentrations.

Table 20. Wet Pond and Wetland Pollutant Decay Rates for Modeling Future Condition BMP Scenarios in *SUSTAIN*.

Pollutant	Decay Rate for Wet Ponds [a] (1/hour)	Decay Rate for Wetlands [b] (1/hour)
TSS	0.0175	0.0275
Total Copper	0.0116	0.0139
Dissolved Copper	0.0045	0.0045
Total Zinc	0.0151	0.0180
Dissolved Zinc	0.0125	0.0149
Chrysene	0.0045	0.0045

[a] Decay rates reflect pollutant removal with 3 CSTRs (see Appendix E)

[b] Decay rates reflect pollutant removal with 5 CSTRs (see Appendix E)

BMP Cost Data

BMP construction, design, and operations and maintenance (O&M) costs were input to *SUSTAIN* as lump sum (user defined) costs per BMP area. As part of this project, Herrera developed a BMP cost database for Puget Sound based on data collected in the region (Herrera 2012). Typical costs from the BMP cost database were adjusted to reflect the BMP design and application assumptions for this study (see Tables 11 and 12). Considerations included:

- Bioretention design configuration (e.g., underdrain infrastructure)
- New City of Seattle data on bioretention O&M
- Estimation of design and O&M costs for which data was not collected

- Increased cost due to retrofit (e.g., utilities, existing infrastructure)
- Porous asphalt design (e.g., depth of courses)
- Distinguishing between permeable pavement over outwash soil (with a treatment layer) and permeable pavement over till (without a treatment layer)

The costs used in this study are summarized in Table 21. Note that the costs for the regional BMPs include costs to acquire property based on data from the King County Department of Assessments database. It should also be noted that *SUSTAIN* represents all BMPs as a unit-area cross-section (e.g., bioretention facilities are represented as a unit-area column of surface ponding and soil, neglecting side slopes of the earthen depression). While this unit-area representation works for permeable pavement, it is an over-simplification for facilities with side slopes (e.g., bioretention, wet ponds, and wetlands). For the purposes of this analysis, the wetlands and wet ponds were sized based on facility footprint area (i.e., the side slopes were incorporated into the sizing), so the "per square foot facility" costs can be directly applied to the modeled wetlands and wet ponds. However, for bioretention facilities, the bottom area of the facility was used as the sizing parameter, thus neglecting facility side slopes. To account for this discrepancy, the per-square-foot bioretention costs were adjusted (see more detailed discussion in next subsection).

Bioretention Cost Scaling

SUSTAIN represents bioretention facilities as a unit-area column of surface ponding and soil, neglecting facility side slopes and ultimately underestimating the true facility footprint. Because the costs developed for input to *SUSTAIN* are applied per square foot of facility footprint, direct application of the unit cost to the bioretention facility in *SUSTAIN* results in underestimation of the associated facility cost. While there are a number of ways to address this issue, the approach taken for this effort involved scaling of the per square foot facility cost based on the anticipated "typical" facility geometry. The result is a ratio of bioretention bottom area to top area of each facility that can be applied to scale the cost data.

The design bioretention ponding depth for this study is 6 inches. It was assumed that facilities would also require (on average) 6 inches of freeboard. Given these constraints, and assuming typical facility side slopes of 3 to 1, the footprint area of a 4.1-foot by 4.1-foot bioretention unit was calculated to be 10.1 by 10.1 feet. However, because these facilities are small and the typical application is in the public right-of-way, it is likely that multiple facilities will be combined to create a single, long, linear facility. To account for this anticipated configuration, it was assumed that for each 4.1- by 4.1-foot bioretention unit, side slopes were applied to only two of the four sides of the bioretention unit, resulting in a 4.1- by 10.1-foot facility (see Figure 7, below). Based on the results of this analysis, a scaling factor of approximately 2.5 was applied to the total per square foot facility cost of bioretention. The scaled bioretention cost is provided in Table 21.

Table 21. Summary of BMP Costs Used for This Study.

BMP Type	Units	Property Acquisition Cost [c]	Construction Cost [d]	Design Cost [e]		O&M Cost [f]			TOTAL Cost		
				% Const.		($/yr)	Schedule	PV 30-year Lifecycle	per SF Facility	per SF Unit Area BMP [g]	per SF Mitigated [h]
Rain Garden with Underdrain	SF	--	$35	25%	$8.75	--	--	$40.04	$83.79	$206.42	$3.47
Early (year 2 and 3)	--	--	--	--	--	$1.40	Annual	--	--	--	--
Mature (year 4 to 30)	--	--	--	--	--	$0.70	Annual	--	--	--	--
Porous Asphalt on Till [a]	SF	--	$20	20% [b]	$4.00	$0.05	Annual	$2.75	$26.75	$26.75	$26.75
Porous Asphalt on Outwash [a]	SF	--	$19	20% [b]	$3.80	$0.05	Annual	$2.75	$25.55	$25.55	$25.55
Constructed Wetland	SF	$4	$15	15%	$2.25	--	--	$16.57	$37.82	$37.82	$1.76
Sediment Removal	--	--	--	--	--	$0.64	5-year	--	--	--	--
Vegetation Management	--	--	--	--	--	$0.16	1-year	--	--	--	--
Wet pond	SF	$4	$10	10%	$1.00	$0.35	15-year	$9.70	$24.70	$24.70	$1.15

--: not available

SF: square feet

[a] Study assumes self-mitigating porous asphalt parking lot and driveway (no run-on). Pavement over outwash soil has 4-inch sand treatment layer.

[b] Cost estimate based on recent engineer's estimate for local porous asphalt parking lot retrofit project. In addition to pavement materials and installation, costs include mobilization, removal, and haul of existing pavement, temporary erosion and sediment control, limited traffic control, some extruded curb replacement, limited impermeable liner close to structures and parking stall paint lines. Unit area cost is based on 1,000 square foot project. Porous asphalt on outwash soil includes cost for 4 inch sand treatment layer.

[c] Property acquisition costs are based on the King County Department of Assessments eReal Property tool located at http://info.kingcounty.gov/Assessor/eRealProperty/default.aspx. Site accessed August 30, 2012.

[d] Construction costs in the Puget Sound Database typically did not include mobilization, erosion and sediment control, and traffic control. To account for these components in *SUSTAIN*, construction costs were increased based on engineers estimates of costs for other projects in the region, including Seattle, King County, Kitsap County, Mercer Island, Lacey, and Olympia.

[e] Design costs for this study were estimated as a percentage of the construction costs, based on the Puget Sound Cost Database and engineers estimates of recent Capital Improvement Program (CIP) projects and local jurisdictions (Seattle, King County) planning costs.

[f] O&M costs were assessed as a present value (2012 dollars), assuming a 30-year facility lifecycle and discount rate of 4% per year. O&M costs from the Puget Sound Cost Database were refined for this study based on engineers estimates of recent CIP projects and local jurisdiction (Seattle, Olympia) planning costs.

[g] A scaling factor of approximately 2.5 was applied to the total per square foot facility cost of bioretention to account for *SUSTAIN*'s application of "per square foot facility" costs to the bioretention bottom area only.

[h] Per SF mitigated cost is the total facility cost (per SF unit area cost x facility footprint area) divided by the contributing basin area to facility from Table 12.

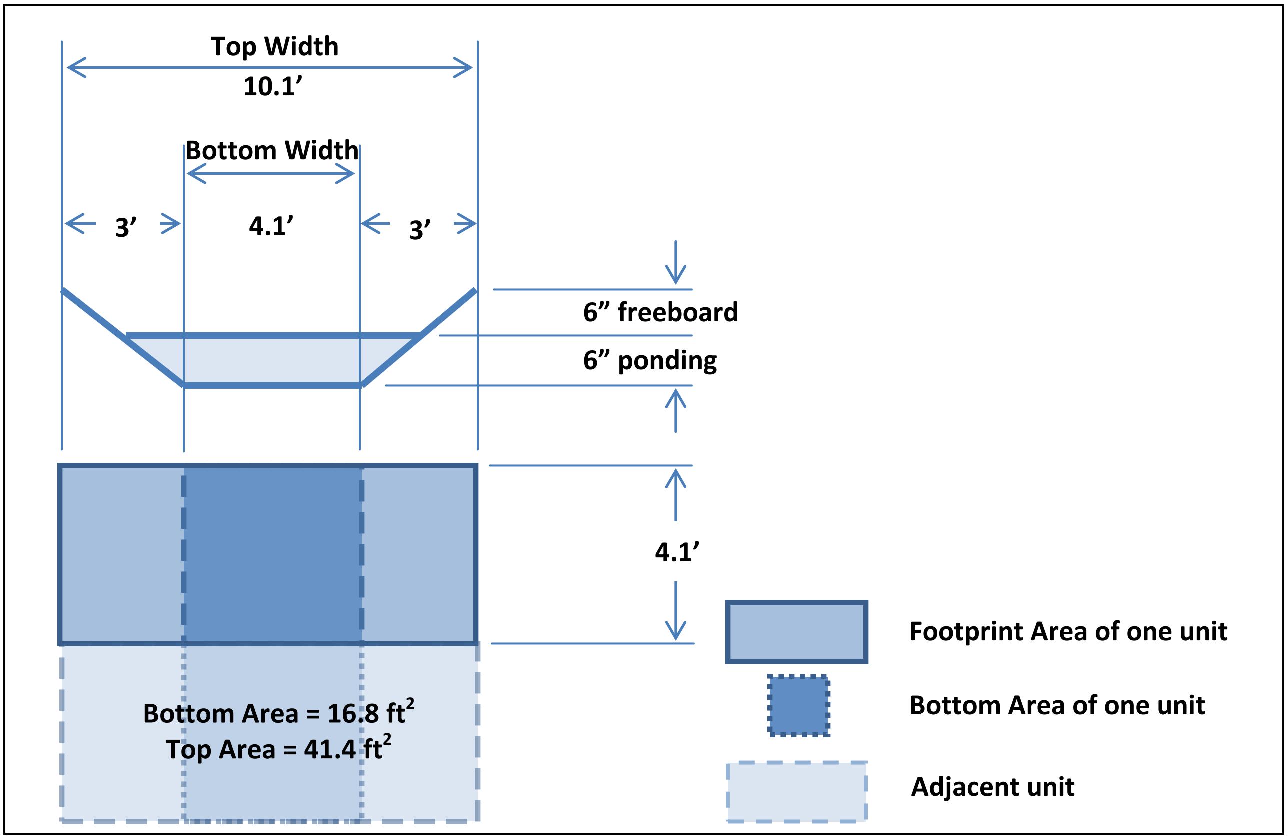


Figure 7. Assumed Bioretention Facility Geometry for Cost Scaling.

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, a management target, and decision variables. Each of these inputs is described in more detail below.

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 is the monitoring location for commercial/industrial basin CBB from the Phase 3 study of toxics in surface runoff (Figure 5).

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., watershed pollutant removal efficiency versus total watershed BMP cost) 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, a number of specific management targets were identified for each of the water quality parameters evaluated in this study. The sections below discuss how each management target was assessed using *SUSTAIN*.

Dissolved Copper, Dissolved Zinc, and Chrysene

State water quality standards for dissolved copper and zinc exist in Washington (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 were identified as primary management targets while chrysene was considered a secondary target. Given this consideration, the scatter search algorithm in *SUSTAIN* was 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 were then evaluated based on this same optimum BMP configuration to determine if the associated national recommended water quality standard were also met at the assessment point.

In these analyses, acute water quality standards of 3.2 ug/L and 25.4 ug/L for dissolved copper and zinc, respectively, were 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 ug/L and 23.2 ug/L for dissolved copper and zinc, respectively, were also assumed based on the same hardness concentration. Finally, the national recommended water quality standard for chrysene is 0.0038 ug/L.

Total Suspended Solids, Total Copper, and Total Zinc

There are no applicable water quality standards for TSS, total copper, and total zinc. Therefore, the NSGA-II algorithm in *SUSTAIN* was 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 one or more decision variables used to explore the various possible BMP configurations. In this study, the decision variable was set as the number of BMPs for both distributed (e.g., bioretention and permeable pavement) and regional (e.g., constructed wetlands and wet ponds) BMPs.

SUSTAIN MODEL RESULTS

All of the model results presented below including BMP selection, distribution, and costs are strongly driven by the assumptions unique to this exploratory analysis of *SUSTAIN*. Therefore, the costs do not necessarily represent an optimum solution for the basin evaluated and are not transferable to other basins. In addition, these results are based on an assessment of water quality at the outlet of the study basin only and do not take into consideration the biological integrity of the system upstream of the assessment point.

Finally, the results from the *SUSTAIN* post processor summarized herein (including the cost-effectiveness curves and the cost distribution by BMP) provide an "effectiveness" metric that is based on the "BMP scenario" performance relative to the "post-developed" scenario performance. However, the "post-developed" scenario assumes a basin configuration with **no** stormwater BMPs (existing and proposed**).** At the same time, the "BMP scenario" does incorporate **both** the existing and proposed BMPs. Therefore, relative to the "post-developed" scenario, the model is skewing (over crediting) the performance of the proposed BMPs because the benefits of the existing BMPs are reflected in the results for "BMP scenario" with no cost implications. This is an important limitation of the *SUSTAIN* post-process that warrants consideration when interpreting the results from this case study.

Model Runtime Considerations

It was originally anticipated that the model would be optimized for a 158-year simulation period (using the MGS extended precipitation series). However, model memory limitations (due to the complexity of the basin hydrologic representation [i.e., total number of unit-area hydrographs]) only allowed simulations of approximately 7 years at a 15-minute time step; any simulation period longer than this threshold caused the model to crash. While it is anticipated that the model would converge on a solution for both NSGA-II and scatter search algorithms using the 7-year simulation period, the required runtime for convergence (greater than 24 hours, and in some cases, greater than 8 days) exceeded the runtime deemed feasible for this effort. To allow *SUSTAIN* exploration consistent with the project objectives, the simulation period was shorted to 2 years, resulting in model runtimes less than 24 hours. Figure 8 provides a comparison of the TSS optimization results for Scenario A for a 2-year and a 7-year simulation. All runtimes are based on simulations performed on a WinXP Pro operating system with Intel Core2 Duo processor (2.93 GHz) and 4 GB RAM.

As evidenced by the plot, the time series used for the simulation has a significant effect on the optimized solution; the optimized solutions are expected to be different due to differences in the precipitation volumes and patterns. For this exercise, the average annual precipitation depth for the 2-year simulation period is 41.8 inches, while only 38.4 inches for the 7-year simulation period. While some of this could be remedied by evaluating the entire rainfall record of interest (e.g., 158-year series) outside of *SUSTAIN* and selecting a shorter period (e.g., 2-year series) that most nearly matches the entire record (e.g., peak flows, average volumes, average durations), it is unclear if the optimized solutions from the shorted time series would be fully representative of the entire period of record.

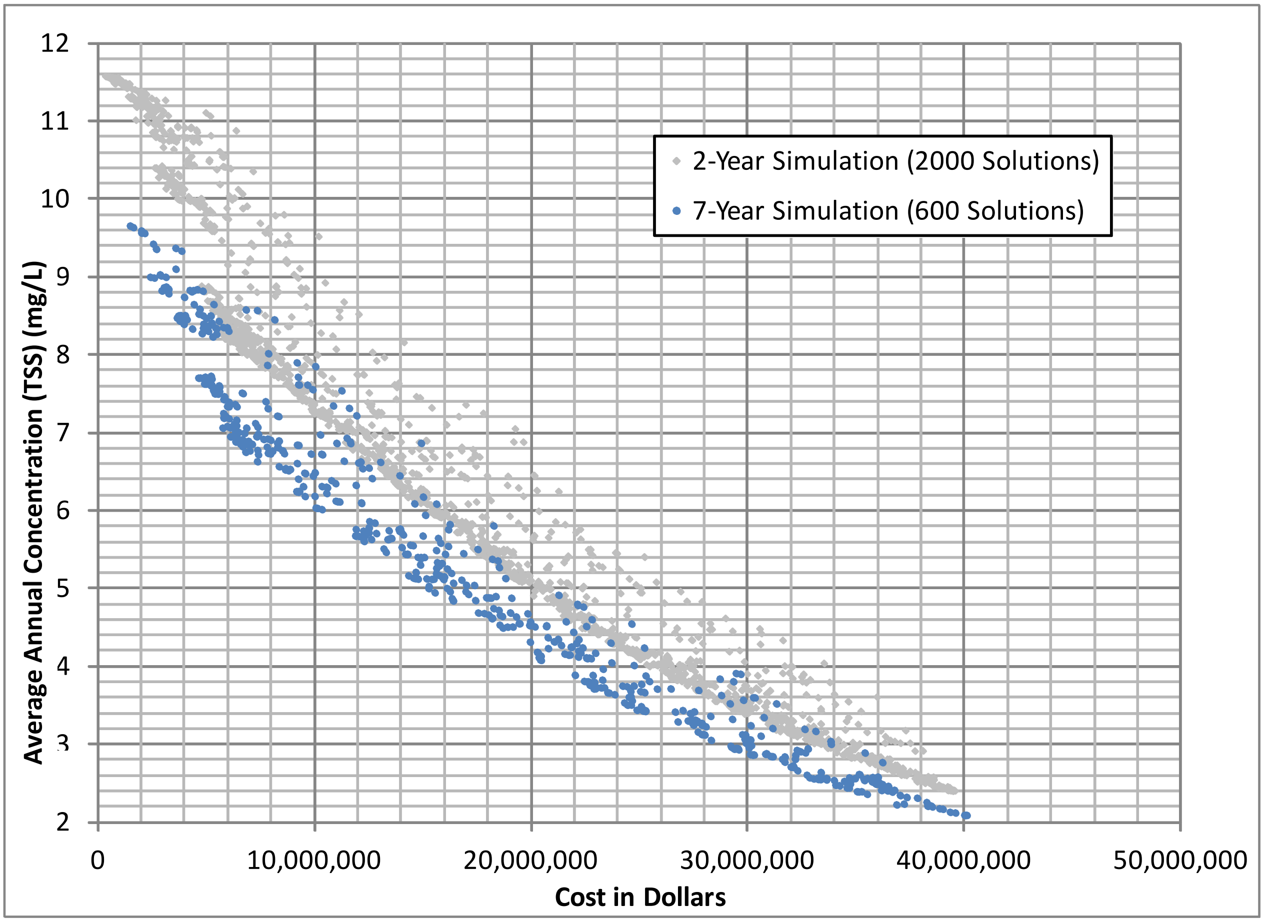


Figure 8. Scenario A NSGA-II Optimization Results.

In addition to total number of unit-area hydrographs, the length of the simulation period, and simulation time step, model runtime is also a function of the number of decision variable combinations, including the maximum number of BMPs and the BMP bin increments (the increment by which the number of BMPs is varied in the model). For Scenario A, the maximum number of BMPs is low enough that a fixed BMP increment of 2 for wet ponds and wetlands and 10 for bioretention and permeable pavement allows the model to converge in a reasonable length of time (5 to 8 hours). Conversely, the additional number of feasible BMPs in Scenario B increases the complexity of the model (4.4E+21 possible combinations of solutions compared to 9.5E+11 combinations for Scenario A), ultimately resulting in infeasible long runtimes. As a result, instead of applying a fixed bin increment for the BMP optimization (as was done in Scenario A), the BMP increment was calculated as a percentage of the maximum number of BMPs deemed feasible in each basin. Specifically, the BMP increment was set at 10 percent of the maximum number of BMPs in a basin for wet ponds and wetlands and 20 percent for bioretention and permeable pavement or a fixed increment of 10, whichever was larger. This decreased the number of permutations (1.3E+14 possible combinations of solutions), ultimately decreasing the number of iterations required to converge on a solution (near convergence occurred after approximately 14 hours of simulation). See Table 22 for a comparison of the bin increment and resulting number of combined solutions.

NSGA-II

The NSGA-II algorithm was used to develop separate cost-effectiveness curves for TSS, total copper, and total zinc. These curves relate the removal efficiency for a given pollutant to various combinations of BMPs throughout the watershed and their associated cost. The following section provides a description and discussion of solution convergence for the NSGA-II model runs and presents the results and discussion of the optimization for the study basin (CBB) under both Scenarios A and B.

Solution Convergence

For NSGA-II optimization runs, the user must select the number of iterated model solutions to be evaluated. The number of runs must be sufficient to achieve convergence, which occurs when the number of iterated solutions does not significantly advance the cost-effectiveness curve (i.e., additional runs do not result in more cost-effective solutions).

To assess the number of model solutions necessary to achieve convergence, a series of TSS optimization runs were compared for a range of iterated solutions. For Scenario A, Figure 9 provides a series of cost-effectiveness curves for 100 to 2,000 solutions. To demonstrate convergence, each optimization run was superimposed on the 2,000-solution optimization. As the number of solutions increase, the cost-effectiveness curves approach that of the 2,000-solution run. The differences between the 1,000- and 2,000-solution runs are minor indicating that the 1,000 iterated solutions is sufficient to reach convergence. Therefore, Scenario A NSGA-II optimization runs were evaluated for 1,000 iterated solutions, requiring approximately 5 hours of runtime.

Scenario B contains more BMPs and decision variables than Scenario A. Therefore, TSS optimization runs were conducted for more iterations, up to 20,000 solutions (Figure 10). Unfortunately, the number of possible permutations in Scenario B (1.3E+14) does not appear to allow the model to converge, even after 20,000 iterations (approximately 95 hours of simulation). However, the incremental benefit of additional iterations marginally improves the cost-effectiveness curve after approximately 3,000 solutions. In the interest of time, the 3,000-iteration optimization was used for Scenario B NSGA-II (approximately 14-hour simulation).

Scenario A

Scenario A included a mix of distributed bioretention systems to treat runoff from the right-of-way and regional treatment systems at the bottom of the basin (constructed wetland and wet pond) to meet water quality goals.

Total Suspended Solids Optimization

Figures 11 through 14 below include sample output from *SUSTAIN*'s post processor. These results correspond to the NSGA-II optimization of TSS removal for

Table 22. Number of Possible Combinations in Scenario A and B Search Space.

BMP ID	Basin ID	BMP	Maximum Number of BMPs		BMP Bin Increment			Number of Combinations		
					Scenario A	Scenario B [a]		Scenario A	Scenario B [a]	
			Scenario A	Scenario B	Fixed	Fixed	Variable	Fixed	Fixed	Variable
78	NA	Wetland	430	430	2	2	43	216	216	11
79	NA	Wet Pond	110	110	2	2	11	56	56	11
82_1	82	Bioretention	750	1,120	10	10	224	76	113	6
82_2	82	Porous Asphalt -Till	--	245	--	10	49	--	26	6
82_3	82	Porous Asphalt -Outwash	--	115	--	10	23	--	13	6
83_4	83	Bioretention	550	970	10	10	194	56	98	6
83_5	83	Porous Asphalt -Till	--	400	--	10	80	--	41	6
83_6	83	Porous Asphalt -Outwash	--	10	--	10	10	--	2	2
84_7	84	Bioretention	40	80	10	10	16	5	9	6
84_8	84	Porous Asphalt -Till	--	40	--	10	10	--	5	5
85_10	85	Bioretention	30	60	10	10	12	4	7	6
85_11	85	Porous Asphalt -Till	--	20	--	10	10	--	3	3
86_14	86	Porous Asphalt -Till	--	30	--	10	10	--	4	4
87_16	87	Bioretention	--	30	--	10	10	--	4	4
87_17	87	Porous Asphalt -Till	--	20	--	10	10	--	3	3
88_19	88	Bioretention	130	165	10	10	33	14	18	6
88_20	88	Porous Asphalt -Till	--	10	--	10	10	--	2	2
88_21	88	Porous Asphalt -Outwash	--	10	--	10	10	--	2	2
89_22	89	Bioretention	100	110	10	10	22	11	12	6
90_25	90	Bioretention	50	85	10	10	17	6	10	6
90_27	90	Porous Asphalt -Outwash	--	20	--	10	10	--	3	3
			Number of Possible Combinations in Search Space					**9.5E+11**	**4.4E+21**	**1.3E+14**

[a] Because the number of decision variables increased from Scenario A to Scenario B, the increased number of possible combinations of solutions resulted in an infeasibly long model runtime. To reduce the runtime, a variable bin increment was applied to Scenario B, calculated as 10 percent of the maximum number of BMPs in a basin for wet ponds and wetlands and 20 percent for bioretention and permeable pavement or a fixed increment of 10, whichever was larger.

