

WATERSHED MANAGEMENT OPTIMIZATION SUPPORT TOOL (WMOST) v3

Theoretical Documentation



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Notice

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Although a reasonable effort has been made to assure that the results obtained are correct, the computer programs described in this manual are experimental. Therefore, the author and the U.S. Environmental Protection Agency are not responsible and assume no liability whatsoever for any results or any use made of the results obtained from these programs, nor for any damages or litigation that result from the use of these programs for any purpose.

Abstract

The Watershed Management Optimization Support Tool (WMOST) is a decision support tool that facilitates integrated water management at the local or small watershed scale. WMOST models the environmental effects and costs of management decisions in a watershed context, accounting for the direct and indirect effects of decisions. The model considers water flows and water quality. It is spatially lumped with options for a daily or monthly modeling time step. In this version (v3), management option cost optimization occurs through nonlinear programming. As a screening tool, WMOST contributes to an integrated watershed management process such as that described in EPA's watershed planning handbook (EPA 2008). WMOST serves as a public-domain tool for local water resources managers and planners to screen a wide range of potential water resources management options across their jurisdiction for cost-effectiveness and environmental and economic sustainability (Zoltay et al., 2010). WMOST includes functions to evaluate various management practices, including projects related to stormwater (including green infrastructure [GI] and combined sewer overflow [CSO] systems), stream restoration, water supply, wastewater and land resources such as low-impact development (LID) and land conservation. WMOST can aid in evaluating LID and GI as alternative or complementary management options in projects proposed for grant funding. WMOST v3 builds on the optimization framework of WMOST v1 by incorporating two new optimization modules: The Water Quality module that allows consideration of water flows and loadings and the CSO module. The new version of WMOST also builds upon the modules added in WMOST v2: The Baseline Hydrology and Loadings and Stormwater Hydrology and Loadings modules. The Baseline Hydrology and Loadings and Stormwater Hydrology and Loadings modules assist users with input data acquisition and pre-processing. The CSO module allows evaluation of management options to minimize the number of CSO events. The Flood module allows the consideration of flood damages and their reduction in assessing the cost-effectiveness of management practices. The target user group for WMOST consists of local water resources managers, including municipal water works superintendents and their consultants.

Keywords: Integrated watershed management, water resources, decision support, optimization, green infrastructure

Preface

Integrated Water Resources Management (IWRM) has been endorsed for use at multiple scales. The Global Water Partnership defines IWRM as “a process which promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (UNEP-DHI, 2009). IWRM has been promoted as an integral part of the “Water Utility of the Future” (NACWA, 2013) in the United States. The American Water Resources Association (AWRA) has issued a position statement calling for implementation of IWRM across the United States and committed the AWRA to help strengthen and refine IWRM concepts.¹

Several states and river basin commissions have started to implement IWRM (AWRA, 2012). Even in EPA Region 1 (New England) where water is relatively plentiful, states face the challenge of developing balanced approaches for equitable and predictable distribution of water resources to meet both human and aquatic life needs during seasonal low flow periods and droughts. For example, the Commonwealth of Massachusetts amended the Water Management Act (WMA) regulations² in 2014 to update the way water is allocated to meet the many and sometimes competing needs of communities and aquatic ecosystems.

Stormwater and land use management are two aspects of IWRM, which include practices such as green infrastructure (GI, both natural GI and structural stormwater best management practices [BMPs]), low-impact development (LID) and land conservation. In a few notable cases, local managers have evaluated the relative cost and benefit of preserving GI compared to traditional approaches. In those cases, the managers have championed the use of GI as part of a sustainable solution for IWRM but these examples are rare.³

In order to assist communities in the evaluation of GI, LID, and land conservation practices as part of an IWRM approach, EPA’s Office of Research and Development, in partnership with EPA’s Region 1, supported the development of several versions of the Watershed Management Optimization Support Tool (WMOST). Table 0-1 below summarizes the supporting organizations and development of WMOST.

¹ <http://www.awra.org/policy/policy-statements-IWRM.html>, January 22, 2011.

² For more information on the WMA, see <http://www.mass.gov/eea/agencies/massdep/water/watersheds/water-management-act-program.html>

³ <http://www.crwa.org/blue.html>, <https://www.mmsd.com/what-we-do/mmsd-tv/greenseams-video>

Table 0-1. Summary of Development of WMOST and Supporting Organizations

Version	Year Released	Supporting Organization(s)	Model Enhancements
Version 1 (v1)	2013	EPA Office of Research and Development (ORD), EPA Region 1	
Version 2 (v2)	2016	RARE grant to EPA Region1 and ORD collaborators, US EPA ORD’s Green Infrastructure Initiative research program	Baseline Hydrology and Stormwater Hydrology modules
			Flood Damage module
Version 3 (v3)	2017	US EPA ORD’s Green Infrastructure Initiative research program	Baseline Hydrology and Loadings and Stormwater Hydrology and Loadings modules
			Water Quality module
			CSO module
			Calibration module

WMOST is based on a prior integrated watershed management optimization model that was created to allow water resources managers to evaluate a broad range of technical, economic, and policy management options within a watershed (Zoltay, V. I. 2007; Zoltay et al. 2010). This model includes evaluation of conservation options for source water protection and infiltration of stormwater on forest lands, GI stormwater BMPs to increase infiltration, and other water-related management options.

Development of each version of the WMOST tool was overseen by an EPA Planning Team. Priorities for update and refinement of the original model (Zoltay V. I. 2007; Zoltay et al. 2010) were established following review by a Technical Advisory Group (TAG) comprised of water resource managers and modelers. Case studies for two communities (Upper Ipswich River and Danvers/Middleton, MA) were developed to illustrate the application of IWRM using WMOST v1. These case studies are available from the WMOST website⁴. WMOST was presented to stakeholders in a workshop held at the EPA Region 1 Laboratory in Chelmsford, MA, in April 2013, with a follow-up webinar on the Danvers/Middleton case study in May 2013. Feedback from the Technical Advisory Group and workshop participants has been incorporated into the user guide and theoretical documentation for WMOST.

The development of the Baseline Hydrology, Stormwater Hydrology, and Flood Damage modules in WMOST v2 was assisted by a TAG with expertise in one or more of these topics. Multiple meetings with stakeholders in the Monponsett Pond watershed (Halifax, MA) were held to engage the

⁴ <https://www.epa.gov/exposure-assessment-models/wmost-20-download-page>

community in a case study application of WMOST v2. Input from the TAG and community members were incorporated in the final methodology for WMOST v2 and the modeling case study.

WMOST v2.1 corrected for known errors in WMOST v2, but did not include significant model changes. The corrections addressed the following issues:

- aquifer storage and recovery (ASR) facility constraint and cost equations were using incorrect variable names
- limits on interbasin transfer volumes
 - limit exclusions were not functioning properly
 - potential additional interbasin transfer volumes were not being correctly multiplied by the number of days in the month when modeling with a monthly time step
- recharge from pervious and impervious areas were not blended when calculating total recharge for a hydrologic response unit (HRU)
- v2 equations inaccurately modeled a time step delay in groundwater discharges from the ASR facility and the septic system
- cost equation for insufficient water penalty (make-up water) did not include an annualization factor
- the calculation of the annualization factor over the modeling period did not take into account leap years

Two training workshops for WMOST v2.1 were held in summer 2016, the first with joint sessions at EPA Region 1 in Boston, MA, and at the University of RI – Kingston, RI, in June and the second during the International LID conference in Portland, Maine, in August. Presentations from the June workshop were recorded and are available on the WMOST website.

Development of Version 3 of WMOST was informed by input from stakeholders involved in three case study applications of WMOST. The first case study, focused on the upper Taunton River watershed in Massachusetts (Wading, Mill, and Threemile River subwatersheds), was coordinated with a consortium (Manomet, Audubon, Nature Conservancy, and the Southeastern Regional Development Commission), which had received a grant from EPA Region 1 to evaluate the potential uses for and to educate municipalities in the Taunton River watershed about the value of natural and constructed GI under both current and future climate and growth scenarios. The second case study, focused on the Cabin John Creek watershed in Montgomery County, MD, was designed for the Maryland Department of the Environment (MDE) to evaluate costs and benefits of different stormwater BMPs while meeting local targets for a sediment total maximum daily load (TMDL) as well as downstream loading targets for total suspended solids, total nitrogen, and total phosphorus for the Chesapeake Bay TMDL. The third case study, focused on subwatersheds of the Middle Kansas River, Kansas, was designed with EPA Region 7 and Kansas Department of Health and Environment (KDHE) to evaluate BMPs (including agricultural BMPs) in a mixed land-use watershed to meet waters quality targets for local TMDLs. Results of these case studies will be made available on the WMOST website when complete.

Two ancillary utilities are being developed in conjunction with WMOST v3: a preprocessor (the Hydroprocessor) and a Scenario Comparison Tool (ScenComp), both funded with support from EPA's Safe and Sustainable Waters research program and from EPA's Air, Climate, and Energy research program. The Hydroprocessor facilitates import and formatting of model outputs from hydrological models such as HSPF and SWAT to provide runoff, recharge, and loading inputs to WMOST. The ScenComp tool facilitates comparison of outputs from multiple WMOST runs, e.g., to evaluate the implications of different climate change scenarios on optimal management actions.

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⁵ Versions 1 through 3

⁶ Version 3

⁷ Version 1

⁸ Version 2

⁹ Versions 1 and 2

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1. Background

1.1 Objective of the Tool

The Watershed Management Optimization Support Tool (WMOST) is a free and open Microsoft® Excel application designed to aid decision making in integrated water resources management. WMOST is intended to serve as an efficient and user-friendly tool for water resources managers and planners to screen a wide-range of strategies and management practices for cost-effectiveness and environmental sustainability in meeting watershed or jurisdiction management goals (Zoltay et al. 2010).

Overall, WMOST is intended to be used as a screening tool as *part* of an integrated watershed management process such as that described in EPA's watershed planning handbook (EPA 2008), to identify the strategies and practices that seem most promising for more detailed evaluation. WMOST identifies the least-cost combination of management practices to meet the user-specified management goals. Management goals may include meeting projected demand for water, in-stream target concentrations, and reducing damages associated with flooding. The tool considers a range of management practices related to water supply, water quality, wastewater, nonpotable water reuse, aquifer storage and recovery, riparian buffers, stormwater, low-impact development (LID), and land conservation, accounting for both the cost and performance of each practice. In addition, WMOST may be run with varying management strategies and goals to inform a cost-benefit analysis¹⁰ or obtain a trade-off curve. For example, running the model for a range of minimum in-stream flow standards provides data to create a trade-off curve between increasing in-stream flow and total annual management cost.

1.2 About this Document

This document provides the theoretical background for WMOST (Section 1), including the objective, conceptual framework, mathematical descriptions of the underlying objective function with cost and revenue components, model constraints associated with the mass balance for water and the loadings of water quality constituents, physical limits on watershed components and management options, variable definitions, and internal configuration. Following an overview of the base model, we describe four additional modules: 1) a combined sewer overflow (CSO) module, 2) a flood damage module, 3) a baseline hydrology and loadings module, and 4) a stormwater hydrology and loadings module. The rest of this document is organized as follows. The model's theoretical approach (i.e., equations) is described in detail in Sections 2 and 3. Readers interested in understanding the watershed system first may consider starting with Sections 2.1 and 2.2, where flow balances and water quality constituent loading balances are presented, and then reading Sections 3.2 to 3.4, which describe the management costs that constitute the objective function. Sections 4 through 7 describe the Combined Sewer Overflow, Flood-Damage, Baseline Hydrology and Loadings, and Stormwater Hydrology and Loadings modules, respectively. These modules assist users with evaluation of management options to minimize the number of combined sewer overflow events, the consideration of flood-damage costs in the optimization function, and input data acquisition and pre-processing. Section 8 describes the configuration of the software components. A series of appendices provides

¹⁰ Future versions of the model may include the option to calculate co-benefits related to the management strategies chosen by WMOST.

complementary information on common errors, parameter default values, variable definitions, and considerations for future development.

A *separate* User Guide document provides detailed direction on using WMOST and performing sensitivity and trade-off analyses. Case study applications are documented individually and are available on the WMOST website. The WMOST files for the case studies are also available and may be used as a source of default data, especially for similar watersheds and similar sized water systems.

1.3 Overview

WMOST combines an optimization framework with water resources modeling to evaluate the effects of management decisions within a watershed context. The watershed system modeled in WMOST is shown in Figure 1-1 through Figure 1-3. Figure 1-1 shows the *possible* watershed system components and *potential* water flows among them, Figure 1-2 shows the *possible* watershed system components and *potential* loadings among them, and Figure 1-3 shows the *possible* watershed system components and *potential* water flows when utilizing the Combined Sewer Overflow (CSO) Module.

The principal characteristics of WMOST include:

- Implementation in Microsoft® Excel 2010, 2013, and 2016 that is linked seamlessly with Visual Basic for Applications (VBA) and NEOS (Czyzyk et al. 1997; Dolan 2001; Gropp and More 1997), a free, online optimizer, eliminating the need for specialized software and using the familiar Excel platform for the user interface;
- User-specified inputs for characterizing the watershed, management practices, and management goals and generating a customized optimization model (see Table 1-1 for a list of available management practices and goals);
- Use of Bonmin (Bonami et al. 2008), a mixed integer nonlinear programming (MINLP) solver (freely available through NEOS), to determine the least-cost combination of practices that achieves the user-specified management goals (See Section 3.1 for details on Bonmin, MINLP optimization, and the software configuration);
- Spatially lumped calculations modeling one basin and one reach but with flexibility in the number of HRUs¹¹, each with an individual runoff and recharge rate time series;
- Modeling time step of a day or month without a limit on the length of the modeling period;¹²
- Solutions that account for both the direct and indirect effects of management practices. For example, the model will account for the fact that 1) implementing water conservation will reduce water revenue, wastewater flow and wastewater revenue if wastewater revenue is calculated based on water flow or 2) implementing infiltration-based stormwater management practices will increase aquifer recharge and baseflow for the stream reach, which can help meet minimum in-stream flow requirements during low precipitation periods, maximum in-stream flow requirements during intense precipitation seasons, and potable/nonpotable water demand;
- Ability to specify up to ten stormwater management options, including traditional, agricultural, GI, or LID practices;

¹¹ Land cover, land use, soil, slope and other land characteristics affect the fraction of precipitation that will run off, recharge and evapotranspire. Areas with similar land characteristics that respond similarly to precipitation are termed hydrologic response units.

¹² While the number of HRUs and modeling period are not limited, solution times are significantly affected by these model specifications.

- Enforcement of physical constraints, such as the conservation of mass (i.e., water), within the watershed; and
- Consideration of water flows and water quality¹³.

¹³ WMOST currently optimizes one water quality constituent at a time. Future versions of WMOST will include the ability to model multiple water quality constituents at the same time.

Figure 1-1. Schematic of Potential Water Flows and Possible Watershed Components in the WMOST

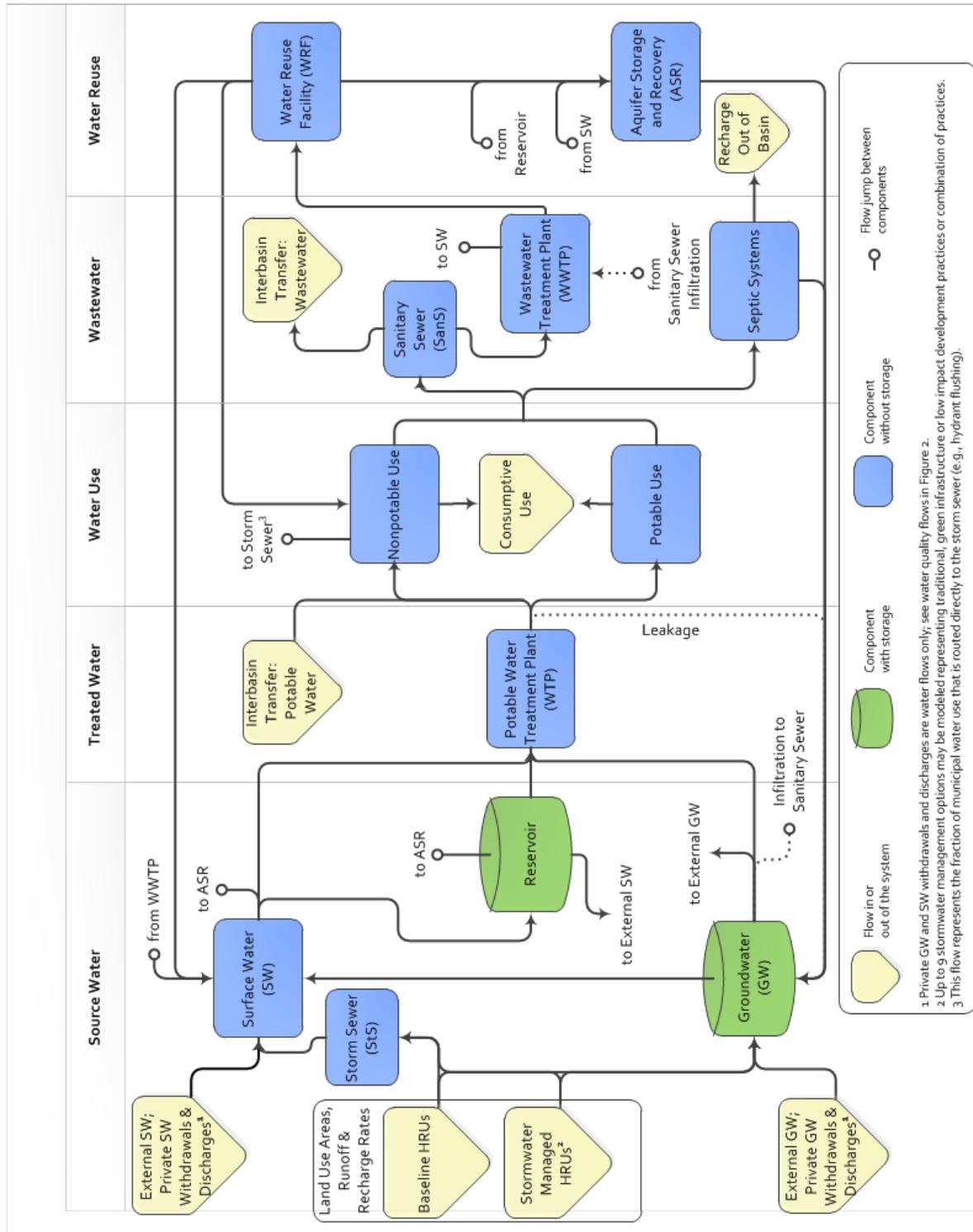


Figure 1-2. Schematic of Potential Loadings Flows and Possible Watershed Components in the WMOST

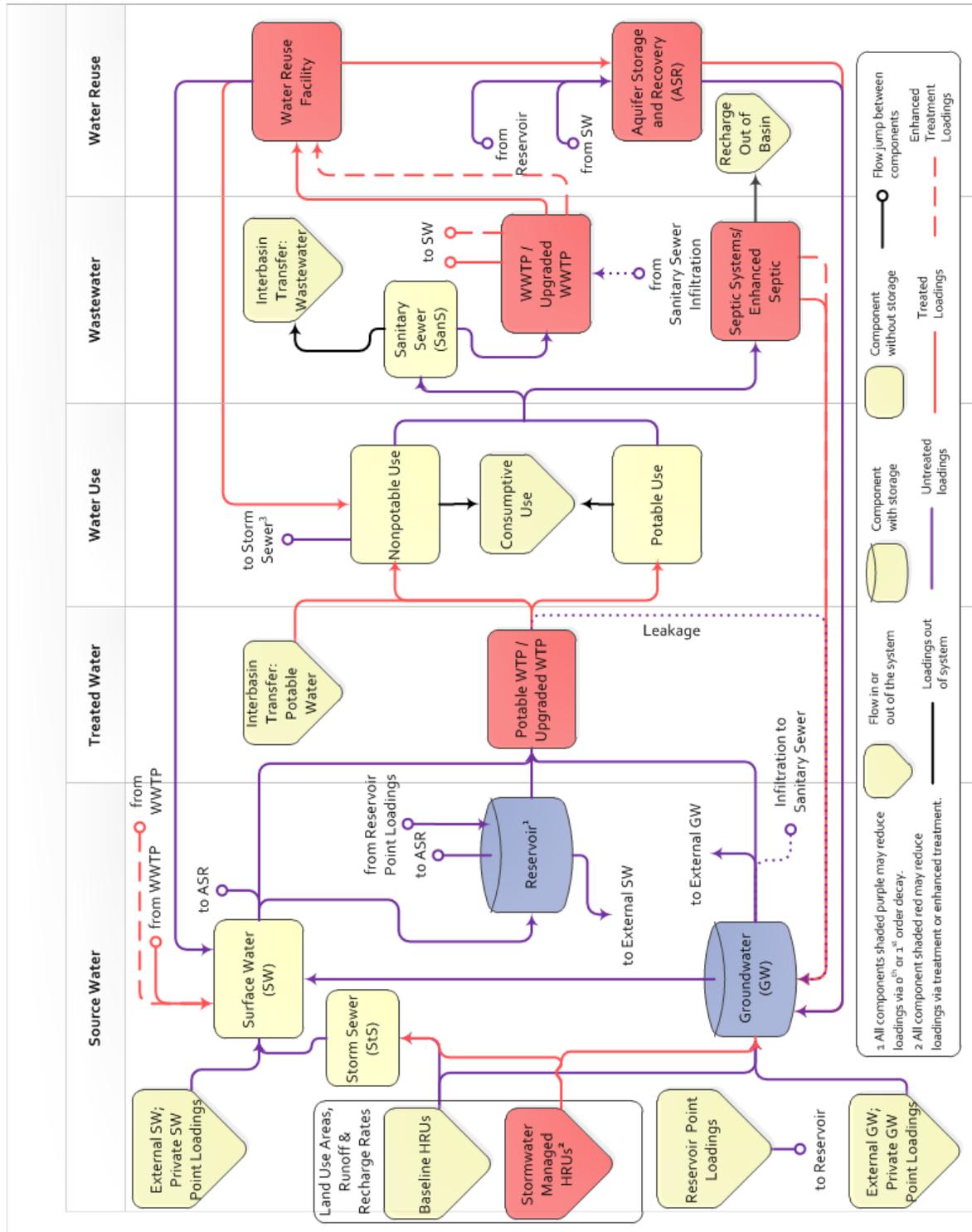


Figure 1-3. Schematic of Potential Combined Sewer Flows and Possible Watershed Components in the WMOST

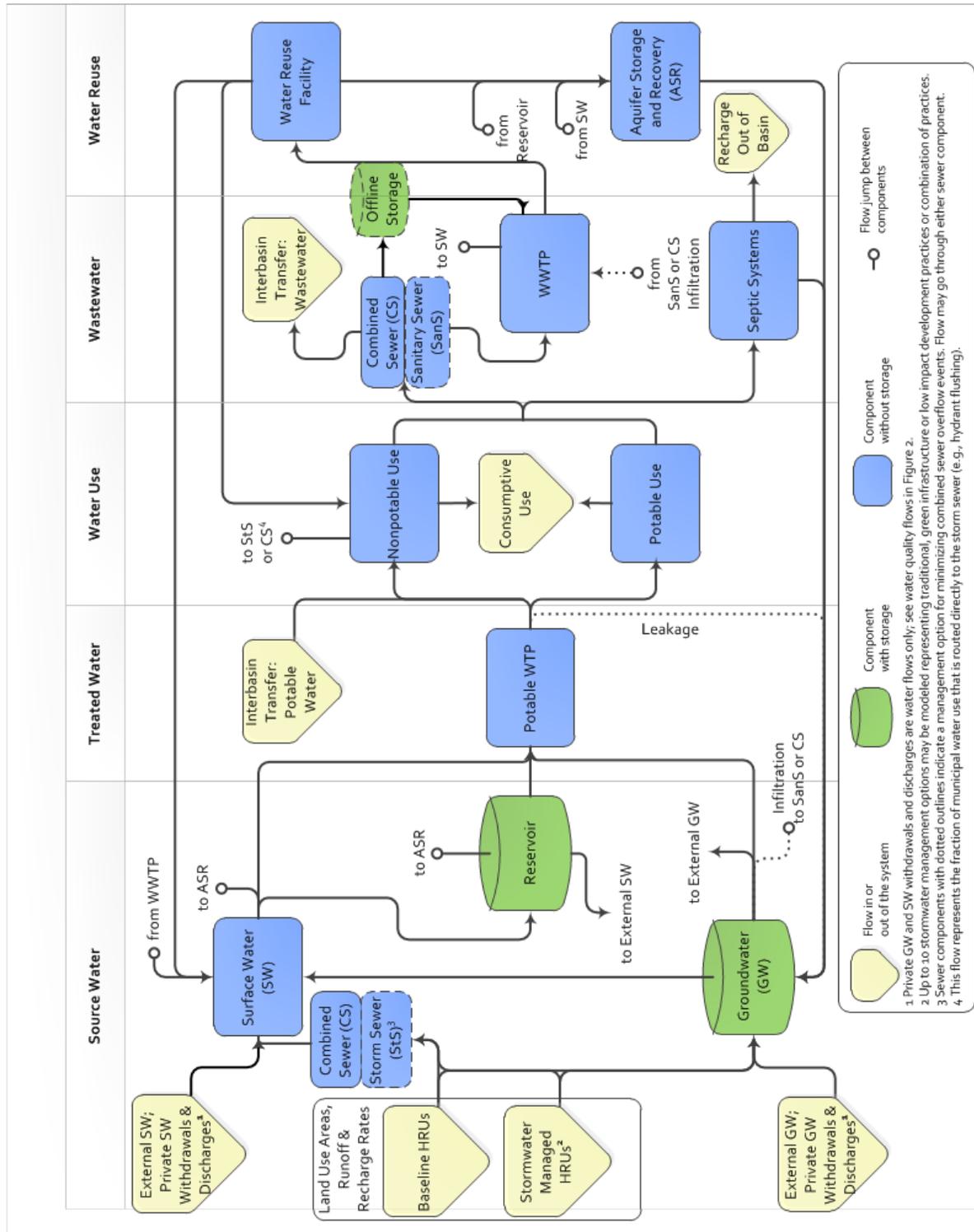


Table 1-1. Summary of Management Goals and Management Practices

Management Practice	Action	Model Component/Flow Affected	Impact
Land conservation	Maintain area of land use type specified as 'conservable'	Land area allocation	Preserve runoff and recharge quantity and quality
Stormwater management via traditional, agricultural, green infrastructure or low impact development practices	Increase area of land use type treated by specified management practice	Land area allocation	Reduce runoff; increase recharge and treatment
Agricultural stormwater runoff management via traditional and green infrastructure	Increase area of land use type treated by specified management practice	Land area allocation	Reduce runoff; increase recharge; increase treatment
Stormwater quality management via street sweeping, tree canopy over impervious/turf, urban nutrient management, or other direct reduction runoff loadings BMPs	Percent reduction of runoff loadings	Runoff loadings	Reduce runoff loadings to meet in-stream or reservoir loading targets
Riparian buffer land use management	Increase area of land use type in the riparian zone	Land area allocation and runoff loadings	Reduce runoff; reduce loadings to stream to help meet in-stream or reservoir loadings targets
Surface water storage capacity	Increase maximum storage volume	Reservoir/Surface Storage	Increase storage; reduce demand from other sources
Surface water pumping capacity	Increase maximum pumping capacity	Potable water treatment plant	Reduce quantity and/or timing of demand from other sources
Groundwater pumping capacity	Increase maximum pumping capacity	Potable water treatment plant	Reduce quantity and/or timing of demand from other sources
Change in quantity of surface versus groundwater pumping	Change in pumping time series for surface and groundwater sources	Potable water treatment plant	Change the timing of withdrawal impact on water source(s)

Table 1-1 (continued)

Management Practice	Action	Model Component/Flow Affected	Impact
Potable water treatment capacity	Increase millions gallons per day (MGD)	Potable water treatment plant	Increase treatment to standards; meet potable human demand
Potable water treatment upgrade	Increase treatment	Potable water treatment plant	Further reduce loadings from potable water treatment
Leak repair in potable distribution system	Decrease % of leaks	Potable water treatment plant	Reduce demand for water quantity
Wastewater treatment capacity	Increase MGD	Wastewater treatment plant	Maintain or improve water quality of receiving water
Wastewater treatment upgrade	Increase treatment	Wastewater treatment plant	Further reduction of loadings from wastewater treatment
Infiltration repair in wastewater collection system	Decrease % of leaks	Wastewater treatment plant	Reduce demand for wastewater treatment capacity
Water reuse facility (advanced treatment) capacity	Increase MGD	Water reuse facility	Produce water for nonpotable demand, ASR, and/or improve water quality of receiving water
Nonpotable distribution system	Increase MGD	Nonpotable water use	Reduce demand for potable water
Aquifer storage & recharge (ASR) facility capacity	Increase MGD	ASR facility	Increase recharge, treatment, and/or supply
Demand management by price increase	Increase % of price	Potable and nonpotable water and wastewater	Reduce demand
Direct demand management	Percent decrease in MGD	Potable and nonpotable water and wastewater	Reduce demand
Interbasin transfer – potable water import capacity	Increase or decrease MGD	Interbasin transfer – potable water import	Increase potable water supply or reduce reliance on out of basin sources
Interbasin transfer – wastewater export capacity	Increase or decrease MGD	Interbasin transfer – wastewater export	Reduce need for wastewater treatment plant capacity or reduce reliance on out of basin services
Enhanced septic treatment	Decrease septic average effluent concentration	Septic	Use upgraded treatment within the septic system
Sewer separation	Decrease flows through the combined sewer	Storm, sanitary, and combined sewers	Minimize combined sewer overflow events

Table 1-1 (continued)

Management Practice	Action	Model Component/Flow Affected	Impact
Streambank restoration or stabilization	Apply a loadings credit to the loadings target in the stream or reservoir	Surface water or reservoir	Meet in-stream or reservoir loading targets
Outfall enhancement or stabilization	Apply a loadings credit to the loadings target in the stream or reservoir	Surface water or reservoir	Reduce loadings to stream or reservoir to meet in-stream or reservoir loading targets
Minimum human water demand	MGD	Groundwater and surface water pumping and/or interbasin transfer	Meet human water needs
Minimum in-stream flow	ft ³ /sec	Surface water	Meet in-stream flow standards; improve ecosystem health and services; improve recreational opportunities
Maximum in-stream flow	ft ³ /sec	Surface water	Meet in-stream flow standards; improve ecosystem health and services by reducing scouring, channel and habitat degradation; decrease loss of public and private assets due to flooding
Target concentration or loadings	mg/L or lbs	Surface water or reservoir	Meet in-stream or reservoir TMDL or water quality criteria targets; improve ecosystem health and services; improve recreational opportunities

2. Watershed System

The objective to minimize costs (Section 3.2) must be met subject to constraints. There are three main categories of constraints: 1) continuity equations that enforce mass balance among watershed components, 2) physical limits on the capacity of watershed components, and 3) constraints associated with management options. This section will focus on the continuity equations that enforce mass balance of flows and loadings among watershed components.

In general, the following naming convention is followed in the constraint equations and objective function.

- The first capital letter indicates the type of quantity (e.g., Q=flow, A=area, L=loadings) except for decision variables that are preceded with the letter “b” (e.g., $bQ_{GWPumpAddl}$ =optimal additional groundwater pumping capacity).
- Primary subscripts provide additional information about the quantity by indicating
 - which component the quantity is associated with (e.g., R_{UseP} =revenue from potable water use) or
 - which components the flow travels between - the source component listed first and the receiving component listed second (e.g., $Q_{UsePWwtp}$ =flow from potable use to the wastewater treatment plant).
- Additional subscripts indicate elements of a variable. In the optimization problem, an individual variable exists for each element, but for documentation these subscripts facilitate brevity and clarity:
 - Variables that change with each time step have t subscripts. The number of variables in the optimization model equals the number of time steps for which data are provided and the model is optimized (e.g., for one year of data at a daily time step, 365 variables of that parameter exist in the mixed integer nonlinear programming model)¹⁴.
 - Additional subscripts are summarized in the table below.

Table 2-1. Summary of Subscripts Used within WMOST

Subscript	Definition	Example
u	Different water users	Residential; Commercial
l	Different HRU types	Residential/Hydrologic Soil Group: B/Slope <5%
s	“Sets” of HRU types that include the baseline HRU set and other sets that have the same HRUs but with management practices implemented	Stormwater management, including rain gardens and bioswales

¹⁴ Exceptions include the variables related to counting CSO events as the events are limited annually.

Table 2-1 (continued)

Subscript	Definition	Example
<i>c</i>	Different riparian buffer land use conversions	Residential to forest; Commercial to forest
<i>g</i>	Different relative loads groups for riparian buffer management	High; Medium; Low
<i>d</i>	Different direct reduction management sets	Street Sweeping; Urban nutrient management

All variables are defined when they are first used in the text. The units and definitions for all variables are summarized in Appendix C – Variable Definitions. Units for input variables are based on the units expected to be found in the most readily-available data sources.

2.1 Watershed Flow Balance

Land Management - Land Conservation and Stormwater Management

The user provides a time series of ‘baseline’ runoff and recharge rates (RRRs, inches/time step) for each HRU in the study area for the time period of analysis. The user may also provide multiple additional time series of RRRs for managed HRU sets. These managed RRR rates, for example, may represent the installation of bioretention basins. Recharge and runoff rates may be derived from a calibrated/validated simulation model such as Hydrological Simulation Program Fortran (HSPF),¹⁵ Soil Water and Assessment Tool (SWAT)¹⁶ and/or the Storm Water Management Model (SWMM).¹⁷

Based on the cost and benefit of land conservation and stormwater management practices, the model may choose to reallocate land area within the watershed among baseline and managed HRU sets. Based on the optimization model’s final allocation of area among baseline and managed HRU sets, the total runoff and recharge volumes in the watershed are calculated. Constraints ensure that area allocations meet physical limits and, as specified by the user, policy requirements.