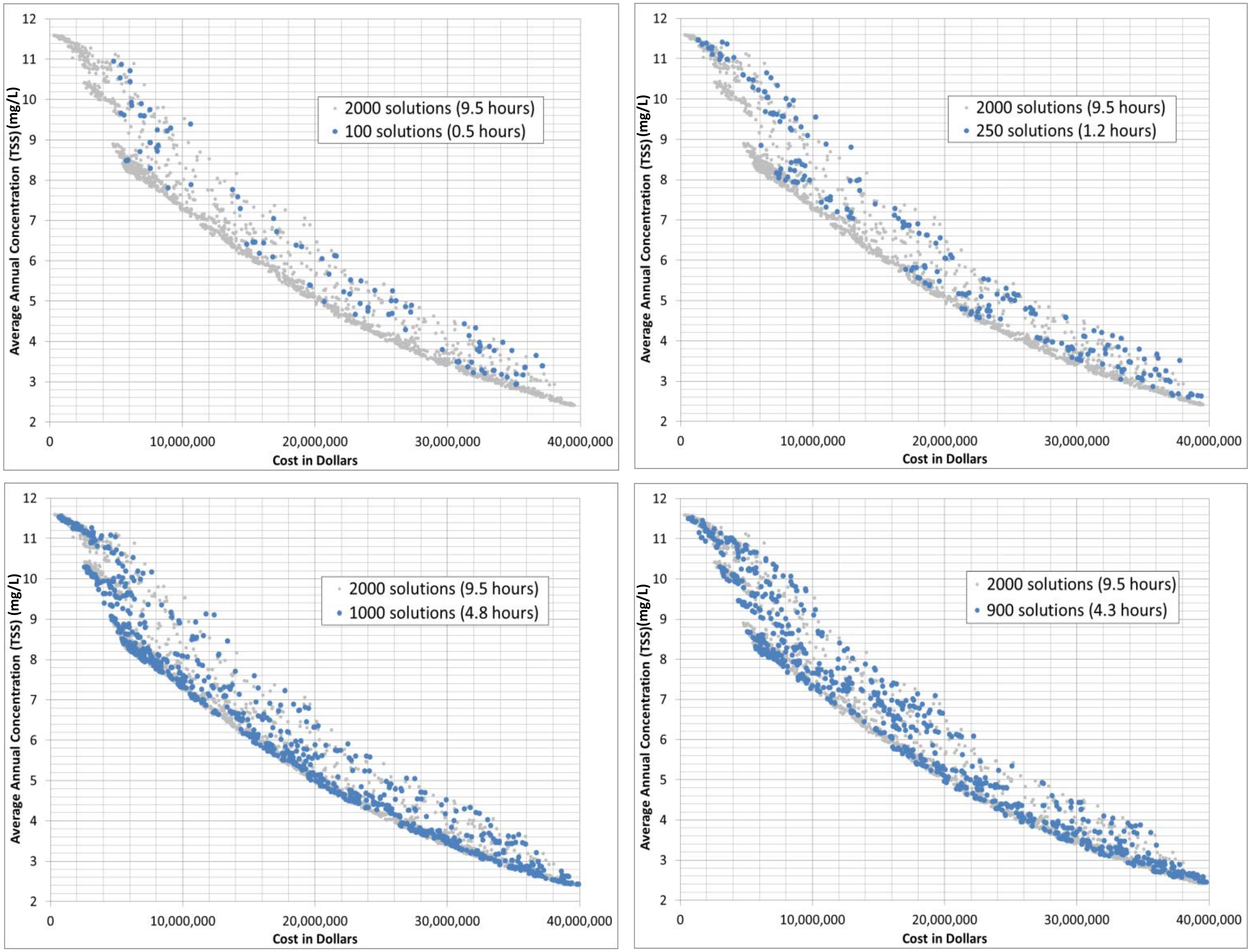


Figure 9. Scenario A NSGA-II Convergence.

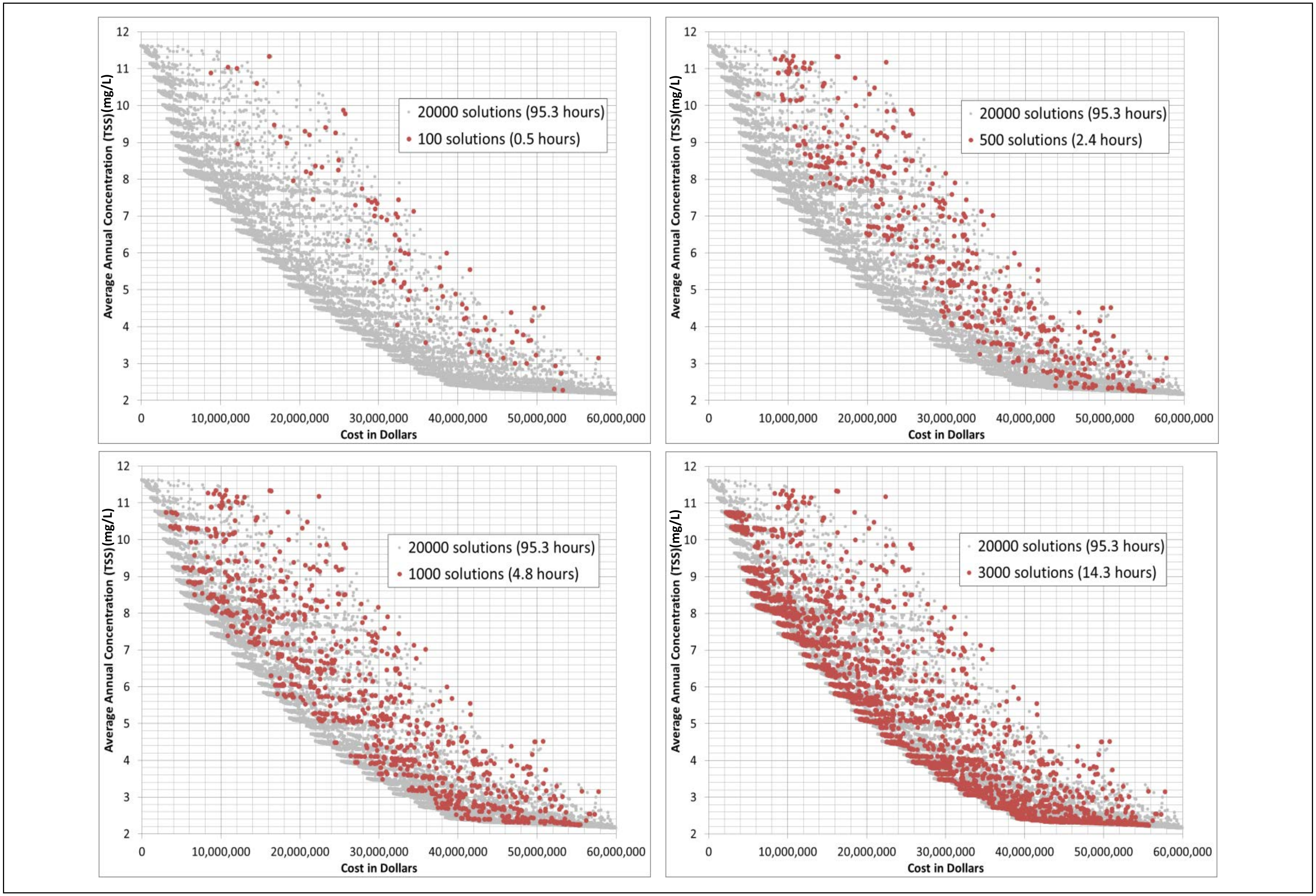


Figure 10. Scenario B NSGA-II Convergence.

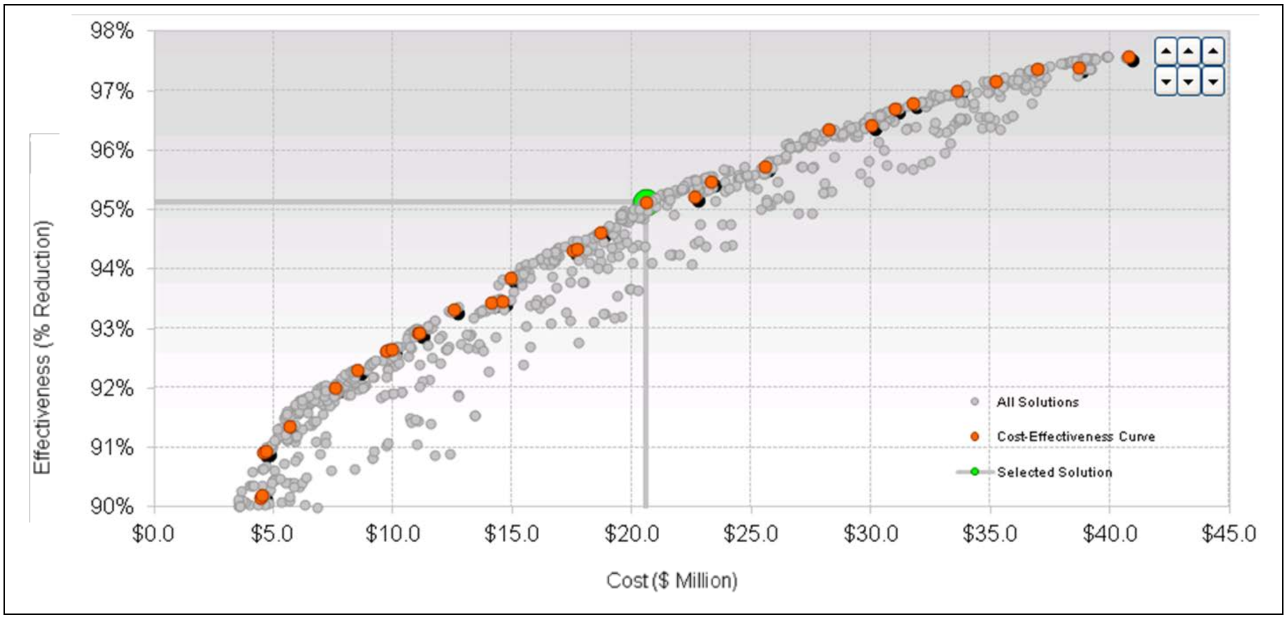


Figure 11. Scenario A Cost-Effectiveness Curve for TSS Removal.

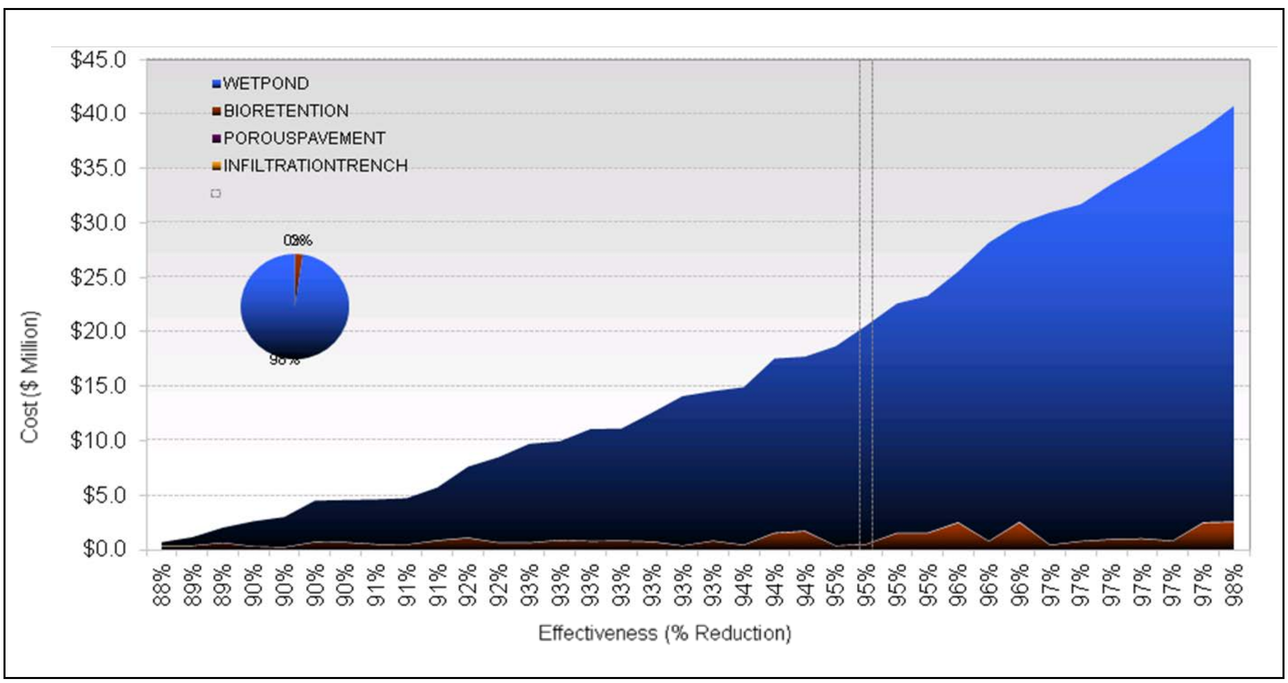


Figure 12. Scenario A Cost Distribution by BMP for TSS Removal.

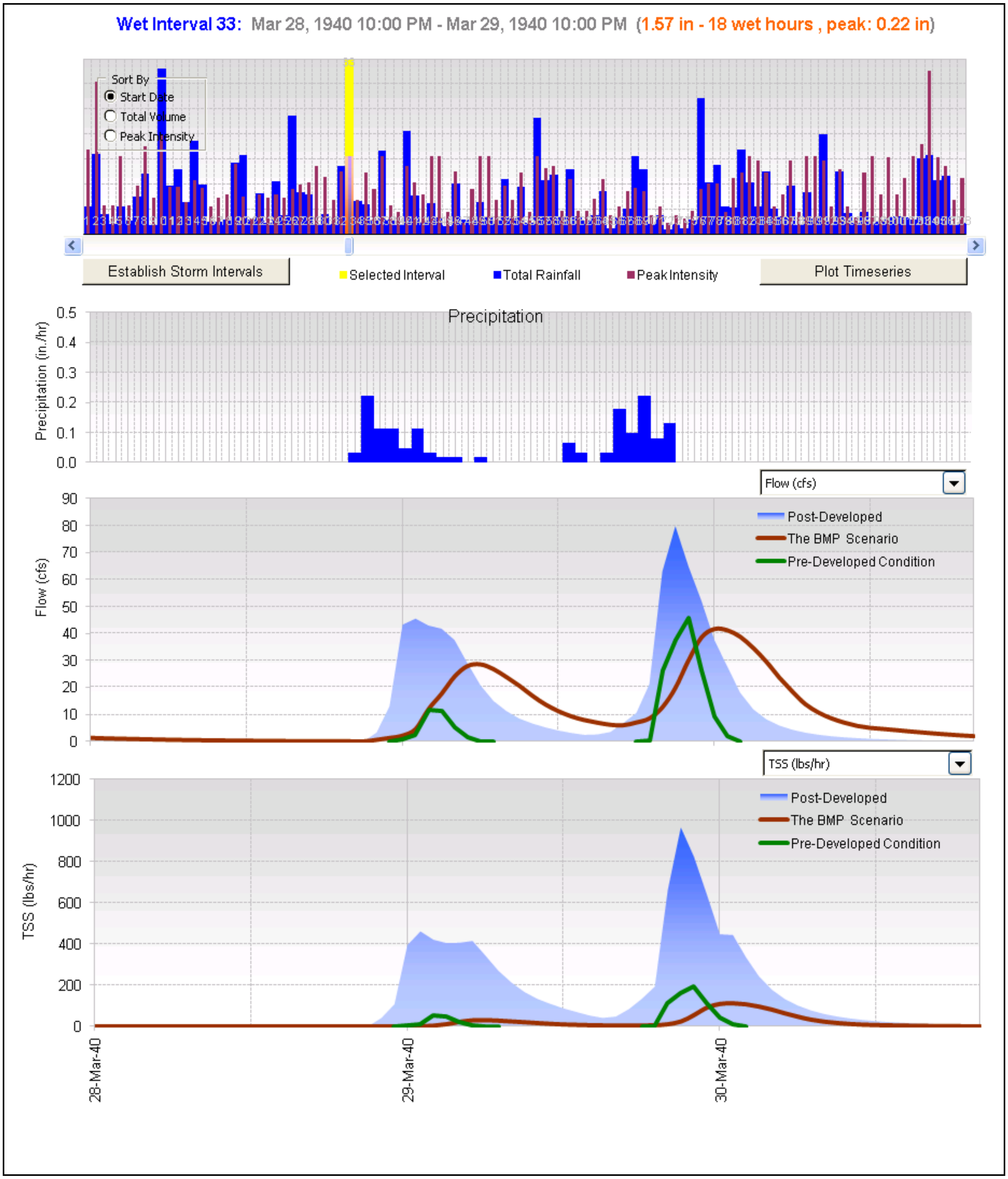


Figure 13. Scenario A Rainfall and Runoff Response for a TSS-Optimized Solution.

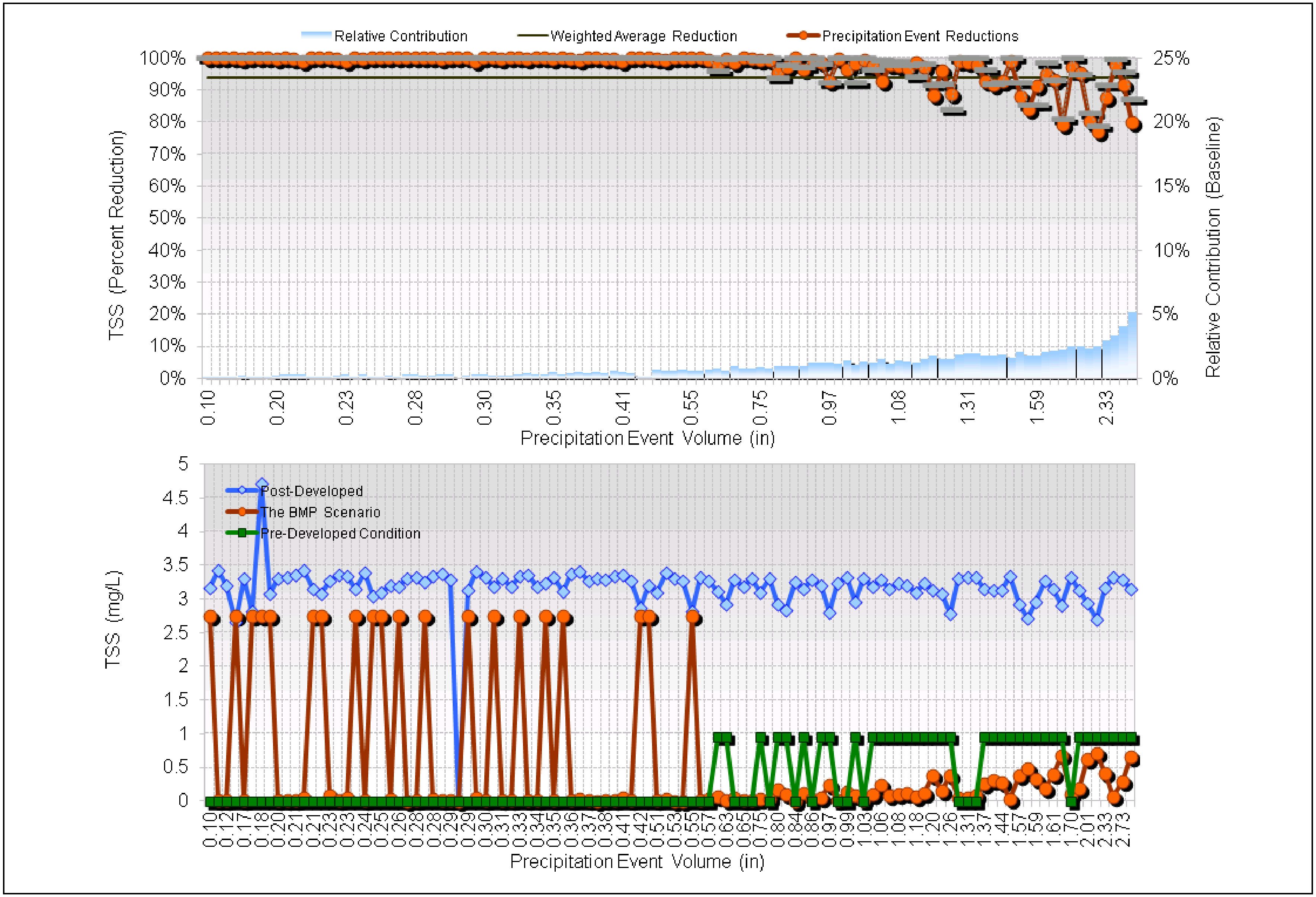


Figure 14. Scenario A TSS Performance Summary.

the Scenario A BMP configuration. The first three plots in the series are from the Cost-Effectiveness Report. (Note the costs presented in these plots are strongly driven by the assumptions unique to this exploratory analysis of *SUSTAIN*. These costs do not necessarily represent an optimum solution for the basin evaluated and are not transferable to other basins.) Figure 11 is the cost-effectiveness curve for TSS removal at the assessment point (outlet of the drainage basin) representing the effectiveness (percent reduction in TSS) and corresponding cost of each solution. This graph displays all iterated solutions (in grey), while highlighting (in orange) the most cost effective configurations to develop a cost-effectiveness curve. For instance, the most cost effective solution for achieving an approximately 95 percent reduction in TSS would cost approximately $21 million. This solution is highlighted on Figure 11 (green circle).

The remaining figures for the NSGA-II solutions (Figures 12 through 14) correspond to this highlighted solution. Note that *SUSTAIN* can only model one of each BMP per aggregate BMP template. In an effort to represent two types of porous asphalt, one on outwash and one on till, the “infiltration trench” BMP was used to represent porous asphalt on outwash soils. In addition, the model aggregates the wetlands and wet pond performance into a single facility when displayed in the post processor. In this case, the wetland and wet pond were modeled independently in *SUSTAIN*; however, both relied on the “wet pond” BMP module. As a result, even though the inputs (e.g., decision variables, decay rates, cost) were different for each facility, the post processor combines the cost and performance associated with the two BMPs into a single “wet pond” facility.

Figure 12 provides a cost distribution by BMP type for each solution on the cost-effectiveness curve. The highlighted solution from Figure 11 corresponds to the solution bound by the two vertical grey lines on the cost distribution plot. The embedded pie chart provides a breakdown of BMP costs associated with the highlighted solution. Note that neither “infiltration trench” nor “porous pavement” shows up in the pie chart. While this would often indicate that neither BMP is part of the optimal solution (in other words, the other BMPs are more cost effective and the number of cost effective BMPs is not limiting), in this particular scenario (Scenario A), only wetlands, wet ponds, and bioretention were deemed feasible.

From the post processor, the user can run a single optimized solution and generate a time series for each storm event over the simulation period (see Figure 13). Note that, for the purposes of this analysis, storms were defined as rainfall events preceded by at least 24 hours of dry time. The first figure (upper) in the series provides the total precipitation and peak precipitation intensity for each defined storm event. This graph is sortable by total precipitation volume or by peak intensity. This feature allows the user to quickly assess a selected storm event relative to the other events evaluated. In this case, the selected storm event (highlighted in yellow) ranks near the 90th percentile for both peak intensity and total rainfall volume.

Once a storm event has been selected, the user can opt to view the storm in the event viewer, which illustrates the change in BMP performance with changing storm size. Figure 13 provides information on the selected storm event, a 1-day storm beginning March 28 and ending March 29. The “post-developed” scenario represents the existing basin conditions with no new stormwater facilities (blue shaded area) while the “pre-developed” scenario represents a forested basin (green line). As expected, the scenario with BMPs (regional wetlands and wet ponds and distributed bioretention [represented as a brown line]) yields a delayed and dampened hydrograph with an elongated receding limb, indicative of attenuation by BMPs in the basin. A similar trend of a reduced and dampened pollutograph was also observed for TSS at the point of compliance.

Also from the post processor, the user can generate BMP performance summaries for the simulation period. The first plot (upper) in Figure 14 illustrates the BMP performance for the selected optimum BMP configuration and compares the reduction in TSS to the reduction that would be observed if the BMP configuration matched a forested pre-developed condition. The orange circles represent the BMP performance scenario while the grey bars represent the reduction associated with matching the pre-developed condition. The pre-developed condition reduction serves as a benchmark for the BMP scenario, providing the user with information on how well the BMP scenario matches the TSS concentrations of the pre-developed condition. As expected, TSS concentration generally increases with larger precipitation volume illustrating how the selected stormwater BMPs can better manage small storm events.

The second plot (lower) in Figure 14 compares TSS concentrations from the BMP scenario to both the pre-and post-developed scenarios for each storm event. Both the time-series plots, as well as the storm-response plots, can be generated for any of the modeled pollutants, not just the optimized pollutant of interest. A significant amount of "noise" was observed at the smaller precipitation depths (less than approximately 0.55 inches). Though the modeled concentration appears to bounce from approximately zero to 2.7 milligram per liter (over five times higher than the next highest modeled concentration), the actual TSS concentrations are expected to be relatively low for the smaller storm events, trending upward as storm volume increases.

Total Copper and Total Zinc Optimization

Appendix F contains similar post-processor output for the remaining NSGA-II optimized configurations for total copper and total zinc removal.

Scenario B

Scenario B included a mix of (1) distributed bioretention and porous asphalt to treat runoff from public/private parcels; (2) distributed bioretention to treat runoff from the right-of-way; and (3) regional treatment systems at the bottom of the basin (constructed wetland and wet pond) to meet water quality goals.

Total Suspended Solids Optimization

Figures 15 through 18 below include sample output from *SUSTAIN*'s post processor. These results correspond to the NSGA-II optimization of TSS removal for the Scenario B BMP configuration. The first three plots in the series are from the Cost-Effectiveness Report. (Note the costs presented in these plots are strongly driven by the assumptions unique to this exploratory analysis of *SUSTAIN*. These costs do not necessarily represent an optimum solution for the basin evaluated and are not transferable to other basins.) Figure 15 is the cost-effectiveness curve for TSS removal at the assessment point (outlet of the drainage basin) representing the effectiveness (percent reduction in TSS) and corresponding cost of each solution. This graph displays all iterated solutions (in grey), while highlighting (in orange) the most cost-effective configurations to develop a cost-effectiveness curve. For instance, the solution (highlighted in a green circle) of Figure 15 represents a solution on the cost-effectiveness curve that utilizes regional wet ponds as well as distributed bioretention and permeable pavement. This solution, however, is not the most cost-effective solution since roughly the same performance (approximately 98 percent reduction in TSS) can be achieved for $40 million, approximately $12 million less than the highlighted solution. This solution was chosen to demonstrate a configuration that includes a significant portion of distributed facilities for discussion purposes.