During the reallocation, the total land area must be preserved¹⁸ according to the following equalities. These equalities show that managed HRU sets are mutually exclusive; that is, one acre of land may only be placed under one of the managed HRU sets.

$$\sum_{l=1 \text{ to } NLu} A_{l,s=1} = \sum_{l=1 \text{ to } NLu} bA_{l,s=1} = \sum_{s=2 \text{ to } NLuSet} \sum_{l=1 \text{ to } NLu} bA_{l,s} \quad (1)$$

¹⁵ <http://water.usgs.gov/software/HSPF/>

¹⁶ <http://swat.tamu.edu/>

¹⁷ <https://www.epa.gov/water-research/storm-water-management-model-swmm>

¹⁸ Due to the precision of optimization calculations, this constraint is represented in the code as an inequality with tight bounds as opposed to an equality constraint.

where

$A_{l,s=1}$	=	user specified HRU areas for each HRU, l , for HRU set 1, $s=1$, acres
$bA_{l,s=1}$	=	baseline HRU areas after reallocation for conservation, acres
l	=	HRU index, 1 to NLu
s	=	HRU set number
NLu	=	number of HRU types
$bA_{l,s}$	=	area allocated to ‘managed’ HRU in set s , acres
$NLuSet$	=	number of HRU sets

In addition, the minimum and maximum areas with respect to conservation must be met, if specified by the user:

$$bA_{l,s} \geq A_{Min,l,s} \quad \text{for } l = 1 \text{ to } NLu \text{ and } s = 1 \quad (2)$$

where

$A_{Min,l,s}$	=	minimum area possible for baseline HRUs, acres
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$$bA_{l,s} \leq A_{Max,l,s} \quad \text{for } l = 1 \text{ to } NLu \text{ and } s = 1 \quad (3)$$

where

$A_{Max,l,s}$	=	maximum area possible for baseline HRUs, acres
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If land can be conserved (e.g., forest area), then the minimum (e.g., amount already in land trust) and maximum (e.g., amount existing or potentially allowed to regrow) can be specified along with the corresponding costs. If an HRU can be reduced in exchange for conserving another land use, the minimum and maximum areas for the HRU may be entered. If an HRU cannot be decreased or increased as part of land conservation, the user may enter the same value for baseline, minimum, and maximum areas under baseline HRU set specifications.

The following additional constraints are added to ensure that HRUs that can be conserved only increase in area and others only decrease in area. The user indicates which HRUs can be conserved by indicating the cost for conservation. The user indicates which HRUs can be decreased to accommodate conservation by entering -9 for costs.

$$\text{where } C_{C,l,s} <> -9, \quad bA_{l,s=1} - A_{l,s=1} \geq 0 \quad (4)$$

$$\text{else,} \quad bA_{l,s=1} - A_{l,s=1} \leq 0 \quad (5)$$

where

$C_{C,l,s}$	=	capital cost associated with land reallocation for each HRU in each set (e.g., purchasing forest land or bioretention basin), \$/acre
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When allocating land area from the baseline to the managed condition for any of the land uses, the area allocated to a managed land use cannot be greater than the area allocated to the corresponding baseline land use chosen under conservation, $bA_{l,s=1}$ (e.g., users can not choose to implement stormwater management on more urban land area than the urban area decided upon by the model). In addition, only one land management practice may be implemented on any given area; therefore, land management practices are mutually exclusive. However, one “management practice” may represent the implementation of multiple GI practices to meet a specific stormwater standard.

$$\sum_{s=2}^{NLuSet} bA_{l,s} \leq bA_{l,s=1} \text{ for each } l \quad (6)$$

In addition, user specified minimum and maximum areas are used to constrain the amount of land that may be placed under each management condition, i.e., each set, s . For example, there may be technical or policy requirements that can be represented with these limits.

$$bA_{l,s} \geq A_{Min,l,s} \quad \text{for } l = 1 \text{ to } NLu \text{ and } s = 2 \text{ to } NLuSet \quad (7)$$

where

$$A_{Min,l,s} = \text{minimum area possible for management for baseline HRU } l \text{ and management set } s,$$

$$bA_{l,s} \leq A_{Max,l,s} \quad \text{for } l = 1 \text{ to } NLu \text{ and } s = 2 \text{ to } NLuSet \quad (8)$$

where

$$A_{Max,l,s} = \text{maximum area possible for management for baseline HRU } l \text{ and management set } s,$$

The total runoff ($Q_{Ru,t}$) and recharge ($Q_{Re,t}$) for each time step are calculated based on the final area allocations for all HRUs and HRU sets.

$$Q_{Ru,t} = \sum_{l=1}^{NLu} (bA_{l,s=1} \times Q_{Ru,l,s=1,t}) + \sum_{s=2}^{NLuSet} \sum_{l=1}^{NLu} ((Q_{Ru,l,s,t} - Q_{Ru,l,s=1,t}) \times bA_{l,s}) \quad (9)$$

where

$$\begin{aligned} Q_{Ru,t} &= \text{total runoff from all land areas, MG/time step} \\ Q_{Ru,l,s,t} &= \text{runoff rate}^{19} \text{ from HRU } l \text{ in HRU set } s \text{ for time step } t, \text{ MG/time step} \end{aligned}$$

$$Q_{Re,t} = \sum_{l=1}^{NLu} (bA_{l,s=1} \times Q_{Re,l,s=1,t}) + \sum_{s=2}^{NLuSet} \sum_{l=1}^{NLu} ((Q_{Re,l,s,t} - Q_{Re,l,s=1,t}) \times bA_{l,s}) \quad (10)$$

where

¹⁹ RRRs may be derived from simulation models such as Soil Water Assessment Tool, Hydrological Simulation Program-Fortran or Storm Water Management Model

$$\begin{aligned}
 Q_{Re,t} &= \text{total recharge from all land areas, MG/time step} \\
 Q_{Re,l,s,t} &= \text{recharge rate}^{19} \text{ from HRU } l \text{ in HRU set } s \text{ for time step } t, \text{ MG/time step}
 \end{aligned}$$

Groundwater (Gw)

The groundwater system, or aquifer, has storage. It may receive inflow from natural infiltration and recharge, groundwater from outside of the watershed, point sources, leakage from the treated water distribution system, recharge from the aquifer storage and recovery (ASR) facility, septic systems, and make-up water (see Section 3.3 regarding make-up water). Outflow from the groundwater system may discharge to surface water via baseflow, be withdrawn by the potable water treatment plant or community or private use via groundwater wells, infiltrate into the wastewater collection system, and discharge to a groundwater system outside of the watershed or deep into the basin.

For $t=1$,

$$\begin{aligned}
 V_{Gw,1} = V_{Gw,1} + (Q_{Re,t} + Q_{ExtGw,t} + Q_{PtGw,t} + Q_{WtpGw,t} + Q_{AsrGw,t} + Q_{SepGw,t} + bQ_{GwMake,t} - \\
 Q_{GwSw,t} - bQ_{GwWtp,t} - Q_{GwWwtp,t} - bQ_{GwExt,t} - Q_{GwPt,t}) \times \Delta t
 \end{aligned} \quad (11)$$

For all other t ,

$$\begin{aligned}
 V_{Gw,t} = V_{Gw,t-1} + (Q_{Re,t} + Q_{ExtGw,t} + Q_{PtGw,t} + Q_{WtpGw,t} + Q_{AsrGw,t} + Q_{SepGw,t} + bQ_{GwMake,t} - \\
 Q_{GwSw,t} - bQ_{GwWtp,t} - Q_{GwWwtp,t} - bQ_{GwExt,t} - Q_{GwPt,t}) \times \Delta t
 \end{aligned} \quad (12)$$

where

$$\begin{aligned}
 V_{Gw,1} &= \text{initial volume of groundwater, MG} \\
 V_{Gw,t} &= \text{volume of groundwater at time } t, \text{ MG} \\
 Q_{ExtGw,t} &= \text{inflow of external groundwater, MG/time step} \\
 Q_{PtGw,t} &= \text{private (point) groundwater discharges, MG/time step} \\
 Q_{WtpGw,t} &= \text{leakage from treated water distribution system, MG/time step} \\
 Q_{AsrGw,t} &= \text{recharge from ASR facility to groundwater, MG/time step} \\
 Q_{SepGw,t} &= \text{inflow from septic system, MG/time step} \\
 bQ_{GwMake,t} &= \text{flow of groundwater “make-up water” into the system, MG/time step} \\
 Q_{GwSw,t} &= \text{baseflow, MG/time step} \\
 bQ_{GwWtp,t} &= \text{withdrawal by water treatment plant, MG/time step} \\
 Q_{GwWwtp,t} &= \text{infiltration into wastewater collection system, MG/time step} \\
 bQ_{GwExt,t} &= \text{groundwater leaving the basin, MG/time step} \\
 Q_{GwPt,t} &= \text{private (point) groundwater withdrawals, MG/time step}
 \end{aligned}$$

Two variables are further defined. The unaccounted-for water leakage from the treated water distribution system is defined as:

$$Q_{WtpGw,t} = Q_{Use1,u=1,t} \times (1 - \frac{bP_{WtpLeakFix}}{100}) \quad (13)$$

where

$$\begin{aligned}
 Q_{WtpGw,t} &= \text{unaccounted-for water flow from treated water distribution system to groundwater,} \\
 &\text{MG/time step} \\
 Q_{Use1,u=1,t} &= \text{initial, unaccounted-for water flow, MG/time step}
 \end{aligned}$$

$bP_{WtpLeakFix}$ = percent of treated water distribution system leakage that is fixed, %

The model assumes that unaccounted-for water infiltrates completely into the groundwater table via leaks in the distribution system.

The contribution of groundwater baseflow to the stream is defined as:

$$Q_{GWSw,t} = k_b \cdot V_{Gw,t-1} \quad (14)$$

k_b = groundwater recession coefficient

Storm Sewer (StS)

The storm sewer receives flows from runoff and municipal water uses including fire hydrant usage and flushing. If the watershed does not include municipal water users that have flows that go directly to the storm sewer, then the storm sewer will only receive flows from runoff. Additionally, if the watershed does not have a storm sewer system, WMOST users can enter -9 for the storm sewer capacity.

$$Q_{StSSw,t} = Q_{UseNpSewer,t} + Q_{Ru,t} \quad (15)$$

$$Q_{StSSw,t} \leq Q_{StSMax} \quad (16)$$

where

$Q_{StSSw,t}$ = flow from storm sewer system to surface water, MG/time step

$Q_{UseNpStS,t}$ = municipal water use flow that goes directly to the storm sewer, MG/time step

Q_{StSMax} = storm sewer capacity, MG

Surface Water (Sw)

The surface water, or stream reach component, does not have storage, that is, it is assumed to completely empty with each time step. To model surface water storage such as lakes, ponds or storage tanks, see the reservoir section below. Wetlands should be modeled as an HRU but may also be modeled as part of surface storage if the user can control wetland releases as described in the next section below.

The surface water component may receive inflow from runoff through the storm sewer, external surface water sources (i.e., an upstream reach), point sources, wastewater treatment plant (WWTP), groundwater baseflow, and a water reuse facility (WRF). Flow from surface water may discharge downstream to a reservoir, be withdrawn by the potable water treatment plant, and be withdrawn by the ASR facility. Surface water only exits the watershed after passing through the reservoir. A reservoir with zero storage may be specified.

$$\begin{aligned} Q_{StSSw,t} + Q_{ExtSw,t} + Q_{PtSw,t} + Q_{GWSw,t} + Q_{WwtpSw,t} + Q_{WrfSw,t} \\ = Q_{SwRes,t} + bQ_{SwWtp,t} + bQ_{SwAsr,t} + Q_{SwPt,t} \end{aligned} \quad (17)$$

where

$Q_{ExtSw,t}$	=	surface water inflow from outside of basin, MG/time step
$Q_{PtSw,t}$	=	discharge from surface water point sources, MG/time step
$Q_{WwtpSw,t}$	=	discharge from primary wastewater treatment plant, MG/time step
Q_{WrfSw}	=	discharge from water reuse facility (advanced treatment), MG/time step
$Q_{SwRes,t}$	=	flow from surface water to reservoir, MG/time step
$bQ_{SwWtp,t}$	=	flow to water treatment plant, MG/time step
$bQ_{SwASr,t}$	=	flow to ASR facility, MG/time step
$Q_{SwPt,t}$	=	private surface water withdrawals, MG/time step

Reservoir (Res)/Surface Water Storage

The reservoir may represent a surface water reservoir, flood control structure, off-stream storage in tanks, and/or ponds. The reservoir component has storage. It may receive inflow from the surface water or stream reach, private (i.e., non-municipal) surface discharge and make-up water (see Section 3.3 regarding make-up water). Water may flow to a downstream reach outside of the basin, potable water treatment plant, and ASR facility. This routing of flows assumes that the reservoir is at the downstream border of the study area and it does not receive flows from the groundwater system. Reservoir storage may be increased (see Section 3.3).²⁰

For $t=1$,

$$V_{Res,t} = V_{Res,I} + (Q_{SwRes,t} - bQ_{SwExt,t} - bQ_{ResWtp,t} - bQ_{ResASr,t} + bQ_{WMake,t} - Q_{ResPt,t} + Q_{PtRes,t}) \times \Delta t \quad (18)$$

For all other t ,

$$V_{Res,t} = V_{Res,t-1} + (Q_{SwRes,t} - bQ_{SwExt,t} - bQ_{ResWtp,t} - bQ_{ResASr,t} + bQ_{WMake,t} - Q_{ResPt,t} + Q_{PtRes,t}) \times \Delta t \quad (19)$$

where

$V_{Res,I}$	=	initial volume of reservoir, MG
$V_{Res,t}$	=	volume of reservoir at time t, MG
$Q_{SwRes,t}$	=	inflow to reservoir from surface water bodies, MG/time step
$bQ_{SwExt,t}$	=	flow to surface water bodies outside of basin; based on user input, this variable may be a decision variable or a user-specified time series, MG/time step
$bQ_{ResWtp,t}$	=	flow to water treatment plant, MG/time step
$bQ_{ResASr,t}$	=	flow to ASR facility, MG/time step
$bQ_{WMake,t}$	=	make-up water, MG/time step
$Q_{ResPt,t}$	=	direct, private withdrawal from reservoir, MG/time step
$Q_{PtRes,t}$	=	direct, private discharge to reservoir, MG/time step

²⁰ Future versions of the model may include the option for flow routing that assumes the reservoir is at the upstream end of the modeled reach segment and models separate off-stream surface storage to represent lakes, ponds and storage tanks.

Water Treatment Plant (Wtp)

The water treatment plant treats water to potable standards. It may receive flow from the reservoir, surface water reach or groundwater aquifer. Water from the plant may be used to meet potable and nonpotable water use demand. In addition, some water is lost to the groundwater through leaks in the treated water distribution system.

$$bQ_{ResWtp,t} + bQ_{SwWtp,t} + bQ_{GwWtp,t} = Q_{WtpUseP,t} + bQ_{WtpUseNp,t} + Q_{WtpGw,t} \quad (20)$$

where

- $Q_{WtpUseP,t}$ = flow from primary WTP to potable water use, MG/time step
 $bQ_{WtpUseNp,t}$ = flow from primary WTP to nonpotable water use, MG/time step

Potable Water Use (UseP)

A water utility may serve residential, commercial, industrial, institutional, and/or agricultural customers. These customers receive flows from the water treatment plant and interbasin transfer. Flows from the different potable water users can go to septic systems draining inside and outside of the drainage area, to the wastewater treatment plant, and out of the drainage basin via interbasin transfer.

$$\sum_{u=2 \text{ to } NUse} ((Q_{WtpUseP,t} + bQ_{IbtWUseP,t}) \times \left(1 - \frac{P_{ConsUseP,u,t}}{100}\right) \times Fr_{PUse,u,t}) = bQ_{UsePSanS,t} + Q_{UsePSep,t} + Q_{UsePSepExt,t} + bQ_{UsePIbtWw,t} \quad (21)$$

where

- u = water user
 $bQ_{IbtWUseP,t}$ = inflow of potable water to water treatment facility via interbasin transfer, MG/time step
 $P_{ConsUseP,u,t}$ = final percent consumptive use for potable water use, %
 $Fr_{PUse,u,t}$ = fraction of potable water use per time step per user type
 $bQ_{UsePSanS,t}$ = flow of potable water through the sanitary sewer to the wastewater treatment plant, MG/time step
 $Q_{UsePSep,t}$ = flow to septic systems within the study area, MG/time step
 $Q_{UsePSepExt,t}$ = flow to septic systems outside the study area, MG/time step
 $bQ_{UsePIbtWw,t}$ = wastewater flow from potable uses to interbasin transfer wastewater services, MG/time step

Consumptive water use

The final percent consumptive use for potable water use, $P_{ConsUseP,u,t}$, is calculated based on the initial percent consumptive use of potable water, $P_{ConsUsePI,u,t}$, maximum percent of potable demand that may be met by nonpotable water $P_{UseNpMax,u}$, and the percent consumptive use of nonpotable water, $P_{ConsUseNp,u,t}$. This adjustment is necessary because nonpotable use may significantly differ from potable water use in its consumptive percentage. For example, non-potable use may be all consumptive such as outdoor watering or agricultural irrigation or almost all non-consumptive such as toilet flushing. Depending on the intended use of the non-potable water, the user can specify the appropriate percent consumptive use. We make the assumption that outdoor water use (e.g., watering

lawns) is fully consumptive via evapotranspiration; therefore, it does not enter the groundwater or, in the case of overwatering, the storm sewer system.

$$P_{ConsUseP,u,t} = \frac{P_{ConsUsePI,u,t} - P_{UseNpMax,u,t} \times P_{ConsUseNp,u,t}}{100 - P_{UseNpMax,u}} \quad (22)$$

Nonpotable Water Use (UseNp)

A water utility may serve residential, commercial, industrial, institutional, and/or agricultural customers. These customers receive flows from the water treatment plant, water reuse facility, and interbasin transfer. Flows from the different potable water users can go to septic systems draining inside and outside of the drainage area, to the wastewater treatment plant, and out of the drainage basin via interbasin transfer.

$$\sum_{u=2 \text{ to } NUse} ((bQ_{WtpUseNp,t} + bQ_{WrfUseNp,t} + bQ_{IbtWUseNp,t}) \times \left(1 - \frac{P_{ConsUseNp,u,t}}{100}\right) \times Fr_{NpUse,u,t}) \quad (23)$$

$$= bQ_{UseNpSanS,t} + Q_{UseNpSep,t} + Q_{UseNpSepExt,t} + bQ_{UseNpIbtWw,t}$$

where

- $bQ_{WrfUseNp,t}$ = inflow of nonpotable water from water reuse facility, MG/time step
- $bQ_{IbtWUseNp,t}$ = inflow of nonpotable water to water treatment facility via interbasin transfer, MG/time step
- $Fr_{NpUse,u,t}$ = fraction of nonpotable water use per time step per user type
- $bQ_{UseNpSanS,t}$ = flow of nonpotable water through the sanitary sewer to the wastewater treatment plant, MG/time step
- $Q_{UseNpSep,t}$ = flow to septic systems within the study area, MG/time step
- $Q_{UseNpSepExt,t}$ = flow to septic systems outside the study area, MG/time step
- $bQ_{UseNpIbtWw,t}$ = flow of nonpotable water to wastewater collection system via interbasin transfer, MG/time step

If the watershed has municipal water users that send flows directly to the sewer system, the equations are as follows:

$$Q_{UseNpSewer,t} = (bQ_{WtpUseNp,t} + bQ_{WrfUseNp,t} + bQ_{IbtWUseNp,t}) \times \left(1 - \frac{P_{ConsUseNp,Municipal,t}}{100}\right) \quad (24)$$

$$\times Fr_{NpUse,Municipal,t} \times Fr_{NpUseMunSewer,t}$$

$$\sum_{u=2 \text{ to } NUse} (bQ_{WtpUseNp,t} + bQ_{WrfUseNp,t} + bQ_{IbtWUseNp,t}) \times \left(1 - \frac{P_{ConsUseNp,Municipal,t}}{100}\right) \quad (25)$$

$$\times Fr_{NpUse,Municipal,t} \times (1 - Fr_{NpUseMunSewer,t})$$

$$= bQ_{UseNpSanS,t} + Q_{UseNpSep,t} + Q_{UseNpSepExt,t} + bQ_{UseNpIbtWw,t}$$

where

- $Fr_{NpUseMunSewer,t}$ = fraction of municipal water flows that go directly to the storm sewer, %

The following equations define the minimum demand for potable and nonpotable use.

For each water user (u),

$$Q_{UseP,u,t} = \left(1 - \frac{P_{UseNpMax,u,t}}{100}\right) \times (Q_{UseI,u,t} + Q_{UseI,u,t} \times \text{ElasPrice}_u \times \frac{bPprice}{100} - bQ_{Dm} \times Fr_{PUse,u,t}) \quad (26)$$

$$Q_{WtpUseP,t} + bQ_{IbtWUseP,t} \geq \sum_{u=2 \text{ to } NUse} Q_{UseP,u,t} \quad (27)$$

$$Q_{UseNp,u,t} = \left(\frac{P_{UseNpMax,u,t}}{100}\right) \times (Q_{UseI,u,t} + Q_{UseI,u,t} \times \text{ElasPrice}_u \times \frac{bPprice}{100} - bQ_{Dm} \times Fr_{NpUse,u,t}) \quad (28)$$

$$bQ_{WtpUseNp,t} + bQ_{WrfUseNp,t} + bQ_{IbtWUseNp,t} \geq \sum_{u=2 \text{ to } NUse} Q_{UseNp,u,t} \quad (29)$$

where

- $Q_{UseI,u,t}$ = initial specified water use, MG/time step
- ElasPrice_u = price elasticity by water user, %
- $bPprice$ = percent change in price, %
- $bQ_{Dm,u}$ = model selected amount of demand reduction per water user, MG/time step
- $Q_{UseP,u,t}$ = potable water demand by water user, MG/time step
- $Q_{UseNp,u,t}$ = nonpotable water demand by water user, MG/time step

Wastewater Treatment Plant (Wwtp) and Sanitary Sewer (SanS)

The wastewater treatment plant receives flows from potable and nonpotable water users through the sanitary sewer as well as infiltration into the wastewater collection system. The flows from the wastewater treatment plant either drain into the surface water system²¹ or receive additional treatment at the water reuse facility.

$$bQ_{UsePSanS,t} + bQ_{UseNpSanS,t} + Q_{GwWwtp,t} = Q_{WwtpSw,t} + bQ_{WwtpWrf,t} \quad (30)$$

where

- $bQ_{WwtpWrf}$ = outflow to water reuse facility from primary WWTP, MG/time step

One variable, infiltration into the wastewater collection system, is further defined as:

²¹ Currently, direct discharges from the WWTP into the reservoir cannot be modeled. However, the reservoir is assumed to be at the downstream border of the drainage area and is, therefore, receiving all flows from the surface water system.

$$\begin{aligned}
 Q_{GwWwtp,t} &= \left(1 - \frac{bP_{WwtpLeakFix}}{100}\right) \times \frac{P_{WwtpLeakI}}{100} \\
 &\times \frac{\sum_{u=2}^{NWuser} Q_{UseI,u,t} \times \left(1 - \frac{P_{ConsUseP,u,t}}{100}\right) \times \left(1 - \frac{P_{ConsUseNp,u,t}}{100}\right) \times \left(1 - \frac{P_{Sep,u} + P_{SepExt,u}}{100}\right)}{\left(1 - \frac{P_{WwtpLeakI}}{100}\right)} \quad (31)
 \end{aligned}$$

where

- $P_{WwtpLeakI}$ = leakage of groundwater into the wastewater collection system, as a percent of wastewater treatment plant inflow that represents I&I, %
- $bP_{WwtpLeakFix}$ = percent of leaks fixed in the wastewater collection system, %
- $P_{Sep,u}$ = percent of users serviced by septic systems recharging inside the study area, %
- $P_{SepExt,u}$ = percent of users serviced by septic systems draining outside the study area, %

Water Reuse Facility (Wrf)

The water reuse facility receives flows from the wastewater treatment plant. After treatment, flows from the water reuse facility drain to the surface water system, are used to meet nonpotable water use demand, or flow to the aquifer storage and recovery facility.

$$bQ_{WwtpWrf,t} = bQ_{WrfUseNp,t} + bQ_{WrfAsr,t} + Q_{WrfSw,t} \quad (32)$$

where

- $bQ_{WrfAsr,t}$ = flow from the water reuse facility to the ASR facility, MG/time step

Septic Systems (Sep)

Consumptive use and demand management affect the amount of wastewater that will flow to septic systems. Septic systems may drain inside the area of analysis or outside; therefore, the user should specify the percent of septic systems draining within and outside of the area of analysis.

Flows to septic systems within the study area are calculated as:

$$Q_{UsePsep,t} = \sum_{u=2 \text{ to } NUse} \left[\left(1 - \frac{P_{ConsUseP,u,t}}{100}\right) \times \frac{P_{Sep,u}}{100} \times Q_{UseP,u,t} \right] \quad (33)$$

$$Q_{UseNpsep,t} = \sum_{u=2 \text{ to } NUse} \left[\left(1 - \frac{P_{ConsUseNp,u,t}}{100}\right) \times \frac{P_{Sep,u}}{100} \times Q_{UseNp,u,t} \right] \quad (34)$$

Consumptive use is assumed to exit the watershed system (e.g., does not runoff or percolate).

Flows to septic systems outside the study area from potable and nonpotable water uses are calculated as:

$$Q_{UseP Sep Ext,t} = \sum_{u=2 \text{ to } NUse} \left[\left(1 - \frac{P_{ConsUseP,u,t}}{100} \right) \times \frac{P_{SepExt,u}}{100} \times Q_{UseP,u,t} \right] \quad (35)$$

$$Q_{UseNp Sep Ext,t} = \sum_{u=2 \text{ to } NUse} \left[\left(1 - \frac{P_{ConsUseNp,u,t}}{100} \right) \times \frac{P_{SepExt,u}}{100} \times Q_{UseNp,u,t} \right] \quad (36)$$

Septic flows entering the groundwater system:

$$Q_{UseP Sep,t} + Q_{UseNp Sep,t} = Q_{SepGw,t} \quad (37)$$

Aquifer Storage and Recovery Facility (Asr):

The Asr facility receives flows from surface water, the reservoir, and the water reuse facility. The user has the option to include treatment at the Asr facility. Flows from the Asr facility go into the groundwater system regardless of treatment.

$$bQ_{SwAsr,t} + bQ_{ResAsr,t} + bQ_{WrfAsr,t} = Q_{AsrGw,t} \quad (38)$$

2.2 Watershed Constituent Loadings Balance

The user has the option to use WMOST to optimize costs based on hydrology (i.e., water quantity) only, or both hydrology and loadings of a single water quality constituent²² (i.e., both water *quantity* and water *quality*). When modeling based on hydrology and loadings, constituent mass balances are calculated for each watershed component and users can specify maximum loading and concentration limits on the surface water system and reservoir.

The units for loadings and concentrations are consistent with what is requested on the WMOST interface, (lbs/time step for loadings and mg/L for concentrations). Conversions are made internally in order to reconcile the two systems of units.

Land Management - Land Conservation and Stormwater Management

As mentioned in Section 2.1, land area in the watershed can be reallocated among baseline and managed HRU sets. The total runoff and recharge loadings in the watershed are calculated based on the optimization model's final allocation of area among HRUs. Constraints ensure that area allocations meet physical limits and, as specified by the user, policy requirements.

The total runoff loadings ($L_{Ru,t}$) and recharge loadings ($L_{Re,t}$) for each time step are calculated based on the final area allocations for all HRUs and HRU sets.

$$L_{Ru,t} = \sum_{l=1}^{Nlu} (bA_{l,s=1} \times L_{Ru,l,s=1,t}) + \sum_{s=2}^{NluSet} \sum_{l=1}^{Nlu} ((L_{Ru,l,s,t} - L_{Ru,l,s=1,t}) \times bA_{l,s}) \quad (39)$$

²² Future versions of WMOST will include the ability to model multiple water quality constituents at the same time.

where

$L_{Ru,l,s,t}$ = runoff loadings from HRU l in HRU set s for time step t , lbs/time step
 $L_{Ru,t}$ = loadings from runoff from all land areas, lbs/time step

$$L_{Re,t} = \sum_{l=1}^{NLu} (bA_{l,s=1} \times L_{Re,l,s=1,t}) + \sum_{s=2}^{NLuSet} \sum_{l=1}^{NLu} ((L_{Re,l,s,t} - L_{Re,l,s=1,t}) \times bA_{l,s}) \quad (40)$$

where

$L_{Re,l,s,t}$ = recharge loadings from HRU l in HRU set s for time step t , lbs/time step
 $L_{Re,t}$ = loadings from recharge from all land areas, lbs/time step

Groundwater (Gw)

The groundwater system, or aquifer, has storage. It may receive constituent loadings from recharge, groundwater from outside of the watershed, point sources, leakage from the treated water distribution system, recharge from the ASR facility, and septic systems.²³ Loadings from the groundwater system may discharge to surface water via baseflow, be withdrawn by the potable water treatment plant via groundwater wells or by other users via private wells, infiltrate into the wastewater collection system, and discharge to a groundwater system outside of the basin.

For $t=1$,

$$L_{Gw,t} = (X_{Gw,1} \times V_{Gw,1}) + L_{Re,t} + L_{ExtGw,t} + L_{PtGw,t} + L_{AsrGw,t} + L_{SepGw,t} + L_{WtpGw} - L_{GwSw,t} - L_{GwPt,t} - L_{GwWtp,t} - L_{GwWwtp,t} - L_{GwExt,t} \quad (41)$$

For all other t ,

$$L_{Gw,t} = L_{Gw,t-1} + L_{Re,t} + L_{ExtGw,t} + L_{PtGw,t} + L_{AsrGw,t} + L_{SepGw,t} + L_{WtpGw,t} - L_{GwSw,t} - L_{GwPt,t} - L_{GwWtp,t} - L_{GwWwtp,t} - L_{GwExt,t} \quad (42)$$

where

$L_{Gw,t}$ = loadings within the groundwater system, lbs/time step
 $X_{Gw,1}$ = initial constituent concentration of groundwater, mg/L
 $L_{ExtGw,t}$ = loadings from external groundwater, lbs/time step
 $L_{PtGw,t}$ = loadings from private groundwater discharges lbs/time step
 $L_{AsrGw,t}$ = loadings from ASR facility to groundwater, lbs/time step
 $L_{SepGw,t}$ = loadings from septic system, lbs/time step
 $L_{WtpGw,t}$ = loadings from leakage of treated water distribution system from WTP, lbs/time step
 $L_{GwSw,t}$ = baseflow loadings, lbs/time step
 $L_{GwPt,t}$ = private groundwater withdrawal loadings, lbs/time step

²³ WMOST does not associate loadings to the volume of make-up water. Accordingly, there is no loading added to groundwater from any make-up water flows necessary to meet system constraints. This allows make-up water to be used as a last resort to meet volumetric or water quality targets, providing users indication that the specified constraints cannot be met using the available resources or management options (see Section 3.3 regarding Make-up Water).

$L_{GwWtp,t}$	=	loadings from withdrawal by water treatment plant lbs/time step
$L_{GwWwtp,t}$	=	loadings from infiltration into wastewater collection system, lbs/time step
$L_{GwExt,t}$	=	loadings from groundwater leaving the basin, lbs/time step

Some constituents attenuate as they flow through surface waters, the subsurface, and reservoirs or lakes. For example, in a groundwater system, denitrification processes can reduce the total load of nitrogen in baseflow. The user has the ability to specify a zero order removal rate, a first order removal rate, or no removal for each constituent to represent denitrification or other removal processes.

If a zero-order removal rate is specified,

$$X_{GwF,t} = \left(\frac{L_{Gw,t}}{V_{Gw,t}} \right) - k_{Gw,0} \times \Delta t \quad (43)$$

where

$k_{Gw,0}$	=	zero-order removal rate, mg/L/time step
$X_{GwF,t}$	=	final groundwater concentration after removal (if applicable), mg/L

If a first-order removal rate is specified,

$$X_{GwF,t} = \frac{L_{Gw,t} \times e^{-k_{Gw,1} \times \Delta t}}{V_{Gw,t}} \quad (44)$$

where

$k_{Gw,1}$	=	first-order removal rate, 1/time step
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If no removal is specified,

$$X_{GwF,t} = \frac{L_{Gw,t}}{V_{Gw,t}} \quad (45)$$

Loadings leaving the groundwater system are based on the concentration of the water quality constituent after removal has occurred and flow determined by the model.

$$L_{GwSw,t} = Q_{GwSw,t} \times X_{GwF,t} \quad (46)$$

$$L_{GwPt,t} = Q_{GwPt,t} \times X_{GwF,t} \quad (47)$$

$$L_{GwWtp,t} = bQ_{GwWtp,t} \times X_{GwF,t} \quad (48)$$

$$L_{GwWwtp,t} = Q_{GwWwtp,t} \times X_{GwF,t} \quad (49)$$

$$L_{GwExt,t} = bQ_{GwExt,t} \times X_{GwF,t} \quad (50)$$

Storm Sewer (StS)

The storm sewer receives loadings from runoff and municipal water uses including fire hydrant usage and flushing. If the watershed does not include municipal water users that have loadings that go directly to the storm sewer, then the storm sewer will only receive loadings from runoff. Additionally, if the watershed does not have a storm sewer system, WMOST users can enter -9 for the storm sewer capacity.

$$L_{StSSw,t} = L_{UseNpSewer,t} + L_{Ru,t} \quad (51)$$

where

- $L_{StSSw,t}$ = loadings from storm sewer system to surface water, lbs/time step
 $L_{UseNpSewer,t}$ = municipal water use loadings that goes directly to the sewer system, lbs/time step

Surface Water (Sw)

The surface water, or stream reach component, does not have storage, that is, it is assumed to completely empty with each time step.

The surface water component may receive loadings from runoff through the storm sewer, baseflow, external surface water sources (i.e., an upstream reach), point source dischargers, the wastewater treatment plant, and the water reuse facility.

$$L_{Sw,t} = L_{StSSw,t} + L_{ExtSw,t} + L_{PtSw,t} + L_{GwSw,t} + L_{WwtpSw,t} + L_{WrfSw,t} \quad (52)$$

Influent constituent concentration is calculated based on the incoming loadings divided by incoming flows.

$$X_{SwF,t} = \frac{L_{Sw,t}}{Q_{ExtSw,t} + Q_{PtSw,t} + Q_{GwSw,t} + Q_{WwtpSw,t} + Q_{WrfSw,t} + Q_{StSSw,t}} \quad (53)$$

Loadings from surface water may discharge downstream to a reservoir, be withdrawn by the potable water treatment plant, and be withdrawn by the ASR facility. The loadings going to each of these components are based on the influent concentration (i.e., stream is fully mixed and no removal occurs in-stream) and respective flows.

Loadings from surface water are based on the concentration of the water quality constituent after removal has occurred and flow determined by the model.

$$L_{SwRes,t} = Q_{SwRes,t} \times X_{SwF,t} \quad (54)$$

$$L_{SwWtp,t} = bQ_{SwWtp,t} \times X_{SwF,t} \quad (55)$$

$$L_{SwAsr,t} = bQ_{SwAsr,t} \times X_{SwF,t} \quad (56)$$

$$L_{SwPt,t} = Q_{SwPt,t} \times X_{SwF,t} \quad (57)$$

where

- $L_{Sw,t}$ = surface water loadings before removal, lbs/time step
 $L_{ExtSw,t}$ = surface water loadings from outside of basin, lbs/time step

$L_{PtSw,t}$	=	loadings from surface water point sources, lbs/time step
$L_{WwtpSw,t}$	=	loadings from primary wastewater treatment plant, lbs/time step
L_{WrfSw}	=	loadings from water reuse facility (advanced treatment), lbs/time step
$X_{SwF,t}$	=	final surface water concentration, mg/L
$L_{SwRes,t}$	=	loadings from surface water to reservoir, lbs/time step
$L_{SwWtp,t}$	=	loadings to water treatment plant, lbs/time step
$L_{SwAsr,t}$	=	loadings to ASR facility, lbs/time step
$L_{SwPt,t}$	=	loadings of private surface water withdrawals, lbs/time step

Reservoir (Res)/Surface Water Storage

The reservoir may represent a surface water reservoir, flood control structure, off-stream storage in tanks, and/or ponds. The reservoir component has storage. It may receive loadings from the surface water or stream reach, and private (i.e., non-municipal) surface discharge²⁴. Loadings out of the reservoir can be removed by private/other withdrawals, move to a downstream reach outside of the basin, and discharge to the potable water treatment plant and ASR facility. This routing of loadings assumes that the reservoir is at the outlet of the study area.²⁵

For $t=1$,

$$L_{Res,t} = (X_{Res,I} \times V_{Res,I}) + L_{SwRes,t} + L_{PtRes,t} - L_{SwExt,t} - L_{ResWtp,t} - L_{ResAsr,t} - L_{ResPt,t} \quad (58)$$

For all other t ,

$$L_{Res,t} = L_{Res,t-1} + L_{SwRes,t} + L_{PtRes,t} - L_{SwExt,t} - L_{ResWtp,t} - L_{ResAsr,t} - L_{ResPt,t} \quad (59)$$

where

$L_{Res,t}$	=	reservoir loadings, lbs
$X_{Res,I}$	=	initial concentration of reservoir, mg/L
$L_{SwRes,t}$	=	loadings to reservoir from surface water, lbs/time step
$L_{PtRes,t}$	=	loadings from direct, private discharge to reservoir, lbs/time step
$L_{SwExt,t}$	=	loadings to surface water outside of basin, lbs/time step
$L_{ResWtp,t}$	=	loadings to water treatment plant, lbs/time step
$L_{ResAsr,t}$	=	loadings to ASR facility, lbs/time step
$L_{ResPt,t}$	=	loadings from direct, private withdrawal from reservoir, lbs/time step

Some constituents, such as sediment and adsorbed phosphorus, can settle out of the water column in the reservoir, improving water quality in the effluent as compared to the influent. The user has the ability to specify a zero order removal rate, a first order removal rate, or no removal for each

²⁴ WMOST does not associate loadings to the volume of make-up water. Accordingly, there is no loading added to the reservoir from any make-up water flows necessary to meet system constraints. This allows make-up water to be used as last resort to meet volumetric or water quality target, providing users indication that the specified constraints cannot be met using the available resources or management options (see Section 3.3 regarding Make-up Water).

²⁵ Future versions of WMOST may provide an option for flow routing that represents the reservoir as being upstream of the modeled reach segment and models separate off-stream surface storage to represent lakes, ponds and storage tanks. Note, however, that this alternative representation is not currently available.

constituent to represent settling or other removal processes. In addition, the user has the ability to model attenuation based on the outflow rate of the reservoir and surface area of the reservoir sediments using a Vollenweider-type model (Schwarz et al., 2006).

If a zero-order removal rate is specified,

$$X_{ResF,t} = \left(\frac{L_{Res,t}}{V_{Res,t}} \right) - k_{Res,0} \times \Delta t \quad (60)$$

where

- $k_{Res,0}$ = zero-order removal rate, mg/L/time step
- $X_{ResF,t}$ = final reservoir concentration after removal (if applicable), mg/L

If a first-order removal rate is specified,

$$X_{ResF,t} = \frac{L_{Res,t} \times e^{-k_{Res,1} \times \Delta t}}{V_{Res,t}} \quad (61)$$

If a first-order removal rate is specified and the user chooses to model removal based on the Vollenweider type model,

$$X_{ResF,t} = \frac{L_{Res,t} \times e^{(-k_{Res,1} \times \Delta t \times \frac{ResArea}{V_{Res,t}})}}{V_{Res,t}} \quad (62)$$

where

- $k_{Res,1}$ = first-order removal rate, 1/time step
- $ResArea$ = area of the reservoir, acres
- V_{Res} = volume of reservoir, MG

If no removal rate is specified,

$$X_{ResF,t} = \frac{L_{Res,t}}{V_{Res,t}} \quad (63)$$

Loadings leaving the reservoir system are based on the concentration of the water quality constituent after removal has occurred and flow determined by the model.

$$L_{SwExt,t} = bQ_{SwExt,t} \times X_{ResF,t} \quad (64)$$

$$L_{ResWtp,t} = bQ_{ResWtp,t} \times X_{ResF,t} \quad (65)$$

$$L_{ResAsr,t} = bQ_{ResAsr,t} \times X_{ResF,t} \quad (66)$$

$$L_{ResPt,t} = Q_{ResPt,t} \times X_{ResF,t} \quad (67)$$

Water Treatment Plant (Wtp)

The water treatment plant treats water to potable standards. It may receive loadings from the reservoir, surface water reach or groundwater aquifer. Treated water from the plant may be used to meet potable and nonpotable water use demand.

The user indicates the average effluent concentration achieved by the facility and the maximum influent concentrations for which the designated effluent concentration is achievable.

The maximum influent concentration is used as a model constraint.

$$X_{WtpIn,t} = \frac{L_{SwWtp,t} + L_{ResWtp,t} + L_{GwWtp,t}}{bQ_{SwWtp,t} + bQ_{ResWtp,t} + bQ_{GwWtp,t}} \quad (68)$$

$$X_{WtpIn,t} \leq X_{WtpMaxIn} \quad (69)$$

where

$$\begin{aligned} X_{WtpIn,t} &= \text{model calculated WTP influent concentration, mg/L} \\ X_{WtpMaxIn} &= \text{user defined maximum influent concentration at WTP, mg/L} \end{aligned}$$

The average effluent constituent concentration is used to calculate the loadings to potable and nonpotable water users and the loadings lost to the groundwater through leaks in the treated water distribution system.

$$L_{WtpUseP,t} = Q_{WtpUseP,t} \times X_{WtpAvEff} \quad (70)$$

$$L_{WtpUseNp,t} = bQ_{WtpUseNp,t} \times X_{WtpAvEff} \quad (71)$$

$$L_{WtpGw,t} = Q_{WtpGw,t} \times X_{WtpAvEff} \quad (72)$$

where

$$\begin{aligned} L_{WtpUseP,t} &= \text{loadings from primary WTP to potable water use, lbs/time step} \\ L_{WtpUseNp,t} &= \text{loadings from primary WTP to nonpotable water use, lbs/time step} \\ X_{WtpAvEff} &= \text{average effluent concentration leaving primary water treatment plant, mg/L} \end{aligned}$$

Potable Water Use (UseP):

A water utility may serve residential, commercial, industrial, institutional, and/or agricultural customers. User-specified average daily loadings from each potable water use type are used to model increases in constituent loading.

$$L_{UseP,t} = \sum_{u=2}^{NUse} \left[\left(L_{WtpUseP,t} + (X_{IbtWUse} \times Q_{IbtWUseP,t}) \right) \times \left(1 - \frac{P_{ConsUseP,u,t}}{100} \right) \times Fr_{PUse,u,t} + L_{UsePAddl,u} \right] \quad (73)$$

A new constituent concentration is calculated after adding the loadings from potable water users to determine the loadings to the wastewater treatment plant, septic systems, and out of the basin through interbasin transfer.

$$X_{UseP,t} = \frac{L_{UseP,t}}{Q_{WtpUseP,t} + bQ_{IbtWUseP,t}} \quad (74)$$

$$L_{UsePSanS,t} = bQ_{UsePSanS,t} \times X_{UseP,t} \quad (75)$$

$$L_{UsePsep,t} = Q_{UsePsep,t} \times X_{UseP,t} \quad (76)$$

$$L_{UsePsepExt,t} = Q_{UsePsepExt,t} \times X_{UseP,t} \quad (77)$$

$$L_{UsePIbtWw,t} = bQ_{UsePIbtWw,t} \times X_{UseP,t} \quad (78)$$

where

$L_{UseP,t}$	=	loadings after addition from potable water users, lbs/time step
$X_{IbtWUse}$	=	average interbasin transfer concentration for potable and nonpotable water, mg/L
$L_{UsePAddl,u}$	=	potable water user average loadings, lbs/time step
$X_{UseP,t}$	=	concentration after addition from potable water users, mg/L
$L_{UsePSanS,t}$	=	loadings of potable water to wastewater treatment plant through the sanitary sewer, lbs/time step
$L_{UsePsep,t}$	=	loadings of potable water to septic systems within the study area, lbs/time step
$L_{UsePsepExt,t}$	=	loadings of potable water to septic systems outside the study area, lbs/time step
$L_{UsePIbtWw,t}$	=	wastewater loadings from potable users to interbasin transfer wastewater services, lbs/time step

Nonpotable Water Use (UseNp)

A water utility may serve residential, commercial, industrial, institutional, and/or agricultural users. User input average daily loadings from each nonpotable water user type are used to model increases in constituent loading.

$$L_{UseNp,t} = \sum_{u=2}^{NUse} \left[\left(L_{WtpUseNp,t} + L_{WrfUseNp,t} + (X_{IbtWUse,t} \times bQ_{IbtWUseNp,t}) \right) \times \left(1 - \frac{P_{ConsUseNp,u,t}}{100} \right) \times Fr_{NpUse,u,t} + L_{UseNpAddl,u} \right] \quad (79)$$

A new constituent concentration is calculated after adding the loadings from nonpotable water users to determine the loadings to the wastewater treatment plant, septic systems, and out of the basin through interbasin transfer.

$$X_{UseNp,t} = \frac{L_{UseNp,t}}{bQ_{WtpUseNp,t} + bQ_{WrfUseNp,t} + bQ_{IbtWUseNp,t}} \quad (80)$$

$$L_{UseNpSanS,t} = bQ_{UseNpSanS,t} \times X_{UseNp,t} \quad (81)$$

$$L_{UseNpsep,t} = Q_{UseNpsep,t} \times X_{UseNp,t} \quad (82)$$

$$L_{UseNpSepExt,t} = Q_{UseNpSepExt,t} \times X_{UseNp,t} \quad (83)$$

$$L_{UseNpIbtWw,t} = bQ_{UseNpIbtWw,t} \times X_{UseNp,t} \quad (84)$$

$$L_{UseNpSewer,t} = Q_{UseNpSewer,t} \times X_{UseNp,t} \quad (85)$$

where

$L_{UseNp,t}$	=	loadings after addition from nonpotable water users, lbs/time step
$L_{WrfUseNp,t}$	=	loadings from nonpotable water from water reuse facility, lbs/time step
$L_{UseNpAddl,u}$	=	nonpotable water user average loadings, lbs/time step
$X_{UseNp,t}$	=	concentration after addition from nonpotable water users, mg/L
$L_{UseNpSanS,t}$	=	loadings of nonpotable water to wastewater treatment plant through the sanitary sewer, lbs/time step
$L_{UseNpSep,t}$	=	loadings of nonpotable water to septic systems within the study area, lbs/time step
$L_{UseNpSepExt,t}$	=	loadings of nonpotable water to septic systems outside the study area, lbs/time step
$L_{UseNpIbtWw,t}$	=	loadings of nonpotable water to wastewater collection system via interbasin transfer, lbs/time step

Wastewater Treatment Plant (Wwtp)

The wastewater treatment plant treats water that has not been consumed by potable and non-potable water users to be reused and/or recovered. The user indicates the average effluent concentration achieved by the WWTP and the maximum influent concentrations for which the designated effluent concentration is achievable.

The maximum influent is used as a model constraint.

$$X_{WwtpIn,t} = \frac{L_{UsePSanS,t} + L_{UseNpSanS,t} + L_{GwWwtp,t}}{bQ_{UsePSanS,t} + bQ_{UseNpSanS,t} + Q_{GwWwtp,t}} \quad (86)$$

$$X_{WwtpIn,t} \leq X_{WwtpMaxIn} \quad (87)$$

where

$X_{WwtpIn,t}$	=	model calculated WWTP influent concentration, mg/L
$X_{WwtpMaxIn}$	=	user defined maximum influent concentration at WWTP, mg/L

The average effluent constituent concentration is used to calculate the loadings to the water reuse facility and loadings associated with groundwater infiltration into the wastewater collection system.

$$L_{WwtpSw,t} = Q_{WwtpSw,t} \times X_{WwtpAvEff} \quad (88)$$

$$L_{WwtpWrf,t} = bQ_{WwtpWrf,t} \times X_{WwtpAvEff} \quad (89)$$

where

$L_{WwtpWrf,t}$	=	loadings to water reuse facility from primary WWTP, lbs/time step
$X_{WwtpAvEff}$	=	average effluent concentration leaving primary wastewater treatment plant, mg/L

Water Reuse Facility (Wrf)

The water reuse facility treats water for nonpotable water use and ASR. The user indicates the average effluent concentration achieved by the WRF²⁶. The average effluent constituent concentration is used to calculate the loadings to nonpotable water use, ASR, and surface water.

$$L_{WrfUseNp,t} = bQ_{WrfUseNp,t} \times X_{WrfAvEff} \quad (90)$$

$$L_{WrfAsr,t} = Q_{WrfAsr,t} \times X_{WrfAvEff} \quad (91)$$

$$L_{WrfSw,t} = Q_{WrfSw,t} \times X_{WrfAvEff} \quad (92)$$

where

- $L_{WrfAsr,t}$ = loadings from the water reuse facility to the ASR facility, lbs/time step.
- $X_{WrfAvEff}$ = average effluent concentration leaving water reuse facility, mg/L

Septic Systems (Sep)

Consumptive use and demand management affect the amount of wastewater that flow to septic systems and the influent concentration.

The average effluent concentration achieved by the septic system is a WMOST input. The average effluent constituent concentration is used to calculate the loadings from the septic system to the groundwater system.

$$L_{SepGw,t} = Q_{SepGw,t} \times X_{SepAvEff} \quad (93)$$

where

- $L_{SepGw,t}$ = loadings from primary septic system to groundwater system, lbs/time step
- $X_{SepAvEff}$ = average effluent concentration leaving septic system, mg/L

Aquifer Storage and Recovery Facility (Asr)

In WMOST v3, the user has the option to include treatment at the ASR facility, an option that was not available in WMOST v2.1.

The WMOST user indicates the average effluent constituent concentration achievable by the ASR facility and it is used to calculate the loadings from the ASR to the groundwater system.²⁷

$$L_{AsrGw,t} = Q_{AsrGw,t} \times X_{AsrAvEff} \quad (94)$$

where

- $L_{AsrGw,t}$ = loadings from the ASR facility to groundwater, lbs/time step
- $X_{AsrAvEff}$ = average effluent concentration leaving ASR facility, mg/L

²⁶ The WRF only receives flows from the WWTP so users can control the influent concentration to the WRF by changing the effluent concentration for the WWTP.

²⁷ Future versions of WMOST may include a maximum influent constraint for the ASR facility.

3. Mixed Integer Nonlinear Programming, Objective Function, and Constraints

This section introduces mixed integer nonlinear programming (MINLP), describes the objective function, and provides the cost and constraint equations related to available management options in WMOST.

3.1 Mixed Integer Nonlinear Programming (MINLP)

Unlike WMOST v2, which used a linear programming solver, WMOST v3 uses a mixed integer nonlinear programming (MINLP) solver to find the least-cost solution to the optimization problem in WMOST. The consideration of both water quantity and quality necessitated the switch from a linear solver to a nonlinear solver to accommodate the increased complexity. WMOST uses Bonmin (Basic Open-source Nonlinear Mixed Integer programming) to minimize the total, annualized cost of chosen management options. WMOST users can utilize the capabilities of Bonmin through the NEOS server²⁸, which the University of Wisconsin – Madison hosts. Bonmin has the ability to implement several different algorithms for solving MINLP models. The default algorithm used by WMOST is “B-Hyb”, a hybrid outer approximation based branch-and-cut algorithm, which has the ability to solve most optimization problems within 3 hours (Bonami and Lee, 2013). However, users also have the option of using “B-BB”, a simple branch-and-bound algorithm that is recommended for solving nonconvex MINLPs.

Although the “B-Hyb” algorithm typically solved optimization problems most quickly during testing (Bonami and Lee, 2013), solving time is a significant limitation of MINLP solvers. For reference, the linear solver (Ipsolve) used in WMOST v2.1²⁹, had a run time of about 6 minutes when optimizing over a 5-year modeling time period. Using Bonmin, solving times have varied from 5 minutes to up to 6 hours. In order to decrease the expected solving time, the number of solutions that the optimization algorithm explores is limited to 20. As such, the minimization value reported with optimization results, while a local minimum, might not be the absolute global minimum.

3.2 Objective Function

The objective function is the minimization of the total, annualized cost of all chosen management practices (see equation at the end of Section 3.4). The objective function is minimized by selecting the optimal values for decision variables denoted with the prefix *b*. These decisions determine which management practices are selected to minimize the total cost and meet all the constraints. Any constraint or management option can be excluded by entering -9 instead of an input value, as specified on the user interface pages.

The total, annualized cost includes annualized capital costs and annual operation and maintenance (O&M) costs.

²⁸ The Bonmin solver can be accessed through the NEOS server at the following link: <https://neos-server.org/neos/solvers/minco:Bonmin/AMPL.html>.

²⁹ The incorporation of the Water Quality module in WMOST v3 necessitated the use of a nonlinear solver for optimization.

$$Z = \left(\sum_{i=1}^n C_{T,A_i} \right) \quad (95)$$

where

- Z = total annual cost for all implemented management practices, \$
- C_{T,A_i} = total annualized cost for management option i , \$
- n = total number of management options

Total annual costs are calculated for all implemented management practices. In this section, we describe the generic form of cost equations. In general, total annual cost for a management practice is calculated as the annualized capital cost, $C_{C,A}$, (i.e., incurred once) plus annual O&M costs, C_{Om} .

Capital costs may be annualized using three different annualization factors, F , depending on the management practice types (i.e., new construction, replacements, and implementations).

$$C_{C,A} = F \times C_C \quad (96)$$

where

- $C_{C,A}$ = unit annual capital cost, \$/year
- C_C = unit capital cost, \$
- F = annualization factors

Unit construction costs for new facilities or costs for expanding the capacity of existing facilities (i.e., capital costs) are annualized over the expected lifetime of the new construction (e.g., wastewater treatment plant and bioretention basin). The corresponding annualization factor (F_{New}) is defined as follows (EPA 2002):

$$F_{New} = \frac{i \times (1 + i)^{T_{New}}}{(1 + i)^{T_{New}} - 1} \quad (97)$$

where

- i = interest rate in percent/100, 0 - 1
- T_{New} = lifetime of new construction, years
- F_{New} = annualization factor for new facilities or expansion of existing facilities

Replacement costs for an existing facility are calculated as $C_{C,A}$ annualized over the remaining years in the facility's lifetime, T_{Exist} . The corresponding annualization factor (F_{Exist}) is defined as follows:

$$F_{Exist} = \frac{i \times (1 + i)^{T_{New}}}{(1 + i)^{T_{New}} - 1} \times \frac{T_{Plan} - T_{Exist}}{T_{Plan}} \quad (98)$$

where

- T_{Plan} = planning horizon, years

T_{Exist} = remaining lifetime of existing facility, years
 F_{Exist} = annualization factor for existing facilities

If $T_{Plan} \leq T_{Exist}$, then the existing facility will not need to be replaced within the planning period and $C_{C,A} = 0$.

One-time implementation costs, such as the initial administrative activities associated with instituting a price increase, are annualized over the planning horizon. The corresponding annualization factor (F_{Plan}) is defined as follows:

$$F_{Plan} = \frac{i \times (1 + i)^{T_{Plan}}}{(1 + i)^{T_{Plan}} - 1} \quad (99)$$

where

F_{Plan} = annualization factor for the planning horizon

O&M costs are annualized over the modeling time period, $F_{YrsModel}$.

For a daily time step,

$$F_{YrsModel} = \frac{1}{N_t / 365 + N_{LeapYrs} \times 0.25} \quad (100)$$

For a monthly time step,

$$F_{YrsModel} = \frac{1}{N_t / 12} \quad (101)$$

where

N_t = total number of time steps in the modeling period
 $N_{LeapYrs}$ = number of leap years in the modeling period

3.3 Costs and Constraints Associated with Hydrology Management Options

Land Management

Land cover, land use, soil, slope, and other land characteristics affect the fraction of precipitation that will runoff, recharge, and evapotranspire. Areas with similar characteristics – hydrologic response units (HRUs)³⁰ – respond similarly to precipitation. The user provides unit runoff and recharge rates (RRRs) for each HRU in the watershed for multiple sets of HRUs. For example, a ‘baseline’ set is provided that reflects RRRs without stormwater management. Additional sets of RRRs may be provided that, for example, represent RRRs of HRUs with stormwater management. For example, a baseline HRU may be defined as low density residential land use with hydrologic soil group (HSG) B

³⁰ For example, an HRU may be defined as low density residential land use with hydrologic soil group (HSG) B and another as low density residential with HSG C.

and a stormwater managed HRU may be defined as low density residential land use with HSG B with a bioretention basin sized to capture a one-inch storm event. The user provides both the managed RRRs and the cost associated with the management practice. See Section 2.1 for continuity equations defining total watershed runoff and recharge based on RRRs and the HRU area allocation.

The model provides two land management options as described below.

Land conservation–reallocating area among baseline HRUs:

For a specific scenario, the user may specify the expected, future areas for each HRU as the baseline values that may include projected increases in development.³¹ At the same time, the user can specify the cost to purchase existing, undeveloped forest land. With this information provided, the model can decide whether it is cost effective to reallocate land from projected developed HRUs to undeveloped forest HRUs.

The cost to reallocate land area among baseline HRUs is defined below.

For $s = 1$ (i.e., baseline land use),

$$C_{ATb} = \sum_{l=1}^{nLu} ((F_{Plan} \times C_{C,l,s=1} + C_{Om,l,s=1}) \times (bA_{l,s=1} - A_{l,s=1})) \quad (102)$$

where

C_{ATb}	=	total annual cost of reallocating areas among baseline HRUs from user-specified to model-chosen values, \$/year
$C_{C,l,s=1}$	=	capital cost associated with land reallocation for each HRU in set l (e.g., purchasing forest land), \$/acre
$C_{Om,l,s=1}$	=	annual O&M cost associated with maintaining, for example, the land preservation, \$/acre/year

Stormwater management (traditional, GI, low impact development) – reallocating area from baseline to managed HRUs:

The model may choose implementation of stormwater management practices based on the available area for each HRU after reallocation for land conservation (i.e., $bA_{l,s=1}$). The user may specify multiple managed HRU sets where for each set the user specifies costs and runoff and recharge rates. Each set may be a different management practice such as one set for bioretention basins sized to retain one inch of rain and another set that is a combination of low impact development practices such as impervious area reduction, bioswales, and bioretention basins to match predevelopment hydrology.

When the model chooses to place land area under a management practice, additional costs specified by the equation below are incurred. In addition, the runoff and recharge rates corresponding to that HRU set are used to calculate total runoff and recharge as shown by equations in Section 2.1.

³¹ If a future scenario is modeled, all input data must be values projected for the future scenario (e.g., water demand must be the projected demand corresponding to the project development).

For managed sets, $s = 2$ to $NLuSet$,

$$C_{ATm} = \sum_{s=2}^{NLuSet} \sum_{l=1}^{nLu} ((F_{Plan} \times C_{C,l,s} + C_{Om,l,s}) \times bA_{l,s}) \quad (103)$$

where

C_{ATm} = total annual cost of reallocating areas among managed HRUs from user-specified to model-chosen values, \$/year

Section 2.1 also details constraints to ensure that area allocation among HRUs meet physical constraints such as preserving total original land area and user specified constraints such as limits on developable land based on zoning regulation or the amount of existing forest land which is available for conservation.

Demand Management

There are two demand management options in the model: 1) via pricing and 2) direct reductions through other practices such as rebates for water efficient appliances. When acquiring input data for these practices, the user must be aware of the potential reduction in the individual effectiveness of demand management practices when multiple practices are implemented simultaneously.³²

The user may specify the number of water use categories; however, the first water use category is always unaccounted-for water. Unaccounted-for water is defined as the sum of apparent losses (e.g., unauthorized consumption or inaccurate meters) and real losses (e.g., system leakage). The user only specifies a time series, $Q_{Use1,u=1,t}$ for this water use category; therefore, unaccounted-for water is not affected by demand management or consumptive use and is assumed to entirely drain to the groundwater system.

Pricing change

Initial demand, $Q_{Use1,u,t}$, provided as input, may be reduced by increasing the price of water and decreasing the demand. A flow weighted average price elasticity, $ElasPrice$, is calculated based on each water user's price elasticity and initial demand.

$$ElasPrice = \frac{\sum_u (E_u * \sum_t Q_{Use1,u,t})}{\sum_u \sum_t Q_{Use1,u,t}} \quad (104)$$

where

E_u = price elasticity for water user, u

The initial demand is reduced based on the percent increase in price, $bPprice$, chosen in the solution.

³² For example, rebates for water low flow shower heads will reduce the gallons per minute used in showering. If an increase in water rates is implemented at the same time, the anticipated water use reduction may not be as large with a low flow shower head as with a high flow shower head even if the new water rates induce shorter shower times.

$$bP_{Price} \leq P_{PriceMax} * bD_{price} \quad (105)$$

where

- $P_{PriceMax}$ = one time, maximum percent change in price, %
 bD_{price} = a binary decision variable, 0 or 1

Costs associated with changing the water pricing structure and/or rates may include costs for conducting an initial study to determine the appropriate structure and rates and O&M costs for annual reviews of the rates. The cost to implement changes to the water pricing structure is not dependent on the percent of change in price or other unit of implementation but is a fixed capital cost and fixed annual O&M cost. Because the costs are fixed, a binary variable is introduced that is set equal to one if the price change is implemented and zero for no price change. Therefore, the annual total cost for a pricing change is defined as:

$$C_{ATPrice} = bD_{price} \times (F_{Plan} \times C_{C,Price} + C_{Om,Price}) \quad (106)$$

where

- $C_{ATPrice}$ = total annual cost to implement price changes, \$/year
 $C_{C,Price}$ = capital cost of price change, \$
 $C_{Om,Price}$ = annual O&M costs for implementation of price change, \$/year

Direct demand reduction

The user may provide the aggregate cost of various demand reduction practices and the associated maximum reduction in demand. The model will select the most cost-effective level of demand reduction and the associated cost.

$$C_{ATDmd} = (F_{Plan} \times C_{CDm} + C_{OmDm}) \times \frac{bQ_{Dm}}{Q_{DmMax}} \quad (107)$$

$$bQ_{Dm} \leq Q_{DmMax} \quad (108)$$

where

- C_{ATDmd} = total annual cost to implement direct demand management practices, \$/year
 C_{CDm} = capital cost of direct demand management, \$
 C_{OmDm} = annual O&M costs for direct demand management, \$/year
 Q_{DmMax} = maximum demand reduction available and associated with specified costs, MG/time step

EPA's WaterSense website provides a calculator that together with local or Census data (e.g., number of households) can be used to determine the total potential reductions in water use with the installation of water efficient appliances.³³

³³ <https://www.epa.gov/watersense/watersense-calculator>

Infrastructure Capacity and Use

If modeling for hydrology and loadings, the model assumes that the capital and operation and maintenance costs input by the user for the various model components appropriately reflect the hydrologic and water quality treatment performance of each component, as applicable (i.e., O&M costs for wastewater treatment plant covers both pumping and treatment processes in cases where WMOST optimizes for both hydrology and loadings).

Groundwater and surface water pumping facilities, water and wastewater treatment plants, water reuse facility, aquifer storage and recovery (ASR) facility, and nonpotable distribution systems follow similar forms for total annual costs.

Flow through a facility cannot exceed the pumping or treatment capacity of the facility. The final capacity of the facility is the initial user-specified capacity plus additional capacity built as part of the solution set (additional capacities are available as management options). This constraint applies to surface water pumping, groundwater pumping, water treatment, wastewater treatment, water reuse, and aquifer storage facilities. If upgraded treatment is enabled as a management option for the WTP or WWTP (see Section 3.4), the facility constraints related to flow capacity will not change.

Groundwater pumping

$$C_{ATGWpump} = (F_{GWpumpExist} \times C_{CGWPump} \times Q_{GWpumpI}) + (F_{GWpumpNew} \times C_{CGWPump} \times bQ_{GWpumpAddl}) + (F_{YrsModel} \times C_{OmGWpump} \times \sum_t bQ_{GWtp,t}) \quad (109)$$

$$bQ_{GWtp,t} \leq Q_{GWpumpI} + bQ_{GWpumpAddl} \quad (110)$$

where

$C_{ATGWpump}$	=	total annual cost for groundwater pumping, \$/year
$F_{GWpumpExist}$	=	annualization factor based on remaining lifetime of existing facilities
$C_{CGWPump}$	=	capital costs of new/additional groundwater pumping capacity/facility, \$/MGD
$C_{OmGWpump}$	=	operation and maintenance costs for groundwater pumping, \$/MG
$Q_{GWpumpI}$	=	initial groundwater pumping capacity, MGD
$F_{GWpumpNew}$	=	annualization factor for new capacity or facilities
$bQ_{GWpumpAddl}$	=	additional groundwater pumping capacity, MGD

Surface water pumping

$$C_{ATSwPump} = (F_{SwPumpExist} \times C_{CSWPump} \times Q_{SwPumpI}) + (F_{SwPumpNew} \times C_{CSWPump} \times bQ_{SwPumpAddl}) + (F_{YrsModel} \times C_{OmSwPump} \times \sum_t (bQ_{SwWtp,t} + bQ_{ResWtp,t})) \quad (111)$$

$$bQ_{SwWtp,t} + bQ_{ResWtp,t} \leq Q_{SwPumpI} + bQ_{SwPumpAddl} \quad (112)$$

where

$C_{ATSwPump}$	=	total annual cost for surface water pumping, \$/year
$F_{SwPumpExist}$	=	annualization factor based on remaining lifetime of existing facilities
$C_{CSWPump}$	=	capital costs of new/additional surface water pumping capacity/facility, \$/MGD
$C_{OmSwPump}$	=	operation and maintenance costs for surface water pumping, \$/MG
$Q_{SwPumpI}$	=	initial surface water pumping capacity, MGD

$F_{SwPumpNew}$ = annualization factor for new capacity or facilities
 $bQ_{SwPumpAddl}$ = additional surface water pumping capacity, MGD

Water treatment facility (WTP)

$$C_{ATWtp} = (F_{WtpExist} \times C_{CWtp} \times Q_{WtpMaxI}) + (F_{WtpNew} \times C_{CWtp} \times bQ_{WtpAddl}) + (F_{YrsModel} \times C_{OmWtp} \times \sum_t (bQ_{SwWtp,t} + bQ_{GwWtp,t} + bQ_{ResWtp,t})) \quad (113)$$

$$bQ_{SwWtp,t} + bQ_{ResWtp,t} + bQ_{GwWtp,t} \leq Q_{WtpMaxI} + bQ_{WtpAddl} \quad (114)$$

where

C_{ATWtp} = total annual costs for water treatment, \$/year
 $F_{WtpExist}$ = annualization factor based on remaining lifetime of existing facilities
 C_{CWtp} = capital costs of new or additional water treatment capacity or facility, \$/MGD
 $Q_{WtpMaxI}$ = initial water treatment capacity, MGD
 F_{WtpNew} = annualization factor for new capacity or facilities
 $bQ_{WtpAddl}$ = additional water treatment capacity, MGD
 C_{OmWtp} = O&M costs for water treatment, \$/MG

Reducing unaccounted-for water (Uaw), assumed to be leakage out of the potable distribution system into groundwater

The cost for reducing unaccounted-for water in the treated water distribution system is calculated as:

$$C_{ATUaw} = (F_{Plan} \times C_{CUaw} + C_{OmUaw}) \times \frac{bP_{WtpGwFix}}{100} \quad (115)$$

$$bP_{WtpGwFix} \leq P_{WtpLeakFixMax} \quad (116)$$

where

C_{CATUaw} = total annualized capital cost of reducing unaccounted-for water, \$/year
 C_{CUaw} = capital cost of fixing Uaw such as initial survey and initial work to lower Uaw rate, \$
 C_{OmUaw} = O&M cost to maintain low Uaw rate, \$/year
 $bP_{WtpGwFix}$ = percent of leakage that is fixed, %
 $P_{WtpLeakFixMax}$ = maximum physical limit of leakage reduction in treated water distribution system (e.g., given age of system and the repair costs specified), %

Wastewater treatment plant (WWTP)

$$C_{ATWwtp} = (F_{WwtpExist} \times C_{CWwtp} \times Q_{WwtpMaxI}) + (F_{WwtpNew} \times C_{CWwtp} \times bQ_{WwtpAddl}) + (F_{YrsModel} \times C_{OmWwtp} \times \sum_t (bQ_{UsePSanS,t} + bQ_{UseNpSanS,t} + Q_{GwWwtp,t})) \quad (117)$$

$$bQ_{UsePSanS,t} + bQ_{UseNpSanS,t} + Q_{GwWwtp,t} \leq Q_{WwtpMaxI} + bQ_{WwtpAddl} \quad (118)$$

where

C_{ATWwtp} = total annual costs for wastewater treatment, \$/year

$F_{WwtpExist}$	=	annualization factor based on remaining lifetime of existing facilities
C_{CWwtp}	=	capital costs of new or additional wastewater treatment capacity or facility, \$/MGD
$Q_{WwtpMaxl}$	=	initial wastewater treatment capacity, MGD
$F_{WwtpNew}$	=	annualization factor for new capacity or facilities
$bQ_{WwtpAddl}$	=	additional wastewater treatment capacity, MGD
C_{OmWwtp}	=	O&M costs for wastewater treatment, \$/MG