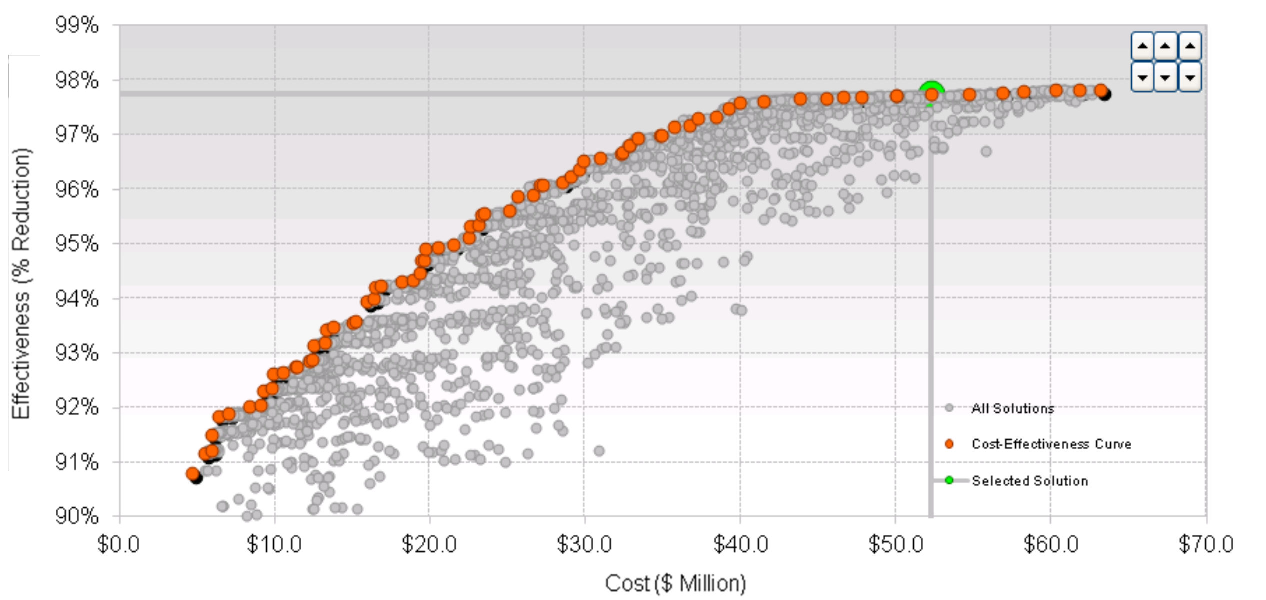


Figure 15. Scenario B Cost-Effectiveness Curve for TSS Removal.

The remaining figures for the NSGA-II solutions (Figures 16 through 18) correspond to this highlighted solution. Figure 16 provides a cost distribution by BMP type for each solution on the cost-effectiveness curve. The highlighted solution from Figure 15 corresponds to solution bound by the two vertical grey lines on the cost distribution plot. The embedded pie chart provides a breakdown of BMP costs associated with the highlighted solution. In this case, all BMPs are utilized in the solution. Note that the centralized facilities (wet ponds and wetlands) are the most cost-effective BMPs while porous asphalt (on both till and outwash) are the least. As explained for Scenario A, the “infiltration trench” BMP was used to represent porous asphalt on outwash soils, and the cost and performance associated with the wetland and wet pond are combined by the post processor and presented as a single “wet pond” facility.

Similar to Scenario A, the user can run a single optimized solution and generate a time series for each storm event over the simulation period from the post processor (see Figure 17). The runoff responses from the Scenario B optimization are very similar to those observed in Scenario A, so a different storm event was selected for this example. This is a 1-day storm beginning September 26 and ending September 27 (highlighted in yellow), and ranks in the 75th percentile for total rainfall volume but only the 50th percentile for peak intensity.

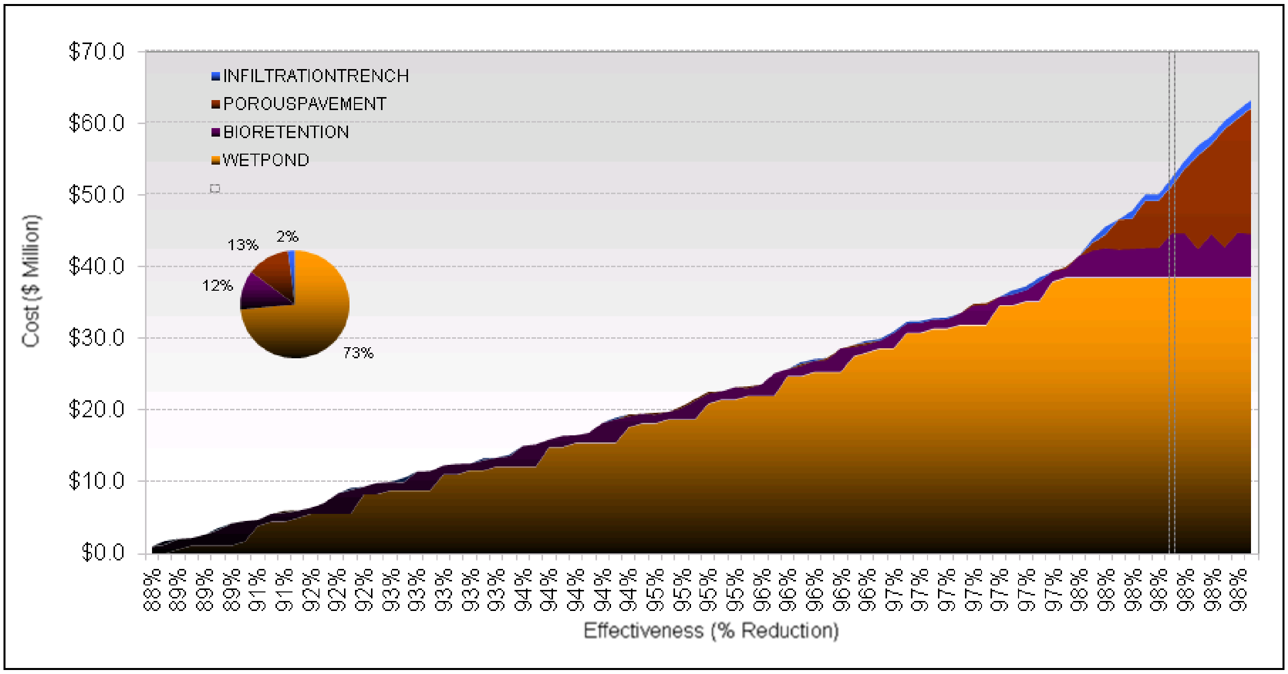


Figure 16. Scenario B Cost Distribution by BMP for TSS Removal.

The first plot (upper) in Figure 18 illustrates the BMP scenario performance for the selected optimum BMP configuration and compares the reduction in TSS to the reduction that would be observed if the BMP configuration matched a forested pre-developed condition. The second plot (lower) in Figure 18 compares TSS concentrations from the BMP scenario to both the pre- and post-developed scenarios for each storm event.

Total Copper and Total Zinc Optimization

Appendix F contains similar post-processor output for the remaining NSGA-II optimized configurations for total copper and total zinc removal.

Scenario Comparison

To better evaluate the incremental benefit of BMP retrofits on private property (bioretention and porous asphalt), the cost-effectiveness curve for Scenarios A and B were compared. The results of this comparison for TSS, total copper, and total zinc removal are presented in Figures 19, 20, and 21, respectively.

Both scenarios appear to converge on a similar solution for all three pollutants of interest. While the NSGA-II cost-effectiveness curve does not appear to have fully converged on a solution for Scenario B, the optimized solutions for both scenarios rely heavily on the regional wet ponds and wetlands to reduce target pollutant concentrations, thus this similarity is not surprising. This also indicates that the wet pond and wetland provide the most benefit per dollar spent for reducing TSS concentrations in CBB when compared to the distributed bioretention and permeable pavement facilities. Consequently, this also indicates that the

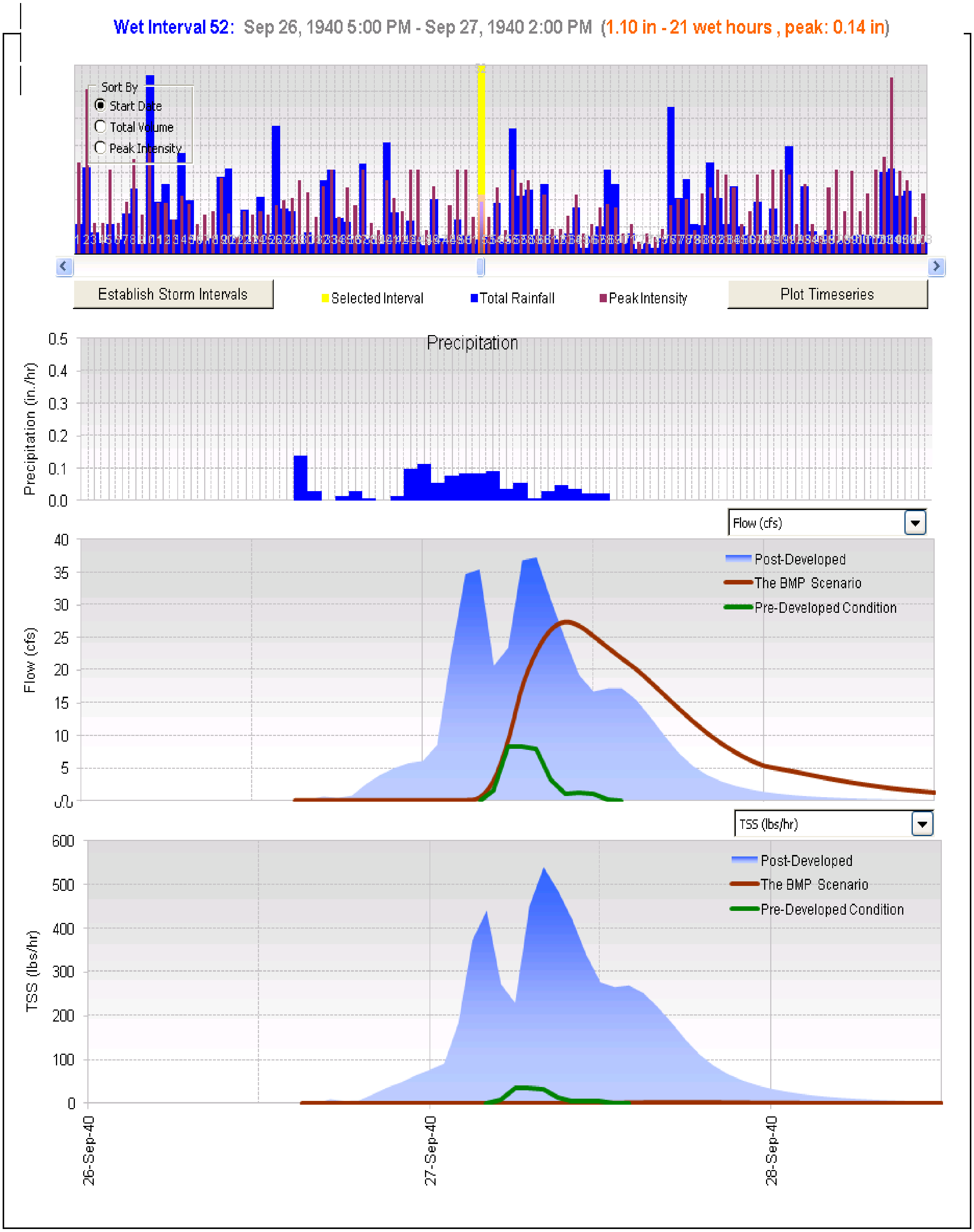


Figure 17. Scenario B Rainfall and Runoff Response for a TSS-Optimized Solution.

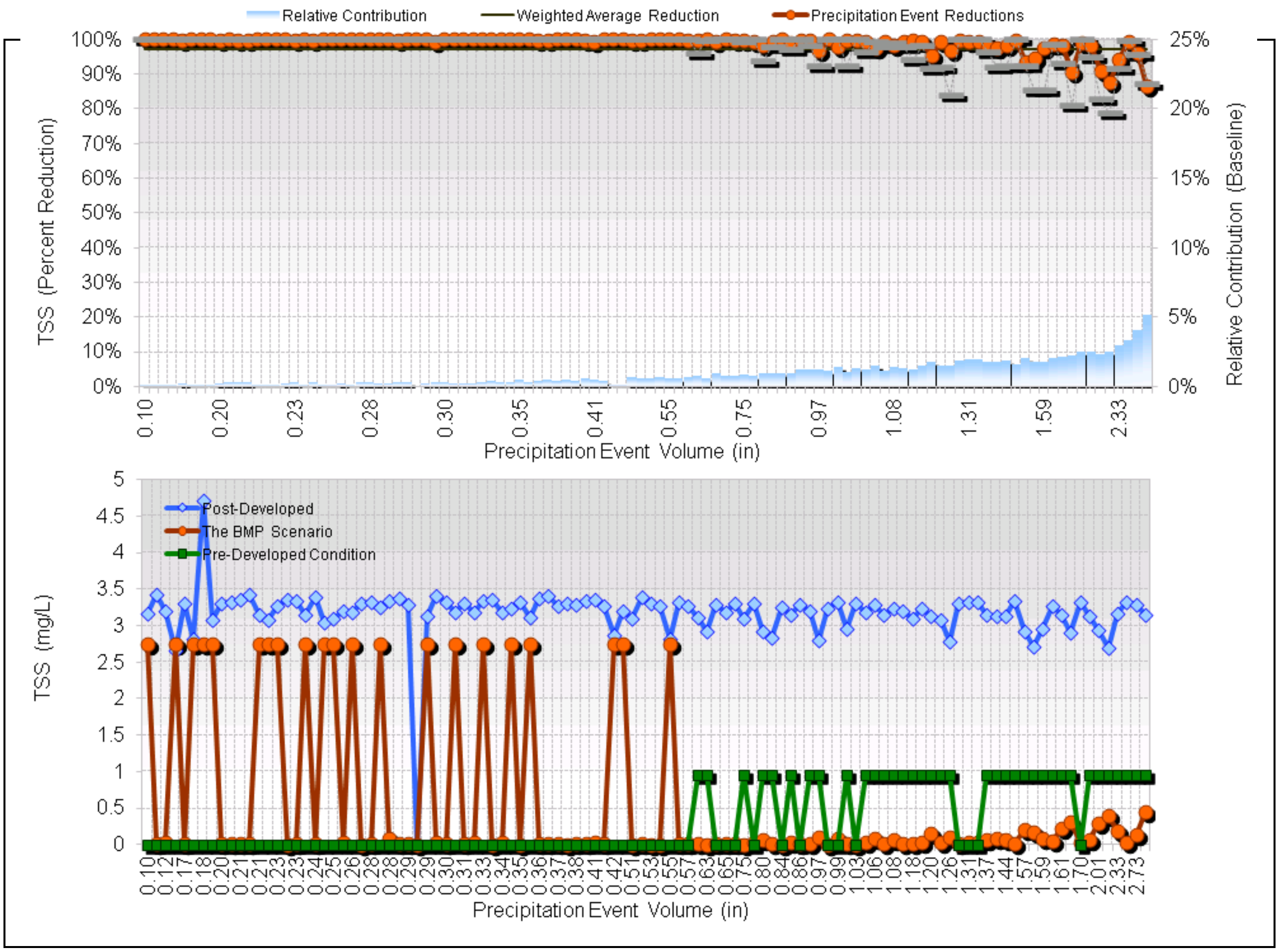


Figure 18. Scenario B TSS Performance Summary.

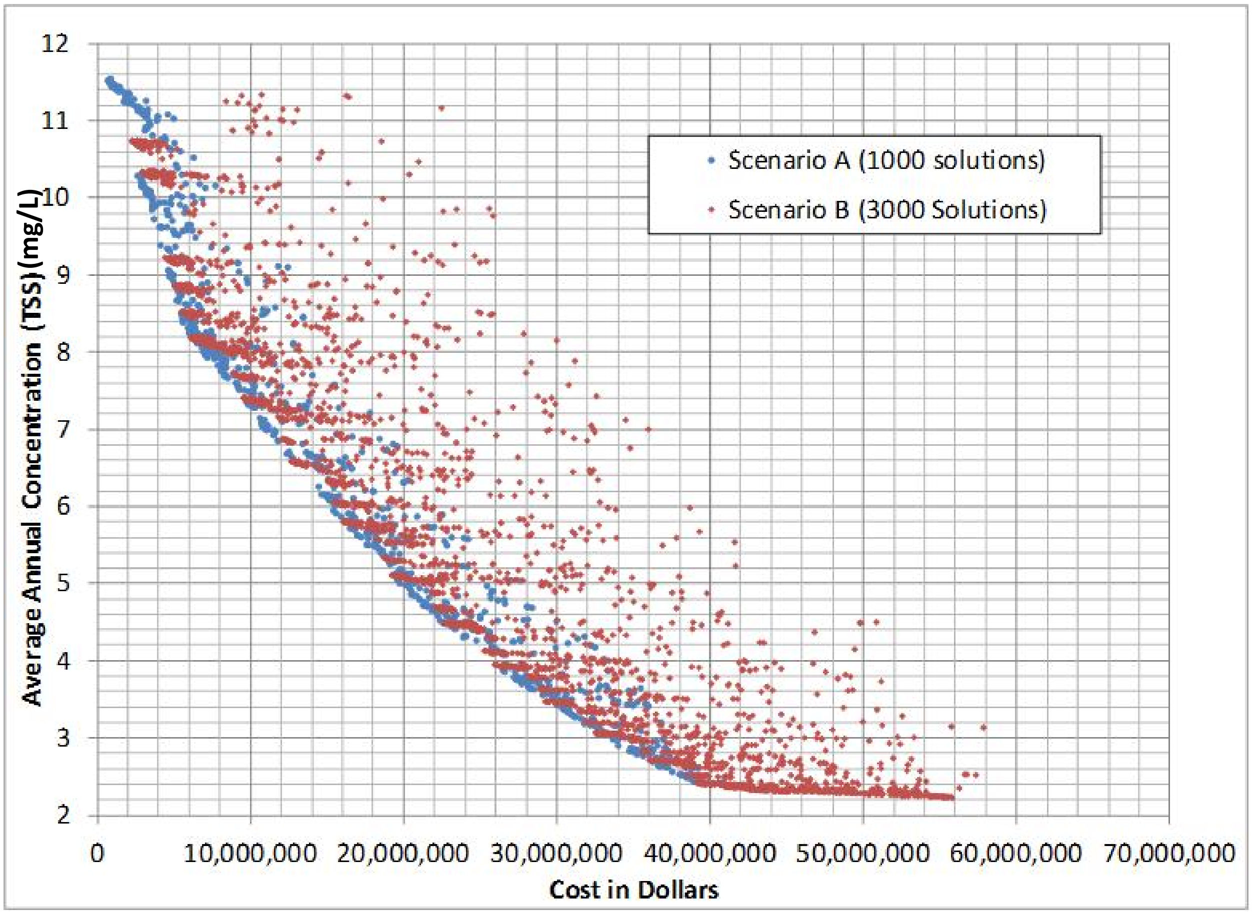


Figure 19. Comparison of TSS-Optimized NSGA-II Solutions for Scenario A and B.

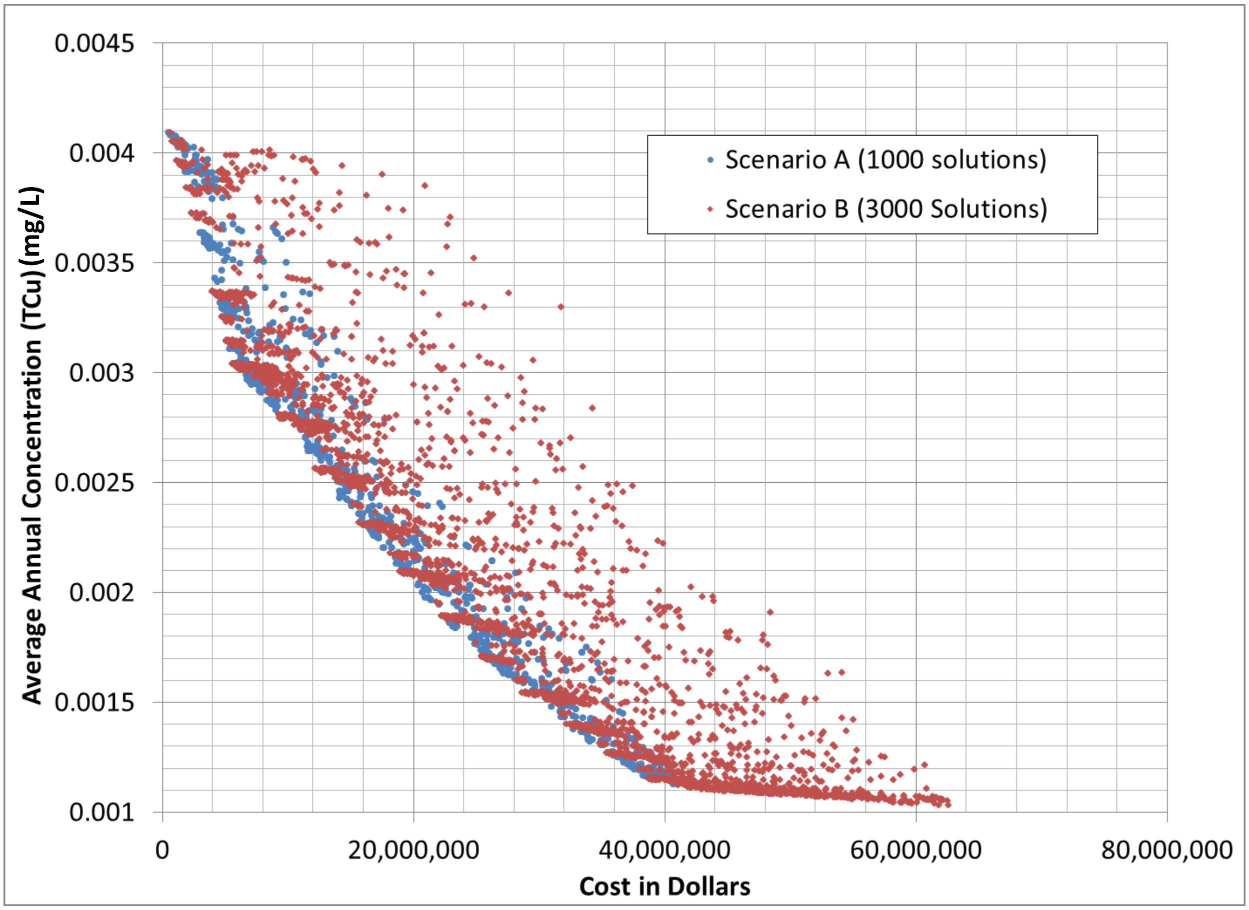


Figure 20. Comparison of Total Copper (TCu) Optimized NSGA-II Solutions for Scenario A and B.

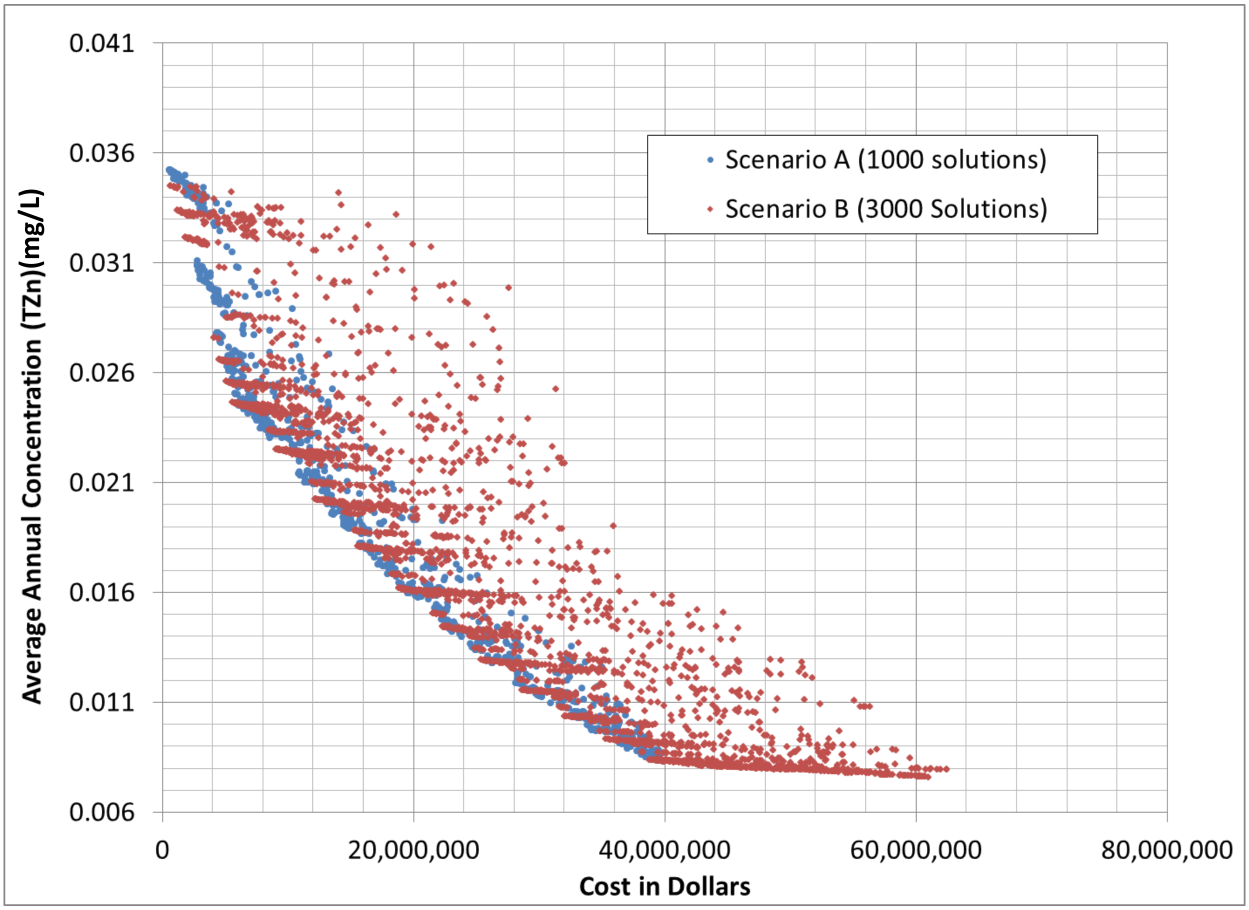


Figure 21. Comparison of Total Zinc (TZn) Optimized NSGA-II Solutions for Scenario A and B.

incremental benefit of additional distributed facilities does not significantly improve the optimized solutions.