Reducing infiltration into wastewater collection system

The cost for repairing leaks and reducing groundwater infiltration into the wastewater collection system is calculated as:

$$C_{ATGwWwtp} = (F_{Plan} \times C_{CGwWwtp} + C_{OmGwWwtp}) \times \frac{bP_{GwWwtpFix}}{100} \quad (119)$$

$$bP_{GwWwtpFix} \leq P_{WwtpLeakFixMax} \quad (120)$$

where

$C_{ATGwWwtp}$	=	total annualized cost of reducing groundwater infiltration into the wastewater collection system, \$/year
$C_{CGwWwtp}$	=	capital cost of fixing infiltration such as initial survey and initial repairs to lower infiltration rate, \$
$C_{OmGwWwtp}$	=	annual O&M cost to maintain low infiltration rate, \$/year
$bP_{WwtpGwFix}$	=	percent of groundwater infiltration that is fixed, %
$P_{WwtpLeakFixMax}$	=	maximum physical limit of repairing infiltration into the wastewater collection system (e.g., given age of system and the repair costs specified), %

Water reuse facility (WRF)

$$C_{ATWrf} = (F_{WrfExist} \times C_{CWrf} \times Q_{WrfMaxl}) + (F_{WrfNew} \times C_{CWrf} \times bQ_{WrfAddl}) + (F_{YrsModel} \times C_{OmWrf} \times \sum_t bQ_{WwtpWrf,t}) \quad (121)$$

$$bQ_{WwtpWrf,t} \leq Q_{WrfMaxl} + bQ_{WrfAddl} \quad (122)$$

where

C_{ATWrf}	=	total annual costs for water reuse, \$/year
$F_{WrfExist}$	=	annualization factor based on remaining lifetime of existing facilities
C_{CWrf}	=	capital costs of new or additional WRF capacity, \$/MGD
$Q_{WrfMaxl}$	=	existing maximum WRF capacity, MGD
F_{WrfNew}	=	annualization factor for new capacity or facilities
C_{OmWrf}	=	O&M costs for WRF, \$/MG
$bQ_{WrfAddl}$	=	additional or new WRF capacity, MGD

Nonpotable distribution system (Npdist), for flows from the water reuse facility for nonpotable water use

$$C_{ATNpdist} = (F_{NpdistExist} \times C_{CNpdist} \times Q_{NpdistI}) + (F_{NpdistNew} \times C_{CNpdist} \times bQ_{NpdistAddl}) + (F_{YrsModel} \times C_{OmNpdist} \times \sum_t bQ_{WrfUseNp,t}) \quad (123)$$

$$bQ_{WrfUseNp,t} \leq Q_{NpdistMaxI} + bQ_{NpdistAddl} \quad (124)$$

where

$C_{ATNpdist}$	=	total annual costs for nonpotable water distribution, \$/year
$F_{NpdistExist}$	=	annualization factor for existing capacity or facilities
$Q_{NpdistI}$	=	existing capacity of nonpotable distribution system, MGD
$F_{NpdistNew}$	=	annualization factor for new capacity or facilities
$bQ_{NpdistAddl}$	=	new or additional capacity, MGD
$C_{CNpdist}$	=	capital costs for Npdist, \$/MGD
$C_{OmNpdist}$	=	O&M costs for Npdist, \$/MG

Aquifer storage and recovery (ASR)

ASR costs may represent the conveyance and injection infrastructure necessary to operate an ASR facility or it may also include treatment required by an injection permit or other operational requirements. In this version of WMOST, only one capital and one O&M cost may be specified for ASR. In future versions, separate costs may be programmed for each source depending on the need for treatment (e.g., water from a WRF likely does not need treatment while water from surface water or reservoir likely needs some treatment prior to injection to prevent clogging of the injection well and/or aquifer and/or to meet permit requirements).

$$C_{ATAsr} = (F_{AsrExist} \times C_{CAsr} \times Q_{AsrMaxI}) + (F_{AsrNew} \times C_{CAsr} \times bQ_{AsrAddl}) + (F_{YrsModel} \times C_{OmAsr} \times \sum_t (bQ_{WrfAsr,t} + bQ_{SwAsr,t} + bQ_{ResAsr,t})) \quad (125)$$

$$bQ_{SwAsr,t} + bQ_{ResAsr,t} + bQ_{WrfAsr,t} \leq Q_{AsrMaxI} + bQ_{AsrAddl} \quad (126)$$

where

C_{ATAsr}	=	total annual costs for ASR, \$/year
$F_{AsrExist}$	=	annualization factor based on remaining lifetime of existing facilities
C_{CAsr}	=	capital costs for ASR, \$/MGD
C_{OmAsr}	=	operation and maintenance costs of ASR, \$/MG
$Q_{AsrMaxI}$	=	existing maximum capacity for ASR, MGD
F_{AsrNew}	=	annualization factor for new or additional capacity
$bQ_{AsrAddl}$	=	new or additional capacity, MGD

Groundwater Storage and Discharge

For groundwater, the minimum storage volume may be specified to reflect the maximum desired drawdown (e.g., to avert land subsidence). The maximum volume may also be specified to reflect the size of the aquifer and the maximum storage capacity.

$$V_{Gw,Min} \leq V_{Gw,t} \leq V_{Gw,Max} \quad (127)$$

where

$$\begin{aligned} V_{Gw,Max} &= \text{maximum groundwater storage volume, MG} \\ V_{Gw,Min} &= \text{minimum groundwater storage volume, MG} \end{aligned}$$

If known and desired, the user may set minimum groundwater outflows from the study area. If the optimization solution chooses unrealistic values for groundwater exiting the study area (e.g., large flow one time step and no flow the next time step), then these constraints can help generate more realistic solutions.

$$Q_{GwExtMin,t} \leq bQ_{GwExt,t} \quad (128)$$

where

$$Q_{GwExtMin,t} = \text{minimum groundwater outflow from the basin, MG/time step}$$

WMOST gives the user an option to allow “make up” of water shortfalls within the watershed system by adding water to the groundwater system. This is a virtual flow of water which, if needed during the optimization, indicates that it is otherwise impossible to meet the specified constraints given available resources and management options.

If this option is enabled, the user specifies a large penalty for needing to add this make-up water and this penalty is included when estimating the total cost. Using a penalty that exceeds any of the other available management practices ensures that use of the “make up” water is a last resort during optimization.

$$C_{ATMUGw} = \sum_t F_{YrsModel} \times C_{GwMake} \times bQ_{GwMake,t} \quad (129)$$

where

$$\begin{aligned} C_{ATMUGw} &= \text{total annualized cost of groundwater make-up water, \$/year} \\ C_{GwMake} &= \text{penalty for groundwater make-up water, \$/MG} \end{aligned}$$

Reservoir or Surface Storage (e.g., storage tank and pond)

For the reservoir, the minimum storage volume may be specified to reflect “dead storage” (i.e., what cannot be released from the reservoir) or the quantity that is required to be maintained for emergencies. The maximum volume may be specified to reflect the physical size of the reservoir (note that additional surface water storage capacity is one of the management options in Table 1-1).

$$V_{Res,Min} \leq V_{Res,t} \leq V_{Res,MaxI} + bV_{Res,Addl} \quad (130)$$

where

- $V_{Res,MaxI}$ = maximum reservoir volume, MG
- $bV_{Res,Addl}$ = additional surface water storage capacity, MG
- $V_{Res,Min}$ = minimum reservoir storage volume (i.e., “dead storage”), MG

The cost for additional reservoir storage is defined as follows:

$$C_{ATRes} = (F_{Plan} \times C_{CRes} \times bV_{Res,Addl}) + (F_{YrsModel} \times C_{OmRes} \times \sum_t (bV_{Res,Addl} + V_{Res,MaxI})) \quad (131)$$

where

- C_{ATRes} = total annual costs for reservoir/surface storage, \$/year
- C_{CRes} = capital costs of new or additional reservoir capacity, \$/MG
- C_{OmRes} = annual O&M cost for reservoir, \$/MG/year

WMOST gives the user an option to allow “make up” of water shortfalls within the watershed system by adding water to the reservoir located at the outlet of the watershed. This is a virtual flow of water which, if needed during the optimization, indicates that it is otherwise impossible to meet the specified constraints given available resources and management options. For example, more water may be necessary to meet specified in-stream flow targets in cases where runoff, recharge, and inflow are insufficient on certain days.

If this option is enabled, the user specifies a large financial penalty for needing to add this make-up water and this penalty is included when estimating the total cost. Using a penalty that exceeds the cost of any of the other available management practices ensures that use of the “make up” water is a last resort during optimization.

$$C_{ATMUW} = \sum_t F_{YrsModel} \times C_{WMake} \times bQ_{WMake,t} \quad (132)$$

where

- C_{ATMUW} = total annualized cost of make-up water, \$/year
- C_{WMake} = penalty for make-up water, \$/MG

In-stream Flow and Surface Water Discharges

Minimum and maximum flows may be specified for the surface water reach and for flows exiting the reservoir and basin. These constraints can be used to ensure that minimum flow targets are met or that peak flows are not exceeded.

$$Q_{SwMin,t} \leq Q_{SwRes,t} \quad (133)$$

$$Q_{SwMax,t} \geq Q_{SwRes,t} \quad (134)$$

$$Q_{SwExtMin,t} \leq bQ_{SwExt,t} \quad (135)$$

$$Q_{SwExtMax,t} \geq bQ_{SwExt,t} \quad (136)$$

where

$Q_{SwMin,t}$ = minimum in-stream flow for basin reach, ft³/sec

$Q_{SwMax,t}$ = maximum in-stream flow for basin reach, ft³/sec

$Q_{SwExtMin,t}$ = minimum flow exiting the reservoir and basin, ft³/sec

$Q_{SwExtMax,t}$ = maximum flow exiting the reservoir and basin, ft³/sec

Interbasin Transfer (IBT) for Water and Wastewater

Maximum IBT flows can be specified as daily, monthly, and/or annual limits. IBT may be excluded by the user or additional IBT volume may be purchased.

Exclude IBT

If the user excludes IBT as a management option by entering -9 for the purchase cost of IBT, then the associated flows and costs are declared equal to zero.

If $C_{IbtW} < 0$, then

$$bQ_{IbtWUseP,t} = 0 \quad (137)$$

$$bQ_{IbtWUseNp,t} = 0 \quad (138)$$

$$C_{ATIbtW} = 0 \quad (139)$$

where

C_{IbtW} = cost of purchasing IBT water, \$/MG

C_{ATIbtW} = total annualized cost of interbasin transfer of water, \$/year

If $C_{IbtWw} < 0$, then

$$bQ_{UsePIbtWw,t} = 0 \quad (140)$$

$$bQ_{UseNPIbtWw,t} = 0 \quad (141)$$

$$C_{ATIbtWw} = 0 \quad (142)$$

where

$$\begin{aligned} C_{IbtWw} &= \text{cost of IBT wastewater services, \$/MG} \\ C_{ATbtWw} &= \text{total annualized cost of interbasin transfer of wastewater, \$/year} \end{aligned}$$

If IBT is allowed as a management option, the user may specify a limit on IBT flows as daily, monthly, and/or annual limits. In addition, the user may specify whether additional volume may be purchased to increase these limits and the limit to the additional volume. The user may also enter -9 for any limit to indicate no limit.

Additional volume limits

If the user excludes the option to purchase additional volume, the additional volume is set to zero.

$$\text{If } C_{IbtW} < 0, \text{ then } bQ_{IbtWAddl} = 0 \quad (143)$$

$$\text{If } C_{IbtWw} < 0, \text{ then } bQ_{IbtWwAddl} = 0 \quad (144)$$

If the user specifies a limit for the additional volume that may be purchased, then the constraint is written. Otherwise the constraint is not written and the volume is unlimited.

$$\text{If } Q_{IbtWAddlMax} \geq 0, \text{ then } bQ_{IbtWAddl} \leq Q_{IbtWAddlMax} \quad (145)$$

$$\text{If } Q_{IbtWwAddlMax} \geq 0, \text{ then } bQ_{IbtWwAddl} \leq Q_{IbtWwAddlMax} \quad (146)$$

where

$$\begin{aligned} Q_{IbtWAddlMax} &= \text{maximum additional IBT water capacity, MGD} \\ bQ_{IbtWAddl} &= \text{additional IBT water capacity, MGD} \\ Q_{IbtWwAddlMax} &= \text{maximum additional IBT wastewater capacity, MGD} \\ bQ_{IbtWwAddl} &= \text{additional IBT wastewater capacity, MGD} \end{aligned}$$

Depending on the combinations of existing limits specified, the constraints listed below will exist in the model **for each time step in the period of analysis**.

Daily specification of existing IBT limits

For a **daily** time step model, the daily limits apply as follows.

If $Q_{IbtWMaxDay} \geq 0$, then

$$bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq Q_{IbtWMaxDay} + bQ_{IbtWAddl} \quad (147)$$

Else if $Q_{IbtWMaxDay} < 0$, then no constraints are specified and flow may be unlimited.

If $Q_{IbtWwMaxDay} \geq 0$, then

$$bQ_{UsePIbtWw,t} + bQ_{UseNPIbtWw,t} \leq Q_{IbtWwMaxDay} + bQ_{IbtWwAddl} \quad (148)$$

Else if $Q_{IbtWwMaxDay} < 0$, then no constraints are specified and flow may be unlimited.

For a **monthly** time step model, the daily values are multiplied up to a monthly value as follows.

If $Q_{IbtWMaxDay} \geq 0$, then

$$\begin{aligned} bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \\ \leq Q_{IbtWMaxDay} \times NDay(month(t)) + bQ_{IbtWAddl} \times NDay(month(t)) \end{aligned} \quad (149)$$

Else if $Q_{IbtWMaxDay} < 0$, then no constraints are specified and flow may be unlimited.

If $Q_{IbtWwMaxDay} \geq 0$, then

$$\begin{aligned} bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \\ \leq Q_{IbtWwMaxDay} \times NDay(month(t)) + bQ_{IbtWwAddl} \times NDay(month(t)) \end{aligned} \quad (150)$$

Else if $Q_{IbtWwMaxDay} < 0$, then no constraints are specified and flow may be unlimited.

where

- $Q_{IbtWMaxDay}$ = maximum potable water transfers from/to outside the basin for each day in the optimization period, MGD
- $Q_{IbtWwMaxDay}$ = maximum potable wastewater transfers from/to outside the basin for each day in the optimization period, MGD
- $NDay(month(t))$ = number of days in the month

Monthly specification of existing IBT limits

Since the period of analysis may start and/or end on a day other than the start or end of a month, the monthly limits are prorated to keep the limits accurate for partial months in the modeling time period.

For a **daily** time step model, the monthly limit is prorated for the number of days in the month and the additional capacity limit is multiplied by the number of days in that month of the modeling period.

If $Q_{IbtWMaxMonth,m} \geq 0$, then

$$\begin{aligned} \sum_{t=1 \text{ to } NdtM} bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \\ \leq Q_{IbtWMaxMonth,m} \times \frac{NdtM}{NDay(month(t))} + bQ_{IbtWAddl} \times NdtM \end{aligned} \quad (151)$$

Else if $Q_{IbtWMaxMonth,m} < 0$, then no constraints are specified and flow may be unlimited.

If $Q_{IbtWwMaxMonth,m} \geq 0$, then

$$\begin{aligned} \sum_{t=1 \text{ to } NdtM} bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \\ \leq Q_{IbtWwMaxMonth,m} \times \frac{NdtM}{NDay(month(t))} + bQ_{IbtWwAddl} \times NdtM \end{aligned} \quad (152)$$

Else if $Q_{IbtWwMaxMonth,m} < 0$, then no constraints are specified and flow may be unlimited.

where

- $Q_{IbtWMaxMonth,m}$ = maximum potable water transfers from/to outside the basin for each month, m, MG/month

$Q_{IbtWwMaxMonth,m}$ = maximum potable wastewater transfers from/to outside the basin for each month, m, MG/month
 $NdtM$ = number of time steps in the month

For the **monthly** time step model, the additional capacity limit is multiplied by the number of days in the month.

If $Q_{IbtWwMaxMonth,m} \geq 0$, then

$$bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq Q_{IbtWwMaxMonth,m} + bQ_{IbtWwAddl} \times NDay(month(t)) \quad (153)$$

Else if $Q_{IbtWwMaxMonth,m} < 0$, then no constraints are specified and flow may be unlimited.

If $Q_{IbtWwMaxMonth,m} \geq 0$, then

$$bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq Q_{IbtWwMaxMonth,m} + bQ_{IbtWwAddl} \times NDay(month(t)) \quad (154)$$

Else if $Q_{IbtWwMaxMonth,m} < 0$, then no constraints are specified and flow may be unlimited.

Annual specification of existing IBT limits

For both the daily and monthly time step models, the annual limits are prorated for the number of time steps in the year within the period of analysis. The maximum, additional, and daily volume is multiplied up to annual value then prorated for the number of time steps in the year within the period of analysis.

For a **daily** time step model,

If $Q_{IbtWwMaxYr} \geq 0$, then

$$\sum_{t=1 to Ndt} bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq Q_{IbtWwMaxYr} \times \frac{NdtYr}{NDay(year(t))} + bQ_{IbtWwAddl} \times NdtYr \quad (155)$$

Else if $Q_{IbtWwMaxYr} < 0$, then no constraints are specified and flow may be unlimited.

If $Q_{IbtWwMaxYr} \geq 0$, then

$$\sum_{t=1 to Ndt} bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq Q_{IbtWwMaxYr} \times \frac{NdtYr}{NDay(year(t))} + bQ_{IbtWwAddl} \times NdtYr \quad (156)$$

Else if $Q_{IbtWwMaxYr} < 0$, then no constraints are specified and flow may be unlimited.

For a **monthly** time step model,

If $Q_{IbtWwMaxYr} \geq 0$, then

$$\sum_{t=1 \text{ to } Ndt} bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq Q_{IbtWMaxYr} \times \frac{NdtYr}{12} + bQ_{IbtWAddl} \times NDay(year(t)) \times \frac{NdtYr}{12} \quad (157)$$

Else if $Q_{IbtWMaxYr} < 0$, then no constraints are specified and flow may be unlimited.

If $Q_{IbtWwMaxYr} \geq 0$, then

$$\sum_{t=1 \text{ to } Ndt} bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq Q_{IbtWwMaxYr} \times \frac{NdtYr}{12} + bQ_{IbtWwAddl} \times NDay(year(t)) \times \frac{NdtYr}{12} \quad (158)$$

Else if $Q_{IbtWwMaxYr} < 0$, then no constraints are specified and flow may be unlimited.

where

- $Q_{IbtWMaxYr}$ = maximum potable water transfers from/to outside the basin for a given year in the optimization period, MG/year
 $Q_{IbtWwMaxYr}$ = maximum potable wastewater transfers from/to outside the basin for a given year in the optimization period, MG/year
 $NdtYr$ = number of time steps in the year
 $NDay(year(t))$ = number of days in the year

As shown in Figure 1-1, IBT water is routed directly to water users and is assumed to be treated, potable water. Therefore, costs should reflect the total cost of purchasing and delivering IBT water to users. The total annual cost of interbasin transfer of imported potable water, C_{ATIbtW} , is calculated as:

$$C_{ATIbtW} = F_{Plan} \times C_{CIbtW} \times bQ_{IbtWAddl} + F_{YrsModel} \times C_{IbtW} \times \sum_t (bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t}) \quad (159)$$

where

- C_{CIbtW} = initial cost of purchasing additional water rights for IBT and construction of necessary infrastructure, \$/MGD

IBT wastewater is transferred directly from users to the service provider outside of the basin; therefore, costs should reflect the collection and transport of wastewater from users to the out of basin provider. The total annual cost of exporting wastewater via interbasin transfer, $C_{ATIbtWw}$, is calculated as:

$$C_{ATIbtWw} = F_{Plan} \times C_{CIbtWw} \times bQ_{IbtWwAddl} + F_{YrsModel} \times C_{IbtWw} \times \sum_t (bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t}) \quad (160)$$

where

- C_{CIbtWw} = initial cost of purchasing additional wastewater transfer rights for IBT and construction of necessary infrastructure, \$/MGD

Flood Damages

The annualized cost of damage from flood flow is calculated as the damage times the inverse of the recurrence interval of the flow:

$$C_{FA_n} = C_{F_n} \times \frac{1}{T_n} \quad \text{for } Q_n \quad (161)$$

where

C_{FA_n}	=	annualized cost of damage caused by flood flow n , \$/year
C_{F_n}	=	cost of damage caused by flood flow n , \$
T_n	=	recurrence interval of flood flow n , years
Q_n	=	flood flow n , ft ³ /sec
n	=	one element of the sets of flood flow data entered by user

Linear interpolation between flood flow and annualized damage cost provides a linear cost curve for a specific flow interval. With a minimum of three sets of input data for the flood damage modeling, there will be at least two equations representing the damages corresponding to possible flows. Flow below the lowest flood flow specified is assumed to cause no flood damages. Flow above the largest flood flow specified is assumed to cause the same damage as the largest specified flood flow. The final total flood damages incurred over the modeling period is the sum of all flows that cause flood damages as calculated by the appropriate corresponding cost curve:

$$C_{FA} = \sum_t (m_{F_{n12}} \times Q_{SwRes,t} + b_{F_{n12}}) \quad \text{for flow between } Q_n \text{ and } Q_{n+1} \quad (162)$$

where

C_{FA}	=	annualized cost of damage caused by flood flows over the modeling time period, \$/year
$m_{F_{n12}}, b_{F_{n12}}$	=	constants of equation describing linear interpolation between Q_n and Q_{n+1}
$Q_{SwRes,t}$	=	flow in the stream channel, ft ³ /sec

Combined Sewer Overflow Management

WMOST defines CSO events as instances where the volume of runoff routed to the combined sewer exceeds the user-defined hydraulic control capacity of the sewers from HRU areas serviced by the combined sewer system (CSS) and/or the sum of the runoff flowing through the combined sewer, flows from potable and nonpotable water users, and groundwater infiltration exceeds the hydraulic control capacity of the interceptor sewer connected to the wastewater treatment plant³⁴. If more than the user specified maximum number of CSO events occurs, then WMOST will utilize stormwater management BMPs and CSO control methods to decrease the number of sewer overflow events. The CSO control methods discussed in this section include sewer separation and offline storage. See Section 4 for additional information on the CSO Module.

Sewer separation

A CSS is a sewer system that conveys both stormwater and sewage (EPA 1994). CSS separation allows for stormwater to be separately conveyed to surface water bodies (via a storm sewer) and

³⁴ The WMOST user may also use the WWTP treatment capacity.

sanitary waste to be conveyed to a treatment plant (via a sanitary sewer). Within WMOST, the model will be able to choose what fraction of the CSS is separated, which will be constrained by facility capacity and costs. The equation for the cost of sewer separation is defined as follows:

$$C_{ATC\text{SewSep}} = F_{C\text{SewSepNew}} \times C_{CC\text{SewSep}} \times [Q_{\text{SansMax}} + Q_{\text{StMax}}] \times \left(1 - \frac{bP_{CS}}{100}\right) \quad (163)$$

where

bP_{CS}	=	percentage of sewer system that is combined, %
Q_{SansMax}	=	maximum sanitary sewer capacity, MGD
Q_{StMax}	=	maximum storm sewer capacity, MGD
$C_{ATC\text{SewSep}}$	=	total annual costs for sewer separation, \$/year
$F_{C\text{SewSepNew}}$	=	annualization factor for new facilities
$C_{CC\text{SewSep}}$	=	capital costs for sewer separation, \$/MGD

Offline storage

Off-line storage is used during wet weather events to temporarily detain sewage and decrease the volume reaching the WWTP at once. The detained volume is released to the system once treatment capacity becomes available. The cost and capacity equations related to offline storage include a *virtual* daily charge to limit unnecessary flows through the offline storage facility and ensure that the volume is released to the WWTP as rapidly as practicable (the price signal essentially goes against the model's effort to minimize total costs). The equation for the cost of offline storage is defined as follows:

$$C_{ATOS} = F_{YrsModel} \times C_{OmOS} \times \sum_t bD_{OS,t} \times k_{VC} + V_{OSTotal,t} \quad (164)$$

where

$V_{OSTotal,t}$	=	total volume in offline storage, MG (initial offline storage volume is 0)
$bD_{OS,t}$	=	binary decision variable for use of offline storage, 0 or 1
C_{ATOS}	=	total annual costs for offline storage, \$/year
k_{VC}	=	virtual daily charge, \$
C_{OmOS}	=	O&M costs for use of offline storage, \$/MG

The offline storage volume balance and facility constraint equations are as follows:

$$V_{OSTotal,t} = (V_{OSTotal,t-1} + bD_{OS,t} \times bQ_{CSOS,t} - bQ_{OSWwtp,t}) \times \Delta t \quad (165)$$

$$V_{OSTotal,t} \leq V_{OSMax} \quad (166)$$

where

$bQ_{CSOS,t}$	=	flow from combined sewer to offline storage, MG/time step
$bQ_{OSWwtp,t}$	=	flow from offline storage to WWTP, MG/time step
V_{OSMax}	=	maximum offline storage capacity, MG

3.4 Costs and Constraints Associated with Loadings Management Options

Infrastructure Capacity and Use

As mentioned in Section 3.3, if modeling for hydrology and loadings, the model assumes that the capital and operation and maintenance costs input by the user for the various model components appropriately reflect the hydrologic and water quality treatment performance of each component, as applicable.

Water treatment plant (WTP)

If the user allows for upgraded treatment at the WTP as a management option, a capital cost for new construction will be incurred if upgraded treatment is needed. Therefore, the cost equation for the upgraded treatment is defined as follows:

$$C_{ATUWtp} = F_{UWtpNew} \times C_{CUWtp} \times Q_{WtpMaxI} \times bP_{UWtp} \quad (167)$$

where

bP_{UWtp}	=	portion of flows receiving upgraded treatment at WTP, %
C_{ATUWtp}	=	total annual costs for upgraded water treatment, \$/year
C_{CUWtp}	=	capital costs of upgraded water treatment capacity, \$/MGD
$F_{UWtpNew}$	=	annualization factor for new upgraded water treatment capacity

If the user includes upgraded treatment at the WTP as a management option, the optimization model may have a proportion of the loadings to the water treatment plant receive upgraded treatment in order to meet in-stream target concentrations. The user indicates the average effluent concentration ($X_{UWtpOut}$) achieved by the upgraded treatment, which is used to calculate the reduced loadings from the WTP facility to potable and nonpotable water users and what is lost through leakage in the treated water distribution system. Loadings receiving upgraded treatment are subject to the same physical capacity constraints as the WTP.

The changes to the WTP loadings equations would be as follows:

$$L_{WtpUseP,t} = [(1 - bP_{UWtp}) \times Q_{WtpUseP,t} \times X_{WtpOut}] + [bP_{UWtp} \times Q_{WtpUseP,t} \times X_{UWtpOut}] \quad (168)$$

$$L_{WtpUseNp,t} = [(1 - bP_{UWtp}) \times bQ_{WtpUseNp,t} \times X_{WtpOut}] + [bP_{UWtp} \times bQ_{WtpUseNp,t} \times X_{UWtpOut}] \quad (169)$$

$$L_{WtpGw,t} = [(1 - bP_{UWtp}) \times Q_{WtpGw,t} \times X_{WtpOut}] + [bP_{UWtp} \times Q_{WtpGw,t} \times X_{UWtpOut}] \quad (170)$$

where

$X_{UWtpOut}$	=	average effluent concentration achieved by upgraded water treatment, mg/L
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Wastewater treatment plant (WWTP)

If the user allows for upgraded treatment at the WWTP as a management option, a capital cost for new construction will be incurred if upgraded treatment is needed. Therefore, the cost equation for the upgraded treatment is defined as follows:

$$C_{ATUWwtp} = F_{UWwtpNew} \times C_{CUWwtp} \times bP_{UWwtp} \times Q_{WwtpMaxI} \quad (171)$$

where

- bP_{UWwtp} = portion of flows receiving upgraded treatment at WWTP, %
- $C_{ATUWwtp}$ = total annual costs for upgraded wastewater treatment, \$/year
- C_{CUWwtp} = capital costs of upgraded wastewater treatment capacity, \$/MGD
- $F_{UWwtpNew}$ = annualization factor for new upgraded wastewater treatment capacity

If the user includes upgraded treatment at the WWTP as a management option, the optimization model may have a proportion of the loadings flowing to the water treatment plant receive upgraded treatment in order to meet in-stream target concentrations. The user indicates the average effluent concentration ($X_{UWwtpOut}$) achieved by the upgraded treatment, which is used to calculate the reduced loadings to the water reuse facility and reduced loadings associated with groundwater infiltration into the wastewater collection system. Loadings receiving upgraded treatment are subject to the same physical capacity constraints as the WWTP.

The changes to the WWTP loadings equations would be as follows:

$$L_{WwtpSw,t} = [(1 - bP_{UWwtp}) \times Q_{WwtpSw,t} \times X_{WwtpOut}] + [bP_{UWwtp} \times Q_{WwtpSw,t} \times X_{UWwtpOut}] \quad (172)$$

$$L_{WwtpWrf,t} = [(1 - bP_{UWwtp}) \times bQ_{WwtpWrf,t} \times X_{WwtpOut}] + [bP_{UWwtp} \times bQ_{WwtpWrf,t} \times X_{UWwtpOut}] \quad (173)$$

where

- $X_{UWwtpOut}$ = average effluent concentration achieved by upgraded wastewater treatment, mg/L

Enhanced septic

If additional treatment is required for the septic system (i.e., enhanced treatment), the following cost equation describes the total annual costs. Costs incurred are based on the amount of flows, and correspondingly, loadings chosen by the model to receive enhanced treatment.

Flow through the enhanced septic system cannot exceed the user-defined maximum capacity of the system.

$$C_{ATESep} = F_{Plan} \times C_{OmESep} \times \sum_t Q_{ESep,t} \quad (174)$$

$$Q_{ESep,t} = bP_{ESep} \times (Q_{UsePSep,t} + Q_{UseNPSep,t}) \quad (175)$$

$$Q_{ESep} \leq Q_{ESepMax} \quad (176)$$

where

- C_{ATESep} = total annual costs for enhanced septic system, \$/year
- C_{OmESep} = O&M costs for enhanced septic system, \$/MG
- bP_{ESep} = portion of flows routed for enhanced treatment within the septic system, %
- $Q_{ESepMax}$ = maximum enhanced septic system capacity, MGD

The user indicates the average effluent concentration (X_{ESepF}) achieved by the enhanced septic system. The average effluent constituent concentration is used to calculate the loadings to the groundwater system.

The changes to the septic system loadings equations would be as follows:

$$L_{SepGw,t} = [(1 - bP_{ESep}) \times Q_{SepGw,t} \times X_{SepF}] + [(bP_{ESep}) \times Q_{SepGw,t} \times X_{ESepF,t}] \quad (177)$$

Surface Water and Reservoir

The WMOST user can specify a target concentration or loading to meet in the stream reach and reservoir.

Target concentrations

$$X_{SwF,t} \leq X_{SwTarget} \quad (178)$$

$$X_{ResF,t} \leq X_{ResTarget} \quad (179)$$

where

$X_{SwTarget}$ = surface water target concentration, mg/L
 $X_{ResTarget}$ = reservoir target concentration, mg/L

Target loadings

$$L_{Sw,t} \leq L_{SwTarget} \quad (180)$$

$$L_{Res,t} \leq L_{ResTarget} \quad (181)$$

where

$L_{SwTarget}$ = surface water target loadings, lbs/time step
 $L_{ResTarget}$ = reservoir target loadings, lbs/time step

Runoff Loadings Direct Reduction

There are four BMP types available for modeling in WMOST v3 that directly reduce runoff loadings: 1) Riparian Buffers, 2) Street Sweeping, 3) Tree Canopy, and 4) Urban Nutrient Management. The modeling approach for riparian buffers is unique; thus, we discuss riparian buffers separately from the latter three direct reduction options.

Riparian buffers

Riparian buffers are vegetated areas adjacent to water bodies that are used to reduce excess nutrients and sediment in surface runoff from land areas that are upgradient to the buffer area (USDA 2009). Riparian buffers intercept and slow surface runoff from the upgradient land areas, which allows vegetation to absorb nutrients and sediment to settle out before the pollutants reach the stream.

WMOST users may want to analyze the effects of land use conversions in riparian zones to and from more developed land uses in order to calculate the benefits of riparian buffer management. These benefits can arise both from reductions in runoff and pollutant loadings associated with management

of the riparian area itself, and from the removal of pollutants contributed by upgradient land areas. Table 3-1 provides examples of different riparian buffer management scenarios and their effect on in-stream loadings.

Table 3-1: Scenario Options and Costs for Modeling Riparian Buffer and Riparian Buffer Land Conversion Co-benefits and Trade-offs

Initial Land Use	Converted Land Use	Effect on Loadings	Type of Costs Associated with Land Conversion
Forested Buffer	Conserved Forested Buffer	No additional reduction in loads beyond modeled land use time series	Land Conservation Cost
Agricultural Buffer	Forested Buffer	Reduction in loads based on land conversion and reduction in upgradient loads	Land Restoration Cost, and Land Conservation Cost (optional)
Developed Buffer	Forested Buffer	Reduction in loads based on land conversion and reduction in upgradient loads	Land Restoration Cost, and Land Conservation Cost (optional)
Forested Buffer	Agricultural Buffer	Increase in loads associated with land conversion and loss in riparian buffer function	No associated cost, or negative cost to represent economic benefit of change
Forested Buffer	Developed Buffer	Increase in loads associated with land conversion and loss in riparian buffer function	No associated cost, or negative cost to represent economic benefit of change

Unlike other BMPs for which the treated area and BMP implementation location are coincident, riparian buffers are implemented on a given plot of land. Buffers treat not only the runoff from that land, but as explained above, also that of all upgradient land. The effects of different types of riparian buffers on in-stream pollutant loadings first account for any changes in runoff and recharge hydrologic flows and loadings from land use conversion (of the land to be converted or conserved as riparian buffer). A percent adjustment in the runoff loadings is also applied to the HRU areas located upgradient from that riparian buffer. Since the combination of HRU areas upgradient from a riparian buffer determine the amount of loads delivered to the buffer, WMOST allows for the area of each possible land use conversion to be divided into (up to) five different relative loads groups (i.e., high, medium, and low loads).

Without the consideration of riparian buffers, the runoff flows and loadings equations within WMOST summed loadings from baseline HRU areas and managed set areas. With the addition of riparian buffers as a management option, the runoff flows and loadings equations from all HRU areas sum the following components (see equations below):

1. Unadjusted loadings from the converted/conserved buffer area;
2. Unadjusted loadings from baseline and managed set areas that are not upgradient of the buffer area; and
3. Percent adjusted loadings from baseline and managed set areas upgradient of the buffer area.

Costs for riparian buffers will depend on the HRU conversion selected by the user and specified on a per acre basis, as shown in the equation below. Table 3-1 shows the set of land use conversions that may be modeled and the type of costs associated with the land conversion.

$$C_{ATRB} = \sum_{c=1}^{NRipConv} \sum_{g=1}^{NRipLoads} [(F_{plan} \times C_{CCRB,c} + C_{OMRB,c}) \times A_{RB,c,g} \times bD_{RB,c,g}] \quad (182)$$

where

C_{ATRB}	=	total annual costs for riparian buffer implementation, \$/year
c	=	land use conversion number
$NRipConv$	=	total number of possible land use conversions
g	=	relative loads group
$NRipLoads$	=	total number of relative loads groups
$C_{CCRB,c}$	=	initial cost to convert riparian land area, \$/acre
$C_{OMRB,c}$	=	O&M cost for riparian land area conversion, \$/acre/year
$A_{RB,c,g}$	=	riparian land area for each land use conversion and relative loads group, acres
$bD_{RB,c,g}$	=	binary decision variable for each land use conversion and relative loads group, 0 or 1

Changes (shown in red) to runoff flow and loadings equations are defined as follows:

$$Q_{Ru,t} = \sum_{l=1}^{NLu} (bA_{l,s=1} \times Q_{Ru,l,s=1,t}) + \sum_{c=1}^{NRipConv} \sum_{g=1}^{NRipLoads} \sum_{l=1}^{NLu} \pm A_{RB,c,g} \times bD_{RB,c,g} \times Q_{Ru,l,s=1,t} + \sum_{s=2}^{NSet} \sum_{l=1}^{NLu} ((Q_{Ru,l,s,t} - Q_{Ru,l,s=1,t}) \times bA_{l,s}) \quad (183)$$

The \pm symbol indicates that the runoff contribution from the riparian land area is positive or negative depending on whether the HRU is one that users are converting to or converting from.

Baseline loadings for HRUs:

$$L_{Ru,t} = \sum_{l=1}^{NLu} (bA_{l,s=1} \times L_{Ru,l,s=1,t}) + \sum_{s=1}^{NLuSet} \sum_{l=1}^{NLu} [bA_{l,s} \times (L_{Ru,l,s,t} - L_{Ru,l,s=1,t})] \quad (184)$$

Loadings for HRUs that are upgradient to a buffer area that experience a loadings adjustment:

$$L_{RuAdjUp,t} = \sum_{c=1}^{NRipConv} \sum_{l=1}^{NLu} L_{Ru,l,s=1,t} \times bA_{l,s=1} \times \sum_{g=1}^{NRipLoads} F_{RBArea,l,g} \times (P_{RBAAdj,c}) \times bD_{RB,c,g} + \sum_{s=1}^{NLuSet} \sum_{c=1}^{NRipConv} \sum_{l=1}^{NLu} bA_{l,s} \times \left[(L_{Ru,l,s,t} - L_{Ru,l,s=1,t}) \times \left(\sum_{g=1}^{NRipLoads} F_{RBArea,l,g} \times (P_{RBAAdj,c}) \times bD_{RB,c,g} \right) \right] \quad (185)$$

where

- $L_{RuAdjUp,t}$ = loadings from HRUs upgradient to a buffer area that have a loadings adjustment, lbs/time step
 $F_{RBArea,l,g}$ = fraction of HRU land use area that is upgradient from the riparian buffer for each land use and relative loads group
 $P_{RBAAdj,c}$ = load adjustment efficiency for each land use conversion, %

Loadings for HRU land areas that are riparian buffer conversions:

For HRU areas that users are converting from

$$L_{RuAdd,t} = \sum_{c=1}^{NRipConv} \sum_{l=1}^{NLu} \sum_{g=1}^{NRipLoads} (-A_{RB,c,g} \times bD_{RB,c,g}) \times L_{Ru,l,s=1,t} \quad (186)$$

For HRU areas that users are converting to

$$L_{RuAdd,t} = \sum_{c=1}^{NRipConv} \sum_{l=1}^{NLu} \sum_{g=1}^{NRipLoads} (A_{RB,c,g} \times bD_{RB,c,g}) \times L_{Ru,l,s=1,t} \quad (187)$$

where

- $L_{RuAdd,t}$ = loadings changes from converted HRU land areas, lbs/time step

Changes (shown in red) to surface water loadings and storm sewer loadings equations are defined as follows:

Storm sewer loadings

$$L_{StSSw,t} = L_{UseNpSewer,t} + L_{Ru,t} + L_{RuAdjUp,t} \quad (188)$$

Surface water loadings

$$L_{Sw,t} = L_{StSSw,t} + L_{RuAdd,t} + L_{ExtSw,t} + L_{PtSw,t} + L_{GWSw,t} + L_{WwtpSw,t} + L_{WrfSw,t} \quad (189)$$

Street sweeping, tree canopy, and urban nutrient management

Street sweeping, increasing tree canopy, and urban nutrient management are BMPs that can directly reduce runoff loadings (definitions in Table 3-2).

Table 3-2: Description of Loadings Direct Reduction BMPs

BMP Type	BMP Description
Street Sweeping	Pavement cleaning practices to minimize pollutant export to urban waterways by removing sediment debris and other pollutants (EPA 2004)
Tree Canopy	Tree canopy in urban areas can help improve water quality by filtering pollutants. (EPA 2016)
Urban Nutrient Management	Identifying how the major plant nutrients are to be annually managed to minimize adverse environmental effects upon water quality and avoid unnecessary nutrient applications (CBP 2012)

Costs for street sweeping, tree canopy over turf/impervious land, and urban nutrient management will depend on the acres treated by the management practice, as shown in the general equation below.

$$C_{ATDR} = \sum_{d=1}^{NDRSet} bD_{DR,d} \times \sum_{l=1}^{NLu} (F_{YrsModel} \times C_{CDR,l,d} + C_{OmDR,l,d}) \times A_{DR,l,d} \quad (190)$$

where

$C_{ATDR,d}$	=	total annual costs for direct reduction set, d , \$/year
$C_{CDR,l,d}$	=	capital cost for direct reduction on HRU, l , in direct reduction set, d , \$/acre
$C_{OmDR,l,d}$	=	O&M cost for direct reduction on HRU, l , in direct reduction set, d , \$/acre/year
$A_{DR,l,d}$	=	area receiving treatment within HRU, l , from direct reduction set, d , acres

For each of the three practices, associated percent loading reductions are multiplied by baseline and managed runoff sets to calculate final runoff loadings to surface water as shown in the general equation below.

$$L_{Ru,t} = \sum_{l=1}^{NLu} \left[(bA_{l,s=1} \times L_{Ru,l,s=1,t}) \times \prod_{d=1}^{NDRSet} (1 - (P_{DR,l,d} \times bD_{DR,d})) \right] + \sum_{s=2}^{NLuSet} \sum_{l=1}^{NLu} \left[L_{Ru,l,s,t} - \left(L_{Ru,l,s,t} \times \prod_{d=1}^{NDRSet} P_{DR,l,s} \times bD_{DR,d} \right) - L_{Ru,l,s=1,t} \right] \times bA_{l,s} \quad (191)$$

where

N_{DRSet}	=	number of runoff loadings direct reduction sets
$P_{DR,l,d}$	=	direct reduction for each land use, c , in direct reduction set, d , %
$bD_{DR,d}$	=	binary decision variable for direct reduction set, d , 0 or 1

Any combination of up to three direct reduction BMP sets can be selected. If all three sets are unique (i.e., represent different types of BMPs), then WMOST optimization can turn on all BMPs by setting their respective binary variable to 1. If the user specifies the same type of BMP (e.g., three different treatment levels of street sweeping), then the model will identify and select only the most cost-effective treatment level for any given treated land area.

Loadings Target Adjustment

Since the stream reach component within WMOST does not have storage and equations only track what is flowing in and out of the system with each time step, constituent loadings from in-stream sources or outfalls are not explicitly defined and tracked. Therefore, BMPs that reduce loadings from in-stream sources or outfalls but do not affect hydrologic flows, such as streambank stabilization/restoration, outfall stabilization, and outfall enhancement, are modeled in WMOST by crediting the loading reduction directly out of the targets specified by the user. This approach essentially reduces the stringency of the loading target specified by the user, at a cost of implementing these BMPs.

Streambank stabilization/restoration

Streambank stabilization, or streambank restoration, is a non-structural on-channel BMP that aims to restore and protect streambanks from erosion, thereby reducing sediment and nutrient loadings to the waterbody. This practice uses vegetative plantings, soil bioengineering, and structural systems to prevent erosion.

The total annual streambank stabilization/restoration cost varies in proportion with the number of stream feet restored that is determined by the model during optimization.

$$C_{ATSR} = F_{YrsModel} \times C_{CSR} \times bFt_{Str} \quad (192)$$

where

C_{ATSR}	=	total annual cost for streambank restoration loadings target adjustments, \$/year
C_{CSR}	=	capital cost for loadings target adjustment BMP, \$/stream feet restored
bFt_{Str}	=	number of stream feet restored or number of outfalls stabilized or enhanced

The management practice is modeled by increasing the in-stream or reservoir loading target constraint equation, which acts as an upper limit on in-stream and reservoir loadings, with the loadings reduction term. The loadings reduction term represents the loadings that were prevented from entering the stream because of the streambank stabilization project; and thus, represent a credit towards meeting the user-specified loadings targets. For streambank stabilization and restoration, the revised target equations and constraint equation are:

$$L_{Sw,t} \leq L_{SwTarget} + L_{RR,SR} \times bFt_{Str} \quad (193)$$

$$L_{Res,t} \leq L_{ResTarget} + L_{RR,SR} \times bFt_{Str} \quad (194)$$

$$bFt_{Str} \leq Ft_{StrMax} \quad (195)$$

where

$L_{RR,SR}$	=	loading removal rate due to streambank restoration, lb/ft/time step
Ft_{StrMax}	=	maximum number of linear stream length that can be stabilized or restored, feet

Outfall stabilization and outfall enhancement

Like streambank stabilization, outfall stabilization and outfall enhancement reduce in-stream constituent loadings contributions by reducing erosion near the outfall. Outfall enhancement includes upgrades to outfall piping, while outfall stabilization is characterized by operation and maintenance of combined sewer outfalls.

The total annual outfall stabilization and/or outfall enhancement cost varies in proportion with the number of outfalls stabilized or enhanced that is determined by the model during optimization.

$$C_{ATOut} = F_{YrsModel} \times C_{COut} \times bN_{Out} \quad (196)$$

where

C_{ATOut}	=	total annual costs for outfall enhancement or stabilization loadings target adjustments, \$/year
C_{COut}	=	capital cost for loadings target adjustment BMP, \$/outfalls stabilized or enhanced
bN_{Out}	=	number of outfalls stabilized or enhanced

The management practice is modeled by using the loadings reduction term to adjust the upper limit on in-stream and reservoir loadings. The loadings reduction term represents the loadings that were prevented from entering the stream because of the outfall stabilization or outfall enhancement project; and thus, represent a credit towards meeting the user-specified loadings targets. For outfall stabilization and outfall enhancement, the revised target equations and constraint equation are:

$$L_{Sw,t} \leq L_{SwTarget} + L_{RR,Out} \times bN_{Out} \quad (197)$$

$$L_{Res,t} \leq L_{ResTarget} + L_{RR,Out} \times bN_{Out} \quad (198)$$

$$bN_{Out} \leq N_{OutMax} \quad (199)$$

where

$L_{RR,Out}$	=	loading removal rate due to outfall enhancement or stabilization, lb/outfall/time step
N_{OutMax}	=	maximum number of outfalls than can be stabilized or enhanced

Total Costs

Total annual costs for all management options, C_{AT} , is calculated as the sum of all annualized capital and O&M costs as defined in Sections 3.3 and 3.4.

$$\begin{aligned}
 C_{AT} = & C_{ATb} + C_{ATm} + C_{ATPrice} + C_{ATDmd} + C_{ATGwPump} + C_{ATSwPump} + C_{ATWtp} + C_{ATUWtp} + \\
 & C_{ATUaw} + C_{ATWwtp} + C_{ATUWwtp} + C_{ATGwWwtp} + C_{ATWrf} + C_{ATNpdist} + C_{ATAsr} + C_{ATESep} + \\
 & C_{ATRes} + C_{ATibtW} + C_{ATibtWw} + C_{ATMUW} + C_{ATMUGw} + C_{FA} + C_{ATCSewSep} + C_{ATOS} + C_{ATRB} + \\
 & C_{ATDR} + C_{ATSR} + C_{ATOut}
 \end{aligned} \quad (200)$$

4. Combined Sewer Overflow Module

The “presumption” approach outlined in EPA’s CSO Control Policy (EPA 1994) states that any system that experiences no more than an average of four overflow events per year, provided that the permitting authority may allow up to two additional overflow events per year, as the result of a precipitation event can be presumed to have the appropriate level of control to meet surface water quality standards.

The Long-Term Control Plan-EZ (LTCP-EZ) template (EPA 2007) is a framework for generalized quantification of CSO volume, cost estimation of various CSO control methods and their impact, and assessment of the affordability of control methods based on the financial capability of the permittee and the residents served by the combined sewer system (CSS).

Using LTCP-EZ concepts, the quantification of CSO volume in order to evaluate the need for and optimize the costs of implementing CSO control methods was incorporated into WMOST through the CSO Module.³⁵ Although EPA’s CSO Control Policy recommends the implementation of management options if a system is experiencing more than an average of four overflow events per year, WMOST users have the ability to specify the maximum allowable number of CSO events per calendar year to represent their state or local CSO policy.

4.1 Combined Sewer System

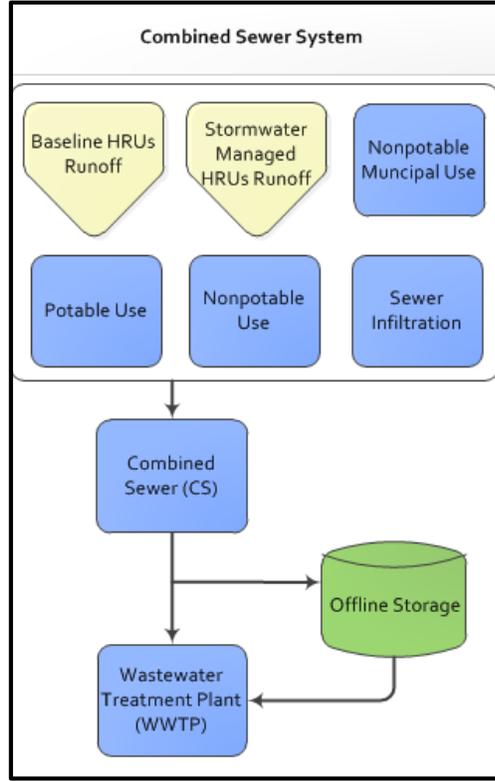
The presence of CSO events is predicated on having a CSS that routes both stormwater runoff and sewage flows from potable and nonpotable water users to a WWTP. Users define the HRU areas that are served by the CSS and the total maximum runoff volume delivered to the interceptor sewer (e.g., large sewer pipes that convey dry weather flow and a portion of wet weather combined sewage flow to the WWTP). Users can also define the capacity of the interceptor sewer, which may or may not be equal to the capacity of the WWTP.

Figure 4-1 highlights the different components and connections that WMOST uses when running the CSO module. Currently, the CSO module is only available when running WMOST without modeling loadings in “Hydrology Only” mode³⁶. Refer to Figure 1-3 to see how the CSO components fit into the overall WMOST flow schematic.

³⁵ Future versions of WMOST may include the incorporation of LTCP-EZ’s methodology for affordability analysis as an analysis of the cost estimates provided by WMOST for the lowest-cost solution.

³⁶ Future versions of WMOST may include the capability to use the CSO module when running WMOST in “Hydrology and Loadings” mode.

Figure 4-1: Schematic of CSO Module Water Flows³⁷



Since the CSO module models different connections between components, the watershed system constraint equations also differ (changes shown in red).

Runoff

The user defines the HRU areas that are served by the CSS, requiring the need for separate runoff equations that route flows either straight to the surface water system, through the CSS, or if modeling sewer separation, through the storm sewer.³⁸

$$Q_{Ru,t} = \sum_{l=1}^{NLu} (bA_{l,s=1} \times Q_{Ru,l,s=1,t}) \times (1 - Fr_{CSS,l}) \tag{201}$$

$$+ \sum_{s=2}^{NLuSet} \sum_{l=1}^{NLu} ((Q_{Ru,l,s,t} - Q_{Ru,l,s=1,t}) \times bA_{l,s} \times (1 - Fr_{CSS,l})) \tag{202}$$

$$Q_{RuCS,t} = \frac{bP_{CS}}{100} \times \sum_{l=1}^{NLu} (bA_{l,s=1} \times Q_{Ru,l,s=1,t}) \times Fr_{CSS,l}$$

$$+ \sum_{s=2}^{NLuSet} \sum_{l=1}^{NLu} ((Q_{Ru,l,s,t} - Q_{Ru,l,s=1,t}) \times bA_{l,s} \times Fr_{CSS,l})$$

³⁷ Potable and nonpotable water use in this schematic and associated equations refers to flows that were not consumed by water users.

³⁸ If the user does not model sewer separation, bP_{CS} is set to 100.

$$Q_{RuStS,t} = \left(1 - \frac{bP_{CS}}{100}\right) \times \sum_{l=1}^{NLu} (bA_{l,s=1} \times Q_{Ru,l,s=1,t}) \times Fr_{CSS,l} \quad (203)$$

$$+ \sum_{s=2}^{NLuSet} \sum_{l=1}^{NLu} ((Q_{Ru,l,s,t} - Q_{Ru,l,s=1,t}) \times bA_{l,s} \times Fr_{CSS,l})$$

where

$Fr_{CSS,l}$	=	fraction of HRU area that is serviced by the CSS
$Q_{RuCS,t}$	=	total runoff from land areas serviced by the CSS, MG/time step
$Q_{RuStS,t}$	=	total runoff from land areas previously serviced by the CSS and currently serviced by a separate storm/sanitary sewer system, MG/time step

Storm Sewer

Runoff flows can be split between the combined sewer and storm sewer when modeling sewer separation, therefore the change to the storm sewer flow equation is defined as follows:

$$Q_{StSSw,t} = \left(1 - \frac{bP_{CS}}{100}\right) \times Q_{UseNpSewer,t} + Q_{RuStS,t} \quad (204)$$

Surface Water

The surface water component may receive loadings from runoff from areas not serviced by a sewer system and, when modeling sewer separation, runoff through the storm sewer as well.

$$Q_{Ru} + Q_{StSSw,t} + Q_{ExtSw,t} + Q_{PtSw,t} + Q_{GWSw,t} + Q_{WwtpSw,t} + Q_{WrfSw,t} \quad (205)$$

$$= Q_{SwRes,t} + bQ_{SwWtp,t} + bQ_{SwAsr,t} + Q_{SwPt,t}$$

Potable Water Use

Flows from the different potable water users, after consumption, can go to either septic systems draining inside and outside of the watershed, out of the watershed via interbasin transfer, through the combined sewer to the WWTP, or if modeling sewer separation, through the separate sanitary sewer to the WWTP.

$$\sum_{u=2}^{NUse} ((Q_{WtpUseP,t} + bQ_{IbtWUseP,t}) \times \left(1 - \frac{P_{ConsUseP,u,t}}{100}\right) \times Fr_{PUse,u,t}) \quad (206)$$

$$= Q_{UsePSep,t} + Q_{UsePSepExt,t} + bQ_{UsePIbtWw,t} + \left(1 - \frac{bP_{CS}}{100}\right)$$

$$\times bQ_{UsePSans,t} + \left(\frac{bP_{CS}}{100}\right) \times bQ_{UsePCS,t}$$

where

$bQ_{UsePCS,t}$	=	flow of potable user flows through the combined sewer to the wastewater treatment plant, MG/time step
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Nonpotable Water Use

Flows from the different nonpotable water users, after consumption, can go to either septic systems draining inside and outside of the watershed, out of the watershed via interbasin transfer, through the combined sewer to the WWTP, or if modeling sewer separation, through the separate sanitary sewer to the WWTP.

$$\begin{aligned} \sum_{u=2}^{NUse} ((bQ_{WtpUseNp,t} + bQ_{WrfUseNp,t} + bQ_{IbtWUseNp,t}) \times \left(1 - \frac{P_{ConsUseNp,u,t}}{100}\right) \times Fr_{NpUse,u,t}) \\ = Q_{UseNpSep,t} + Q_{UseNpSepExt,t} + bQ_{UseNpIbtWw,t} + \left(1 - \frac{bP_{CS}}{100}\right) \\ \times bQ_{UseNpSanS,t} + \left(\frac{bP_{CS}}{100}\right) \times bQ_{UseNpCS,t} \end{aligned} \quad (207)$$

where

$bQ_{UseNpCS,t}$ = flow of nonpotable user flows through the combined sewer to the wastewater treatment plant, MG/time step

If the watershed has municipal water users that send flows directly to the storm sewer, the equation is defined as follows:

$$\begin{aligned} \sum_{u=2}^{NUse} (bQ_{WtpUseNp,t} + bQ_{WrfUseNp,t} + bQ_{IbtWUseNp,t}) \times \left(1 - \frac{P_{ConsUseNp,Municipal,t}}{100}\right) \\ \times Fr_{NpUse,Municipal,t} \times (1 - Fr_{NpUseMunSewer,t}) \\ = Q_{UseNpSep,t} + Q_{UseNpSepExt,t} + bQ_{UseNpIbtWw,t} + \left(1 - \frac{bP_{CS}}{100}\right) \times bQ_{UseNpSanS,t} \\ + \left(\frac{bP_{CS}}{100}\right) \times bQ_{UseNpCS,t} \end{aligned} \quad (208)$$

Sanitary Sewer

Since flows from potable and nonpotable water users can be split between the combined sewer and sanitary sewer when modeling sewer separation, the equations for sanitary sewer flows and capacity are defined as follows:

$$Q_{SanSWwtp,t} = \left(1 - \frac{bP_{CS}}{100}\right) \times (bQ_{UseNpSanS,t} + bQ_{UsePSanS,t} + Q_{GWWwtp,t}) \quad (209)$$

$$Q_{SanSWwtp,t} \leq Q_{SanSMax} \quad (210)$$

where

$Q_{SanSWwtp,t}$ = sanitary sewer flows to the wastewater treatment plant, MG/time step

Combined Sewer

The combined sewer includes flows from runoff, potable and nonpotable water users, and groundwater infiltration that go to the WWTP. If modeling sewer separation, however, flows from the aforementioned sources may be split between the combined sewer system and separate storm/sanitary sewer system.

$$\begin{aligned} \frac{bP_{CS}}{100} \times (Q_{UseNpSewer,t} + bQ_{UsePCS,t} + bQ_{UseNpCS,t} + Q_{GwWwtp,t}) + Q_{RuCS,t} & \quad (211) \\ & = Q_{CSWwtp,t} + bD_{OS,t} \times bQ_{CSOS,t} \end{aligned}$$

$$\frac{bP_{CS}}{100} \times (Q_{UseNpSewer,t} + bQ_{UsePCS,t} + bQ_{UseNpCS,t} + Q_{GwWwtp,t}) + Q_{RuCS,t} \leq Q_{CSMax} \quad (212)$$

where

$$\begin{aligned} Q_{CSWwtp,t} & = \text{combined sewer flows to the wastewater treatment plant, MG/time step} \\ Q_{CSMax} & = \text{combined sewer maximum, MG} \end{aligned}$$

Wastewater Treatment Plant

If modeling sewer separation, the WWTP can receive flows from the combined sewer and/or sanitary sewer. Therefore, the flow, capacity, and cost equation changes are calculated as follows:

$$Q_{SanSWwtp,t} + Q_{CSWwtp,t} + bQ_{OSWwtp,t} = Q_{WwtpSw,t} + bQ_{WwtpWrf,t} \quad (213)$$

$$Q_{SanSWwtp,t} + Q_{CSWwtp,t} + bQ_{OSWwtp,t} \leq Q_{WwtpMaxI} + DQ_{WwtpAddI} \quad (214)$$

$$\begin{aligned} C_{ATWwtp} = (F_{WwtpExist} \times C_{CWwtp} \times Q_{WwtpMaxI}) + (F_{WwtpNew} \times C_{CWwtp} \times bQ_{WwtpAddI}) & \quad (215) \\ + \left(F_{YrsModel} \times C_{OmWwtp} \times \sum_t (Q_{SanSWwtp,t} + Q_{CSWwtp,t} + bQ_{OSWwtp,t}) \right) \end{aligned}$$

4.2 CSO Events

WMOST defines CSO events as instances where 1) the runoff fraction routed to the combined sewer exceeds the specified hydraulic control capacity and/or 2) the sum of the runoff from those HRUs or HRU fractions, flows from potable and nonpotable water users, and groundwater infiltration³⁹ exceeds the hydraulic capacity of the interceptor sewer that flows to the WWTP. The CSO events are counted using binary variables ($bD_{CSWwtp,t}$ and $bD_{RuCS,t}$) that, when multiplied by a large constant, are forced to be a value of 1 when the aforementioned flows exceed the specified hydraulic capacities

If more than the user specified maximum number of CSO events occur, then WMOST determines the methods, from the menu of available CSO control methods or other management practices, which are needed to decrease the number of sewer overflow events.

$$Q_{CSWwtp,t} - Q_{CSWwtpMax} \leq k \times bD_{CSWwtp,t} \quad (216)$$

$$Q_{RuCS,t} - Q_{RuCSMax} \leq k \times bD_{RuCS,t} \quad (217)$$

³⁹ The LTCP-EZ framework accounts for increased inflow and infiltration into the CSS during wet weather events.

WMOST, by contrast, defines infiltration into the wastewater collection system as a fixed percentage (subject to leak repair management actions) of wastewater treatment plant inflow calculated based on non-consumptive water use and therefore unrelated to groundwater volumes or flows. Future versions of WMOST may include accounting for increased inflow associated with management actions through the analysis of precipitation time series and an explicit relationship between groundwater volume and infiltration rate.

$$\sum_t^{NDtYear} bD_{CSWwtp,t} + bD_{RuCS,t} \leq N_{CSOMax} \quad (218)$$

where

- $Q_{CSWwtpMax}$ = hydraulic capacity of interceptor sewer that flows to the WWTP, MG/time step
- k = large constant (e.g., 100,000)
- $bD_{CSWwtp,t}$ = binary decision variable used to count hydraulic capacity exceedances for the interceptor sewer, 0 or 1
- $Q_{RuCSMax}$ = hydraulic capacity of flows to the interceptor sewer, MG/time step
- $bD_{RuCS,t}$ = binary decision variable used to count hydraulic capacity exceedances for the fraction of runoff routed to the combined sewer, 0 or 1
- N_{CSOMax} = maximum number of allowable CSO events

5. Flood-Damage Module

The goal of the flood-damage module is to provide WMOST with flood-damage costs so that WMOST can utilize that information when determining the least-cost set of actions to meet watershed goals. Medina et al. (2011) found that the present value of avoided flood damages was equivalent to 20 percent of the annualized cost of retrofitting a highly urbanized watershed with GI BMPs. Therefore, including flood damages and their reduction from reduced flood flows provides a more comprehensive accounting of costs and benefits in the WMOST optimization and may result in selecting a different mix of practices for meeting water resources management goals.

5.1 Considerations for the Flood-Damage Module

The general methodology for modeling flood damages in risk assessments includes the following steps. Data for one or more of these steps may be available from an existing flood insurance study:

1. **Peak flow:** Hydrologic analysis is conducted to estimate the peak streamflow for various recurrence intervals (e.g., 10-year streamflow). Depending on the modeling accuracy desired, hydrologic modeling may be performed using a watershed simulation model such as Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS)⁴⁰, or values may be obtained from existing statistical analyses (e.g., USGS PeakFQ⁴¹).
2. **Flooding:** Hydraulic analysis is conducted to estimate the extent and depth of water in the floodplain associated with various recurrence interval flows. This analysis is generally performed using geospatial data and software such as Hydrologic Engineering Center River Analysis System (HEC-RAS)⁴².
3. **Damage:** Geospatial and economic analysis is applied to determine the location and value of assets in the floodplain and estimate the direct damages (e.g., flooding of building's basement) and additional indirect economic damages (e.g., loss of income due to direct damages) from various recurrence interval floods. The primary software and approach used to assess damages is FEMA's HAZUS MH⁴³.

Repeating the three-step process for multiple recurrence intervals provides data for developing a flow-damage cost curve. The annualized loss (AL) is calculated by multiplying the damages with their respective probability of occurrence.

To incorporate flood-damage costs in the optimization module of WMOST, we identified the following requirements: 1) new input data on flood flows, their recurrence interval and the cost of associated damages; 2) piece-wise representation of flood-damages in the calculation of total management costs; 3) translation between peak flood flows considered in flood-damage modeling and average daily flow calculated by WMOST; 4) input data and linearization with sufficient accuracy to

⁴⁰ <http://www.hec.usace.army.mil/software/heh-hms/>

⁴¹ <http://water.usgs.gov/software/PeakFQ/>

⁴² <http://www.hec.usace.army.mil/software/heh-ras/>

⁴³ <https://www.fema.gov/hazus>

determine the relative cost-effectiveness of management actions; and 5) usability without extensive effort or flood modeling expertise.

As described above, the standard approach to derive a flood-damage cost curve involves three analyses. Completing these analyses within WMOST would duplicate existing, publicly available methods and tools and require considerable programming efforts. Therefore, we considered two main approaches for the flood module. The first approach would accept results from flood-damage modeling, flows and associated damage costs, and construct a linear cost curve based on the data. The second approach would use a regression equation to relate flows and watershed characteristics to flood damages. The regression could be programmed within WMOST and the user would provide values for the required explanatory variables. The criterion to provide an option without extensive effort or flood modeling expertise initially suggested that a regression approach would be an ideal match for WMOST. However, existing regression approaches do not meet the requirement for sufficient accuracy. The project's Technical Advisory Group (TAG) consistently emphasized that at the local scale, infrastructure (e.g., culverts and impoundments) has a significant impact on flooding. Local infrastructure is not likely captured in regional or national regression analyses, given more significant explanatory variables at that scale and the lack of data sources for the location of local infrastructure. A review of two national-scale regression approaches (AECOM 2013 and Medina et al. 2011; Atkins 2013) found that the explanatory variables did not include the consideration of infrastructure, and that assumptions that were valid to make at the national scale are not appropriate for local scale application. We considered developing new regression equations specific for New England and including infrastructure among the explanatory variables. Discussions with U.S. Army Corps of Engineers Institute for Water Resources indicated that a generalized equation for predicting local flooding damage is a long-sought goal by USACE and FEMA (White and Baker 2015). However, they did not expect a regional equation to provide sufficient accuracy for local, screening level decisions, similar to the TAG input cited above regarding existing national regressions.

5.2 Integrating Flood-Damages in WMOST Optimization

The two goals of providing accuracy while circumventing the need for a high level of effort or technical expertise in specific topics are challenges for WMOST development based on its objective to inform municipal and regional scale decision making without time-consuming or costly studies. The result has been using output from existing detailed simulation models within the region or in similar watersheds for input data as done for baseline hydrology and loadings and stormwater management, which are facilitated by the Baseline Hydrology and Loadings and Stormwater Hydrology and Loadings modules in WMOST v3. The Flood-Damage module follows a similar approach by accepting input data based on results from flood-damage modeling within the watershed of interest, constructing a linear cost curve based on those data and including the cost in the total management cost calculation. The User Guide provides instructions for conducting new flood damage modeling based on publicly available data sources. The instructions should allow someone without flood modeling expertise to perform the analyses needed to generate input data for the Flood-Damage Module.

The Flood-Damage module in WMOST implements the following steps:

- **Input Data:** The user provides at least three sets of data points consisting of flows, their return period and associated flood damage costs. These data points may be based on HEC/HAZUS modeling or historic flood events. Directions in the User Guide emphasize that additional values beyond the minimum requirement of three and values for a zero-damage and a maximum-damage

flow will increase the accuracy of results. The minimum requirement for three values follows a similar requirement in HAZUS and discussion with the TAG.

The requested data points are daily flows for given return intervals and associated damage values since WMOST calculates daily flows. Users should have access to the daily flow equivalents of peak or flood flows based on the flood damage analyses. In general, stream gage data are daily measurements and instantaneous peak flows are estimated based on the daily data. In case the user does not have access to the daily flow corresponding to the flood damages, the User Guide refers users to USGS resources such as PeakFQ and state level regression equations to estimate such flows.

- **Linear Interpolation:** The flood module fits linear equations between user-provided data points. These equations are used to interpolate flood damage costs for flow values that fall between data points. Following the methodology of Medina et al. (2011) and Atkins (2013), the module will calculate the annualized losses from each data point by multiplying the flood damage and the inverse of the return period. Equations are fit between the data pairs of annual loss and flow. The module does not perform extrapolation; that is, damages are assumed to be zero for flows below the lowest flood flow specified. Damages from flows above the highest flood flow specified are assumed to be the same as those from the highest flood flow. Changes in streamflow are not linearly related to resulting changes in flood plain and damages; therefore, extrapolating beyond the data points in either direction may lead to over-estimating damages and benefits of avoiding damages⁴⁴. In addition, one cannot assume a specific form for the flow-damage curve, as evidenced in discussions with the TAG and literature (USACE 2013, Prettenthaler et al. 2010, Mays 2010).
- **Adding to the Objective Function:** The linear equations are programmed in the nonlinear programming problem as piece-wise linear approximation of one equation. This approach provides limits for the applicability of each equation for the segment of flow values specified.

A limitation of the Flood-Damage module is that WMOST must be run on a daily time step, thus requiring more memory-intensive processing. In addition, flooding is evaluated for each daily time step; therefore, each day that streamflow exceeds the smallest flood flow, an individual flooding event is considered to take place with associated flood damages. If a flood persists for multiple consecutive days, flood damages will be incurred each day and overestimated. The user may evaluate whether this occurred during the modeling time period by assessing whether daily modeled streamflow exceeded minimum flood flow within a minimum time period, for example, within a week or month. Within these time periods, it may be reasonable to assume that a second flood would not cause additional damage. This limitation may be addressed automatically for users in future versions of WMOST. Second, the module will only affect results if the modeled time period includes flood flows. The User Guide suggests that users view the precipitation data available from the Baseline Hydrology module to identify and run wet years when using the Flood-Damage module. The User Guide also suggests that the user run the model with and without the flood module. The two results will show any differences in the mix of practices and associated direct costs (direct capital and annual operations costs versus indirect flood damage costs). Since the costs of flood damages are

⁴⁴ For example, extrapolating below the lowest flow may assume damages when the streamflow is contained in the channel. Extrapolating above the highest flow may assume damages when little additional assets may be damaged by the incremental change in flow.

incurred across multiple stakeholders, the user may want to consider the difference in direct costs between the two runs to determine whether to make the additional investment in flood prevention and/or pursue joint funding with the other beneficiaries of reduced flooding.