Scatter Search

The scatter search algorithm was used to determine the most cost-effective solutions for meeting multiple targets including dissolved copper and dissolved zinc for acute and chronic exposure. Chrysene was also evaluated for the optimized solutions against the national recommended standard.

Acute Water Quality Standards Optimization

A near-optimal solution, modeled to achieve acute water quality standards for both dissolved copper (3.2 ug/L) and dissolved zinc (25.4 ug/L), was identified after approximately roughly 1,600 and 7,200 model runs for Scenarios A and B, respectively, using the scatter search method. Figures 22 and 23 show the associated solutions for dissolved copper and dissolved zinc, respectively. (Note the costs presented in these figures are strongly driven by the assumptions unique to this exploratory analysis of *SUSTAIN*. These costs do not necessarily represent an optimum solution for the basin evaluated and are not transferable to other basins.) The light blue and red data points represent all model iterations, while the dark blue and red series represent solutions of the optimization (i.e., model iterations that meet both dissolved copper and dissolved zinc targets). The blue and red squares represent the best solution for Scenarios A and B, respectively.

Based on comparisons of Figures 22 and 23, the dissolved zinc concentration controls the best solutions. The acute water quality standards for dissolved copper and dissolved zinc can be met for Scenario A for approximately $1.9 million, while it would take approximately $5.8 million to meet the standards under Scenario B. These results are not consistent with what was expected for this analysis. Since all BMPs in Scenario A are also optional facilities in Scenario B, one would not expect the cost associated with Scenario B to exceed that of Scenario A. However, based on the graphs above, it appears that Scenario B may not be fully converging on a solution. It is hypothesized that this lack of convergence may be due to the model simplifications that were made in an effort to reduce model runtime; Scenario B runtimes without these simplifications became prohibitively long (see “Model Runtime Considerations” in the *SUSTAIN* Model Results section for more information).

Chronic Water Quality Standards

A near-optimal solution, modeled to achieve acute water quality standards for both dissolved copper (2.5 ug/L) and dissolved zinc (23.2 ug/L), was identified after approximately 1,400 and 6,800 model runs for Scenarios A and B, respectively. Figures 24 and 25 represent the scatter search solutions for dissolved copper and dissolved zinc, respectively. (Note the costs presented in these figures are strongly driven by the assumptions unique to this exploratory analysis of *SUSTAIN*. These costs do not necessarily represent an optimum solution for the basin evaluated and are not transferable to other basins.) The light blue and red data points represent all model iterations, while the dark blue and red series represent solutions of

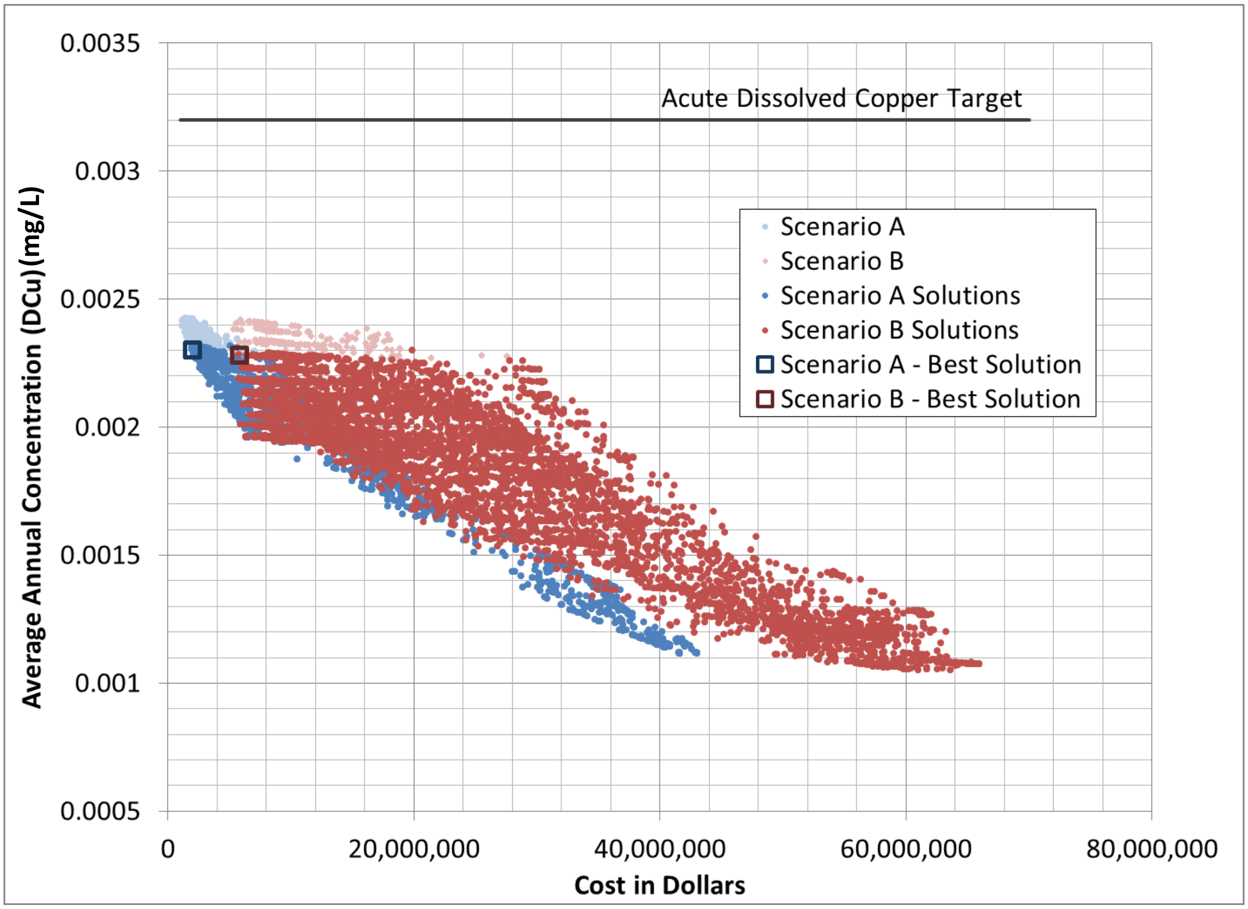


Figure 22. Scatter Search Solutions of Dissolved Copper (DCu) Concentrations for Scenario A and B, Optimized for Acute Water Quality Standards.

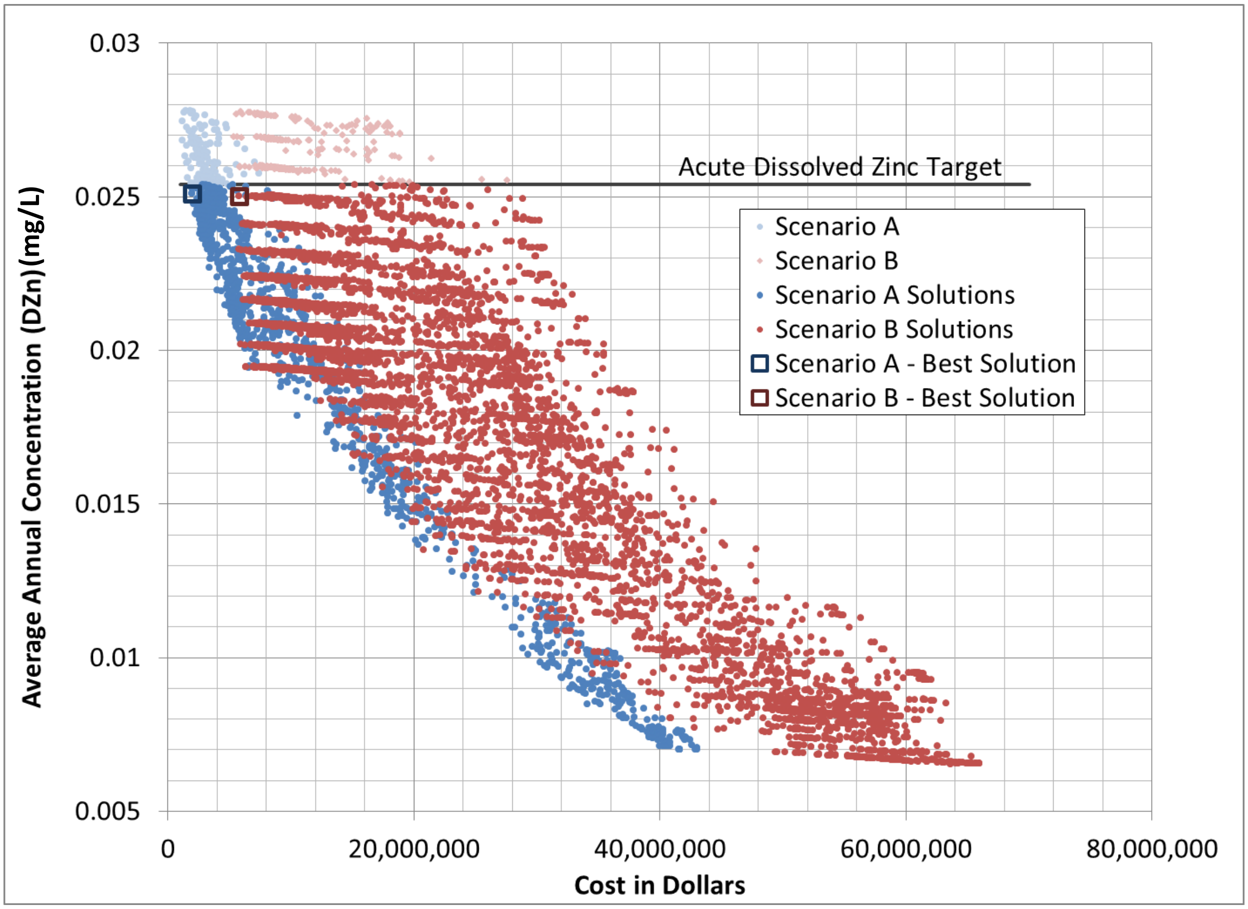


Figure 23. Scatter Search Solutions of Dissolved Zinc (DZn) Concentrations for Scenario A and B, Optimized for Acute Water Quality Standards.

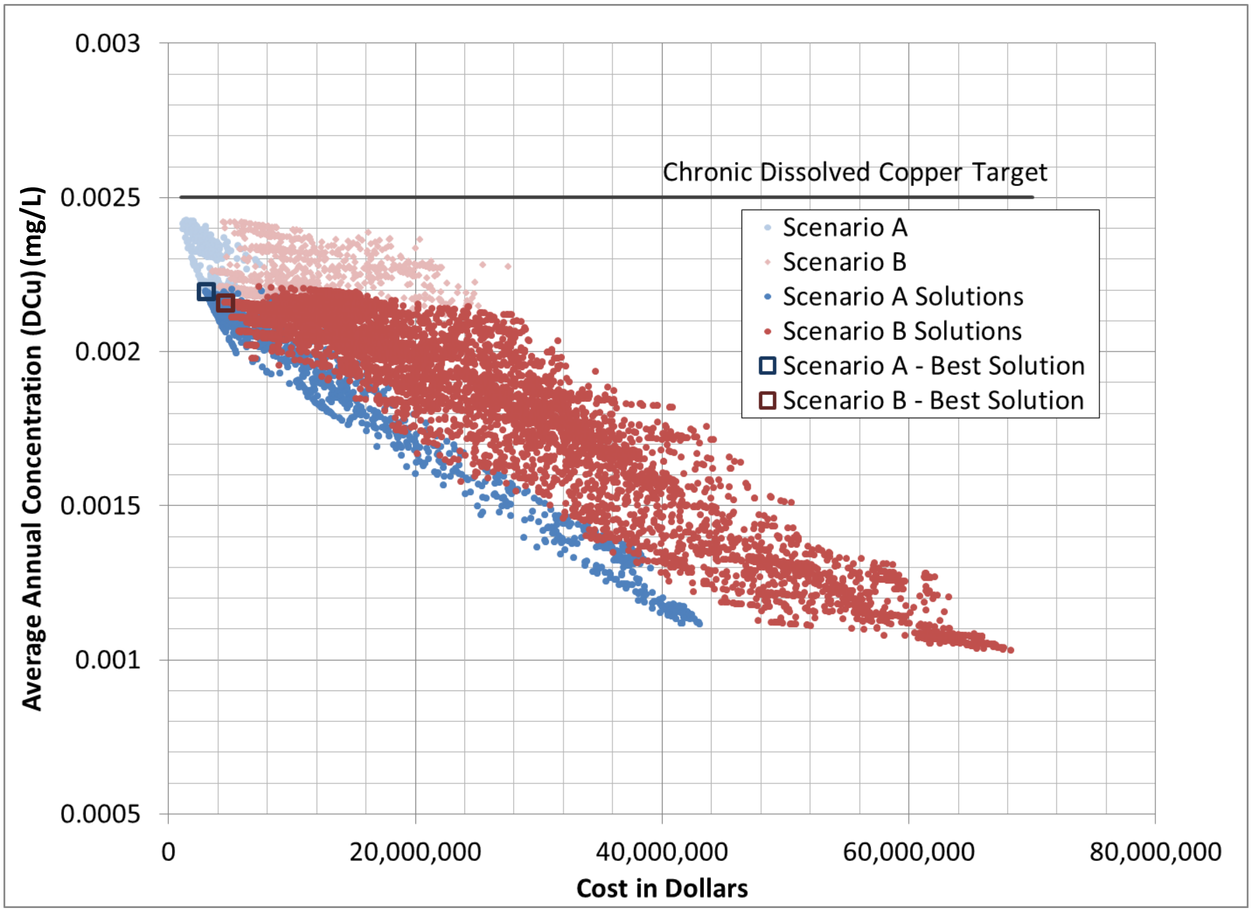


Figure 24. Scatter Search Solutions of Dissolved Copper (DCu) Concentrations for Scenario A and B, Optimized for Chronic Water Quality Standards.

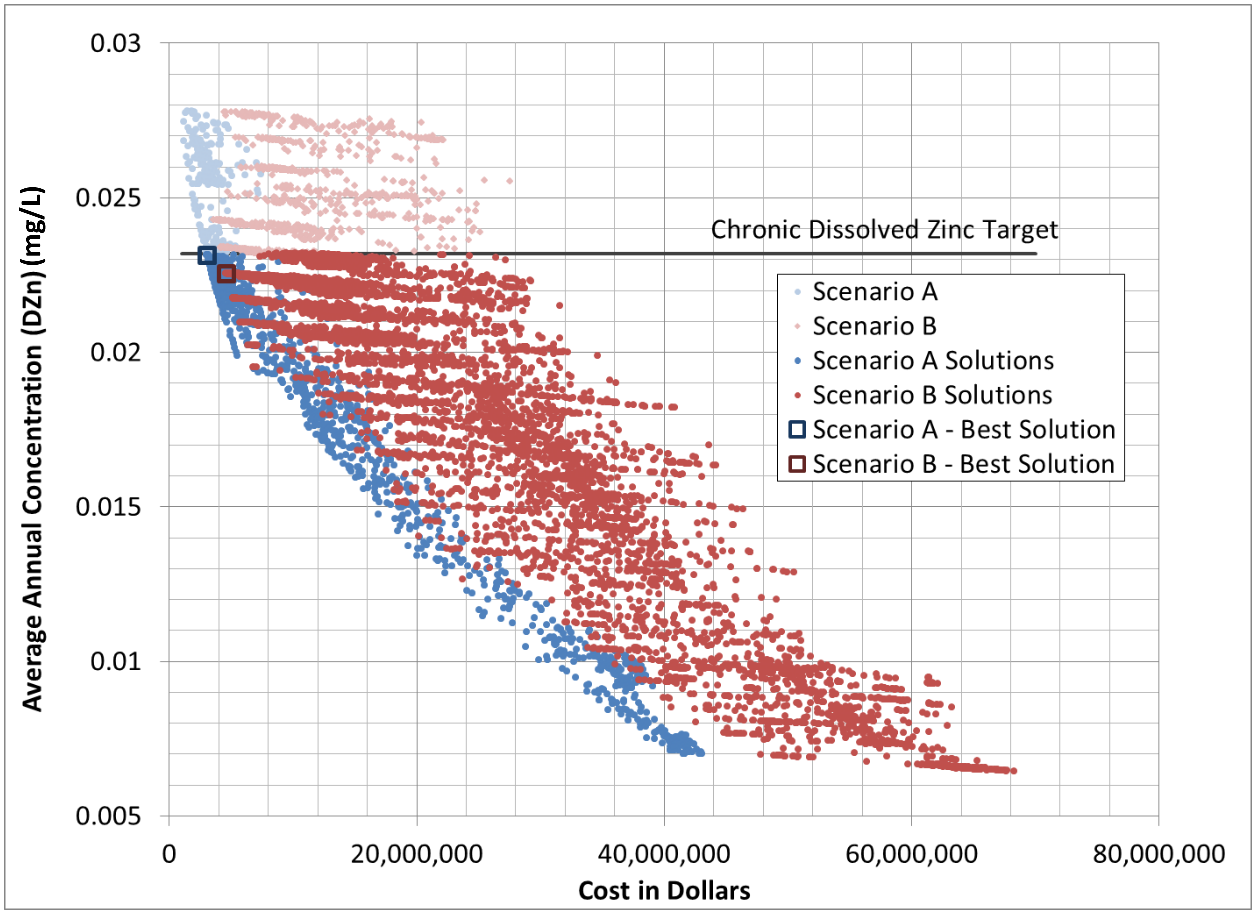


Figure 25. Scatter Search Solutions of Dissolved Zinc (DZn) Concentrations for Scenario A and B, Optimized for Chronic Water Quality Standards.

the optimization (i.e., model iterations that meet both dissolved copper and dissolved zinc targets). The blue and red squares represent the best solution for Scenarios A and B, respectively.

Similar to what was observed for the acute water quality standards optimization, the dissolved zinc concentration controls the best solutions. The acute water quality standards for dissolved copper and dissolved zinc can be met for Scenario A for approximately $1.9 million, while it would take approximately $5.8 million to meet the standards under Scenario B. Again, these results are not consistent with what was expected for this analysis. Since all BMPs in Scenario A are also optional facilities in Scenario B, one would not expect the cost associated with Scenario B to exceed that of Scenario A. The pattern of the series indicates that Scenario B may not be fully converging on a solution, likely due to model simplifications made in an effort to reduce model runtime.

Chrysene Removal

Once the models were optimized for both acute and chronic water quality standards, they were evaluated against the national standard for chrysene, 0.0038 ug/L. For all scatter search optimization runs (Scenarios A and B for both acute and chronic water quality standards), the reduction in peak chrysene concentration is approximately 87 percent. While this is a sizable reduction, Chrysene concentrations for all BMP configurations presented in these solutions still exceed the national standard.

Sensitivity Analysis

A sensitivity analysis was conducted based on a TSS optimization for Scenario A. This intent of this analysis was to test the sensitivity of BMP costs on *SUSTAIN*'s BMP selections. Since the regional facilities proved to be the most cost-effective strategies for reducing TSS in the original model runs, the cost of both the wetlands and wet ponds was increased by 100 percent and the results were observed (Figures 26 and 27). As expected, the total cost of mitigation increased, though the model still prioritizes the use of wetlands and wet ponds over bioretention and permeable pavement. This is because, although the cost associated with wetlands and wet ponds was increased, these regional facilities still provide the most cost-effective means of reducing TSS concentrations in the basin. Therefore, the uncertainty in BMP costs does not substantially affect the recommended solution.

Ancillary Flow Control Benefits

The ancillary flow control benefits (i.e., runoff volume and peak flow reduction) provided by the Scenario A scatter search optimization runs for acute and chronic water quality standards for dissolved copper and dissolved zinc were evaluated (Table 23). Scatter search results were selected for evaluation instead of NSGA-II results because scatter searches produce a single optimized BMP configuration to meet the water quality management target, instead of the series of best solutions provided by NSGA-II that ultimately form the cost-effectiveness curve. The Scenario A scatter search optimization runs were selected for evaluation, instead of those for Scenario B, because the runs fully converged on a near-optimal solution.

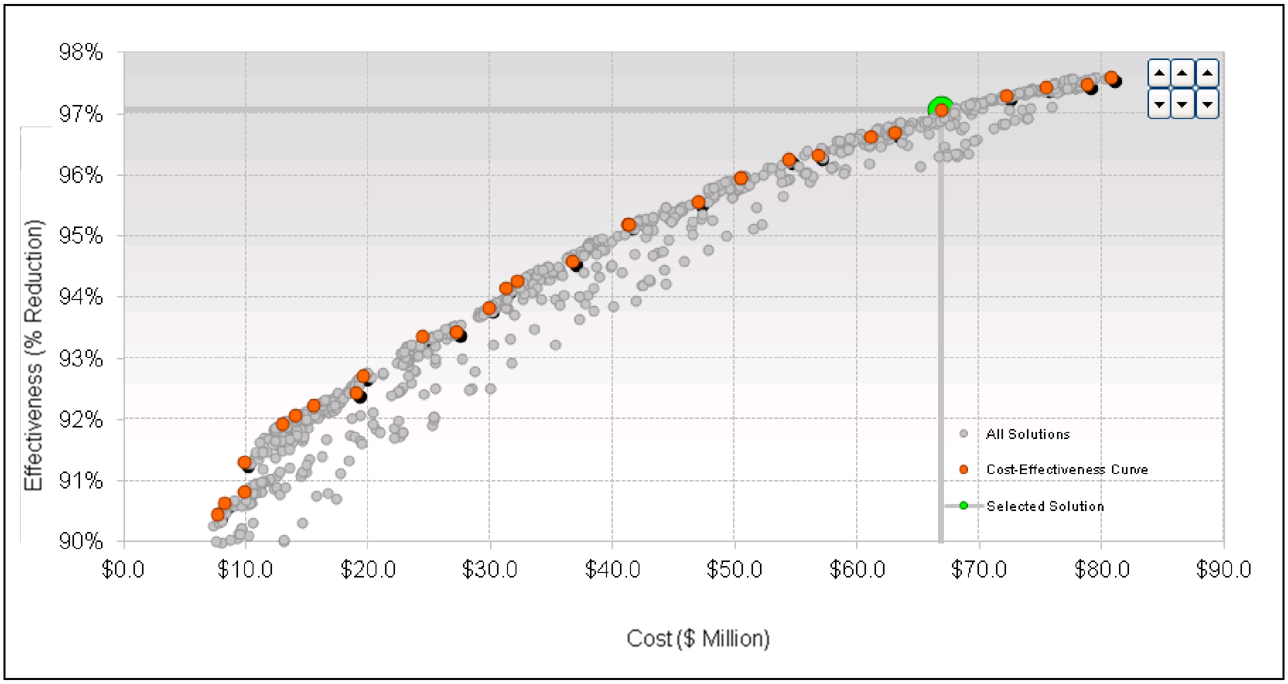


Figure 26. Scenario A Cost-Effectiveness Curve for TSS Removal Assuming 100 Percent Increase in Regional Facility Costs.

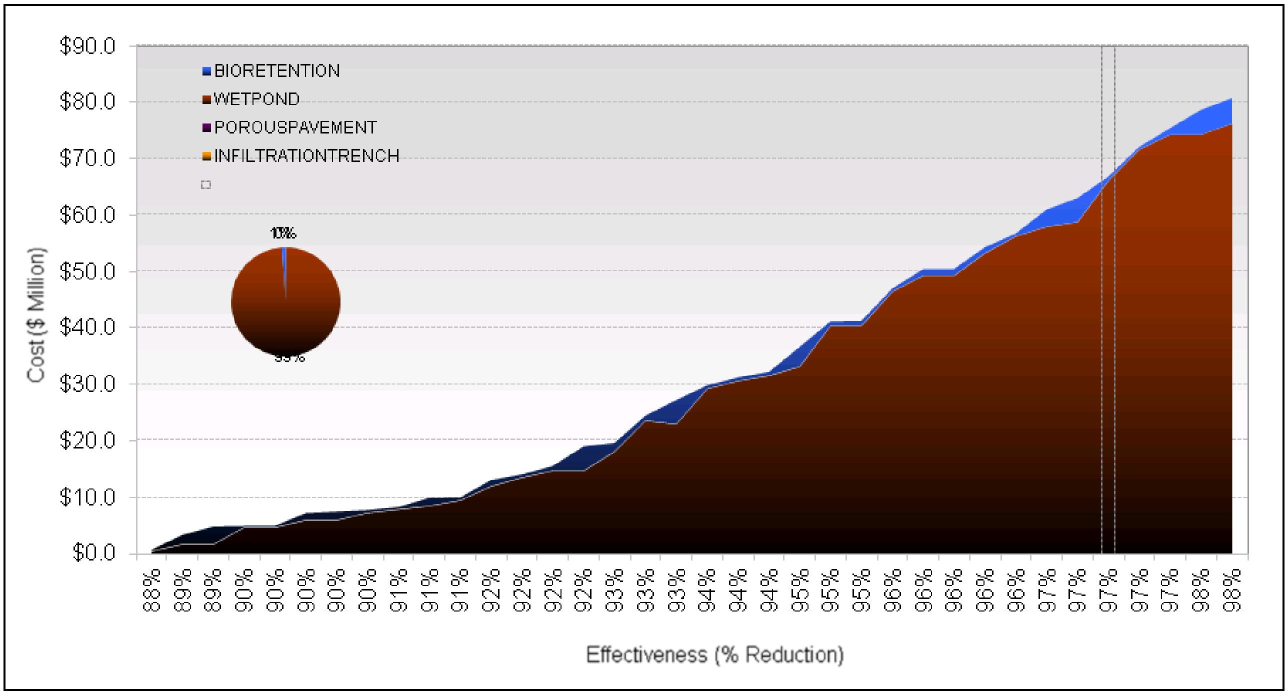


Figure 27. Scenario A Cost Distribution by BMP for TSS Removal Assuming 100 Percent Increase in Regional Facility Costs.

Though only Scenario A scatter search scenarios are presented in Table 22, several NSGA-II solutions, as well as Scenario B scatter search runs, were visually inspected to assess the flow control benefits. All of the scenarios inspected produced results nearly identical to the Scenario A scatter search. The similarity in the outflow hydrographs from these different optimization runs could be due to the heavy reliance of all solutions on the regional wet pond and wetland facilities that receive runoff from the entire basin, ultimately dictating the BMP scenario hydrograph at the basin outlet.

Table 23. Summary of Flow Benefits.

Scenario	Optimization	Volume (cf)	Volume Reduction (%)[a]	Maximum Peak Flow[b] (cfs)	Maximum Peak Flow Reduction[b] (%)[a]
Existing Conditions	NA	126,343,000	--	137.9	--
A	Acute	99,922,000	21%	64.0	54%
A	Chronic	99,663,000	21%	64.0	54%

[a] Volume and flow reductions are calculated relative to the existing conditions (without BMPs).

[b] Flow reduction for the maximum peak flow in the 2-year simulation period.

These results indicate that BMP scenarios optimized for water quality management targets can provide flow control benefits as well. In this case, the Scenario A scatter search optimization solutions included wet ponds and constructed wetland BMPs that reduce the total runoff volume for the entire simulation period by roughly 20 percent and the maximum peak flow occurring in the simulation period by roughly 50 percent.

SUSTAIN Model Evaluation

The goal of this effort was to develop a case study for the *SUSTAIN* model based on a "real world" application. It specifically involved the development of a *SUSTAIN* model for basin CBB in Federal Way to evaluate the water quality treatment benefits of two retrofit scenarios. Both scenarios were developed based on discussions with City of Federal Way staff and generally evaluate the cost effectiveness of regional treatment facilities (wetlands and wet ponds) versus distributed treatment using LID facilities (permeable pavement and bioretention). Scenario A limits retrofit options to publicly-owned roadside (right-of-way) applications and regional facilities, while Scenario B includes private property retrofits in addition to roadside and regional facilities. More generally, these scenarios represent very typical management decisions for local jurisdictions in their stormwater planning efforts.

However, results of this evaluation cannot be applied directly to other basins as a treatment cost per unit area, and this report does not necessarily describe an optimal solution for basin CBB in Federal Way. The objective of this study was to test *SUSTAIN* on a real-world example to identify its capabilities and limitations as well as the gaps in information that significantly affect stormwater management decisions.

The *SUSTAIN* model incorporates a number of different simulation and optimization methods that can be selected based on user defined needs for specific modeling applications. In developing the *SUSTAIN* model for this case study, the following methods were specifically demonstrated:

- External generated time series in SWMM for hydrographs and pollutographs
- Both explicit (for wetland and wet ponds) and aggregate (for bioretention and permeable pavement) representation of BMPs in the model
- BMP pollutant routing with CSTRs in series and removal with first-order decay rates
- Optimizing using both the NSGA-II and scatter search algorithms

The subsection below characterizes the user experience for developing this case study given these attributes of the resultant *SUSTAIN* model. A subsequent subsection describes the applicability of the *SUSTAIN* model for evaluating the stormwater management decisions posed through this case study. Specific recommendation for using *SUSTAIN* are then presented at the end of this document.

User Experience

In general, the *SUSTAIN* model represents a novel approach to optimizing basin-wide stormwater improvements based on cost and performance. Through this case study, the following attributes of the model were specifically identified as being unique and useful for this task:

- The optimization module provides a powerful tool for developing robust cost-effectiveness curves based on an examination of hundreds to thousands of discrete solutions.
- The post processor provides a number of different approaches for viewing and interpreting model output.
- The model is pre-configured to include a useful suite of BMPs, including several types of LID facilities.
- The model allows substantial flexibility for defining land surfaces, routing, and BMP configurations.
- Through its editable input files, the model provides a relatively open platform for making modifications to modeling scenarios outside its ArcGIS extension.
- The model allows significant flexibility for incorporation of time series (hydrographs and pollutographs) developed outside of the *SUSTAIN* platform.

It is recognized that this case study was developed using a very early version (v1.2) of the model, and improvements will undoubtedly be made if the USEPA decides to fund additional releases. However, in accessing *SUSTAIN*'s numerical engine through the current user interface for the model, the following issues were noted:

- **Error Catching and Bugs:** On numerous occasions during development of the *SUSTAIN* model for this case study, errors and/or bugs were encountered while performing routine operations. Following are a few selected examples that demonstrate this issue at different phases of model development:
    - While completing tutorials for the *SUSTAIN* model, one slight change in the order of operations for providing input specified in the tutorial resulted in bioretention and rain barrel BMP templates having their parameters confused (e.g., the bioretention dialog showed pictures of rain barrels with rain barrel parameters).
    - When entering data for the land simulation module for the first time, ArcMap would crash each time it was run. The problem was subsequently traced to minor differences in headers for the external hydrographs text files. Because no error code was provided by the model, this problem took many days to resolve.

- When entering data in the BMP module, a zero infiltration rate was specified for several ponds; however, a review of the model's output showed the ponds were actually infiltrating substantial quantities of water. With assistance from the model developer, the source of the problem was traced to the user-specified Green Ampt infiltration rate of zero, which the model recognized as an invalid entry. Because this value caused an error within the model, it was automatically replaced with the model's non-zero default value. The model would then run without any warnings that a change in model input had occurred. The workaround used for this effort was to select the Holtan infiltration method for all wet ponds (*SUSTAIN* recognized infiltration rates of zero when this method was selected).

- **Model Documentation:** The existing documentation and tutorials for *SUSTAIN* provide an acceptable overview of the model's capabilities; however, more detailed documentation is needed on the model's input parameters and the required workflow for model development. Without this additional documentation, many users will find it difficult to develop *SUSTAIN* models for applications more complex than those identified in the model's tutorials.

- **Complex Model Directory Structure:** Over the period required to develop the *SUSTAIN* model for this case study, hundreds of temporary folders were created in the model directory. Some user inputs are stored in the ArcMap document and some are stored in DBF files. The documentation for the model does not provide a definitive list of requirements to maintain or transfer a working model. On multiple occasions over the course of this effort, the model crashed, resulting in corruption of the model and its files. While we had anticipated being able to restore previously backed-up versions of the model, these efforts proved unsuccessful (i.e., *SUSTAIN* continued to register the same error messages), even when there was no apparent connection between the new files and backup files. We were eventually able to develop a successful backup strategy that included creating copies of the entire *SUSTAIN* "projects" directory (not just the individual model directory). This backup method allowed us to restore several corrupted models that occurred during the remainder of the project.

  One of the issues with this backup method is that it utilizes a significant amount of memory on the hard drive or file storage network. A more simplified model directory and/or better documentation on the interworkings of the model directory would likely result in a more streamlined (and less space-intensive) model backup strategy.

- **User Interface Design:** The user interface design is not intuitive in that many of the input parameters shown on different screens are irrelevant. For example, all the pollutant decay parameters from three different methods are shown on the same screen without being partially grayed out and disabled based on the selected pollutant routing equations. Other parameter entries are not intuitive. The result is a confusing user interface that makes it unclear what values the model is using for the simulation.

- **Post Processor Provides Limited Capabilities for Reviewing Model Quality:** The tutorial workflows direct the user to the MS-Excel post processor after running the model. However, the post processor does not show the raw time-series data output;

rather, the post processor only shows the time series divided into discrete storms based on user defined criteria. In the initial phases of developing the *SUSTAIN* model for this case study, the raw time-series data output was reviewed outside the *SUSTAIN* framework (using Python) for quality assurance purposes. Because of these reviews, a number of the initial model runs were shown to be producing erroneous results because of bugs in the model or misinterpretations of model input requirements. These bugs and misinterpretations would not have been detected if the model output was only reviewed using the post processor.

- **Software Compatibility:** *SUSTAIN* relies on ArcGIS version 9.3 to run, a version that is now outdated by two releases (10 and 10.1) and has limited compatibility with the latest software. For the duration of this project, one GIS license was allocated to this older version of software, rendering it almost unusable for any other GIS efforts outside of *SUSTAIN*. Additionally, it limited modeling in *SUSTAIN* to just one work station. Compatibility issues were also encountered when using *SUSTAIN*'s post processor with Excel 2012.

Limitations of *SUSTAIN*

The following limitations of the *SUSTAIN* model were identified based on its application to the specific stormwater management scenarios posed through this case study:

- **Routing Network:** For this case study, the Herrera SWMM model included a detailed routing network for basin CBB. Due to limitation of the user interface, this routing network could not be directly imported to the *SUSTAIN* model from GIS; rather, each individual attribute of the network (e.g., pipe lengths, diameters, junctions) had to be manually entered to rebuild the model. Once these attributes were entered, no straightforward tools are provided within the *SUSTAIN* model to facilitate checking and editing of these inputs. This greatly complicated the *SUSTAIN* model development process.

- **Runtime Considerations Related to Complexity of Basin Representation:** Model runtime is a function of the complexity of the basin hydrologic representation (i.e., total number of unit-area hydrographs), length of the simulation period, simulation time step, and the complexity of the optimization scenarios (i.e., number of decision variable combinations). When modeling the existing conditions scenario, model memory limitations only allowed simulations for an approximately 7-year period at a 15-minute time step; any simulation period longer than 7 years caused the model to crash. This instability may be attributed to *SUSTAIN*'s simulation approach, which involves reading the entire pollutographs and hydrographs into memory before simulation. For the purposes of this study (a water quality-focused effort), land use is a key parameter in the optimization of BMPs to meet treatment objectives because event mean concentrations vary by land use type. As a result, unique hydrograph and pollutographs was generated for each land use type to accurately estimate their corresponding pollutant loads. In addition, hydrographs and pollutographs were generated for each subcatchment. We felt that this approach was necessary to achieve a calibrated model (unique hydrographs by subcatchment) and to sufficiently represent pollutant concentrations at the mouth of the basin (unique pollutographs by land use designation). However, if the application were different (e.g., optimizing for flow control performance), the user may be able to simplify the basin hydrologic representation (e.g., one impervious and one pervious hydrograph per subcatchment), ultimately allowing for longer simulation periods prior to running into these apparent memory limitations.

- **Runtime Considerations Related to Complexity of Optimization Scenarios:** The complexity of the optimization scenarios is a function of the number of decision variable combinations, including the maximum number of BMPs and the BMP bin increments (the increment by which the number of BMPs is varied in the model). To complete this case study, *SUSTAIN* model runs were performed for existing conditions, Scenario A, and Scenario B. The complexity of the *SUSTAIN* model increased across each of these model runs as additional BMPs were successively added. For example, Scenario A included only the existing and regional BMPs and one type of distributed BMP (bioretention), while Scenario B included these same BMPs plus an additional distributed BMP (porous asphalt).

  It was initially hoped that these scenarios could be evaluated using a long-term precipitation series (i.e., the 158-year extended series). However, as the complexity of the model increased, model runtimes also increased. When the NSGA-II and scatter search algorithms were applied to optimize BMP selection for Scenarios A and B, the required runtimes for convergence were greater than 24 hours and, in some cases, greater than 8 days. These runtimes were deemed infeasible for this effort. Therefore, in the interest of time, the simulation period was shortened to 2 years and adjustments were made to BMP bin increments for Scenario B. While these changes reduced model runtimes to less than 24 hours, they also reduced overall confidence in the model results. Meeting water quality management targets over a short period is not as meaningful and long-term compliance, and a 2-year simulation period does not allow for evaluation of flow control measures commonly used in the region (e.g., recurrence interval flows and duration statistics).

- **BMP Representation:** In this case study, several existing BMPs within basin CBB were explicitly represented in the *SUSTAIN* model. In some cases, these BMPs had complex outlet structures that could be explicitly represented in the Herrera SWMM model but not in *SUSTAIN*. A number of "workarounds" were used to approximate the hydraulic characteristics of these BMPs in *SUSTAIN*. For example, a pump curve function was developed to represent the compound outlet structures of the existing regional detention ponds. Similarly, outflow from the Belmor Regional Detention Facility is partially controlled by an adjustable sluice gate that changes the storage capacity of the facility seasonally to better accommodate flow control demands in the basin. *SUSTAIN*, unlike SWMM, is not capable of capturing this function of the wet pond; therefore, seasonal outlet control was neglected. Incorporating these workarounds reduced the accuracy of the *SUSTAIN* model that was eventually developed.

- **BMP Selection:** This case study used the aggregate BMP approach to determine what area of each subcatchment should be treated by distributed bioretention and permeable pavement facilities. However, only one aggregate BMP type can be applied to each unit area in a subcatchment. In other words, if both BMP types are feasible for a given area, the model cannot select the best BMP for that unit area based its cost effectiveness. In this case study, bioretention and porous asphalt were each applied to up to half of the public and private parcel areas for which treatment is feasible as workaround for this limitation. However, this workaround did not allow for the preferential selection of bioretention over permeable pavement facilities, and vice versa. This is a fundamental limitation of the current *SUSTAIN* model with no known workaround.

- **BMP Differentiation:** In this case study, two types of porous asphalt were represented in the *SUSTAIN* model, one on outwash and one on till. Because *SUSTAIN* can only model one type of BMP per aggregate BMP template (i.e., only one type of bioretention, one type of porous pavement, etc.), the "infiltration trench" BMP template was used to represent porous asphalt on outwash soils. While this approach worked, it would be easier to track BMP allocation and associated costs if multiple BMPs were allowed per template with proper BMP naming. In addition, the model aggregates the wetlands and wet pond performance into a single facility when displayed in the post processor. As a result, even though the inputs (e.g., decision variables, decay rates, cost) were different for each facility, the post processor combines the cost and performance associated with the two BMPs into a single "wet pond" facility. This made interpretation of the model results more complicated.

- **First-Order Decay Rates:** Pollutant removal in this case study was simulated in *SUSTAIN* using first-order decay rates. While several published reports (Tetra Tech 2007, 2010) provide representative decay rates for the BMPs used in this case study, these reports are limited to a few selected pollutants with decay rate calculations based on small sample sizes. Therefore, decay rates had to be derived for this case study for each combination of BMP and pollutant through a separate modeling exercise. While percent removal targets were applied to bioretention facilities with underdrains, the theoretical basis for using first-order decay rates to represent pollutant removal processes in all other BMPs may not be applicable and warrants further research. Furthermore, local performance data indicate that first-order decay rates may not adequately represent systems used locally, but *SUSTAIN* does not allow any other parameterization.

- **Flow Duration Assessments:** Pursuant to Ecology requirements for western Washington, facility performance criteria for flow control are based on matching flow durations using continuous hydrologic modeling. The current release of *SUSTAIN* does not support optimization based on this standard.

SUSTAIN MODEL RECOMMENDATIONS

If the USEPA decides to fund additional development of *SUSTAIN*, it is anticipated that the limitations identified above could be addressed in future versions of the *SUSTAIN* model. In addition, improvements could be made to better integrate the individual *SUSTAIN* modules. For example, this case study included an external evaluation to determine the number and type of BMPs that were feasible in each subcatchment. However, this exercise was not spatially explicit. While the current version of the *SUSTAIN* model incorporates a stand-alone BMP siting tool that is spatially explicit, this tool does not interface with other modules in the model. If this siting tool was better integrated in the *SUSTAIN* model, the user could utilize the spatial elements from the siting tool to populate BMP feasibility inputs within *SUSTAIN*. This would leverage the power of the ArcGIS platform that provides the interface for the *SUSTAIN* numerical engine.

When this study initiated, we recognized that the national cost and performance databases for stormwater BMPs distributed with the *SUSTAIN* software were not necessarily representative of Puget Lowland conditions. Therefore, we gathered site-specific cost information as a first attempt to provide regionally relevant cost information (Herrera 2012). We recommend that this be further developed as a regional resource for stormwater managers. We also compiled information on traditional and enhanced BMPs but found only limited information on treatment performance for dissolved copper and dissolved zinc, and even less for parameters like chrysene. We recommend that additional research be performed to characterize removal of toxics using traditional and enhanced BMPs. These recommendations apply for any future stormwater management evaluations either with *SUSTAIN* or with other decision-support tools.

A series of assumptions were required to complete this study that strongly influenced the results of the optimization. While these assumptions were necessary to test the capabilities and limitations of *SUSTAIN*, they severely limit the applicability of the results presented in this report to other basins. We recommend that stormwater managers thoroughly evaluate the following assumptions and modify them in future stormwater management decisions either within *SUSTAIN* or using other decision-support tools:

- *SUSTAIN* requires performance for most BMPs to be expressed as first-order decay rates. Limited performance information suggests that many parameters do not follow first-order decay patterns but exhibit reductions to a particular effluent concentration or breakthrough curve beyond a specific concentration. These relationships should be further explored.

- A more thorough basin feasibility assessment is recommended to develop site-specific guidance on the placement of different BMPs. The two scenarios evaluated in this study were developed with guidance from the local government. The areas potentially treated were further reduced by approximating the technical feasibility as 50 percent of the area, and even further limited by incorporating participation factors. Using a 20 percent participation factor for private lands likely dictated the outcome on private lands. *SUSTAIN* currently does not incorporate a methodology for deriving these factors. Future users may need to develop these factors based on independent assessment of feasibility and overall modeling objectives.

- The BMP cost database was strongly driven by land acquisition costs, which may be substantially higher in other regions of the Puget Lowland. This assumption alone limits applicability to more intensely developed regions where real estate is more expensive.

- Permeable pavement was only applied to parking lots and driveways and not to active roadbeds. This may be somewhat conservative, and permeable pavement may be applicable to road surfaces with varying use intensities.

- The selection of dissolved and total metals plus chrysene as stormwater management targets was unique to this effort and intended to explore the capabilities of *SUSTAIN* on a real-world question involving the control of toxics. Stormwater managers often focus on flow and sediment control and rarely consider toxics. Future users should carefully consider all modeling assumptions depending on the specific management scenario in question.

- The target for compliance with the water quality standards was at the bottom of basin CBB where monitoring data were available. This influenced the outcome by neglecting the water quality within upper reaches of the watershed. Therefore, the regional BMPs near the outlet of the basin were found to be more effective. Distributed BMPs might be favored if the goal was to protect water quality throughout the basin.

- Pursuant to state water quality standards (WAC 173 201A), acute and chronic water quality standards for dissolved copper and zinc are to be assessed based on 1-hour and 4-day average concentrations, respectively. In this case study, optimization was formulated to minimize the annual average concentration for each metal. While it may be appropriate to use annual average concentration as a suitable measure of the effects from chronic toxicity, a different temporal basis may be more appropriate for evaluating the effects from acute toxicity.

- The complicated hydrology and hydraulics in the upper portions of basin CBB were not resolved for this application. Existing facilities were simplified as a single composite storage vault, which may not fully capture the associated treatment. Given the upper portions of basin CBB are dominated by commercial land cover that likely contributes the highest concentrations and loads for toxic chemicals, a more detailed evaluation of these ultra-urban areas would be warranted to optimize a solution for the entire basin.

- This basin benefited from an existing SWMM application, and the basin land cover had not changed considerably since its development in 1994. We incorporated several simplifications to the existing SWMM model to accommodate the limitations of *SUSTAIN* itself. In this case study, the existing SWMM model provided an acceptable solution for generating external hydrographs and pollutographs for input to *SUSTAIN*. However, future users may want to consider other models (e.g., Hydrologic Simulation Model-FORTRAN) depending on the specific application.

Finally, *SUSTAIN* itself has a number of limitations that will severely affect future applications to similar stormwater management questions. We recommend that stormwater managers consider the following carefully before moving forward with *SUSTAIN*:

- The current version of *SUSTAIN* requires ArcGIS 9.3 and is not compatible with ArcGIS 10. Future users will either need an update to *SUSTAIN* or will need to dedicate an ArcGIS 9.3 computer to the *SUSTAIN* application. At present, USEPA has no plans to fund future development of *SUSTAIN*.

- Model complexity and long runtimes limited the time period for simulation to 2 years instead of the planned 158-year time series. This eliminated the option to evaluate recurrence intervals, which are of prime consideration to stormwater managers. Future users should consider tradeoffs between simplified routing and long-term simulations in addition to time steps and duration. The 2-year simulation used for this evaluation may not be representative of typical or even extreme conditions.

- The BMP templates allow for only a single circular orifice and single weir outlet structure. However, many BMPs have much more complicated geometry that could be represented as a stage discharge curve. Future users will need to develop workarounds (e.g., rating curves per the methods used in this study) to model these structures. In addition, *SUSTAIN* does not allow for time-variable controls, such as the adjustable sluice gate used to adjust geometry seasonally. At present, we have not been able to identify a workaround for this limitation.

- The vertical side walls for several BMPs do not represent typical configurations and required several workarounds to accommodate this limitation of *SUSTAIN* including an approximation of unit-area BMP costs that represent unit-area facility costs. This has led to a significant amount of confusion with regard to the bioretention costs used in this study. Future users should incorporate adjustments (e.g., cost or facility sizing) in recognition of this issue.

- *SUSTAIN* allows only one aggregate BMP to be applied to each unit area in a subcatchment. This is a fundamental limitation of the current *SUSTAIN* model that should be recognized by future users in any application.

Basin planning requires numerous decisions that influence the outcome, whether using *SUSTAIN*, SWMM, or other modeling tools. We recommend that stormwater managers consider a range of options and identify information limitations prior to selecting a model.

References

CH2M Hill. 1994. WH08, WH10, and WH1 Regional Drainage Analysis and WH08-CIP01 Project Predesign Report. Prepared for City of Federal Way by CH2M Hill in association with Aqua Terra Consultants and Watershed Dynamics. December 1994.

Herrera. 2011. Toxics in Surface Runoff to Puget Sound: Phase 3 Data and Loading Estimates. Prepared for the Washington State Department of Ecology by Herrera Environmental Consultants, Inc., Seattle, Washington. April 2011.

Herrera. 2012. Puget Sound BMP cost database memorandum. Prepared for the Washington State Department of Ecology by Herrera Environmental Consultants, Inc., Seattle, Washington. December 21, 2012.

King County. 2009. Surface Water Design Manual. King County Department of Natural Resources and Parks, Seattle, Washington. January 9, 2009.

King County. 2011. Stormwater retrofit plan for WRIA 9 website. Project plan available at: http://your.kingcounty.gov/dnrp/library/water-and-land/watersheds/green-duwamish/stormwater-retrofit-project/stormwater-retrofit-workplan.pdf.

Lee, J.G., A. Selvakumar, K. Alvi, J. Riverson, J.X. Zhen, L. Shoemaker, and F-H. Lai. 2012. A watershed-scale design optimization model for stormwater best management practices. *Environmental Modeling & Software* 37:6-18.

MGS Engineering Consultants, Inc. 2002. Extended Precipitation Time-series for Continuous Hydrological Modeling in Western Washington. Prepared for the Washington State Department of Transportation by MGS Engineering Consultants, Inc., Olympia, Washington. April 2002. Available at: www.mgsengr.com/downloads/ExtendedTimeSeriesReport_WSDOT.pdf.

Milesi, C., S.A. de Ridder, D. DeLeon, and H. Wachter. 2006. A comparison of two media filtration BMP treatments for the removal of PAHs and phthalates from roadway runoff. Presented at StormCon 2006, Denver, Colorado.

O'Brien, Ed. April 23, 2012. Personal communication (e-mail to John Lenth with BMP removal assumptions for use in *SUSTAIN* modeling). Washington State Department of Ecology, Olympia, Washington.

PSAT. 2005. Low Impact Development Technical Guidance Manual for Puget Sound. Puget Sound Action Team and the Washington State University Pierce County Extension, Olympia, Washington. May 2005.

Roberts, Mindy. December 12, 2011. Personal communication (e-mail to John Lenth with spreadsheet 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). Washington State Department of Ecology, Olympia, Washington.

Shoemaker, L., J. Riverson, K. Alvi, J. X. Zhen, and R. Murphy. 2012. Report on Enhanced Framework (*SUSTAIN*) and Field Applications to Placement of BMPs in Urban Watersheds. US Environmental Protection Agency, Washington, D.C. EPA/600/R-11/144.

Shoemaker, L., J. Riverson, K. Alvi, J. Zhen, S. Paul, and T. Rafi. 2009. *SUSTAIN*—A Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality. US Environmental Protection Agency, Washington, D.C. EPA/600/R-09/095.

Tetra Tech. 2007. Prince George's County BMPDSS calibration/validation using field monitoring data. Prepared for Prince George's County Government, Environmental Services Division, Department of Environmental Resources, by Tetra Tech, Inc.

Tetra Tech. 2010. Stormwater best management practices (BMP) performance analysis. Prepared for US Environmental Protection Agency – Region 1, by Tetra Tech, Inc.

Tetra Tech. 2011. Evaluation of Water Quality Design Storms. Prepared for the County of Los Angeles, Watershed Management Division, Department of Public Works, by Tetra Tech, Inc.

USEPA. 2009. National Recommended Water Quality Criteria. US Environmental Protection Agency. http://water.epa.gov/scitech/swguidance/standards/current/.

APPENDIX A

Herrera SWMM Model Conveyance Network Inputs

This page is purposely left blank

Table A1. Weir properties in the Herrrera SWMM model.