6. Baseline Hydrology and Loadings Module

W MOST v3 includes two modules and an external tool that can be used to assist users with retrieving and processing required input data for baseline hydrology and loadings and stormwater hydrology and loadings. W MOST requires time series of runoff and recharge flows and loadings for the hydrologic response units (HRUs)⁴⁵ in the study area and a groundwater recession coefficient. This input data is incorporated using three associated datasets – one for flow time series data, one for loadings time series data, and one for HRU characteristics. The time series data include the runoff and recharge time series for each HRU and precipitation and temperature time series for each watershed. The HRU characteristics data include groundwater recession coefficients, effective impervious area (EIA)⁴⁶, and infiltration data for each HRU.

Previous applications of W MOST v1 required obtaining these data from a calibrated/validated simulation model such as Hydrological Simulation Program--Fortran (HSPF)⁴⁷, Soil Water Assessment Tool (SWAT), or the Storm Water Management Model (SWMM). W MOST v2 included a database of selected HSPF model outputs that the user selected from via the user interface rather than cutting and pasting model output from an external source. W MOST v3's Baseline Hydrology module provides users automated functionality to retrieve pre-processed hydrology and loadings HSPF, SWAT, and SWMM model outputs and populate the appropriate W MOST input fields. W MOST v3 also includes an external preprocessing tool, HydroProcessor, which processes HSPF and SWAT model outputs so they are ready for input into W MOST. Users will have the option to either use the HydroProcessor to process HSPF or SWAT model outputs from their study watershed or select a watershed with pre-processed hydrology and loadings data that is most similar to their study watershed.

6.1 Module Setup

The user first chooses to either import the necessary data from a set of pre-processed databases or to use the HydroProcessor to create W MOST-ready input files from existing watershed model outputs. The user then selects the HRUs that exist in their study area and the time period of interest. The hydrology module extracts those data and sums the hourly time series data to the appropriate daily or monthly time step based on user specification. Finally, the module populates the appropriate W MOST input fields.

The groundwater recession coefficient is calculated based on the hydrology data. On the Groundwater tab, the user can initiate this calculation by clicking on the “Calculate and Populate the Groundwater Recession Coefficient” button. The calculation estimates one lumped groundwater recession coefficient for the study area by averaging the HRU specific recession coefficients weighted by their respective areas and annual flows.

⁴⁵ In W MOST, an HRU is a land area with characteristics (e.g., land cover, soil type) that responds similarly to precipitation.

⁴⁶ Effective impervious area is impervious area in catchment that is directly connected to stream channels (i.e., precipitation falling on that area is effectively transported to the stream). http://www.epa.gov/caddis/ssr_urb_is2.html

⁴⁷ U.S. Geological Survey (USGS) has developed numerous Hydrologic Simulation Program – Fortran (HSPF) watershed models that include hourly time series of precipitation, runoff and subsurface flows for the modeled region. <http://water.usgs.gov/software/HSPF/>

6.2 Hydrology and Loadings Databases

Here we describe the process of extracting data from HSPF, SWAT, and SWMM model outputs to provide the pre-packaged inputs to WMOST in the Baseline Hydrology and Loadings module. The aforementioned watershed models are detailed simulation models that define flow components and are run at a different time step than WMOST. As such, the following considerations and assumptions are important to note about the derivation of the hydrology and loadings databases.

HSPF Model Output Conversions

Runoff from pervious and impervious Areas

Within a given HRU, HSPF delineates land into pervious and impervious areas. Different pervious time series represent different types of developed land uses (e.g., residential) and undeveloped land uses (e.g., forest). There is only one impervious runoff time series⁴⁸. WMOST does not have different runoff time series by impervious and pervious cover within an HRU. Thus, runoff data for developed WMOST HRUs (e.g., residential, commercial) require combining pervious and impervious HSPF time series. The percentages of EIA for developed land uses provide the ratio for combining the pervious and impervious time series. For example, medium density residential land use may be 12 percent EIA and its time series is calculated as 12 percent residential impervious time series and 88 percent low density residential pervious time series. The HSPF model documentation provides the percent EIA value for each developed land use.

Subsurface flow under pervious areas

HSPF delineates four subsurface storage components for pervious areas: interflow (*IFWS*), upper zone (*UZS*), lower zone (*LZS*), and active groundwater (*AGWS*) (Figure 6-1). Two subsurface components have outflows to the stream reach: interflow outflow (*IFWO*) and active groundwater outflow (*AGWO*). WMOST delineates one subsurface storage component with one outflow to the stream reach.

Figure 6-1 shows the schematic for HSPF hydrologic storage components and flows and their corresponding variable names.

⁴⁸ Although HSPF models have impervious areas differentiated by name (e.g., residential and commercial/industrial/transportation), they are hydrologically identical time series. They have been differentiated in case of future water quality modeling with the HSPF model. This differentiation does not affect WMOST hydrology or future water quality modeling.

Figure 6-1: HSPF Hydrologic Flows Schematic (EPA 2005, ET = evapotranspiration)

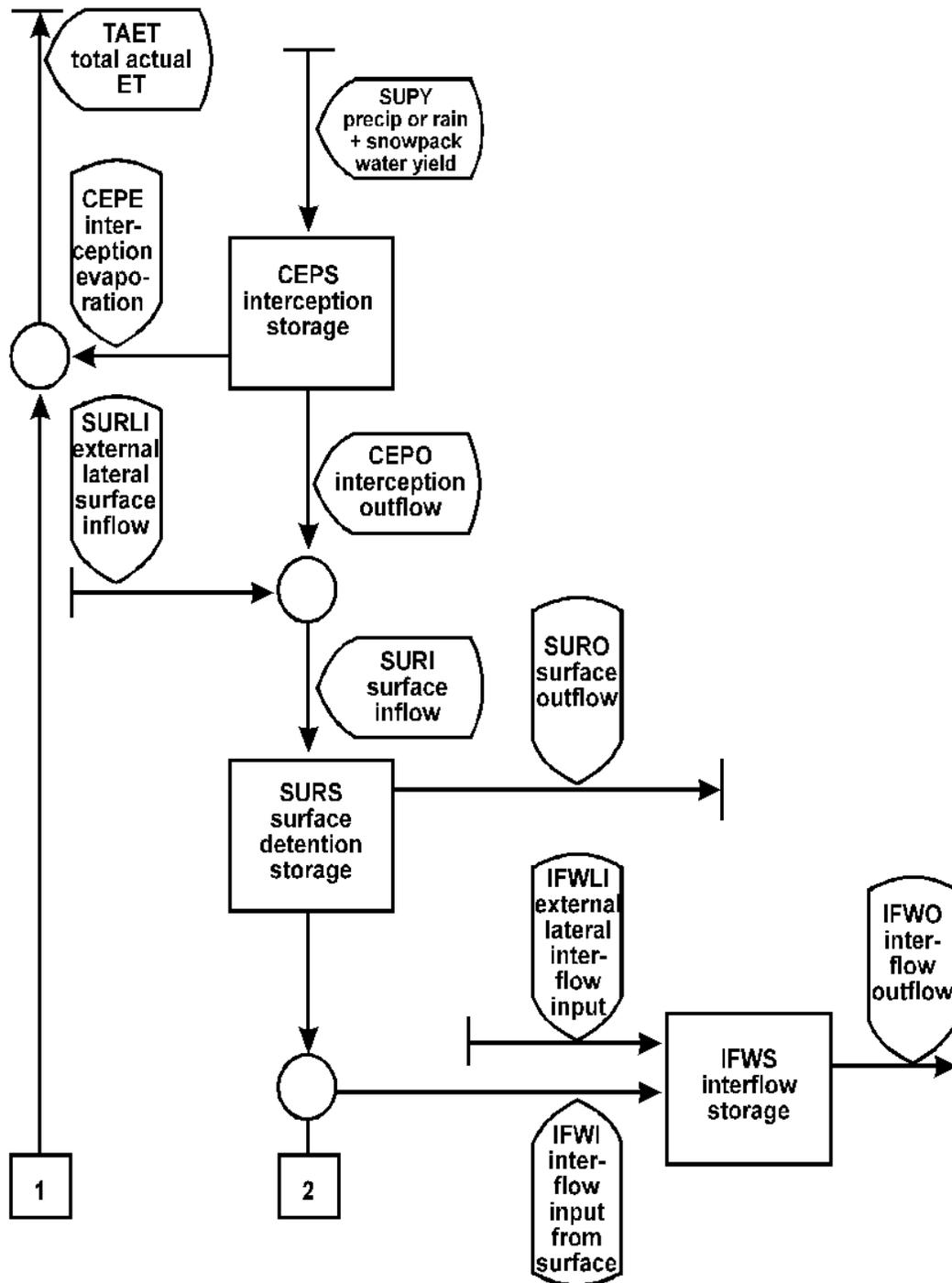
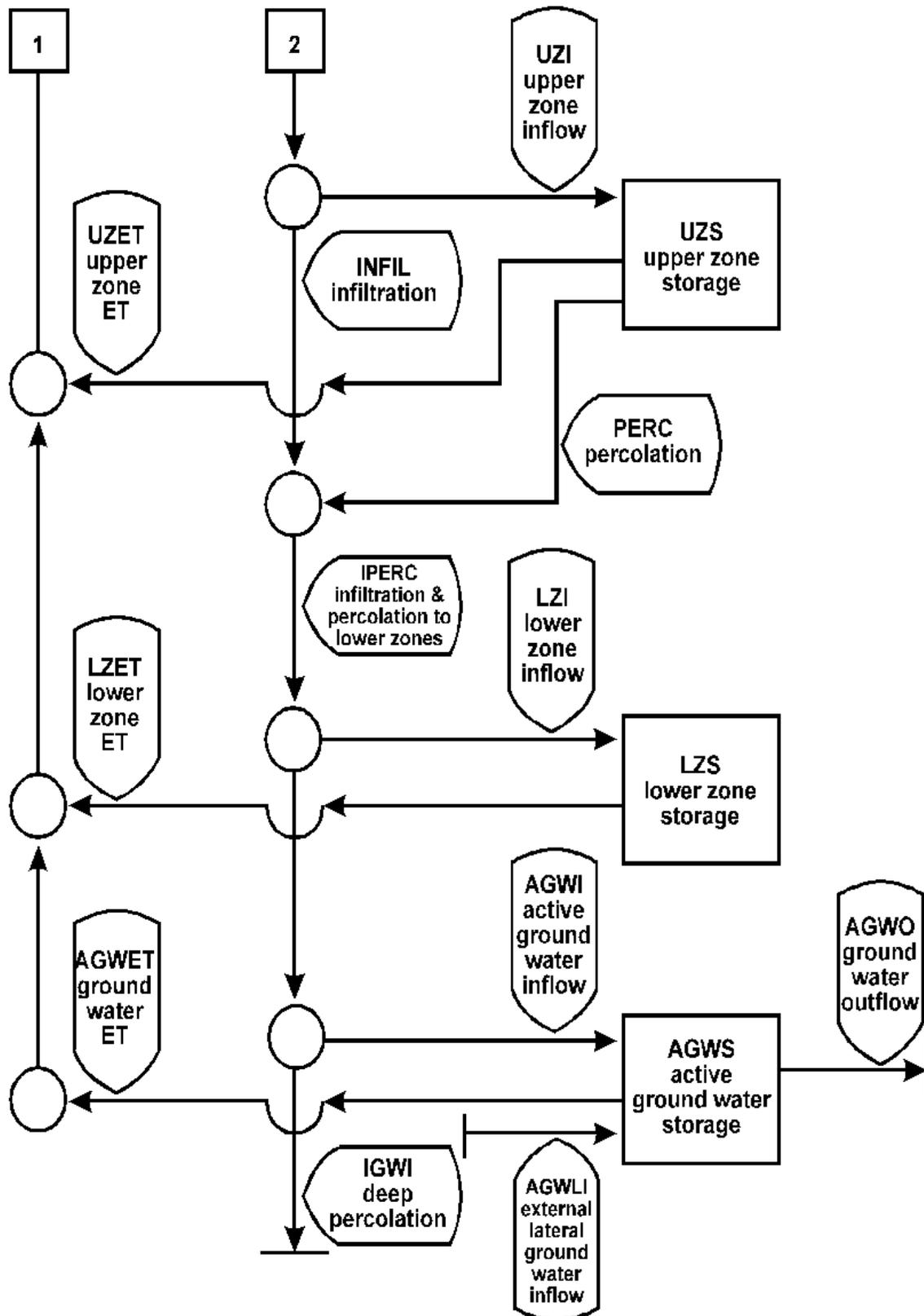


Figure 6-1 (continued)



To develop WMOST input data from HSPF data, we summed subsurface flows to derive one subsurface flow time series. This process follows methods used by DeSimone et al. (2002) and EPA's System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN; EPA 2014), where interflow and active groundwater outflows (*IFWO* and *AGWO*) are summed to represent the total groundwater outflow to the stream reach. The process in WMOST differs in that WMOST models groundwater storage and outflow to the stream reach; therefore, WMOST requires inflow to the two subsurface components rather than outflow. Inflow to interflow is represented by one distinct variable *IFWI*. Inflow to *AGWS* must be calculated as the difference between inflow (*AGWI*) and evapotranspiration (*AGWET*). Therefore, the final groundwater recharge for WMOST equals $IFWI + AGWI - AGWET$. The external lateral inflows shown in the diagram do not exist in HSPF models used to derive the WMOST hydrology database; therefore, this variable and associated flow is excluded from consideration.

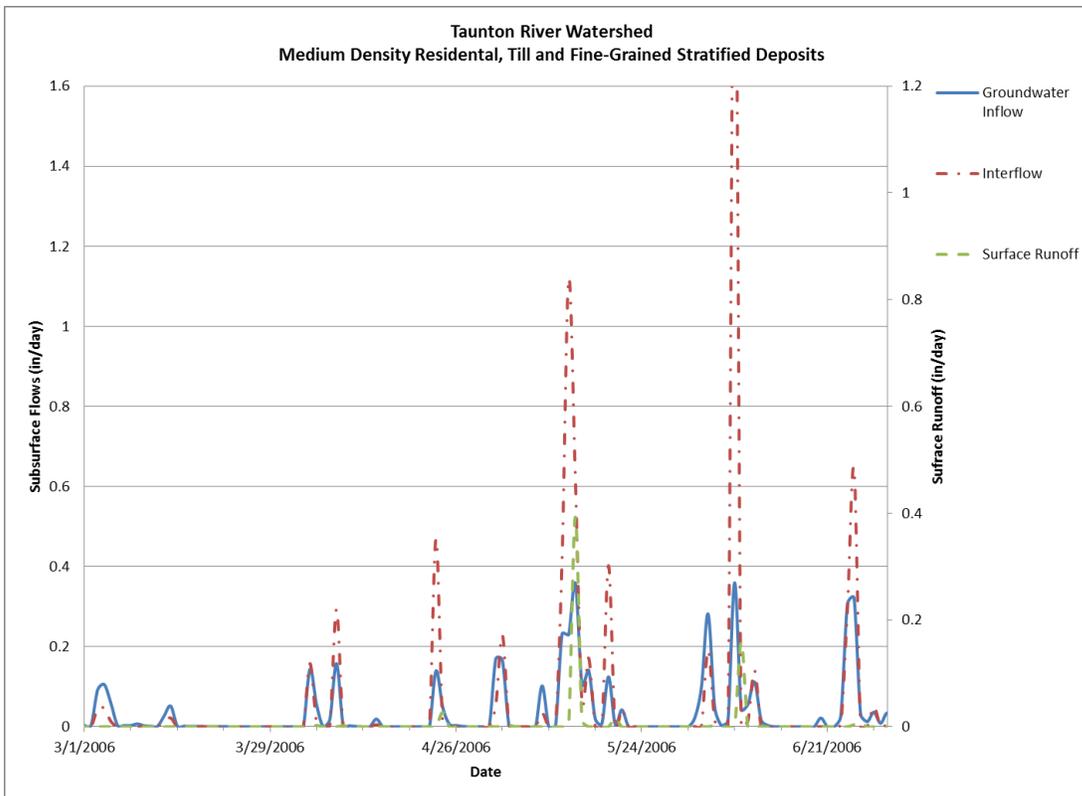
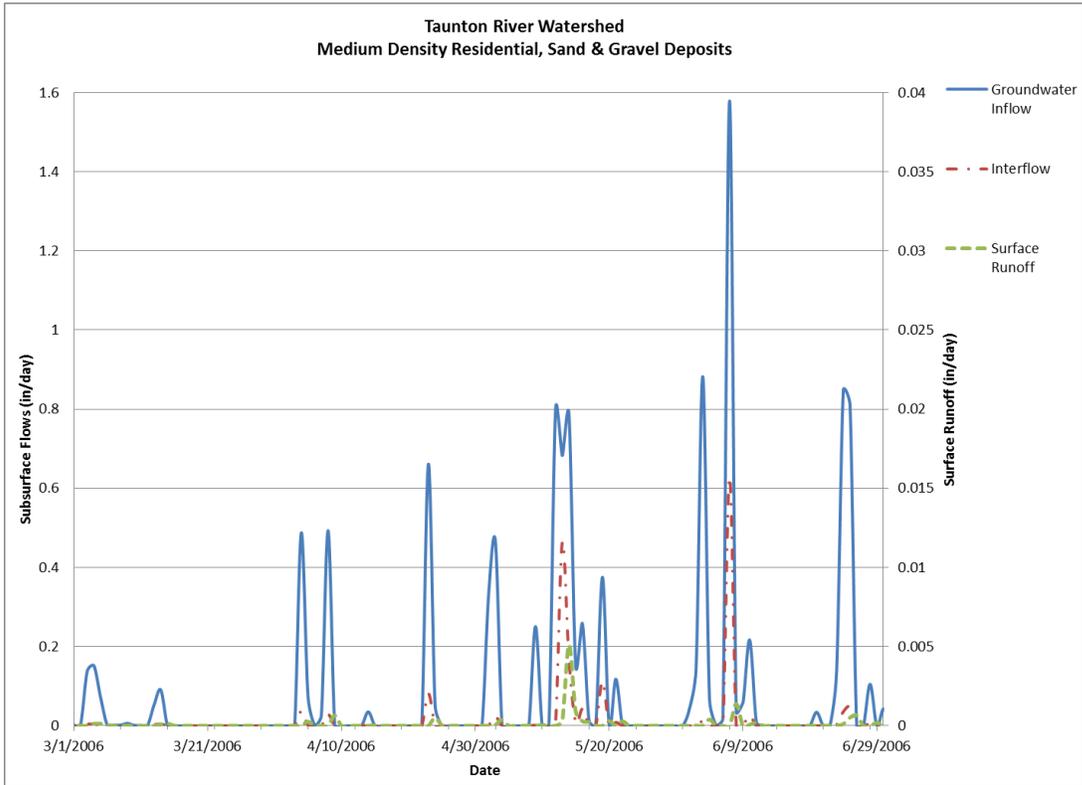
The aforementioned methodology required the validation of the following: 1) the change in variables (subsurface inflow rather than subsurface outflow) and 2) the timing of interflow resembling surface flow (*SURO*) more than groundwater flow depending on the watershed, the model and the model calibration. Time series are graphed below for three flows (*SURO*, *IFWI*, *AGWI*) for two HRUs in the Taunton watershed (Figure 6-2). *AGWET* was zero for both HRUs. The graphs show that the magnitude and behavior of interflow resembles groundwater flow more than surface runoff. The results are the same for different soil types. From these results, we conclude that the approach is appropriate for WMOST.

Although HSPF delineates subsurface storage components for pervious areas, recharge from impervious areas is assumed to be zero. Therefore, in order to represent developed HRUs with pervious and impervious areas in WMOST, the converse of the percentage of effective impervious area ($1 - EIA$) must be multiplied by the final groundwater recharge time series to accurately represent recharge over the HRU.

Subsurface flow adjustments

Within HSPF models, when evapotranspiration is greater than infiltration, negative net flow is the result. However, the solver in WMOST cannot accept negative flows. We assessed the magnitude of these negative flows in the Sudbury watershed and found that they range from 7% in high-density residential HRU to 20% in forest HRU for daily data as assessed for the entire period of record (50 years). (Impacts at the monthly time step reduce to only 2-5% because there are fewer instances of negative values.) Depending on the HRU configuration of a study area and time period selected, these values can have a significant impact. To accommodate the solver and maintain accuracy, we replaced all negative recharge values with zero and provide the negative recharge values as separate database files called "RechargeAdjustment". The user may aggregate these time series to their desired time step and enter the data under "Other groundwater withdrawal" on the groundwater worksheet. Note that the recharge adjustment time series contain positive values but since they are used as a withdrawal time series, the negative net flow is maintained.

Figure 6-2: HSPF Time Series for Two Pervious HRUs



Constructed water HRU areas

HSPF models can be set up so that the watershed includes or does not include water HRU area. Water HRU areas, however, are important for accurately capturing precipitation within the watershed. Therefore, for any HSPF models with a WMOST hydrology and loadings time series database that do not model the water HRU, the database includes a “constructed” water HRU. In order to accurately capture precipitation over this HRU, the runoff for the water HRU is calculated by subtracting the hourly potential evapotranspiration from the hourly precipitation depth. For hours where the estimated potential evapotranspiration is greater than precipitation, the water HRU runoff is zero. Similarly, the recharge hydrology and runoff and recharge loadings are all zero.

Developed areas with public water and public sewer

HSPF models delineate separate pervious areas for developed land uses for various combinations of public or private water supply and sewerage or septic wastewater disposal. Areas with private water supply (i.e., private wells) assume a specific water withdrawal rate from the subsurface. Areas with septic disposal assume a specific discharge rate into the subsurface. WMOST accounts for water withdrawals and septic discharges; therefore, HSPF runoff and recharge time series are used only to represent the land area’s response to precipitation without adjustments for human withdrawals and discharges. As such, for developed pervious areas, only land use time series that are designated as public water and public sewer areas were extracted. HSPF time series for developed pervious areas that are designated other than public water and public sewer (i.e., private water and septic, public water and septic, private water and public sewer) were not used since use of these time series would have resulted in double accounting for human use impacts on HRU hydrology.

Groundwater recession coefficient

For recession coefficients, the HSPF models have two calibrated recession coefficients – one for interflow and one for groundwater flow – for each pervious land use. (Impervious areas do not have infiltration and subsurface flow.) WMOST has one subsurface storage and hence one recession coefficient. Similar to other hydrology models, WMOST represents subsurface flow as a linear relationship between groundwater storage and discharge. That is, groundwater discharge is the product of the groundwater recession coefficient and groundwater storage. To calculate one recession coefficient, each of the two HSPF recession coefficients were weighted based on their corresponding average annual flow as fractions of total subsurface flow.

Infiltration rate

For infiltration, HSPF uses two parameters: *INFILT* (index to mean soil infiltration rate) and *INTFW* (coefficient that determines the amount of water which enters the ground from surface detention storage and becomes interflow).⁴⁹ HSPF documentation specifies that the average measured soil infiltration rate can be calculated as two times *INFILT* times *INTFW*. To support data needs of the Stormwater Hydrology module, we extracted these two parameters from the HSPF UCI files, calculated infiltration rates for HRUs according to the formula in the HSPF documentation and included them in the hydrology dataset to serve as default infiltration values for stormwater modeling.

⁴⁹ http://water.epa.gov/scitech/datait/models/basins/upload/2000_08_14_BASINS_tecnote6.pdf

Subsurface loadings

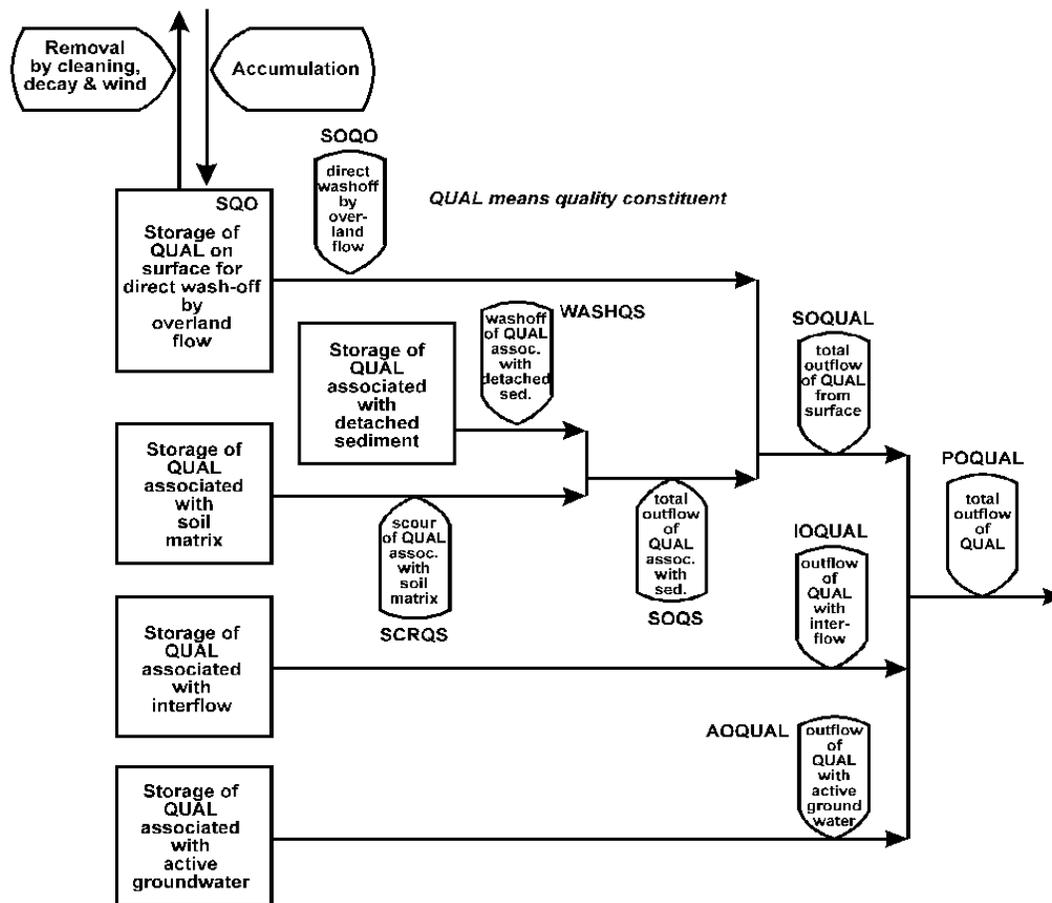
For subsurface loadings, there are two associated loadings time series: *IOQUAL* and *AOQUAL* (see Figure 6-3). These time series are modeled for pervious land areas only. *IOQUAL* and *AOQUAL* also have corresponding concentration time series, which are *IOQC* and *AOQC*, respectively.

From the diagram in Figure 6-3 and HSPF variable definitions, it can be inferred that HSPF does not track loadings or concentrations that are associated with the subsurface inflow, only the subsurface outflow. To calculate the loadings associated with *IFWI* and *AGWI* (HSPF variables related to subsurface inflow that are used by WMOST to calculate recharge), we must assume that:

- The subsurface model component is perfectly mixed, such that inflow concentrations equal outflow concentrations for each of the constituents; and
- Constituent concentrations in the subsurface model component are constant (i.e., no decay or transformation).

Using the assumptions listed above, we calculated the average inflow concentration based on the flow-weighted average outflow concentration timeseries (*IOQC* and *AOQC*) for the time period. The average inflow concentration and the subsurface inflow were then used to calculate subsurface inflow loadings.

Figure 6-3: HSPF Loadings Schematic (EPA 2005)



Overview of HSPF model output conversions

Based on the above considerations, the following tables (Table 6-1 and Table 6-2) summarize the variables and calculations required to create WMOST-ready input data from HSPF model outputs.

Table 6-1: Raw HSPF Data

Variable Type	HSPF Variable	Description
Calculated Water Flows – Time Series	<i>AGWI</i>	Active groundwater inflow
	<i>AGWET</i>	Active groundwater evapotranspiration
	<i>IFWI</i>	Interflow input from surface
	<i>SURO</i>	Surface outflow
	<i>IFWO</i>	Interflow outflow
	<i>AGWO</i>	Active groundwater outflow
Calculated Loadings – Time Series	<i>SOQUAL</i>	Total outflow of QUAL from the impervious land segment (ILS)
	<i>SOSED</i>	Total removal of soil and sediment from the pervious land segment (PLS)
	<i>SOSLD</i>	Washoff of solids from surface from the ILS
	<i>IOQUAL</i>	Outflow of QUAL in interflow from the PLS
	<i>AOQUAL</i>	Outflow of QUAL in active groundwater outflow
Measured Data – Time Series	<i>PET</i>	Potential evapotranspiration
	<i>PREC</i>	Precipitation
	<i>TEMP</i>	Air temperature
Watershed Parameters	<i>IRC</i>	Interflow recession parameter (1/day)
	<i>AGWRC</i>	Daily recession constant of groundwater flow if there is no inflow to groundwater (unitless)
	<i>INFILT</i>	Infiltration parameter (in/time step)
	<i>INTFW</i>	Interflow inflow parameter (unitless)

Note: Data Series Numbers (DSNs) are not specified because they vary among models (e.g., Taunton versus Blackstone HSPF models).

Table 6-2: HSPF to WMOST Crosswalk

Purpose	WMOST Variable	HSPF Variable
For use in WMOST calculations	Runoff – Hydrology	$EIA \times SURO + (1 - EIA) \times SURO$
	Runoff – Nutrients	$EIA \times SOQUAL + (1 - EIA) \times SOQUAL$
	Runoff – Sediment	$EIA \times SOSLD + (1 - EIA) \times SOSED$
	Recharge – Hydrology	$(1 - EIA) \times (IFWI + AGWI - AGWET)$
	Recharge - Nutrients ⁵⁰	$IOQC \times IFWI + AOQC \times AGWI$ where IOQC and AOQC are flow-weighted average concentrations
For use in SUSTAIN calculations (Stormwater Module)	Groundwater Recession Coefficient (KGw)	$\left(\frac{IFWI}{IFWI + AGWI} \right) \times IRC + \left(\frac{AGWI}{IFWI + AGWI} \right) \times AGWRC$ where IFWI and AGWI represent the sum of IFWI and AGWI over the entire time period
	Air Temperature	$TEMP$
For user’s reference	Infiltration Rate	$2 \times INFILT \times INTFW$
	Precipitation	$PREC$
	Potential Evapotranspiration	PET

SWAT Model Output Conversions

Groundwater recession coefficient

Although SWAT requires a baseflow recession constant as a model input (*ALPHA_BF* in the .gw input file), the coefficient is only related to active groundwater flowing to the stream. The incorporation of lateral flow contributions to streamflow (*LATQ*) in the calculation of the groundwater recession coefficient for WMOST provides a more holistic approach to calculating baseflow and is consistent with processing of HSPF model data.

Infiltration rate

The final rate of infiltration is equal to the saturated hydraulic conductivity of a soil. Since SWAT is capable of modeling separate soil layers, the infiltration rate is calculated as the depth-weighted average of saturated hydraulic conductivity (*SOL_K*) across all soil layers.

Effective impervious area

Unlike HSPF, SWAT is capable of modeling combined pervious and impervious areas for a given HRU. Although the pervious and impervious areas are combined, SWAT is still able to differentiate between impervious areas that are directly connected to the drainage system and impervious/pervious

⁵⁰ HSPF does not track sediment in the subsurface so sediment recharge is assumed to be zero.

areas that are disconnected. Surface runoff for urban areas that have combined pervious and impervious areas is calculated separately for the directly connected and disconnected HRU areas (Neitsch et al., 2011). Runoff from directly connected impervious areas is always calculated with a curve number of 98, while runoff from disconnected impervious/pervious areas is calculated using composite curve numbers that differ based on whether or not the fraction of HRU area that is impervious (both directly connected and disconnected) is greater or less than 0.3. Therefore, effective impervious area (EIA) fractions, which are used by the Stormwater Module, are calculated using the same thresholds.

Output file changes

One of the largest limitations for SWAT model output conversion was the output file size. In order to match the spatial scale of WMOST optimization and decrease processing time, SWAT 2005 and SWAT 2012 executables were adapted by SWAT developers to output HRU-level data separately for each subbasin as opposed to outputting one file of HRU-level data for the entire watershed (output.hru). The edited SWAT executables can be found on the SWAT website⁵¹.

Subsurface loadings

SWAT enables users to print the amounts of the various forms of sediment, nitrogen, and phosphorus passing through surface water components. However, despite tracking some constituents internally, SWAT does not allow users to print which forms and in what amounts nitrogen and phosphorus are present in the subsurface.

Therefore, in addition to printing new subbasin scale HRU data output files, the SWAT 2005 and SWAT 2012 executables also print a new variable, *RCHG_N*, that indicates the amount of nitrate present in recharge entering the shallow and deep aquifers. The SWAT model previously tracked nitrate levels in the groundwater system, but did not give users the option to print the outputs.

By contrast, the SWAT model does not track phosphorus levels in the subsurface and uses a fixed phosphorus concentration (*GWSOLP*) to estimate the soluble phosphorus present in the groundwater contribution to streamflow. Based on SWAT documentation, we can make the assumption that

- The subsurface model component is perfectly mixed, such that inflow concentrations equal outflow concentrations for each of the constituents; and
- Constituent concentrations in the subsurface model component are constant (i.e., no decay or transformation).

Based on these assumptions, we multiplied the groundwater outflow concentration (*GWSOLP*) by the total recharge entering aquifers during each time step to estimate recharge phosphorus loadings.

Overview of SWAT model output conversions

Based on the above considerations, the following tables (Table 6-3 and Table 6-4) summarize the variables and calculations required to create WMOST-ready input data from SWAT model outputs.