Name	Inlet Node	Outlet Node	Weir Type	Crest Height	Discharge Coefficient	Flap Gate	End Constriction	End Coefficient	Link Shape	Link Geom1	Link Geom2	Link Geom3	Link Geom4	Barrel Count
Outlet1b	StoreBasin	Outlet2Node	V-NOTCH	1.5	2.6	NO	0	0	TRIANGULAR	2.25	4.5	0	0	NULL
Outlet3	StoreBasin	34	TRANSVERSE	11.5	2.5	NO	0	0	RECT_OPEN	2	90	0	0	NULL
Outlet2	StoreBasin	Outlet2Node	TRANSVERSE	10	2.9	NO	0	0	RECT_OPEN	1.72	25	0	0	NULL
4	DetentionA	2	TRANSVERSE	12.13	2.9	NO	0	0	RECT_OPEN	2	8	0	0	NULL
Emergency Spillway	DetentionA	26	TRANSVERSE	13.1	2.9	NO	0	0	RECT_OPEN	1.5	30	0	0	NULL

a The geometry columns have different meanings for the different conduit shapes. For RECT_OPEN shapes, Geom1 and Geom2 are the full height and top width in feet. For TRIANGULAR shapes, Geom1 is the full height in feet and Geom2 is the top width in feet.

Table A2. Conduit properties in the Herrera SWMM model.

Name	Inlet Node	Outlet Node	Length	Manning N	Inlet Offset	Outlet Offset	Initial Flow	Max. Flow	Link shape	Link Geom1	Link Geom2	Link Geom3	Link Geom4	Barrel Count	Notes
P8_9	8	9	60.17035	0.02	0	0	0	0	CIRCULAR	4	0	0	0	1	Conduit
P26_3	26	3	270.7036	0.02	0	0	0	0	CIRCULAR	4	0	0	0	1	Conduit
P6_7	6	7	28.42974	0.02	0	0	0	0	CIRCULAR	4	0	0	0	1	Conduit
P4_5	4	5	109.0499	0.02	0	0	0	0	CIRCULAR	4	0	0	0	1	Conduit
P28_17	28	17	836.1067	0.02	0	0	0	0	CIRCULAR	4.5	0	0	0	1	Conduit
P35_20	35	20	450.4131	0.02	0	0	0	0	CIRCULAR	3	0	0	0	1	Conduit
P33_35	33	35	418.1501	0.02	0	0	0	0	CIRCULAR	3	0	0	0	1	Conduit
P21_33	21	33	48.9432	0.02	0	0	0	0	CIRCULAR	3.5	0	0	0	1	Conduit
P14_27	14	27	154.4497	0.02	0	0	0	0	CIRCULAR	4	0	0	0	1	Conduit
P31_30	31	30	734.8772	0.02	0	0	0	0	CIRCULAR	2.5	0	0	0	1	Conduit
P23_31	23	31	262.9904	0.02	0	0	0	0	CIRCULAR	2	0	0	0	1	Conduit
P16_28	16	28	338.1179	0.02	0	0	0	0	CIRCULAR	4	0	0	0	1	Conduit
P2_26	2	26	218.1559	0.02	0	0	0	0	CIRCULAR	4	0	0	0	1	Conduit
P10_11	10	11	365.1612	0.02	0	0	0	0	CIRCULAR	4	0	0	0	1	Conduit
P12_13	12	13	125.1393	0.02	0	0	0	0	CIRCULAR	3.5	0	0	0	2	Conduit
P27_15	27	15	71.71392	0.02	0	0	0	0	CIRCULAR	4	0	0	0	1	Conduit
S3_4	3	4	162.8473	0.3	0	0	0	0	TRAPEZOIDAL	10	4	0.333	0.333	1	Wetland Channel
S7_8	7	8	296.6204	0.3	0	0	0	0	TRAPEZOIDAL	10	20	0.333	0.333	1	Wetland Channel
S9_10	9	10	459.7885	0.3	0	0	0	0	TRAPEZOIDAL	10	20	0.333	0.333	1	Wetland Channel
S11_12	11	Wetland1	295.5956	0.3	0	0	0	0	TRAPEZOIDAL	10	75	0.333	0.333	1	Wetland Channel
S22_21	22	21	527.5168	0.3	0	0	0	0	TRAPEZOIDAL	10	30	0.333	0.333	1	Wetland Channel
S5_6	5	6	51.8898	0.3	0	0	0	0	TRAPEZOIDAL	10	4	0.333	0.333	1	Wetland Channel
S13_14	13	Wetland2	973.805	0.3	0	0	0	0	TRAPEZOIDAL	10	35	0.333	0.333	1	Wetland Channel
S15_16	15	Wetland3	602.8079	0.3	0	0	0	0	TRAPEZOIDAL	10	250	0.333	0.333	1	Wetland Channel
S20_18	20	18	861.8539	0.3	0	0	0	0	TRAPEZOIDAL	10	90	0.333	0.333	1	Wetland Channel
S17_18	17	18	256.7153	0.3	0	0	0	0	TRAPEZOIDAL	10	90	0.333	0.333	1	Wetland Channel
S18_19	18	Wetland4	140.8097	0.3	0	0	0	0	TRAPEZOIDAL	10	90	0.333	0.333	1	Wetland Channel
60in_RCP	Outlet2Node	34	18	0.02	0	0	0	0	CIRCULAR	5	0	0	0	1	Conduit
30_StoreBasin	30	StoreBasin	10	0.02	0	0	0	0	RECT_OPEN	3	20	0	0	1	Conduit
1	19	30	371.3	0.02	0	0	0	0	CIRCULAR	6	0	0	0	1	Conduit
2	19	34	400	0.02	0	0	0	0	CIRCULAR	2	0	0	0	1	Conduit
3	1	DetentionA	229.9	0.02	0	8	0	0	CIRCULAR	7	0	0	0	1	Conduit

a The geometry columns have different meanings for the different conduit shapes. For RECT_OPEN shapes, Geom1 and Geom2 are the full height and top width in feet. For CIRCULAR shapes, Geom1 is the diameter in feet. For TRAPEZOIDAL shapes, Geom1 is full height in feet, Geom2 is base width in feet, Geom3 is the slope of left bank in feet/feet, and Geom4 is the slope of the right bank.

Table A3. Orifice parameters used in the Herrera SWMM model

Name	Inlet Node	Outlet Node	Orifice Type	Crest Height	Discharge Coefficient	Flap Gate	Open/Close Time	Link Shape	Link Geom1	Link Geom2	Link Geom3	Link Geom4	Barrel Count
Orifice1	DetentionA	2	SIDE	3.08	0.65	NO	0	RECT_CLOSED	2	2	0	0	NULL
Orifice2	DetentionA	2	SIDE	7.08	0.65	NO	0	RECT_CLOSED	2.5	2.5	0	0	NULL
Store53Orifice1	Store53	1	SIDE	0	0.65	NO	0	CIRCULAR	0.58333	0	0	0	NULL
Store53Orifice2	Store53	1	SIDE	0	0.65	NO	0	CIRCULAR	0.583333	0	0	0	NULL
Store53Orifice3	Store53	1	SIDE	0	0.65	NO	0	CIRCULAR	0.583333	0	0	0	NULL
Store53Orifice4	Store53	1	SIDE	0	0.65	NO	0	CIRCULAR	0.583333	0	0	0	NULL
Store53Orifice5	Store53	1	SIDE	0	0.65	NO	0	CIRCULAR	0.583333	0	0	0	NULL
Wetland1Orifice1	Wetland1	12	SIDE	0.5	0.65	NO	0	CIRCULAR	3.5	0	0	0	NULL
Wetland1Orifice2	Wetland1	12	SIDE	0.5	0.65	NO	0	CIRCULAR	3.5	0	0	0	NULL
8	Wetland2	14	SIDE	0.5	0.65	NO	0	CIRCULAR	4	0	0	0	NULL
9	Wetland3	16	SIDE	0.5	0.65	NO	0	CIRCULAR	4	0	0	0	NULL
10	Wetland4	19	SIDE	0.5	0.65	NO	0	CIRCULAR	5	0	0	0	NULL

a The geometry columns have different meanings for the different conduit shapes. For RECT_CLOSED shapes, Geom1 and Geom2 are the full height and top width in feet.
For CIRCULAR shapes, Geom1 is the diameter in feet.

This page is purposely left blank

APPENDIX B

Stage-Discharge Curves for Regional Facility Outlet Control

This page is purposely left blank

This appendix contains the stage-discharge curves that represent outflows from the Kitts Corner, Belmor, and aggregate vault facilities, developed outside of the model and input into SUSTAIN using the BMP module pump curve function.

Table B1. Stage-Discharge Curves for Regional Facility Outlet Control.

Belmor		Kitts Corner		Aggregate Vault	
Depth (ft)	Flow Rate (cfs)	Depth (ft)	Flow Rate (cfs)	Depth (ft)	Flow Rate (cfs)
0	0	0	0	0	0
3	0	1	0	0.5	2.98
3.5	2.009	1.5	0	1	5.86
4	6.51	2	5.25	1.5	7.662
4.5	12.48	2.5	19.37	2	9.11
5	19.63	3	29.57	2.5	10.35
5.5	24.86	3.5	37.11	3	11.47
6	26.55	4	44.23	3.5	12.485
6.5	26.55	4.5	47.89	4	13.422
7	26.55	5	51.09	4.5	14.29
7.5	26.55	5.5	53.96	5	15.12
8	26.55	6	56.6	5.5	15.907
10	26.55	6.5	59.04	6	16.65
25	26.55	7	61.34	6.5	17.36
		7.5	63.506	7	18.05
		8	65.56	7.5	18.71
		8.5	67.52	8	19.35
		9	69.03	8.5	19.96
				9	20.56
				9.5	21.15
				10	21.71
				11	22.809
				12	23.85
				13	25.807
				14	26.77
				20	26.77

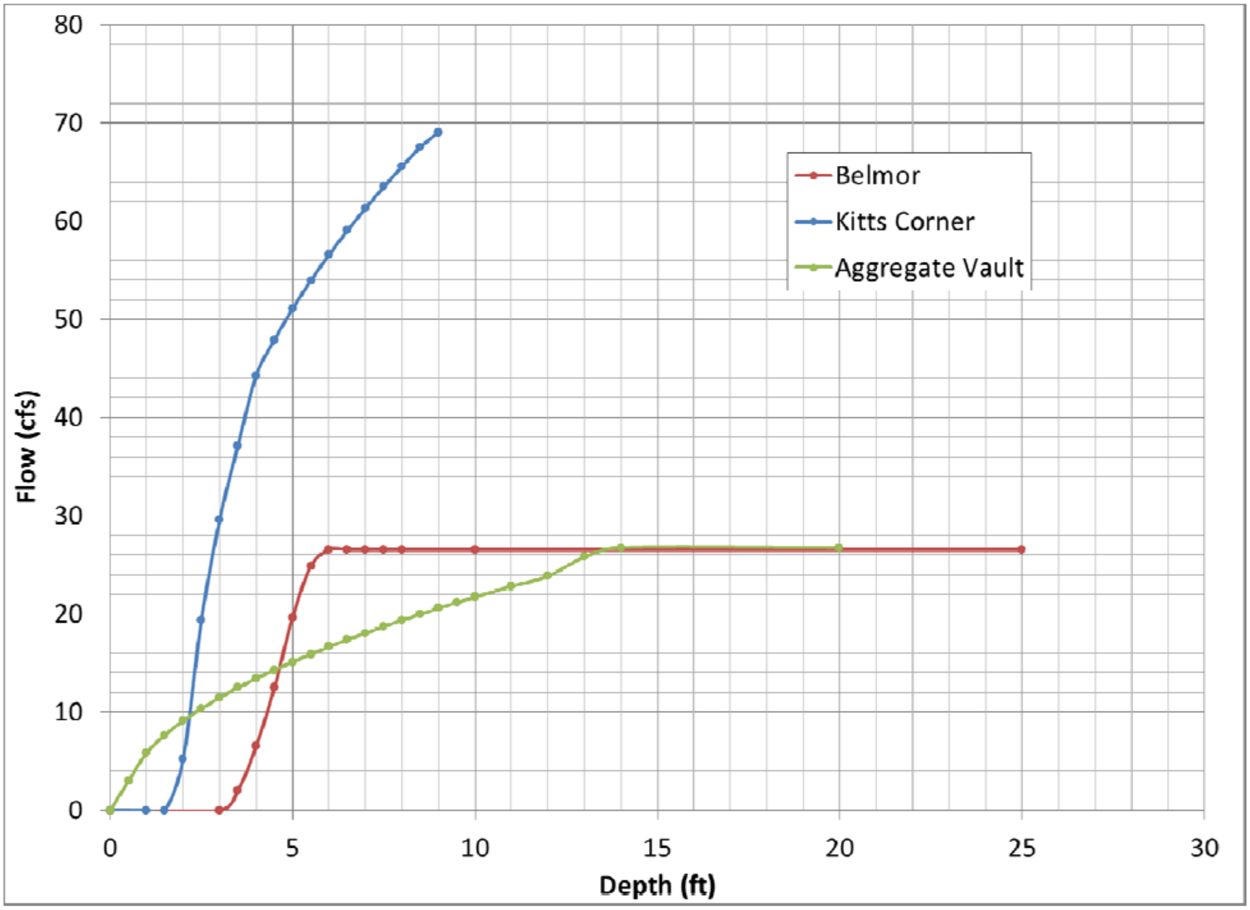


Figure B1. Stage-Discharge Curves for Regional Facility Outlet Control.

APPENDIX C

Results from Repeat *SUSTAIN* to Derive Pollutant Decay Rates for Modeling Existing Conditions in *SUSTAIN*

This page is purposely left blank

Table C1. Results from repeat SUSTAIN model runs to derive wetland and regional detention ponds pollutant decay rates for modeling existing conditions in SUSTAIN.

Flow Weighted TSS Concentration at Basin CBB Outlet (mg/L)	TSS Mass at Basin CBB Outlet (lbs)	Decay Rate (1/hr)	# of CSTRs	Mass Percent Removal	Concentration Percent Removal
64.3	407,981.00	0	1	0.0%	0.0%
42.0	266,297.00	0.02	1	34.7%	34.7%
29.9	189,345.00	0.05	1	53.6%	53.6%
20.0	126,559.00	0.1	1	69.0%	69.0%
11.3	71,615.00	0.2	1	82.4%	82.4%
7.4	46,938.00	0.3	1	88.5%	88.5%
5.3	33,318.00	0.4	1	91.8%	91.8%
3.9	24,906.00	0.5	1	93.9%	93.9%
42.2	267,554.00	0.02	3	34.4%	34.4%
29.6	187,765.00	0.05	3	54.0%	54.0%
19.3	122,285.00	0.1	3	70.0%	70.0%
10.3	65,439.00	0.2	3	84.0%	84.0%
6.4	40,453.00	0.3	3	90.1%	90.1%
4.3	27,068.00	0.4	3	93.4%	93.4%
3.0	19,092.00	0.5	3	95.3%	95.3%
42.9	272,069.00	0.02	5	33.3%	33.3%
30.3	191,975.00	0.05	5	52.9%	52.9%
19.8	125,424.00	0.1	5	69.3%	69.3%
10.6	67,092.00	0.2	5	83.6%	83.6%
6.5	41,249.00	0.3	5	89.9%	89.9%
4.3	27,343.00	0.4	5	93.3%	93.3%
3.0	19,047.00	0.5	5	95.3%	95.3%

This page is purposely left blank

APPENDIX D

Assumptions for Percent Removal Targets to be Applied to BMPs for Modeling Future Conditions in *SUSTAIN*

This page is purposely left blank

Assumptions for Percent Removal Targets to be Applied to BMPs for Modeling Future Conditions in SUSTAIN

Source: O'Brien 2012 personal communication

1. TSS percent removal = 70%

2. Dissolved Zinc pecent removal =
   a. 70% for bioretention
   b. 50% for wetponds and wetlands
   c. 0% for permeable pavement routed to surface water; 100% where it infiltrates to the ground

3. Total Zinc percent removal =

   a. 70%*(1-DISSFRAC)+70%*DISSFRAC = 70% for bioretention
   b. 70%*(1-DISSFRAC)+50%*DISSFRAC = 50.0% for wetponds and wetlands
   c. 0% for permeable pavement routed to surface water; 100% where it infiltrates to the ground

   where: DISSFRAC = average dissolved zinc/total zinc ratio (0.48) from monitoring data compiled by Phase 1 jurisdictions pursuant the NPDES Muncipal Stormwater Permit

4. Dissolved Copper percent removal =

   a. 40% for bioretention
   b. 18% for Wetponds and wetlands
   c. 0% for permeable pavement routed to surface water; 100% where it infiltrates to the ground

5. Total Copper percent removal =

   a. 70%*(1-DISSFRAC)+40%*DISSFRAC = 56.5% for bioretention
   b. 70%*(1-DISSFRAC)+18%*DISSFRAC = 46.6% for wetponds and wetlands
   c. 0% for permeable pavement routed to surface water; 100% where it infiltrates to the ground

   where: DISSFRAC = average dissolved copper/total copper ratio (0.45) from monitoring data compiled by Phase 1 jurisdictions pursuant the NPDES Muncipal Stormwater Permit

6. Chrysene pŜlcent reϒov al Γ

   a. 34% assumed for bioretention based on compiled data from Milesi et al. (2006)
   b. 18% assumed for wetponds and wetlands based on removal rates for dissolved zinc and copper
   c. 0% for permeable pavement routed to surface water; 100% where it infiltrates to the ground

This page is purposely left blank

APPENDIX E

Future Conditions Wetland and Wet Pond Decay Rate Calibration Results (Performed in SUSTAIN)

This page is purposely left blank

Table E1. Future Conditions Wetland and Wet Pond Decay Rate Calibration Results (Performed in *SUSTAIN*).

TSS Flow Weighted Concentration at BMP Outlet (mg/L)	TSS Mass at BMP Outlet (lbs)	TSS Mass at BMP Inlet (lbs)	BMP Type	Decay Rate (1/hr)	# of CSTRs	Concentration Percent Removal	Mass Percent Removal
77.3	14,346	14,360	Wetland	0.00	1	0%	0%
31.2	5,789	14,360	Wetland	0.02	1	60%	60%
22.7	4,207	14,360	Wetland	0.05	1	71%	71%
17.4	3,227	14,360	Wetland	0.10	1	78%	78%
12.6	2,337	14,360	Wetland	0.20	1	84%	84%
9.9	1,845	14,360	Wetland	0.30	1	87%	87%
8.2	1,514	14,360	Wetland	0.40	1	89%	89%
6.8	1,271	14,360	Wetland	0.50	1	91%	91%
24.9	4,618	14,360	Wetland	0.02	3	68%	68%
15.8	2,941	14,360	Wetland	0.05	3	79%	80%
11.2	2,075	14,360	Wetland	0.10	3	86%	86%
7.7	1,432	14,360	Wetland	0.20	3	90%	90%
6.1	1,132	14,360	Wetland	0.30	3	92%	92%
5.1	951	14,360	Wetland	0.40	3	93%	93%
4.5	829	14,360	Wetland	0.50	3	94%	94%
25.5	4,728	14,360	Wetland	0.02	5	67%	67%
16.0	2,971	14,360	Wetland	0.05	5	79%	79%
11.2	2,075	14,360	Wetland	0.10	5	86%	86%
7.7	1,421	14,360	Wetland	0.20	5	90%	90%
6.0	1,120	14,360	Wetland	0.30	5	92%	92%
5.1	939	14,360	Wetland	0.40	5	93%	93%
4.4	818	14,360	Wetland	0.50	5	94%	94%
77.3	14,338	14,360	WetPond	0.00	1	0%	0%
23.7	4,408	14,360	WetPond	0.02	1	69%	69%
16.6	3,075	14,360	WetPond	0.05	1	79%	79%
12.4	2,306	14,360	WetPond	0.10	1	84%	84%
8.8	1,639	14,360	WetPond	0.20	1	89%	89%
6.9	1,280	14,360	WetPond	0.30	1	91%	91%
5.6	1,043	14,360	WetPond	0.40	1	93%	93%
4.7	872	14,360	WetPond	0.50	1	94%	94%
15.5	2,884	14,360	WetPond	0.02	3	80%	80%
8.7	1,623	14,360	WetPond	0.05	3	89%	89%
5.7	1,065	14,360	WetPond	0.10	3	93%	93%
3.7	689	14,360	WetPond	0.20	3	95%	95%
2.8	525	14,360	WetPond	0.30	3	96%	96%
2.3	430	14,360	WetPond	0.40	3	97%	97%
2.0	368	14,360	WetPond	0.50	3	97%	97%
14.8	2,742	14,360	WetPond	0.02	5	81%	81%
7.8	1,456	14,360	WetPond	0.05	5	90%	90%
5.0	920	14,360	WetPond	0.10	5	94%	94%
3.1	576	14,360	WetPond	0.20	5	96%	96%
2.3	432	14,360	WetPond	0.30	5	97%	97%
1.9	350	14,360	WetPond	0.40	5	98%	98%
1.6	297	14,360	WetPond	0.50	5	98%	98%

This page is purposely left blank

APPENDIX F

NSGA-II Optimization for Total Copper and Total Zinc

This page is purposely left blank

This appendix contains the post-processor output from the NSGA-II optimization of total copper and total zinc removal for both Scenario A and Scenario B BMP configurations. The costs are strongly driven by the assumptions unique to this exploratory analysis of *SUSTAIN*. The costs do not necessarily represent an optimum solution for the basin evaluated and are not transferable to other basins. The optimum solution identified may provide more or less treatment than would be needed to meet a particular water quality target.

Scenario A

Total Copper Optimization

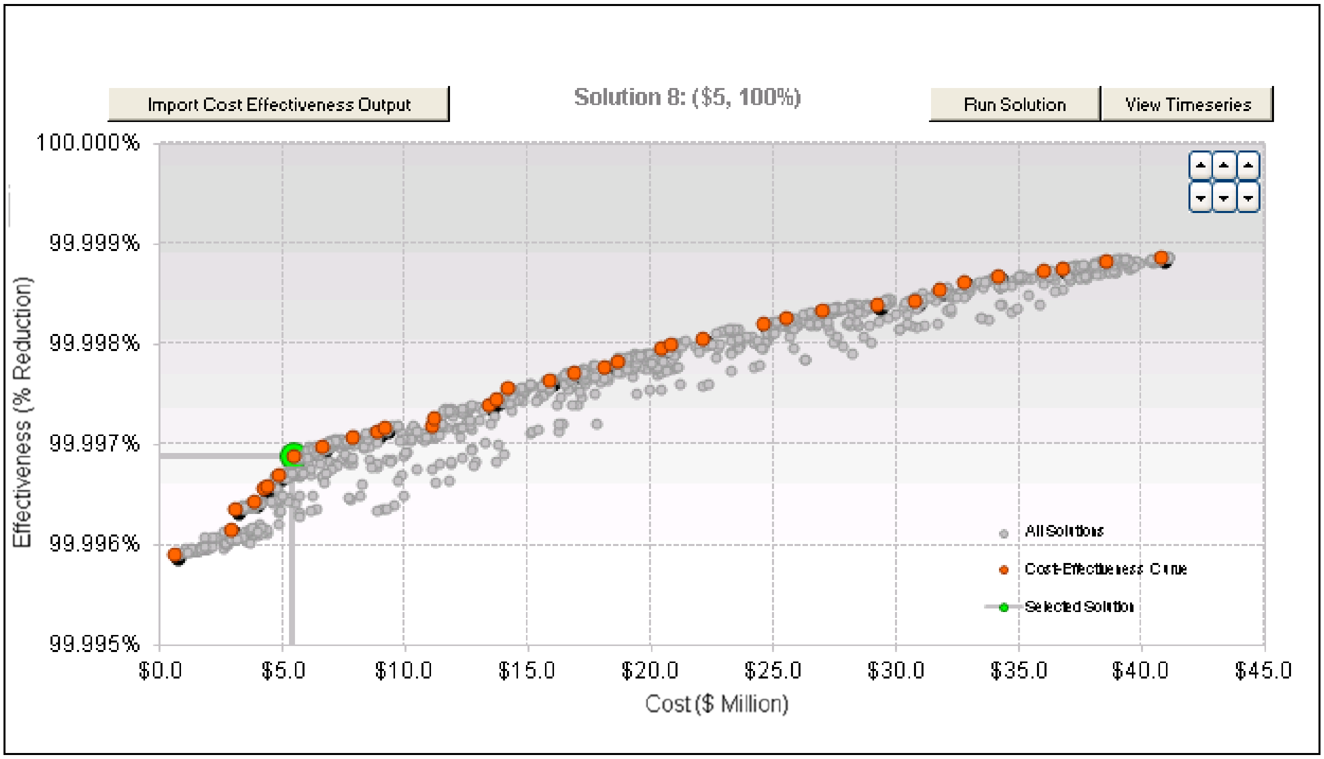


Figure F-1. Scenario A Cost-Effectiveness Curve for TCu Removal.