⁵¹ <http://swat.tamu.edu/>

Table 6-3: Raw SWAT Data

Variable Type	HSPF Variable	Description
Calculated Water Flows – Time Series	<i>SURQ_GEN</i>	Surface runoff
	<i>PERC</i>	Recharge entering aquifers during time step (total amount of water entering shallow and deep aquifers)
	<i>LATQ</i>	Lateral flow contribution to streamflow
	<i>GWQ</i>	Groundwater contribution to streamflow
	<i>SA_ST</i>	Amount of water in shallow aquifer storage
	<i>SW_INIT</i>	Soil water content
Calculated Loadings – Time Series	<i>ORGN</i>	Organic N contributed by HRU to reach
	<i>NSURQ</i>	NO ₃ contributed by HRU in surface runoff to reach
	<i>RCHG_N</i>	Amount of nitrate in recharge entering the aquifers
	<i>ORGP</i>	Organic P contributed by HRU to reach
	<i>SEDP</i>	Mineral P attached to sediment contributed by HRU to reach
	<i>SOLP</i>	Soluble phosphorus contributed by HRU in surface runoff to reach
	<i>GWSOLP</i>	Concentration of soluble phosphorus in groundwater contribution to streamflow from subbasin
Measured Data – Time Series	<i>SYLD</i>	Sediment yield, sediment from the HRU that is transported into the main channel
	<i>PET</i>	Potential evapotranspiration
	<i>PRECIP</i>	Precipitation
HRU Parameters	<i>TMP_AV</i>	Average daily air temperature
	<i>SOL_K</i>	Saturated hydraulic conductivity (mm/hr)
	<i>SOL_Z</i>	Depth from soil surface to bottom of layer (mm)
	<i>FIMP</i>	Fraction total impervious area in urban land type
	<i>FCIMP</i>	Fraction directly connected impervious area in urban land type

Table 6-4: SWAT to WMOST Crosswalk

Purpose	WMOST Variable	HSPF Variable
For use in WMOST calculations	Runoff – Hydrology	$SURQ_{GEN}$
	Runoff – Nitrogen	$ORGN + NSURQ$
	Runoff - Phosphorus	$ORGP + SEDP + SOLP$
	Runoff – Sediment ⁵²	$SYLD$
	Recharge - Hydrology	$PERC$
	Recharge – Nitrogen	$RCHG_N$
	Recharge - Phosphorus	$PERC \times GWSOLP$
	Groundwater Recession Coefficient (KGw)	$\frac{LATQ + GWQ}{SA_{ST} + SW_{INIT}}$
For use in SUSTAIN calculations (stormwater module) and metadata to aid user with watershed and time period selection (hydrology module)	Air Temperature	TMP_AV
	Infiltration Rate	$\frac{(K_1 \times Z_1) + (K_2 \times (Z_2 - Z_1))}{Z_1 + (Z_2 - Z_1)}$ where K is hydraulic conductivity and Z is soil layer depth
	EIA	If $FIMP > 0.3$, $EIA = FIMP$ If $FIMP < 0.3$, $EIA = FIMP - 0.5(FIMP - FCIMP)$
For user's reference	Precipitation	$PREC$
	Potential Evapotranspiration	PET

SWMM Model Output Conversions

SWMM input files created first for EPA's OptiTool (Stormwater Nutrient Management Optimization Tool) were modified to create generic New England hydrology and loading databases for WMOST (EPA 2017). OptiTool is a planning and implementation level tool to compare the cost effectiveness of multiple BMP types. OptiTool uses SUSTAIN to model BMPs, which was developed with SWMM as the background model. SWMM requires as input daily climate time series (temperature, evaporation, and wind speed), and hourly precipitation data. The SWMM modeled setup used EIA and infiltration values from the previously discussed HSPF setup.

Buildup/washoff coefficients

SWMM was set up to model pervious and impervious HRUs separately to account for pollutant buildup/washoff calculations. Buildup/Washoff coefficients were calibrated for impervious HRUs in the New England Region (Technical Memorandum addendum to EPA 2017). Time series for combined pervious/impervious HRUs were combined for use in WMOST as described for HSPF model output.

⁵² SWAT does not track sediment through the subsurface so sediment recharge is assumed to be zero.

Infiltration

The infiltration method in the original Opti-Tool SWMM model setup was changed from Horton to Modified Horton. The limitation of the Horton infiltration method is that it only applies when the infiltration capacity is exceeded during a rainfall event. The Modified Horton method provides more accurate infiltration estimates during small precipitation events, by calculating the cumulative infiltration volume difference between the actual and minimum infiltration rate (Rossman and Huber, 2015).

Aquifer parameters and groundwater coefficients

The Opti-Tool SWMM model set up was modified to include simulation of the aquifer and groundwater components. Aquifer parameters, including porosity, wilting point, field capacity, and saturated hydraulic conductivity, were defined using literature reviewed default aquifer parameters from the SWMM documentation (Rossman and Huber, 2015) to simulate groundwater flow in each HRU/subcatchment. The groundwater setup requires subcatchment specific coefficients such as groundwater elevation of a subcatchment to model lateral groundwater flow. The coefficients were calculated using equations found in the SWMM documentation (Rossman and Huber, 2015).

Overview of SWMM model output conversions

SWMM outputs one large text file. Each subcatchment can output runoff, Gw flow, and pollution concentration values. Table 6-5 provides the crosswalk between SWMM output variables and WMOST inputs.

Table 6-5: SWMM to WMOST Crosswalk

Purpose	WMOST Variable	SWMM Variable
For use in WMOST calculations	Runoff – Hydrology	<i>Runoff</i>
	Runoff – Nitrogen	<i>Runoff * TN conc</i>
	Runoff - Phosphorus	<i>Runoff * TP conc</i>
	Runoff – Sediment	<i>Runoff * TSS conc</i>
	Recharge - Hydrology	<i>Gw Flow</i>
	Recharge – Nitrogen	<i>Gw Flow * TN conc</i>
	Recharge - Phosphorus	<i>Gw Flow * TP conc</i>

6.3 Data Input Sources to Hydrology and Loadings Module

Hydrology Data Processor (HydroProcessor)

The HydroProcessor is an external tool which will be made available on the WMOST web site that reads information from the Soil and Water Assessment Tool (SWAT) or the Hydrological Simulation Program--Fortran (HSPF) model files and creates as output the following input databases required by the WMOST hydrology and water quality modules:

1. Hydrologic response unit (HRU) characteristics: groundwater recession coefficient, effective impervious area (EIA) fraction, infiltration rate, and HRU name
2. Time series: runoff and recharge for each HRU (expressed as a depth per unit area per unit time e.g., inches/acre/day), runoff and recharge loadings for each HRU for total nitrogen (TN), total phosphorus (TP), and total suspended sediments (TSS) (expressed as a mass per

unit area per unit time e.g., lbs/acre/day), precipitation, temperature, and potential evapotranspiration

Estuary Data Mapper (EDM)

Databases are available for automatic import from EPA's Estuary Data Mapper (EDM). These data serve as generic time series of land response to precipitation, similar to curve numbers or loading coefficients. Therefore, the user's study area does not need to overlap with the specific watersheds. Rather the modeled time series of runoff and recharge for an HRU is expected to behave similarly in a comparable watershed (e.g., similar climate, topography).

Metadata are compiled for all the hydrologic and water quality model outputs and may aid the user in selecting the appropriate watershed and hydrologic time period of interest. Metadata include the location of the watershed, description of basic watershed characteristics, time period for available time series, and calibration time period. An inventory of the models available on EDM provides the details and references for the watershed simulation models, including the simulation model type, watershed location, number of available subbasins, and the land use and climate scenarios. Maps of the watersheds and their available subbasin are available from the WMOST website for selecting the appropriate HUC number and resolution for the selected watershed simulation model.

7. Stormwater Hydrology and Loadings Module

The Stormwater Hydrology and Loadings module transforms baseline runoff and recharge hydrology and loadings time series into corresponding time series reflecting implementation of stormwater best management practices (BMPs) chosen by the user. Previous applications of WMOST that included the assessment of stormwater management required the user to derive these data using an external model. The Stormwater Hydrology and Loadings Module automates this process by dynamically linking with EPA’s SUSTAIN model to derive the necessary input data for WMOST (EPA 2014a).

7.1 BMP Selection

SUSTAIN uses input from EPA’s Storm Water Management Model (SWMM) or a similar model for runoff volume and pollutant loads and calculates changes in runoff due to a stormwater BMP using a combination of SWMM and HSPF algorithms. It can also calculate BMP costs and select among BMP configurations to meet an objective such as a load and/or flow reduction target at minimum cost. WMOST uses SUSTAIN in simulation, not optimization, mode. WMOST optimizes for one or more water management objectives utilizing not only stormwater but other watershed management practices in drinking water, wastewater, and land conservation programs. (See WMOST User Guide for complete description of management options.) Therefore, WMOST needs simulation data from SUSTAIN so that WMOST may optimize across watershed practices.

In the Stormwater Hydrology and Loadings module, the user selects the type(s) of BMP to consider and specifies the desired design size(s). If the Baseline Hydrology and Loadings module is not used, the user must also provide the percent impervious area, infiltration rate of HRUs, and hourly time series for the baseline runoff data. Based on the selection and input, the module runs the selected BMP types and sizes through SUSTAIN in simulation mode. These setups simulate one type of BMP per HRU. The user may perform sequential runs of the stormwater BMP module in WMOST for a defined sequence to simulate multiple BMPs. If more complex stormwater modeling with a wider range of BMP options is desired or warranted based on WMOST results, the user may still run a stormwater model outside of WMOST and manually input those results.

WMOST v3 has the capability to simulate 17 different types of BMPs within SUSTAIN; of which, 13 are urban BMPs applied to developed land and four are agricultural BMPs applied to undeveloped land. We selected the urban BMPs from the BMP types used in Opti-Tool version 2⁵³, and we selected the agricultural BMPs from the BMPs used in the Middle Kansas watershed⁵⁴. These BMPs are available in SUSTAIN and have available default design parameters from the Opti-Tool development (EPA 2017). BMPs are highly flexible and may be parameterized for the following hydrologic processes: evaporation from standing surface water, transpiration from vegetation, infiltration of ponded water into soil media, percolation of infiltrated water into groundwater, and/or outflow through an orifice or weir.⁵⁵

⁵³ Opti-Tool is a spreadsheet-based optimization tool developed by EPA Region 1 for municipal stormwater managers who are interested in identifying a suite of BMPs that provide the most effective stormwater/nutrient treatment.

⁵⁴ The Kansas Department of Health and Environment (KDHE) detailed agricultural BMP application in the Middle Kansas Watershed in the Watershed Restoration and Protection Strategy (WRAPS) report (2011).

⁵⁵ HSPF BMP Web Toolkit categorizes BMPs according to hydrologic functions as follows: 1) storage BMPs without infiltration (“grey”), 2) infiltration BMPs with surface ponding (“green- surface storage”) and 3) infiltration BMPs with surface ponding and subsurface storage (“green – surface and subsurface storage”).

Table 7-1 displays the BMPs that are available to the user to evaluate. These selections are based on meeting WMOST's two primary application objectives at lowest unit cost: 1) to achieve minimum in-stream flows for aquatic health while meeting water supply needs (infiltration trench) and 2) to reduce flooding related damages (detention pond). We included bioretention basins or rain gardens because of their popularity and aesthetic compatibility with residential and commercial applications⁵⁶. In WMOST v3, the Stormwater Hydrology and Loadings module simulates hydrology and loadings in order to supply the user with managed runoff and recharge hydrology and loadings.

Table 7-1. Selected BMPs for WMOST v3

BMP Type	BMP Description^a
Biofiltration with underdrain	Provides temporary surface ponding storage of runoff for filtering through an engineered soil media. The storage capacity includes void spaces in the filter media and temporary ponding at the surface. After runoff has passed through the filter media it is collected by an under-drain pipe for discharge. Manufactured or packaged bio-filter systems such as tree box filters may be suitable for using the bio-filtration performance results.
Bioretention Basin	Provides temporary storage of runoff through surface ponding and possibly void spaces within the soil/sand/washed stone mixture that is used to filter runoff prior to infiltration into underlying soils.
Enhanced Biofiltration with internal storage reservoir	Provides temporary storage of runoff for filtering through an engineered soil media, augmented for enhanced phosphorus removal, followed by detention and denitrification in a subsurface internal storage reservoir (ISR) comprised of gravel. An elevated outlet control at the top of the ISR is designed to provide a retention time of at least 24 hours in the system to allow for sufficient time for denitrification and nitrogen reduction to occur prior to discharge. The design storage capacity for using the cumulative performance curves is comprised of void spaces in the filter media, temporary ponding at the surface of the practice and the void spaces in the gravel ISR.
Extended Dry Detention Basin	Provides temporary detention storage for the design storage volume to drain in 24 hours through multiple out let controls.
Grass Swale with detention	Conveys runoff through an open channel vegetated with grass with temporary storage provided by permeable check dams. Primary removal mechanism is settling during temporary storage.
Gravel Wetland	Based on design by the UNH Stormwater Center (UNHSC). Provides temporary surface ponding storage of runoff in a vegetated wetland cell that is eventually routed to an underlying saturated gravel internal storage reservoir (ISR) for nitrogen treatment. Outflow is controlled by an elevated orifice that has its invert elevation equal to the top of the ISR layer and provides a retention time of at least 24 hours.

⁵⁶ <http://www.epa.gov/region1/soakuptherain/index.html>,
<http://www.seattle.gov/util/EnvironmentConservation/Projects/GreenStormwaterInfrastructure/RainWise/index.htm>

Table 7-1 (continued)

BMP Type	BMP Description^a
Surface Constructed Wetland	Provides temporary surface ponding storage of runoff in a vegetated wetland cell and filtering through soil media.
Subsurface Gravel Wetland	Provides temporary surface ponding storage of runoff in a vegetated wetland cell that is eventually routed to an underlying saturated gravel internal storage reservoir (ISR) for nitrogen treatment.
Infiltration Basin	Provides temporary storage of runoff through surface ponding (e.g., basin or swale) for subsequent infiltration into the underlying soils.
Infiltration Chamber	Provides temporary storage of runoff using the combination of storage structures (e.g., galleys, chambers, pipes, etc.) and void spaces within the washed stone that is used to backfill the system for subsequent infiltration into the surrounding sub-soils.
Infiltration Trench	Provides temporary storage of runoff using the void spaces within the soil/sand/gravel mixture that is used to backfill the trench for subsequent infiltration into the surrounding sub-soils.
Porous Pavement with subsurface infiltration	Provides filtering of runoff through a filter course and temporary storage of runoff within the void spaces of a subsurface gravel reservoir prior to infiltration into subsoils.
Porous Pavement with underdrain	Provides filtering of runoff through a filter course and temporary storage of runoff within the void spaces prior to discharge by way of an underdrain.
Sand Filter with underdrain	Provides filtering of runoff through a sand filter course and temporary storage of runoff through surface ponding and within void spaces of the sand and washed stone layers prior to discharge by way of an underdrain.
Sediment Basin ^b	A temporary basin formed by excavation or by constructing an embankment so that sediment-laden runoff is temporarily detained under quiescent conditions, allowing sediment to settle out before the runoff is discharged.
Vegetative Filter Strip ^b	Vegetated surfaces designed to treat sheet flow from adjacent surfaces. Vegetative filter strips function by slowing runoff velocities and allowing sediment and other pollutants to settle and by providing some infiltration into underlying soils.
Wet Pond	Provides treatment of runoff through routing through permanent pool.

^a EPA (2017); ^b CASQA (2003)

7.2 Urban BMP Sizing and Parameterization

Urban BMP unit costs originate from EPA (2017) and CRWA (2009) with an adjustment for retrofit conditions that includes a cost multiplier of 2 and a 35 percent add-on for engineering and contingencies (EPA 2011a). (Users can substitute their own costs if desired or reference the Opti-Tool manual for original costs before retrofit multiplier and cost add-on.) Unit costs for urban BMPs are shown in Table 7-2.

The final urban BMP cost is calculated as follows:

$$\text{BMP Cost} = \text{Volume of Runoff to Manage (ft}^3\text{)} \times \text{Retrofit Cost (\$/treated ft}^3\text{)}$$

Table 7-2. Urban BMP Unit Costs in 2016 Dollars

BMP Type	New Development Cost (\$/ft ³)	Retrofit Cost (\$/ft ³)
Biofiltration w/UD	\$15.61	\$29.54
Bioretention Basin	\$15.46	\$30.92
Enhanced Biofiltration w/ISR	\$15.61	\$29.54
Extended Dry Detention Basin	\$6.80	\$13.60
Grass Swale w/detention	\$8.00	\$23.77 ^{a,b}
Gravel Wetland	\$8.78	\$17.56
Infiltration Basin	\$6.24	\$12.48
Infiltration Chamber	\$67.85	\$135.70
Infiltration Trench	\$12.49	\$24.98
Porous Pavement w/SI (Pervious Concrete)	\$5.32	\$36.14
Porous Pavement w/UD (Asphalt Pavement)	\$18.07	\$10.64
Sand Filter	\$17.94	\$35.88
Wet Pond	\$6.80	\$13.60

^a 2010 costs were converted to 2016 dollars to adjust for inflation

^b Report did not include any engineering or contingency costs so 35 percent was added to the original cost estimate from the report before adjusting for inflation.

Design parameters shown in Table 7-3 below are used for BMP sizing. Design parameters shown in Table 7-4 are used for BMP soil and underdrain specification. BMP decay and underdrain removal rates are shown in Table 7-5. All default parameters originate from the parameter defaults used in SUSTAIN Opti-Tool (EPA 2017). After creating the SUSTAIN input file (Input.inp), users can adjust any default parameters.

Table 7-3. Urban BMP Size Specifications

BMP Name	Shape	Width (ft)	Length (ft)	Orifice Height (ft)	Orifice Diameter (in)	Weir Height (ft)	Weir Width (ft)	Pore Space Depth (ft^a)
Biofiltration w/ UD	Square	Sized based on runoff volume treated	Sized based on runoff volume treated	0	0	0.33	30	1.63
Bioretention Basin	Square			0	0	0.5	30	1.00
Enhanced Biofiltration w/ ISR	Square			0	0	0.33	30	2.28
Extended Dry Detention Basin	Square			0	4	6	30	6.00
Grass Swale w/ detention	Fixed-Width Rectangle	5	Sized based on runoff volume treated and fixed width	0	0	2.5	30	2.50
Gravel Wetland	Square	Sized based on runoff volume treated	Sized based on runoff volume treated	0	0	2.2	6	3.27
Infiltration Basin	Square			0	0	2	30	2.00
Infiltration Chamber	Square			0	0	0.2	30	2.60
Infiltration Trench	Fixed-Width Rectangle	5	Sized based on runoff volume treated and fixed width	0	0	0	30	2.40
Porous Pavement w/ SI	Square	Sized based on runoff volume treated	Sized based on runoff volume treated	0	0	0	30	0.70
Porous Pavement w/ UD	Square			0	0	1.75	30	1.75
Sand Filter w/ UD	Square			0	0	0.5	30	1.65
Wet Pond	Square			0	0	6	30	6.00

^a Total pore space is calculated based on the the pore space of the ponding, soil, and underdrain depth, width and length.

Table 7-4. Urban BMP Soil and Underdrain Specifications

BMP Name	Soil Depth (ft)	Soil Porosity (0-1)	Vegetative Parameter A (0.1-1.0)	Soil layer infiltration rate (in/hr)	Underdrain (UD) switch	Depth storage media below UD (ft)	UD void space (0-1)	Background infiltration rate (in/hr)
Biofiltration w/ UD	2	0.45	0.9	2.5	Yes	0	0	Native soil rate
Bioretention Basin	2.5	0.2	0.9	2.5	No	0	0	-
Enhanced Biofiltration w/ ISR	2	0.45	0.6	4.5	Yes	2.5	0.42	Native soil rate
Extended Dry Detention Basin	0	0	0.1	0	No	0	0	-
Grass Swale w/D	0	0	0.9	2.5	No	0	0	-
Gravel Wetland	0.67	0.4	0.9	3.3	Yes	2	0.4	Native soil rate
Infiltration Basin	0	0	0.9	1.5	No	0	0	-
Infiltration Chamber	0	0	0.1	1000	Yes	6	0.4	Native soil rate
Infiltration Trench	6	0.4	0.9	1.5	No	0	0	-
Porous Pavement w/ SI	0	0	0.1	17.42	No?	1.75	0.4	Native soil rate
Porous Pavement w/ UD	0	0	0.1	17.42	Yes	0	0	Native soil rate
Sand Filter w/ UD	2.5	0.3	0.8	2.5	Yes	1	0.4	Native soil rate
Wet Pond	0.001	0.3	0.1	0	No	0	0	-

Table 7-5. Urban BMP Decay and Underdrain Removal Rates

BMP Name	TP Decay Rate (1/hr)	TN Decay Rate (1/hr)	TSS Decay Rate (1/hr)	ZN Decay Rate (1/hr)	TP Removal Rate (%)	TN Removal Rate (%)	TSS Removal Rate (%)	ZN Removal Rate (%)
Biofiltration w/ UD	0.13	0.03	0.79	0.49	46	30	98	96
Bioretention Basin	0.13	0.03	0.79	0	97.25	99.25	100	100
Enhanced Biofiltration w/ ISR	0.065	0.093	0	0	68	69	98	96
Extended Dry Detention Basin	0.018	0.02	0.12	0.54	1	9.91	42	7.05
Grass Swale w/D	0.1	0	0.66	1.78	15	9.91	73	92.5
Gravel Wetland	0.105	0.066	0.36	0.19	54	60.5	93	89
Infiltration Basin	0.27	0.42	0.74	0.45	97.25	99.25	100	100
Infiltration Chamber	-	-	-	-	87.25	97	99	99.75
Infiltration Trench	0.27	0.42	0.74	0.45	87.25	97	99	99.75
Porous Pavement w/ SI	0.0051	0.26	0.22	0.14	87.25	97	99	99.75
Porous Pavement w/ UD	0.0051	0.26	0.22	0.14	72.5	77	95	97
Sand Filter w/ UD	-	-	-	-	68	69	98	96
Wet Pond	0.03	0.3	0.26	1.53	46	29.5	71	86

Based on the user-specified depth, the module calculates the required storage volume for the BMP following the Massachusetts example for the static method⁵⁷:

$$\text{Required storage volume} = \text{Impervious area} \times \text{Runoff depth to be managed}$$

For an acre of soil type B, the required volume for the Massachusetts recharge standard would be 0.35” or approximately 1,271 cubic feet per acre of impervious surface.

The storage volume per square foot of BMP for each type of BMP is calculated as follows:

$$\text{BMP unit storage volume} = \text{Sum of (Depth} \times \text{Porosity) across all components}$$

For example, a bioretention basin with an underdrain has 6 inches of ponding depth (100% storage volume), 30 inches of 0.40 porosity soil mix (40% storage volume) and 8 inches of 0.40 porosity gravel mix (40% storage volume). This results in 1.77 cubic feet of storage volume per square foot of BMP.

Using the unit storage volume, the module calculates the required BMP area. In this example, the BMP area must be approximately 719 square feet or 1.7 percent of the total site area of one acre.

⁵⁷ These baseline runoff and recharge time series reflect runoff and recharge from both pervious and impervious areas of an HRU. However, the BMP sizing will be based on the specified sizing depth and impervious area. This methodology follows SUSTAIN applications and stormwater regulations. For example, Massachusetts Stormwater Handbook states that “for purposes of [recharge and solids standards], only the impervious areas on the project site are used for purposes of calculating the [volumes] (MassDEP 2014).”

7.3 Agricultural BMP Sizing and Parameterization

Agricultural BMP unit costs originate from KDHE (2011). The costs were not adjusted for conditions because undeveloped area receives a cost multiplier of 1, but the costs were adjusted for inflation and have a 35 percent add-on for engineering and contingencies (EPA 2011a). (Users can substitute their own costs if desired.) Default unit costs for agricultural BMPs are specified by land area, rather than by volume of runoff treated. Table 7-6 below shows the unit costs for agricultural BMPs.

The final agricultural BMP cost is calculated as follows:

$$\text{BMP Cost} = \text{Managed area (acre)} \times \text{BMP Cost (\$/BMP acre)} \times \text{Ratio of BMP area (BMP acre) / Managed area (acre)}$$

Table 7-6. Agricultural BMP Unit Costs in 2016 Dollars

BMP Type	EQIP Conservation Practice ID	Default Cost (\$/BMP acre)	Default Treatment Ratio (BMP acre/Managed Acre)
Surface Constructed Wetland	657	\$1,425.45	15
Subsurface Gravel Wetland	657	\$1,425.45	15
Sediment Basin	638	\$388.76	15
Vegetative Filter Strip	393	\$925.25	15

Design parameters shown in Table 7-7 below are used for BMP sizing. Design parameters shown in Table 7-8 are used for BMP soil and underdrain specification. BMP decay and underdrain removal rates are shown in Table 7-9. All defaults parameters originate from the parameter defaults used in SUSTAIN Opti-Tool (EPA 2017). After creating the SUSTAIN input file (Input.inp), users can adjust any default parameters.

Table 7-7. Agricultural BMP Size Specifications

BMP Name	Shape	Width (ft)	Length (ft)	Orifice Height (ft)	Orifice Diameter (in)	Weir Height (ft)	Weir Width (ft)	Total Pore Space (ft)
Surface Constructed Wetland	Square	Sized	Sized	0	0	2.2	30	2.47
Subsurface Gravel Wetland	Square	Sized	Sized	0	0	2.2	30	3.27
Sediment Basin	Square	Sized	Sized	0	4	6	30	6.00
Vegetative Filter Strip	SUSTAIN requires a different input card for sizing a vegetative filter strip, which requires additional user inputs							1.23

Table 7-8. Agricultural BMP Soil and Underdrain Specifications

BMP Name	Soil Depth (ft)	Soil Porosity (0-1)	Vegetative Parameter A (0.1-1.0)	Soil layer infiltration rate (in/hr)	Underdrain (UD) switch	Depth storage media below UD (ft)	UD void space (0-1)	Background infiltration rate (in/hr)
Surface Constructed Wetland	0.67	0.4	0.9	3.3	No	0	0	-
Subsurface Gravel Wetland	0.67	0.4	0.9	3.3	Yes	2	0.4	Native soil rate
Sediment Basin	0	0	0.1	0	No	0	0	-
Vegetative Filter Strip	2	0.45	0.9	2.5	No	0	0	-

Table 7-9. Agricultural BMP Decay and Underdrain Removal Rates

BMP Name	TP Decay Rate (1/hr)	TN Decay Rate (1/hr)	TSS Decay Rate (1/hr)	ZN Decay Rate (1/hr)	TP Removal Rate (%)	TN Removal Rate (%)	TSS Removal Rate (%)	ZN Removal Rate (%)
Surface Constructed Wetland	0.105	0.066	0.36	0.19	0.54	0.605	0.93	0.89
Subsurface Gravel Wetland	0.105	0.066	0.36	0.19	0.54	0.605	0.93	0.89
Sediment Basin	0.018	0.02	0.12	0.54	0.1	0.09909	0.42	0.705
Vegetative Filter Strip	0.13	0.03	0.79	0.49	0.46	0.3	0.98	0.96

Based on the user-specified depth, the module calculates the required storage volume for the BMP following the SCS curve number method used in SWAT (Texas A&M University 2011). The SCS curve number equation estimates the volume of runoff. The equation is:

$$\text{Required storage volume} = (R - 0.2*S)^2 / (R + 0.8*S) * \text{Managed Area}$$

where R is the rainfall depth in inches, which is the design storm depth provided by the user, and S is the retention parameter.

The retention parameter is defined as:

$$S = 1000/CN - 10$$

The storage volume per square foot of BMP for each type of BMP is calculated as follows:

$$\text{BMP unit storage volume} = \text{Sum of (Depth x Porosity) across all components}$$

The module uses the unit storage volume to calculate the required BMP area. Default curve numbers are provided in the module and shown in Table 7-10. Default curve numbers originated from the SWAT model documentation.

Table 7-10. Default Curve Numbers by Land Use Type

Land Use Description	Curve Number for Hydrologic Soil Group			
	A	B	C	D
Agriculture	68	79	86	89
Forest	36	60	73	79
Grass	30	58	71	78
Open	49	69	79	84
Wetland	100	100	100	100
Water	100	100	100	100

Two agricultural BMPs, the sediment basin and the vegetative filter strip, are not sized using the SCS curve number. The sediment basin is sized based on the managed area and the settling velocity of the constituent (CASQA 2003). The equation used to size the sediment basin is:

$$\text{Required storage volume} = \text{Managed Area (acre)} \times \text{Settling velocity (ft/s)} / 1.2$$

Vegetative filter strips are modeled using a specific input card. Users must provide additional BMP parameters in order to use this BMP. Default values for the additional parameters needed for modeling vegetative filter strips are shown in Table 7-11.

Table 7-11. Default Vegetative Filter Strip Parameters⁵⁸

Land Use Description	Flow Length (in)	Surface Depression Storage (in)	Manning's Coefficient (unitless)
Agriculture	75	0.25	0.3
Forest	75	0.25	0.3
Grass	75	0.25	0.2
Open	75	0.25	0.2

7.4 Linking with SUSTAIN

In order to automate the calculation of reduction of runoff volumes by stormwater BMPs, WMOST provides a linkage with one of the modules in EPA's SUSTAIN tool. The Stormwater Hydrology and Loadings Module prepares input files for SUSTAIN, calls SUSTAIN and retrieves outputs. SUSTAIN requires time series data at least at an hourly resolution, which are available to the user if the Baseline Hydrology and Loadings module is used. Sub-daily modeling for stormwater increases the accuracy of the simulated BMP performance and resulting changes in runoff and recharge. The Stormwater Hydrology and Loadings module aggregates the time series to a daily or monthly time step for final use in WMOST. Further details on this process are described in the remainder of this section.

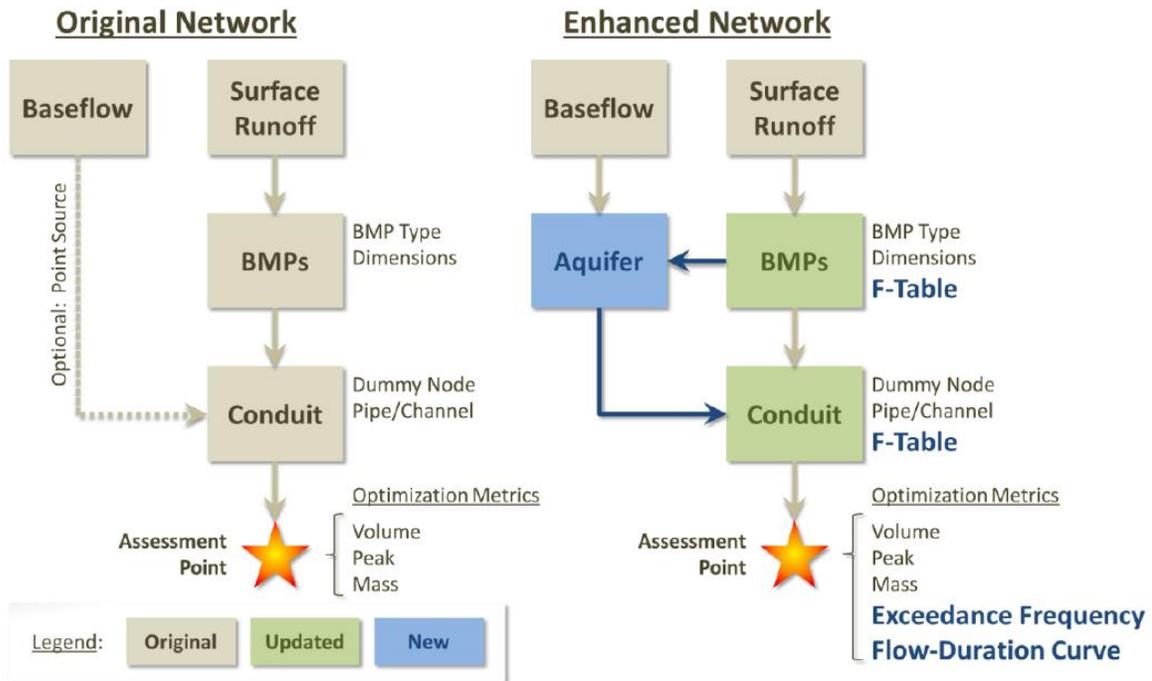
The aquifer component in SUSTAIN tracks water infiltrated through BMPs to the aquifer. The aquifer does not affect the BMP function or performance. Only the aquifer is affected by inflow from

⁵⁸ Default values for vegetative filter strips originated from the Massachusetts Stormwater LID Toolkit Fact Sheet for Grass Filter Strips (MassDEP 2014) and Minnesota Pollution Control Agency https://stormwater.pca.state.mn.us/index.php?title=Vegetated_filter_strips

the BMP (Figure 7-1). WMOST has a component that tracks aquifer inflow and storage as well as baseflow to the stream; therefore, there is no need to repeat this modeling in SUSTAIN.

In addition, inputting an external recharge time series into SUSTAIN does not affect the BMP performance and output. An external recharge time series affects the aquifer component but will not affect BMP performance. Therefore, only the runoff time series is input to SUSTAIN and the aquifer component is not utilized.

Figure 7-1. SUSTAIN Flows With and Without an Aquifer Component (EPA 2014b)



The module prepares the following input files necessary to run SUSTAIN:

- Runoff and runoff loadings time series for each HRU (e.g., HRU1.txt);
- Temperature time series (e.g., climate.swm); and
- Main input file (e.g., input.inp) which requires the information shown in Appendix B.

The module prepares the time series files using data from the hydrology and loadings time series database, user specifications, appropriate default BMP characteristics, and HRU infiltration rates/soil types. If the user does not use the Baseline Hydrology and Loadings Module, the Stormwater Hydrology and Loadings Module will request the necessary data including subdaily HRU runoff time series, temperature time series, infiltration rates, percent impervious area, and latitude of the study area.

The module calls SUSTAIN from WMOST, referencing the input files and the SUSTAIN.dll. The setup initiates one run of SUSTAIN that simulates all combinations of developed HRUs and urban BMPs and undeveloped HRUs and agricultural BMPs. This requires setting up each combination as a separate “subbasin” representing the WMOST HRU routed to one BMP. Each “subbasin” will be

specified as one acre with an appropriately sized BMP in developed areas. In agricultural areas, the subbasin will be specified as the area managed by the BMP, which is specified by the user. These specifications will result in output values for runoff, recharge, and BMP costs that are on a “per acre” basis as required by WMOST. The module will initiate the simulation run by calling “SUSTAINOPT.dll(strFilePath, strScenario, "")”, where the parameters are defined as follows:

- strFilePath indicates the folder location for all input files;
- strScenario specifies which of the following run options to initiate: single run, batch mode, or run for select solutions. In this case, we will specify a single run; and
- “ “ = selection solutions to run if strScenario = run for select solutions. For our purposes, we will leave this blank to indicate that we are initiating a single run.