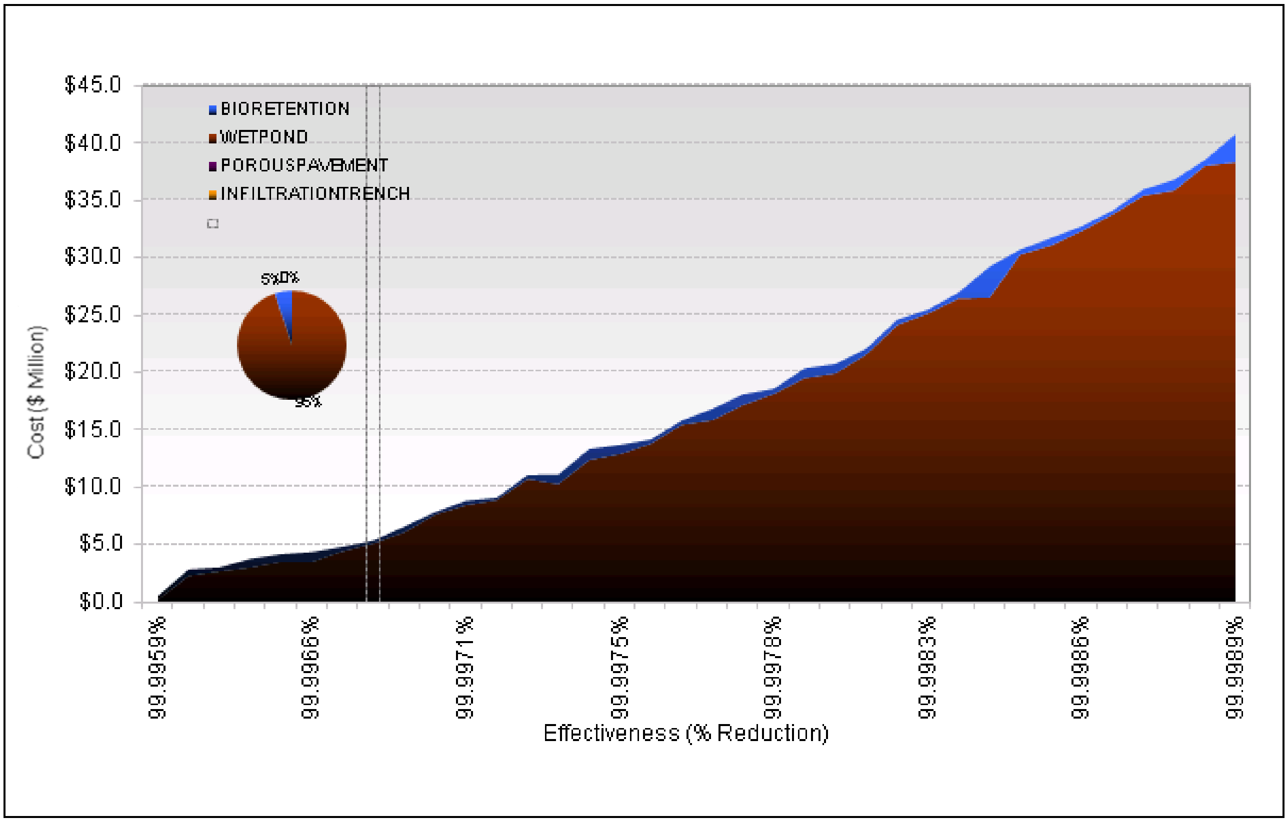


Figure F-2. Scenario A Cost Distribution by BMP for TCu Removal.

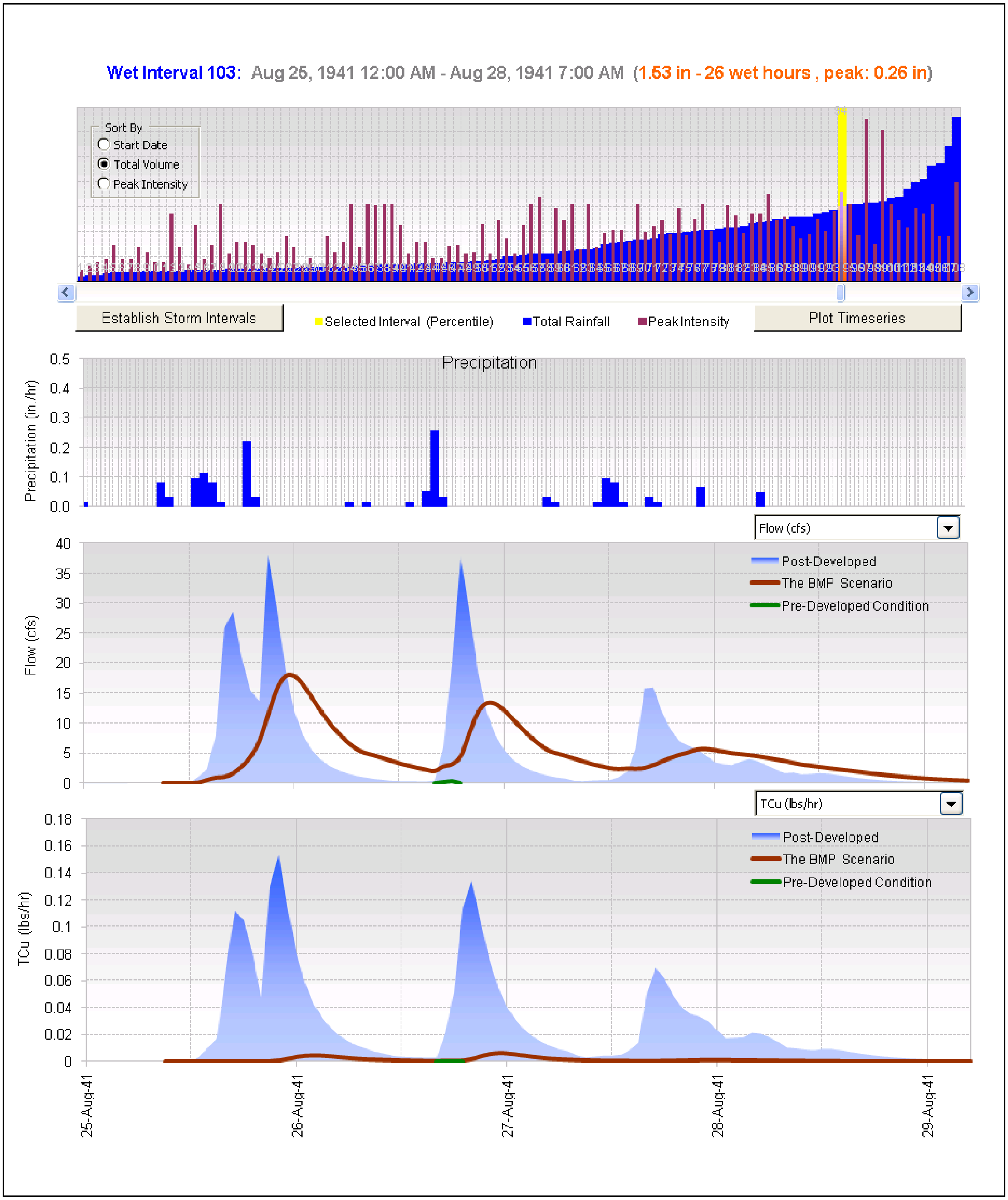


Figure F-3. Scenario A Rainfall and Runoff Response for a TCu-Optimized Solution.

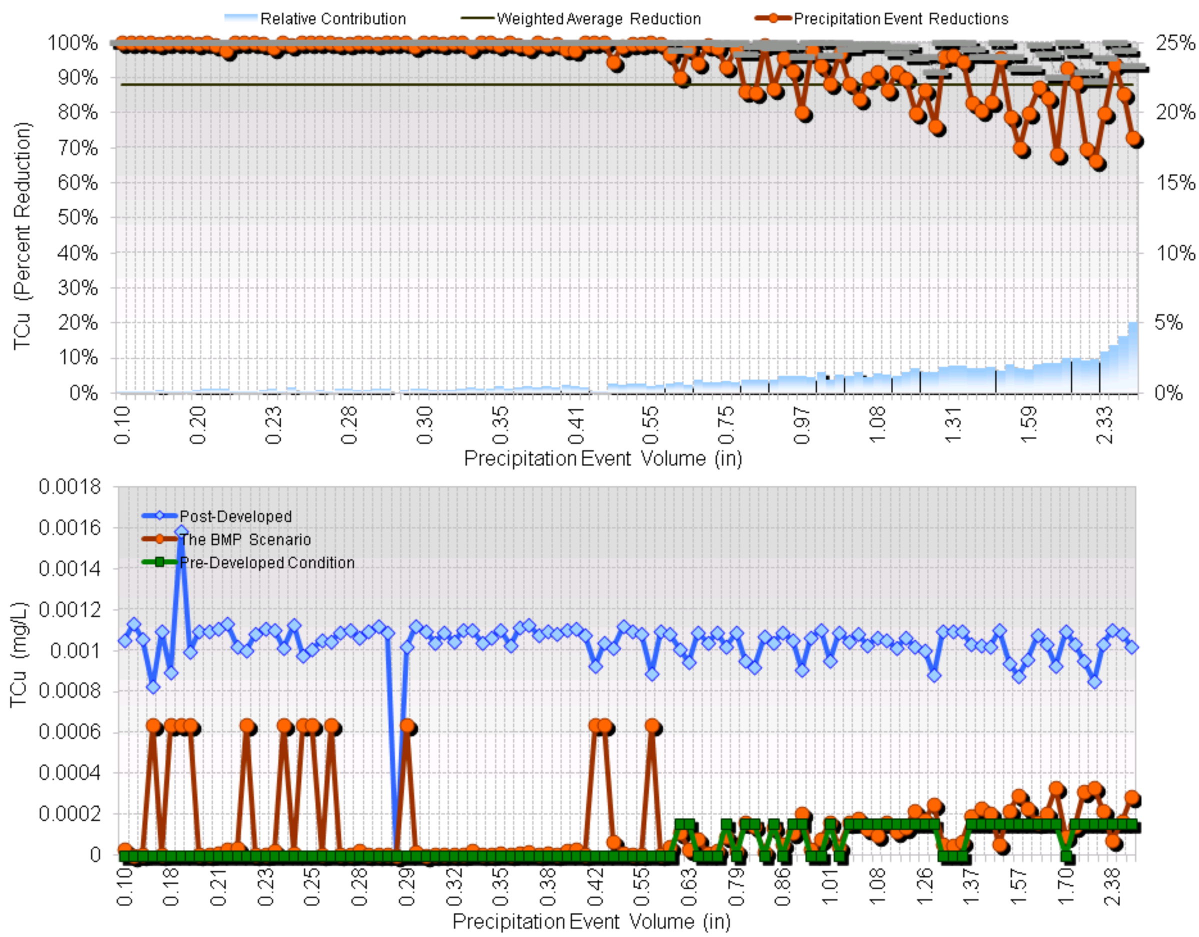


Figure F-4. Scenario A TCu Performance Summary.

Total Zinc Optimization

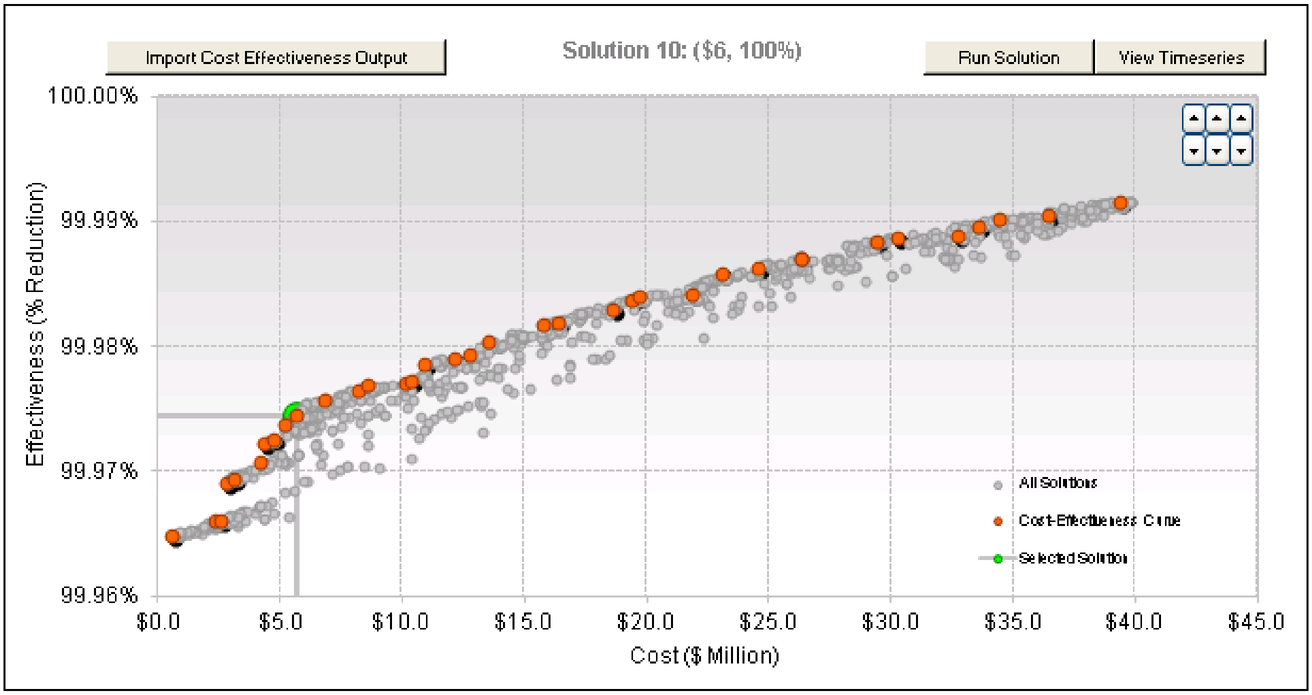


Figure F-5. Scenario A Cost-Effectiveness Curve for TZn Removal.

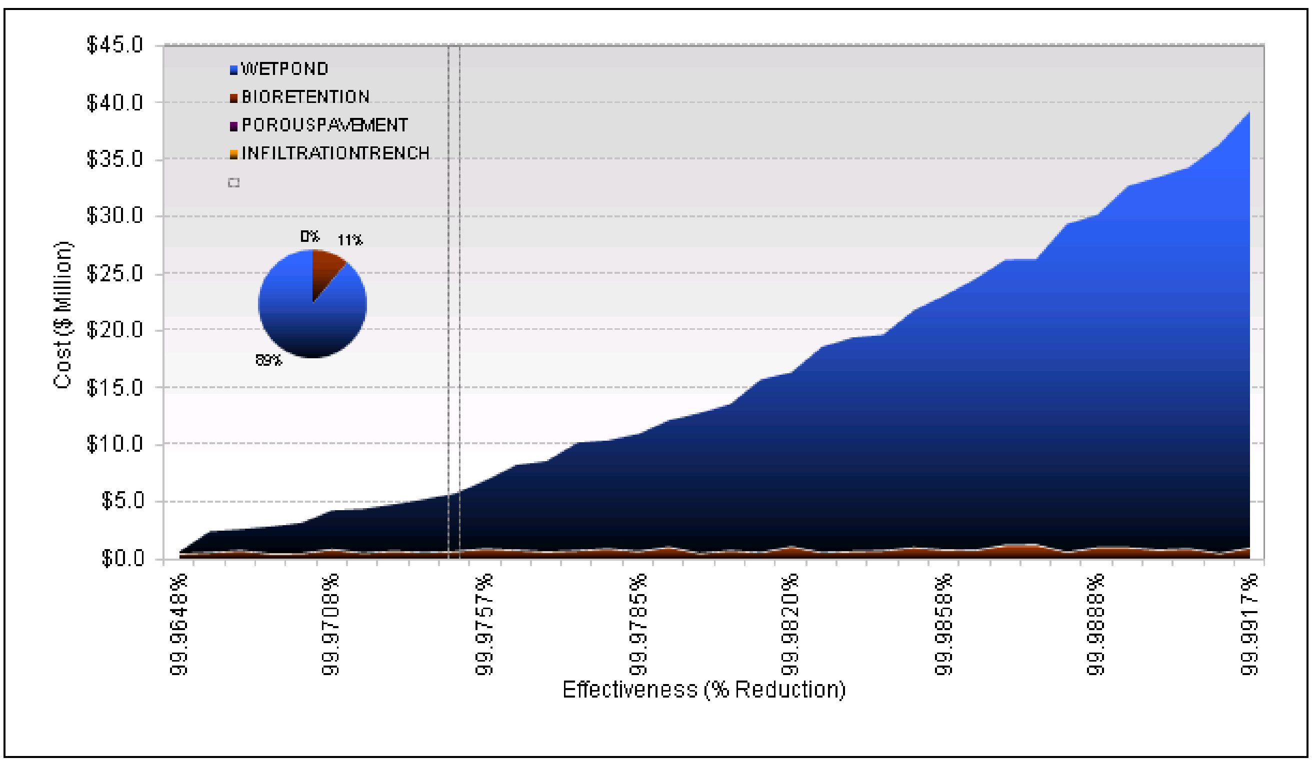


Figure F-6. Scenario A Cost Distribution by BMP for TZn Removal.

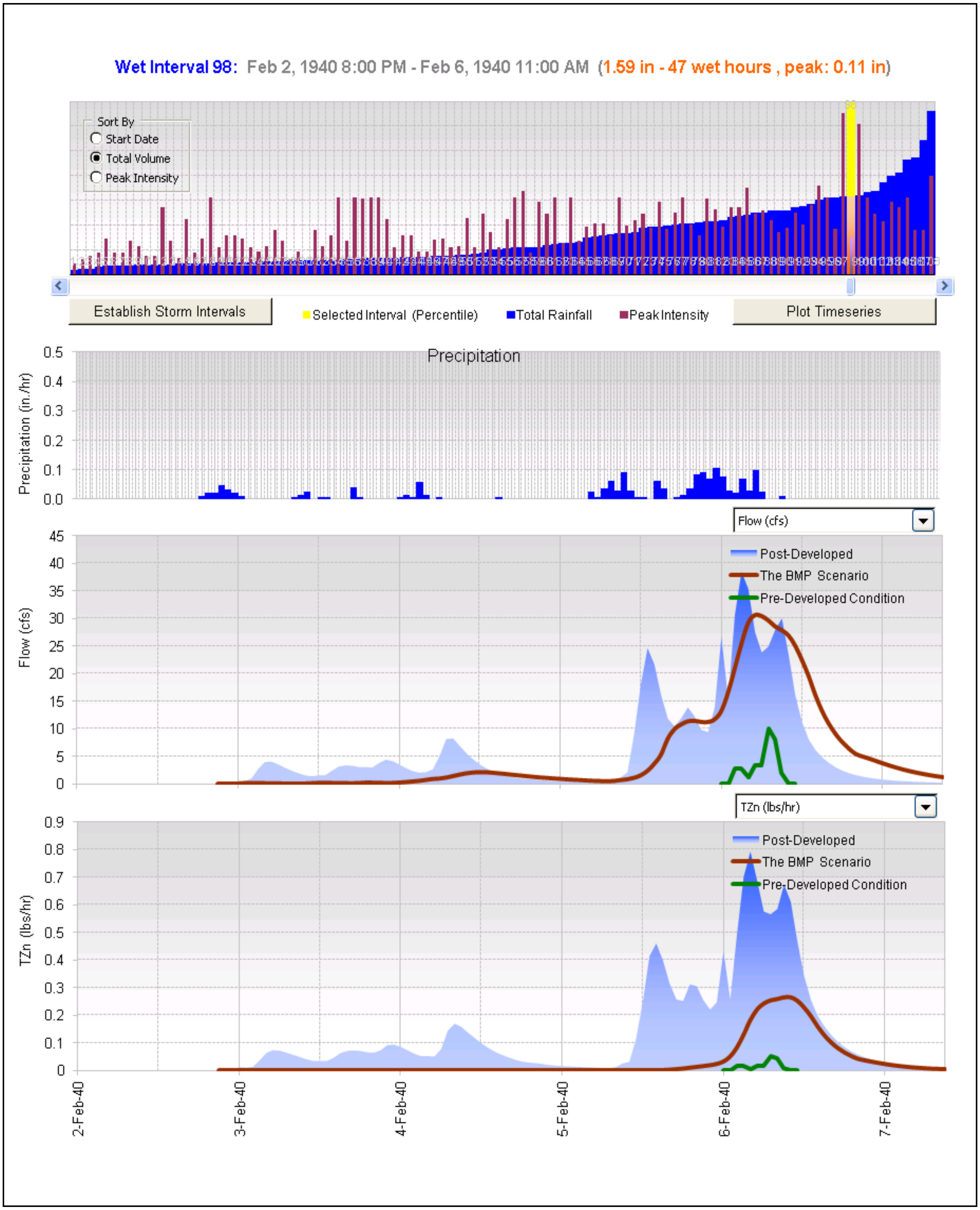


Figure F-7. Scenario A Rainfall and Runoff Response for a TZn-Optimized Solution.

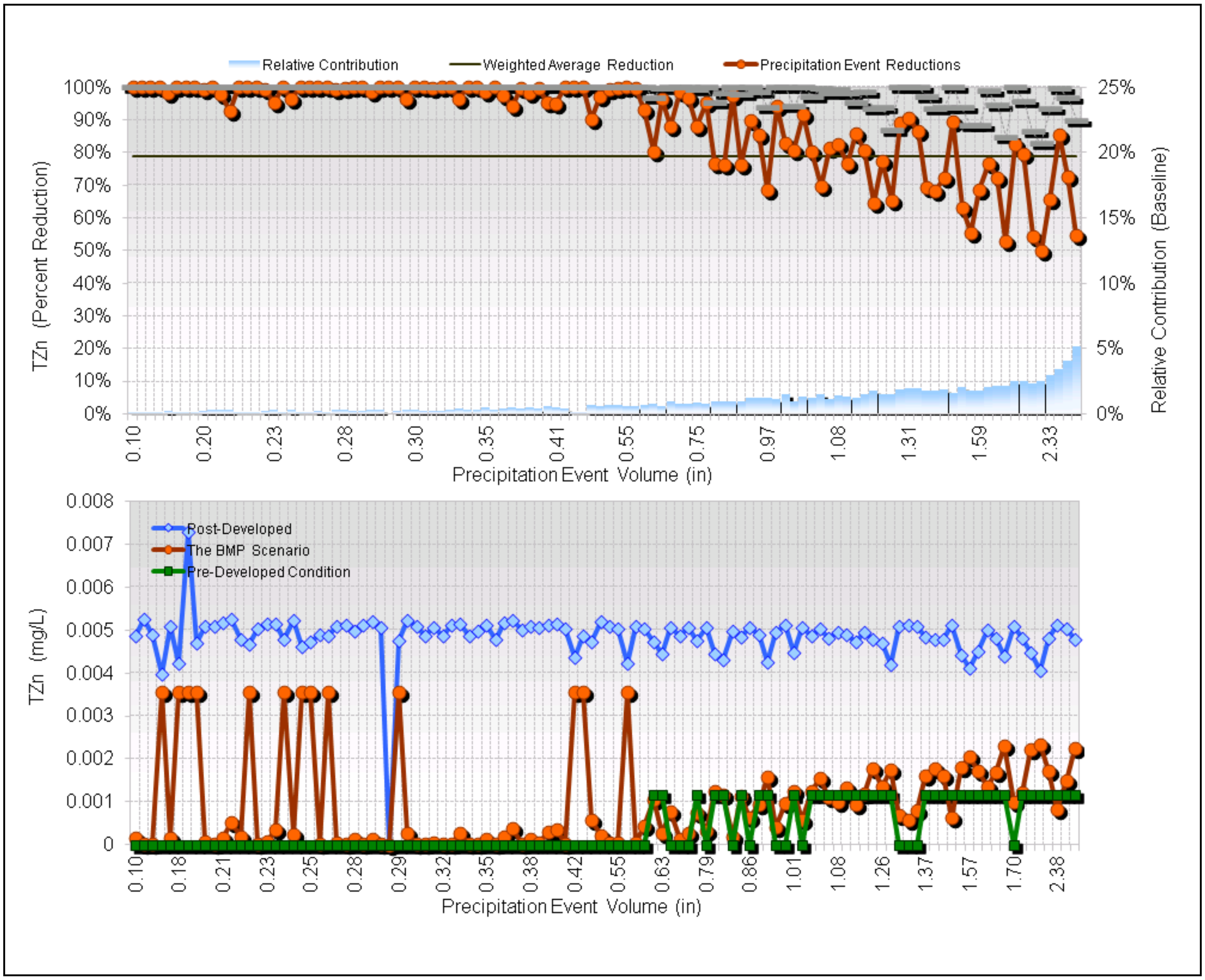


Figure F-8. Scenario A TZn Performance Summary.

Scenario B

Total Copper Optimization

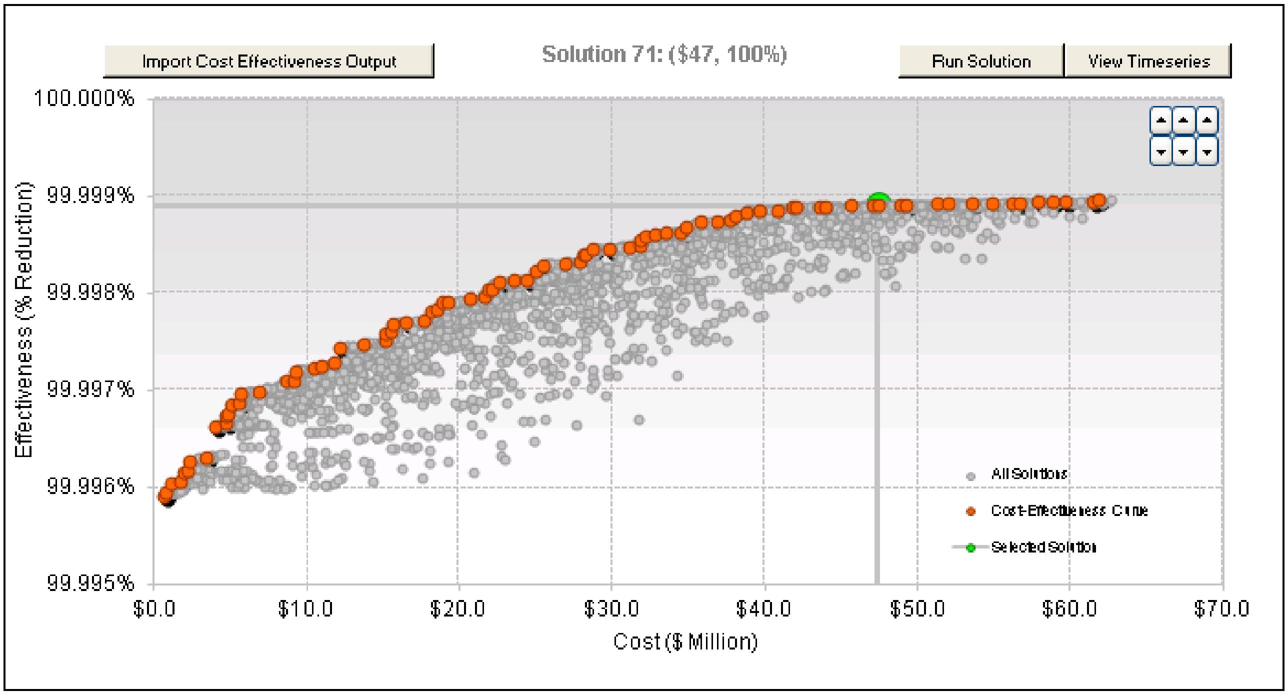


Figure F-9. Scenario B Cost-Effectiveness Curve for TCu Removal.

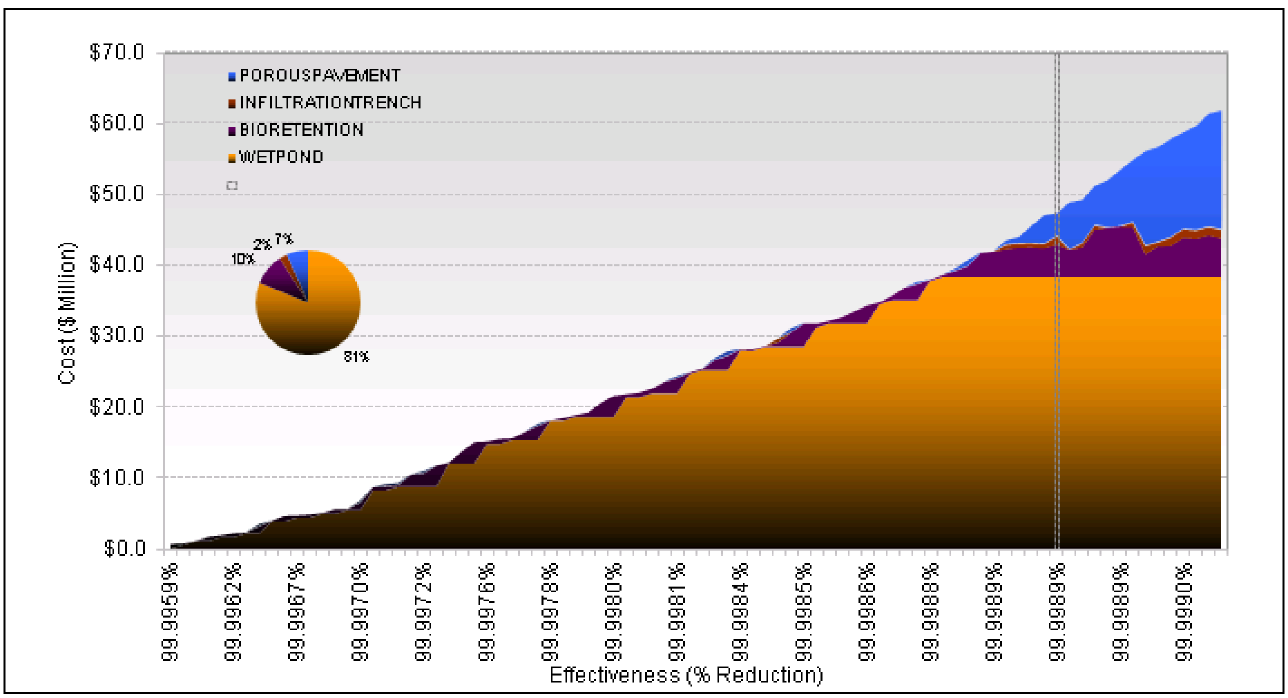


Figure F-10. Scenario B Cost Distribution by BMP for TCu Removal.

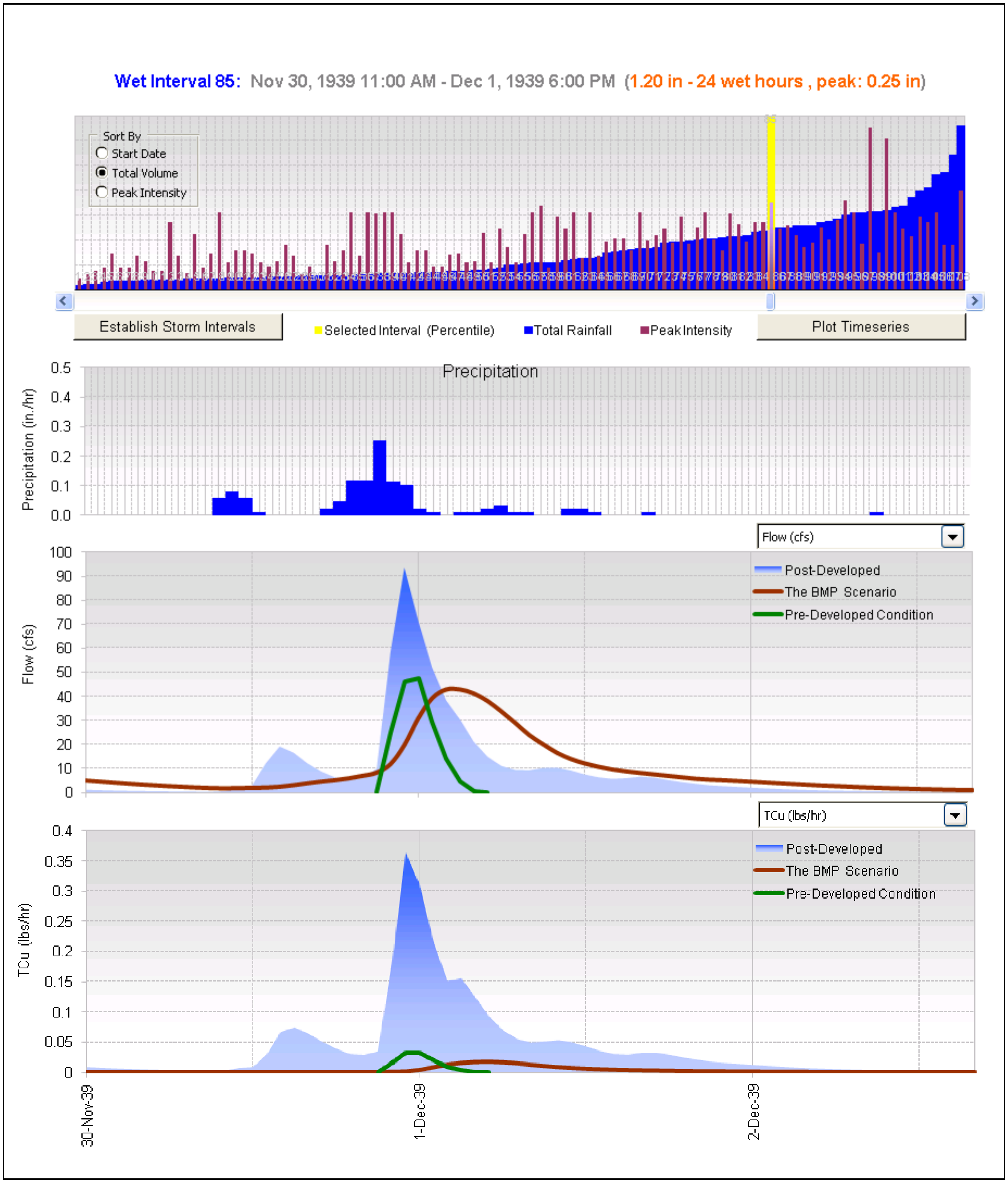


Figure F-11. Scenario B Rainfall and Runoff Response for a TCu-Optimized Solution.

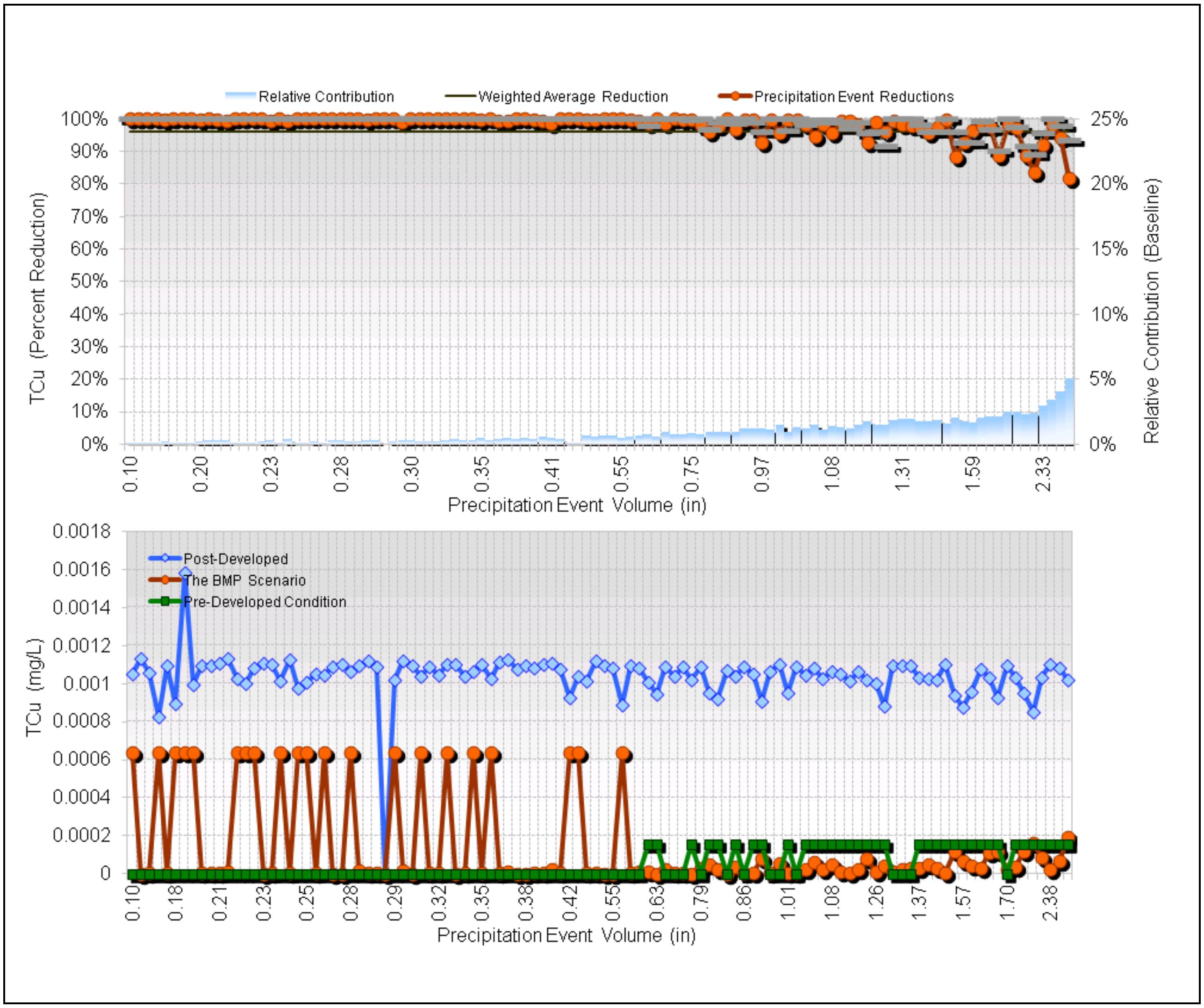


Figure F-12. Scenario B TCu Performance Summary.

Total Zinc Optimization

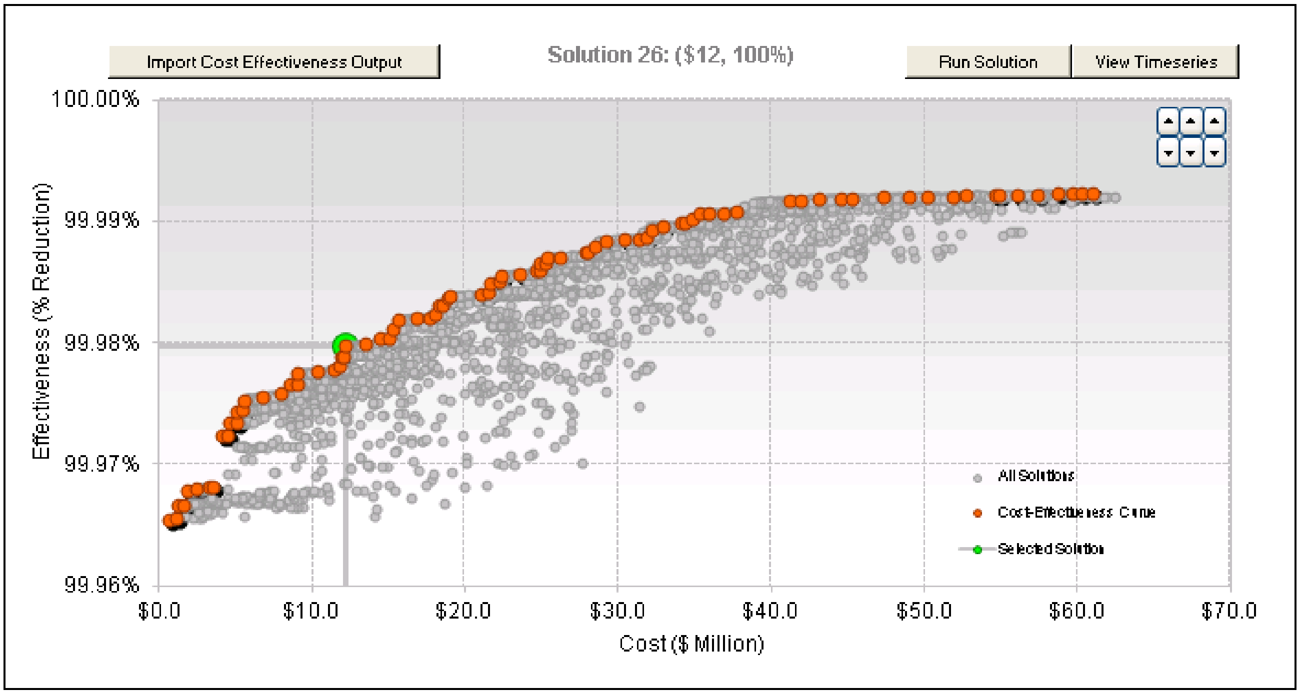


Figure F-13. Scenario B Cost-Effectiveness Curve for TZn Removal.

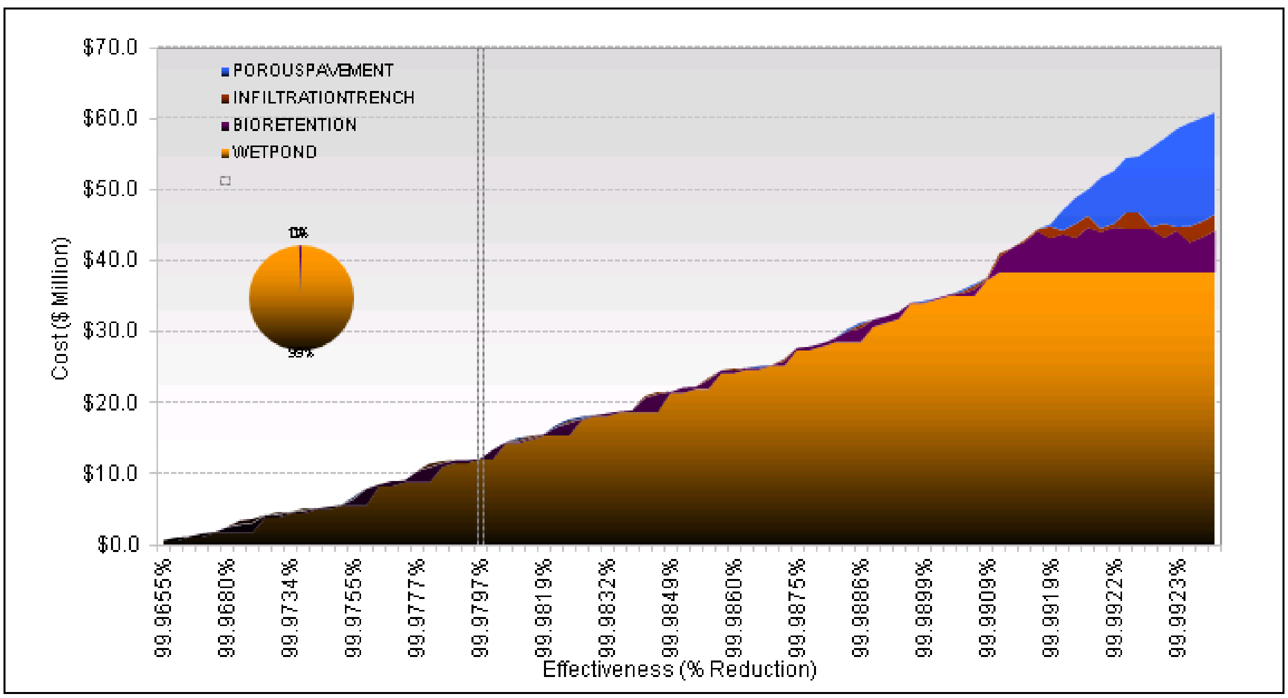


Figure F-14. Scenario B Cost Distribution by BMP for TZn Removal.

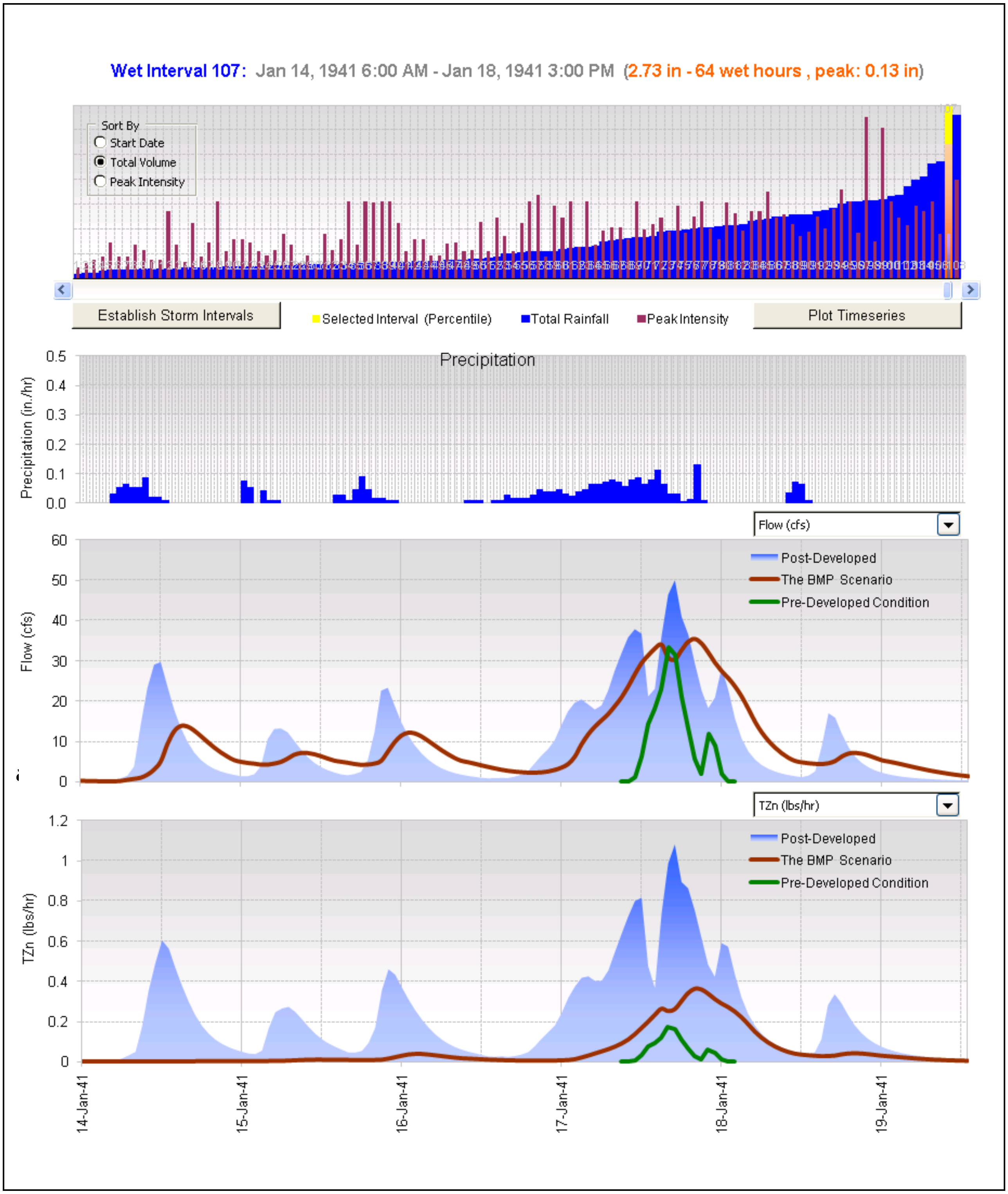


Figure F-15. Scenario B Rainfall and Runoff Response for a TZn-Optimized Solution.

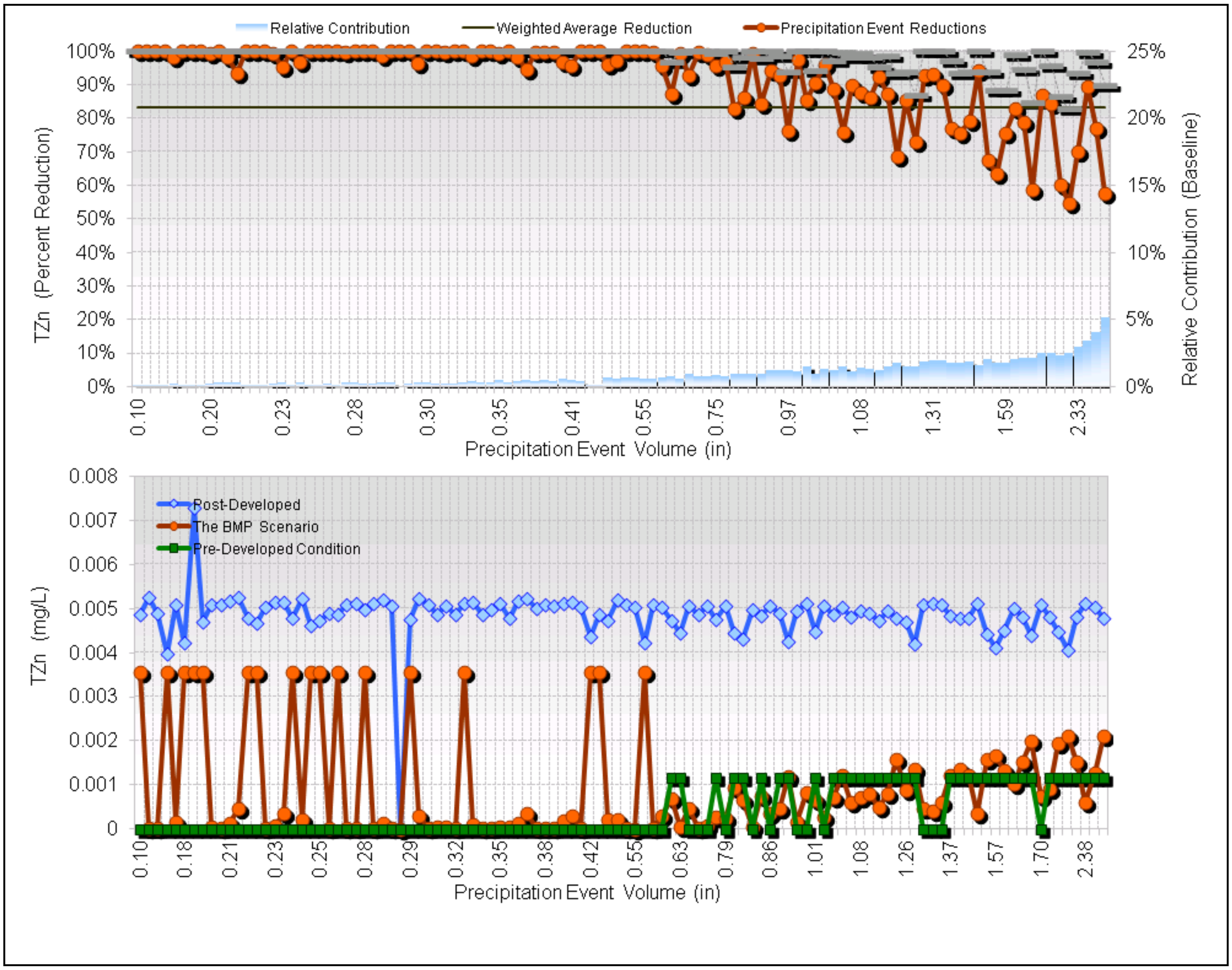


Figure F-16. Scenario B TZn Performance Summary.

This page is purposely left blank

APPENDIX G

Acronyms and Abbreviations

This page is purposely left blank

Acronyms and Abbreviations

BMP	*Best management practice*
CBB	A mixed land-use basin in the Puyallup River watershed in Federal Way, WA, identified in Herrera (2011) as Commercial Basin B
CSTR	Continuously stirred tank reactors
DS	Depression storage
DCu	Dissolved copper
DZn	*Dissolved zinc*
Ecology	*Washington State Department of Ecology*
EMC	Event mean concentration
GIS	Geographic Information Systems
LID	Low impact development
NPDES	National Pollutant Discharge Elimination System
O&M	Operations and maintenance
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
SWMM	Surface Water Management Model
TSS	*Total suspended solids*
TCu	*Total copper*
TZn	*Total zinc*
USEPA	*U.S. Environmental Protection Agency*
WAC	*Washington Administrative Code*
WRIA	*Water Resources Inventory Area*
WY	*Water year*

Units of Measurement

cfs	cubic feet per second
in/hr	inches per hour
ug/L	micrograms per liter
mg/L	milligrams per liter