SUSTAIN outputs results into separate files for each subbasin, in this case a combination of HRU and BMPs. The WMOST Stormwater Hydrology and Loadings Module reads data from these files then deletes them to keep the user’s folder clean.

SUSTAIN provides nine types of outflow in units of cubic feet per second. The module processes these flows as follows:

- $\text{Runoff} = \text{Weir outflow} + \text{Orifice or channel outflow} + \text{Untreated outflow}$
- $\text{Recharge} = \text{Underdrain} + \text{Seepage to Groundwater}$
- Evapotranspiration

The following flows are not used because it would lead to double counting:

- Infiltration;
- Total outflow and
- Percolation to underdrain storage.

For water quality flows, SUSTAIN provides five types of outflow in units of pounds. The module processes these flows as follows:

- $\text{Runoff} = \text{Weir outflow} + \text{Orifice or channel outflow} + \text{Untreated outflow}$
- $\text{Recharge} = \text{Underdrain}$
- Evapotranspiration

The following flows are not used because it would lead to double counting:

- Mass entering the BMP
- Mass leaving the BMP

The module aggregates the hourly time series to a daily or monthly time step of runoff and recharge. Evapotranspiration is retained for potential future use in climate change sensitivity analyses. Final stormwater managed runoff is the runoff from the SUSTAIN simulation as shown above. The SUSTAIN recharge or infiltration is added to the WMOST baseline recharge, reflecting the additional recharge due to BMP implementation. Finally, the module populates the runoff and recharge worksheets with the appropriate time series after post-processing.

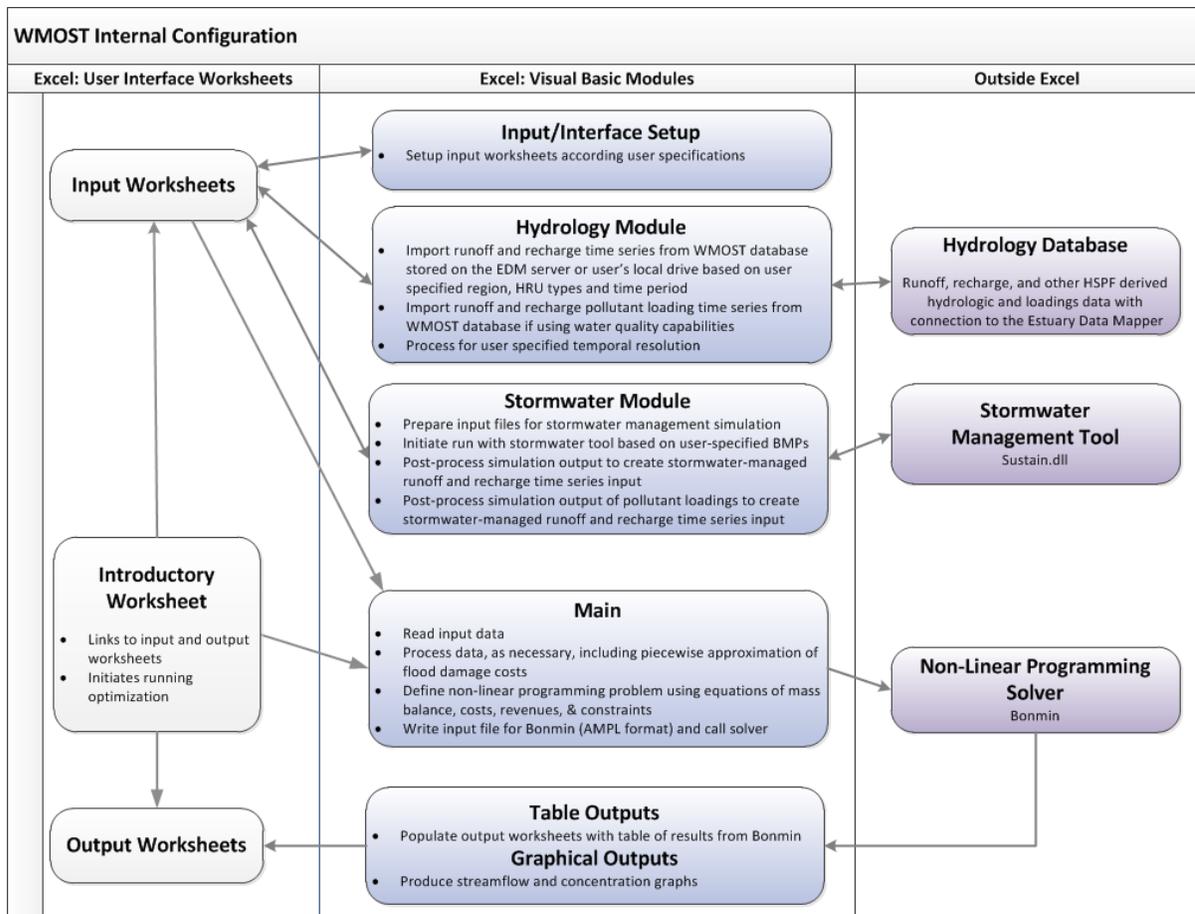
8. Internal Configuration

WMOST is implemented using Excel as the interface software to provide an accessible and familiar platform for users. VBA is used to:

- 1) Automate the setup of input worksheets for different numbers of HRU types, HRU sets, and water user types per user specifications;
- 2) Assist users in navigating among input and output sheets;
- 3) Access and pre-process input data via the Baseline Hydrology, Stormwater Hydrology and Flood-Damage modules;
- 4) Create optimization files written in AMPL for uploading to the NEOS server including a model file, data file, and command file; and
- 5) Process and analyze results from the NEOS server including the calculation of calibration statistics

Figure 8-1 shows the flow of information and process links between components of WMOST.

Figure 8-1: WMOST Internal Configuration



9. References

- AECOM. 2013. The Impact of Climate Change and Population Growth on the National Flood Insurance Program through 2100. Prepared for Federal Insurance and Mitigation Administration and Federal Emergency Management Administration. June 2013.
- American Rivers. 2010. Putting Green to Work: Economic Recovery Investments for Clean and Reliable Water. American Rivers, Washington, D.C.
- American Water Resources Association (AWRA). 2012. Case Studies in Integrated Water Resources Management: From Local Stewardship to National Vision. American Water Resources Association Policy Committee, Middleburg, VA.
- Atkins. 2013. Flood Loss Avoidance Benefits of Green Infrastructure for Stormwater Management. Prepared for the U.S. Environmental Protection Agency, Office of Water. July 2013.
- Bonami, P., Biegler, L. T., Conn, A. R., Cornuejols, G., Grossman, I. E., Laird, C. D., Lee, J., Lodi, A., Margot, F., and Waechter, A. 2008. An Algorithmic Framework for Convex Mixed Integer Nonlinear Programs. *Discrete Optimization* 5(2), 186-204.
- Bonami, P. and Lee, J. 2013. BONMIN User's Manual. https://projects.coin-or.org/Bonmin/browser/stable/1.7/Bonmin/doc/BONMIN_UsersManual.pdf?format=raw
- California Stormwater Quality Association (CASQA). 2003. "Stormwater Best Management Practice Handbook." Chapters on Construction and New Development/Redevelopment.
- Charles River Watershed Association (CRWA). 2009. "Stormwater Management Plan for Spruce Pond Brook Subwatershed". Prepared for the Town of Franklin, Massachusetts.
- Chesapeake Bay Partnership (CBP) Urban Stormwater Workgroup. 2012. "Recommendations of the Expert Panel to Define Removal Rates for Individual Stream Restoration Projects". Prepared by Tom Schueler, Chesapeake Stormwater Network, and Bill Stack, Center for Watershed Protection. Retrieved on January 7, 2017 from http://www.chesapeakebay.net/channel_files/18983/attachment_b1--urban_stream_restoration_panel_final_report_12062012.pdf
- Czyzyk, J., Mesnier, M. P., and Moré, J. J. 1998. The NEOS Server. *IEEE Journal on Computational Science and Engineering* 5(3), 68-75.
- DeSimone, L. A., et al. 2002. Simulation of Ground-Water Flow and Evaluation of Water-Management Alternatives in the Upper Charles River Basin, Eastern Massachusetts. Water-Resources Investigations Report 2002-4234. U.S. Geological Survey, Westborough, Massachusetts.
- Dolan, E. 2001. The NEOS Server 4.0 Administrative Guide. Technical Memorandum ANL/MCS-TM-250, Mathematics and Computer Science Division, Argonne National Laboratory.
- Gropp, W. and Moré, J. J. 1997. Optimization Environments and the NEOS Server. *Approximation Theory and Optimization*, M. D. Buhmann and A. Iserles, eds., Cambridge University Press, p 167-182.
- Kansas Department of Health and Environment (KDHE). 2011. "Watershed Restoration and Protection Strategy (WRAPS) Middle Kansas Watershed." Kansas Center for Agricultural

- Resources and the Environment (KCARE), Kansas Alliance for Wetlands & Streams (KAWS), and Kansas State University Research and Extension.
- Massachusetts Department of Environmental Protection (MassDEP). 2014. Massachusetts Stormwater Handbook. Accessed November 2014, <http://www.mass.gov/eea/agencies/massdep/water/regulations/massachusetts-stormwater-handbook.html>
- Mays, L.W. 2010. Water Resources Engineering. John Wiley & Sons, 890p.
- Medina, D., J. Monfils, and Z. Baccala. 2011. Green Infrastructure Benefits for Floodplain Management: A Case Study. Stormwater. November-December 2011.
- Minnesota Pollution Control Agency (MPCA). “Design Infiltration Rates”. Retrieved on December 16, 2014, http://stormwater.pca.state.mn.us/index.php/Design_infiltration_rates.
- NACWA, WERF, and WEF. 2013. The Water Resources Utility of the Future: A Blueprint for Action. National Association of Clean Water Agencies (NACWA), Water Environment Research Foundation (WERF) and Water Environment Federation (WEF), Washington, D.C.
- Neitsch, S. L., Arnold, J. G., Kiniry, J. R., and J. R. Williams. 2011. Soil and Water Assessment Tool Theoretical Documentation Version 2009. Texas Water Resources Institute Technical Report No. 406.
- Pretenthaler, F., P. Amrusch, and C. Habsburg-Lothringen. 2010. Estimation of an Absolute Flood Damage Curve Based on an Austrian Case Study Under a Dam Breach Scenario. Nat. Hazards Earth Syst. Sci., 10, 881-894.
- Rossman, L. and W. Huber. Storm Water Management Model Reference Manual Volume I, Hydrology. US EPA Office of Research and Development, Washington, DC, EPA/600/R-15/162A, 2015.
- Schwarz, G. E., A. B. Hoos, R. B. Alexander, and R. A. Smith. 2006. The SPARROW Surface Water-Quality Model - Theory, Applications and User Documentation: U.S. Geological Survey, Techniques, and Methods 6-B3.
- Texas A&M University. 2011. “Soil and Water Assessment Tool Theoretical Documentation Version 2009”. Prepared by S.L. Neitsch, J.G. Arnold, J.R. Kiniry, and J.R. Williams. September 2011.
- United Nations Environmental Programme (UNEP)-DHI Centre for Water and Environment. 2009. Integrated Water Resources Management in Action. WWAP, DHI Water Policy, UNEP-DHI Centre for Water and Environment
- U.S. Army Corps of Engineers (USACE). 2013. Flood Risk Management, IWR Report 2013-R-05.
- U.S. Department of Agriculture (USDA). 2009. Conservation Practice Modeling Guide for SWAT and APEX. Prepared by David Waidler, Mike White, Evelyn Steglich, Susan Wang, Jimmy Williams, C. A. Jones, and R. Srinivasan.
- U.S. Environmental Protection Agency (EPA). 1994. Combined Sewer Overflow (CSO) Policy. EPA 830-B-94-001. <https://www.epa.gov/sites/production/files/2015-10/documents/owm0111.pdf>

-
- U.S. Environmental Protection Agency (EPA). 2002. EPA Air Pollution Control Cost Manual. EPA/452/B-02-001. https://www3.epa.gov/ttnca1/dir1/c_allchs.pdf
- U.S. Environmental Protection Agency (EPA). 2004. "The Use of Best Management Practices (BMPs) in Urban Watersheds." Publication No. EPA/600/R-04/184.
- U.S. Environmental Protection Agency (EPA). 2005. HSPF Version 12.2 User's Manual. <http://water.epa.gov/scitech/datait/models/basins/bsnsdocs.cfm#hspf>, accessed 9/30/2014.
- U.S. Environmental Protection Agency (EPA) Office of Water. 2007. The Long-Term Control Plan EZ (LTCP-EZ) Template: A Planning Tool for CSO Control in Small Communities. EPA-833-R-07-005. https://www.epa.gov/sites/production/files/2015-10/documents/cso_ltcp_ez_template.pdf
- U.S. Environmental Protection Agency (EPA). 2008. Handbook for Developing Watershed Plans to Restore and Protect Our Waters. March 2008. Office of Water, Washington, D.C. EPA 841-B-08-002.
- U.S. Environmental Protection Agency (EPA) and Massachusetts Department of Environmental Protection (MassDEP). 2009. Optimal Stormwater Management Plan Alternatives: A Demonstration Project in Three Upper Charles River Communities. Prepared by Tetra Tech, Fairfax, Virginia. <http://www.epa.gov/region1/npdes/stormwater/assets/pdfs/BMP-Performance-Analysis-Report.pdf>.
- U.S. Environmental Protection Agency (EPA). 2009. "SUSTAIN—A Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality". Prepared by Tetra Tech, Inc. in Support of EPA Contract No. GS-10F-0268K.
- U.S. Environmental Protection Agency (EPA). 2010. Stormwater Best Management Practices (BMP) Performance Analysis. Prepared by Tetra Tech, Fairfax, Virginia. <http://www.epa.gov/region1/npdes/stormwater/assets/pdfs/BMP-Performance-Analysis-Report.pdf>
- U.S. Environmental Protection Agency (EPA). 2011a. Memorandum to Project File: Methodology for Developing Cost Estimates for Structural Stormwater Controls for Preliminary Residual Designation Sites for Charles River Watershed Areas in the Communities of Milford, Bellingham and Franklin, Massachusetts. August 9, 2011.
- U.S. Environmental Protection Agency (EPA). 2011b. "Report on Enhance Framework (SUSTAIN) and Field Applications for Placement of BMPs in Urban Watersheds". Prepared by Tetra Tech, Inc. in Support of EPA Contract No. GS-10F-0268K.
- U.S. Environmental Protection Agency (EPA). 2014a. System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN). Accessed August 2014. <http://www2.epa.gov/water-research/system-urban-stormwater-treatment-and-analysis-integration-sustain>
- U.S. Environmental Protection Agency (EPA). 2014b. SUSTAIN Application User's Guide for EPA Region 10. Prepared by Tetra Tech, Fairfax, Virginia. <http://www2.epa.gov/water-research/system-urban-stormwater-treatment-and-analysis-integration-sustain>
- U.S. Environmental Protection Agency (EPA). 2016. "Stormwater Trees: Technical Memorandum". Developed by Tetra Tech.
-

U.S Environmental Protection Agency (EPA). 2017. "Opti-Tool for Stormwater and Nutrient Management (Version 1)." Developed by TetraTech.

Vogel, R.M. and I. Wilson. 1996. Probability Distribution of Annual Maximum, Mean, and Minimum Streamflows in the United States. *Journal of Hydrologic Engineering*. 1:2, pp. 69-76.

White, K. and B. Baker. 2015. USACE Institute for Water Resources. Personal communication, January 29, 2015.

Zoltay, V.I. 2007. Integrated Watershed Management Modeling: Optimal Decision Making for Natural and Human Components. M.S. Thesis, Tufts Univ., Medford, MA.

Zoltay, V.I., R.M. Vogel, P.H. Kirshen, and K.S. Westphal. 2010. Integrated watershed management modeling: Generic optimization model applied to the Ipswich River Basin. *Journal of Water Resources Planning and Management*. 136(5), pp. 566-575.

Appendix A – User Support

User support is provided by checking user entered data for errors via code in the VBA modules and providing the WMOST User Guide and case studies as a source of default data.

A.1 User Error Checks

The user is informed with a message box if any of the following are encountered:

Land Use, Runoff, and Recharge

- stormwater sub-daily time series entered by user (when using manual entry for baseline hydrology) does not match the time period of the baseline runoff and recharge time series
- baseline hydrology modeling time period requested by user is outside of the data available in the watershed's time series file
- supporting documentation, such as the EDM inventory, are not found or are not in the correct format
- user model selections do not match pre-processed watershed files on EDM
- EDM query run by user will overwrite existing files in the EDM database storage folder
- when calculating runoff and recharge, dates, constituent name, or model time step have not been selected
- headers in hydrology and loadings databases do not match the headers expected based on the HRU IDs selected from the characteristics database
- number of HRU types, HRU sets or water users is less than or equal to zero
- time series data, that is runoff (and therefore recharge, water demand, point sources) dates, are not daily or monthly
- time series data is not more than one time step
- user attempts to enter less than 0 or greater than 50 land use sets or water user types
- stormwater simulation is attempted to be run prior to generating the input files
- SUSTAIN simulation failed due to incorrect SUSTAIN input files
- default BMP parameter values for selected constituents are not available
- default CN values for land use do not match any land use types or match multiple land use types
- stormwater set costs could not be calculated without baseline land area
- SUSTAIN output files did not match the expected file names or output file format

Surface Water, Groundwater, and Reservoir

- minimum in-stream flow is greater than maximum in-stream flow
- minimum external groundwater flows are less than zero
- user has not correctly indicated whether reservoir outflow should be modeled as a data time series or allowed to be a decision variable
- when calculating the groundwater recession coefficient,

- the area in the baseline HRUs is empty,
- data is missing from the recharge table, or
- modeling dates have not been entered.
- constituent decay values are negative
- a concentration and loadings target are set for the surface water system and/or reservoir

Potable/Nonpotable Water Use and Watershed Infrastructure

- user inputs more than 8 water users
- user-specified nonpotable water use percentages result in adjusted consumptive potable water use percentages that are out of range (0-100)
- user does not specify an average effluent concentration for a treatment facility
- user specifies a greater average effluent concentration for tertiary treatment compared to primary treatment

Management Options

- price elasticity values are not negative
- less than 3 sets of data have been entered in the Flood Module
- flood input data are negative values
- HRU areas serviced by the combined sewer system are greater than baseline HRU areas
- sanitary and storm sewer capacities are not defined when attempting to model sewer separation
- riparian areas are greater than baseline HRU areas

Results Processing

- results file does not match the expected format or the data in the interface
- the optimization did not result in a solution

A.2 User Manual, Case Studies and Default Data

Case studies are provided which provide default data that the user may draw on in lieu of other data sources.

In general, O&M costs may be assumed to be between 1 and 10% of capital costs depending on the infrastructure or management practice.

Many federal and state websites provide spatial data such as land use, soil, slope, zoning, and protected areas.

Note that the accuracy of the input data will affect the accuracy of the model solutions. Therefore, as described in the user manual, sensitivity analyses are recommended especially for input data with the greatest uncertainty.

Appendix B – SUSTAIN Input Cards

The following table lists and describes the input cards and parameters specified in the main input file (*.inp) for SUSTAIN runs. The SUSTAIN input cards are responsible for specifying the simulation settings, pollutant types, land use types, BMP types and site parameters, and the BMP to land routing network of the SUSTAIN simulation run.

Card No.	Card Name	Notes
700	Model Controls	
Parameters	Parameter Definitions	Notes
LINE1	Land simulation control (0-external,1-internal)	
	Land output directory (containing land output timeseries)	
LINE2	Start date of simulation (Year Month Day)	
LINE3	End date of simulation (Year Month Day)	
LINE4	Land Timeseries time step (Min)	
	BMP simulation time step (Min)	
	CRAAT (The ratio of max velocity to mean velocity under typical flow conditions)	
	Model output control (0-the same time step as land time series; 1-hourly)	
	Model output directory	
LINE5	ET Flag (0-onstant monthly ET,1-daily ET from the timeseries,2-alulate daily ET from the daily temperature data),	
	Climate time series file path	required if ET flag is 1 or 2
	Latitude (Decimal degrees)	required if ET flag is 2
LINE6	Monthly ET rate (in/day) if ET flag is 0 OR	
	Monthly pan coefficient (multiplier to ET value) if ET flag is 1 OR	
	Monthly variable coefficient to calculate ET values	
Card No.	Card Name	Notes
705	Pollutant Definition	
Parameters	Parameter Definitions	Notes
POLLUT_ID	Unique pollutant identifier	(Sequence number same as in land output time series)
POLLUT_NAME	Unique pollutant name	
MULTIPLIER	Multiplying factor used to convert the pollutant load to lbs	external control
SED_FLAG	The sediment flag (0-not sediment,1-sand,2-silt,3-clay,4-total sediment)	
SED_QUAL	The sediment-associated pollutant flag (0-no, 1-yes)	if = 1 then SEDIMENT is required in the pollutant list
SAND_QFRAC	The sediment-associated qual-fraction on sand (0-1)	only required if SED_QUAL = 1
SILT_QFRAC	The sediment-associated qual-fraction on silt (0-1)	only required if SED_QUAL = 1
CLAY_QFRAC	The sediment-associated qual-fraction on clay (0-1)	only required if SED_QUAL = 1

Card No.	Card Name	Notes
710	Land Use Definition	(required if land simulation control is external)
Parameters	Parameter Definitions	Notes
LANDTYPE	Unique land use definition identifier	
LANDNAME	Land use name	
IMPERVIOUS	Distinguishes pervious/impervious land unit (0-pervious; 1-impervious)	
TIMESERIESFILE	File name containing input timeseries	<i>[specify time series input files associated with each WMOST HRU]</i>
SAND_FRAC	The fraction of total sediment from the land which is sand (0-1)	
SILT_FRAC	The fraction of total sediment from the land which is silt (0-1)	
CLAY_FRAC	The fraction of total sediment from the land which is clay (0-1)	
Card No.	Card Name	Notes
712	Aquifer Information	<i>[will not be used in WMOST setup, subsurface dynamic modeled in WMOST]⁵⁹</i>
Card No.	Card Name	Notes
713	Aquifer Pollutant Background Concentration	<i>[will not be used in WMOST setup, subsurface dynamic modeled in WMOST]</i>
Card No.	Card Name	Notes
714	Ftable for BMP Class A, B, and C	Optional for designation of Class A, B and C BMP parameters, unique table for each BMP
Parameters	Parameter Definitions	Notes
FTABLE_ID	Unique Ftable identifier	(continuous string)
FLOW_LENGTH	Flow length (ft)	
BED_SLOPE	Longitudinal bed slope (ft/ft)	
NUM_RECORD	Number of layers in the Ftable	
DEPTH	Water depth (ft)	
SURFACE_AREA	Water surface area at the given depth (acre)	
VOLUME	Storage volume at the given depth (ac-ft)	
FLOW_WEIR	Overflow or weir outflow rate at the given depth (cfs)	
FLOW_ORIFICE	Channel flow or orifice outflow rate at the given depth (cfs)	
BMPSITE	Unique BMP site identifier	
BMPNAME	BMP template name or site name	

⁵⁹ On the basis of the approach used in SWMM, evaporation is subtracted from the rainfall or water storage area prior to calculating infiltration. A differential equation is solved iteratively to determine f (infiltration) at each time step by using Newton-Raphson method. Therefore, evapotranspiration is accounted for at each time step in the infiltration values.

Card No.	Card Name	Notes
715	BMP Site Information	(BIORETENTION, WETPOND, CISTERN, DRYPOND, INFILTRATION TRENCH, GREEN ROOF, POROUS PAVEMENT, RAIN BARREL, SWALE, CONDUIT, BUFFERSTRIP, AREABMP)
Parameters	Parameter Definitions	Notes
BMPTYPE	Unique BMP Types	(must use the exact same keyword)
Darea	Total Drainage Area in acre	
NUMUNIT	Number of BMP structures	
DDAREA	Design drainage area of the BMP structure (acre)	
PreLUType	Predevelopment land use type	(for external land simulation option)
AquiferID	Unique Aquifer ID, 0 --- no aquifer	(for external land simulation option)
FtableFLG	Ftable flag, 0 = no, 1 = yes	(for BMP Class A, B, and C)
FTABLE_ID	Unique Ftable identifier	(continuous string as in card 714)
Card No.	Card Name	Notes
720	Point Source Definition	<i>[will not be used in WMOST setup, accounted for within WMOST]</i>
Card No.	Card Name	Notes
721	Tier-1 Watershed Outlets Definition	<i>[will not be used in WMOST setup]</i>
Card No.	Card Name	Notes
722	Tier-1 Watershed Timeseries Definition	<i>[will not be used in WMOST setup]</i>
Card No.	Card Name	Notes
723	Pump Curve	(applies if PUMP_FLG is ON in card 725) <i>[not applicable to BMPs in WMOST v2]</i>
Card No.	Card Name	Notes
725	Class-A BMP Site Parameters (BMPs with storage)	(required if BMPSITE is CLASS-A in card 715)
Parameters	Parameter Definitions	Notes
BMPSITE	Class A BMP dimension group identifier in card 715	
WIDTH	Basin bottom width (ft)	
LENGTH	Basin bottom length (ft) / diameter (ft) for rain barrel or cistern	
OHEIGHT	Orifice Height (ft)	
DIAM	Orifice Diameter (in)	
EXTP	Exit Type (1 for C=1, 2 for C=0.61, 3 for C=0.61, 4 for C=0.5)	
RELTP	Release Type (1-Cistern, 2-Rain barrel, 3-others)	
PEOPLE	Number of persons (Cistern Option)	
DDAYS	Number of dry days (Rain Barrel Option)	
WEIRTP	Weir Type (1-Rectangular, 2-Triangular)	
WEIRH	Weir Height (ft)	
WEIRW	(weir type 1) Weir width (ft)	
THETA	(weir type 2) Weir angle (degrees)	

Parameters	Parameter Definitions	Notes
ET_MULT	Multiplier to PET	
PUMP_FLG	Pump option (0-OFF, 1-ON)	
DEPTH_ON	Water Depth (ft) at which the pump is started	
DEPTH_OFF	Water Depth (ft) at which the pump is stopped	
PUMP_CURVE	The unique name of pump curve	(continuous string without space)
Card No.	Card Name	Notes
730	Cistern Control Water Release Curve	(applies if release type is cistern in card 720) [not applicable to BMPs in WMOST v2]
Card No.	Card Name	Notes
735	Class B BMP Site Dimension Groups ("Channel" BMPs)	
Parameters	Parameter Definitions	Notes
BMPSITE	BMP Site identifier in card 715	
Parameters	Parameter Definitions	Notes
WIDTH	Basin bottom width (ft)	
LENGTH	Basin bottom length (ft)	
MAXDEPTH	Maximum depth of channel (ft)	
SLOPE1	Side slope 1 (ft/ft)	
SLOPE2	Side slope 2 (ft/ft) (1-4)	
SLOPE3	Side slope 3 (ft/ft)	
MANN_N	Manning 's roughness coefficient	
ET_MULT	multiplier to PET	
Card No.	Card Name	Notes
740	BMP Site Bottom Soil/Vegetation Characteristics	
Parameters	Parameter Definitions	Notes
BMPSITE	BMPSITE identifier in c715	
INFILTM	Infiltration Method (0-Green Ampt, 1-Horton, 2-Holtan)	
POLROTM	Pollutant Routing Method (1-Completely mixed, >1-number of CSTRs in series)	
POLREMM	Pollutant Removal Method (0-1st order decay, 1-kadlec and knight method)	
SDEPTH	Soil Depth (ft)	
POROSITY	Soil Porosity (0-1)	
FCAPACITY	Soil Field Capacity (ft/ft)	
WPOINT	Soil Wilting Point (ft/ft)	
AVEG	Vegetative Parameter A (0.1-1.0) (Empirical),	required for Holtan
FINFILT	Soil layer infiltration rate (in/hr)	
UNDSWITCH	Consider underdrain (1), Do not consider underdrain (0)	
UNDDEPTH	Depth of storage media below underdrain (ft)	
UNVOID	Fraction of underdrain storage depth that is void space (0-1)	

Parameters	Parameter Definitions	Notes
UNDINFILT	Background infiltration rate, below underdrain (in/hr)	
SUCTION	Average value of soil capillary suction along the wetting front, value must be greater than zero (in)	required for Green-Ampt
IMDMAX	Difference between soil porosity and initial moisture content, value must be greater than or equal to zero (a fraction)	required for Green-Ampt
MAXINFILT	Maximum rate on the Horton infiltration curve (in/hr)	required for Horton
Parameters	Parameter Definitions	Notes
DECAYCONS	Decay constant for the Horton infiltration curve (1/hr)	required for Horton
DRYTIME	Time for a fully saturated soil to completely dry (day)	required for Horton
MAXVOLUME	Maximum infiltration volume possible (in)	required for Horton
Card No.	Card Name	Notes
745	BMP Site Holtan Growth Index	
Parameters	Parameter Definitions	Notes
BMPSITE	BMPSITE identifier in card 715	
Gli	12 monthly values for GI in HOLTAN equation where i = jan, feb, mar ... dec	
Card No.	Card Name	Notes
747	BMP Site Initial Moisture Content	
Parameters	Parameter Definitions	Notes
BMPSITE	BMP Site identifier in card 715	
WATDEP_i	Initial surface water depth (ft)	
THETA_i	Initial soil moisture (ft/ft)	
Card No.	Card Name	Notes
750	Class C Conduit Parameters	(required if BMPSITE is CLASS-C in card 715) [not applicable to BMPs in WMOST v2]
Card No.	Card Name	Notes
755	Class C Conduit Cross Sections	[not applicable to BMPs in WMOST v2]
Card No.	Card Name	Notes
760	Irregular Cross Sections	[not applicable to BMPs in WMOST v2]
Card No.	Card Name	Notes
761	Buffer Strip BMP Parameters	(required if BMPTYPE is BUFFERSTRIP in card 715)
Parameters	Parameter Definitions	Notes
BMPSITE	BMP site identifier in card 715	
WIDTH	BMP width (ft)	
FLENGTH	Flow length (ft)	
DSTORAGE	Surface depression storage (in)	
MANNING_N	Overland Manning's roughness coefficient	
POLREMM	Pollutant Removal Method (0-1st order decay, 1-kadlec and knight method)	

Parameters	Parameter Definitions	Notes
ET_MULT	Multiplier to PET	
Card No.	Card Name	Notes
762	Area BMP Parameters	(required if BMPTYPE is AREABMP in card 715)
Parameters	Parameter Definitions	Notes
BMPSITE	BMP site identifier in card 715	
Parameters	Parameter Definitions	Notes
Area	BMP area (ft ²)	
FLength	flow length (ft)	
D	area depression storage (in)	
SLOPE	Overland slope (ft / ft)	
MANNING_N	Overland Manning's roughness coefficient	
SAT_INFILT	Saturated infiltration rate (in/hr)	
POLREMM	Pollutant Removal Method (0-1st order decay, 1-kadlec and knight method)	
DCIA	Percentage of Directly Connected Impervious Area (0-100)	
TOTAL_IMP_DA	Total Impervious Drainage Area (acre)	
Card No.	Card Name	Notes
765	BMP Site Pollutant Decay/Loss Rates	
Parameters	Parameter Definitions	Notes
BMPSITE	BMP site identifier in card 715	
QUALDECAYi	First-order decay rate for pollutant i (hr ⁻¹) where i = 1 to N (N = Number of QUAL from TIMESERIES FILES)	
Card No.	Card Name	Notes
766	Pollutant K' values	(applies when pollutant removal method is kadlec and knight method in card 740)
Parameters	Parameter Definitions	Notes
BMPSITE	BMP site identifier in card 715	
K'i	Constant rate for pollutant i (ft/yr) where i = 1 to N (N = Number of QUAL from card 705)	
Card No.	Card Name	Notes
767	Pollutant C* values	(applies when pollutant removal method is kadlec and knight method in card 740)
Parameters	Parameter Definitions	Notes
BMPSITE	BMP site identifier in card 715	
C*i	Background concentration for pollutant i (mg/l) where i = 1 to N (N = Number of QUAL from card 705)	
Card No.	Card Name	Notes
770	BMP Underdrain Pollutant Percent Removal	(applies when underdrain is on in card 740) [not applicable in WMOST v2 because no water quality modeling]

Card No.	Card Name	Notes
775	Sediment General Parameters	(required if pollutant type is sediment in card 705) [will not be used in WMOST setup, parameters related to in-channel transport of sediment]
Card No.	Card Name	Notes
780	Sand Transport Parameters	(required if pollutant type is sediment in card 705) [will not be used in WMOST setup, parameters related to in-channel transport of sediment]
Card No.	Card Name	Notes
785	Silt Transport Parameters	(required if pollutant type is sediment in card 705) [will not be used in WMOST setup, parameters related to in-channel transport of sediment]
Card No.	Card Name	Notes
786	Clay Transport Parameters	(required if pollutant type is sediment in card 705) [will not be used in WMOST setup, parameters related to in-channel transport of sediment]
Card No.	Card Name	Notes
790	Land to BMP Routing Network	(required for external land simulation control in card 700) [link HRUs with BMPs]
Parameters	Parameter Definitions	Notes
UniqueID	Identifies an instance of LANDTYPE in SCHEMATIC	
LANDTYPE	Corresponds to LANDTYPE in c710	
AREA	Area of LANDTYPE in ACRES	
DS	UNIQUE ID of DS BMP (0 - no BMP, add to end)	
Card No.	Card Name	Notes
795	BMP Site Routing Network	
Parameters	Parameter Definitions	Notes
BMPSITE	BMPSITE identifier in card 715	
OUTLET_TYPE	Outlet type (1-total, 2-weir, 3-orifice or channel, 4-underdrain)	
DS	Downstream BMP site identifier in card 715 (0 - no BMP, add to end)	
Card No.	Card Name	Notes
800	Optimization Controls	
Parameters	Parameter Definitions	Notes
Technique	Optimization Techniques, 0 = no optimization, 1 = Scatter Search, 2 = NSGAI	
Option	Optimization options, 0 = no optimization, 1 = specific control target and minimize cost, 2 = generate cost effectiveness curve	
StopDelta	Criteria for stopping the optimization iteration	(in dollars (\$))

Parameters	Parameter Definitions	Notes
MaxRuns	Maximum number of iterations	(for Option 2)
NumBest	Number of best solutions for output	(for Option 1)
Card No.	Card Name	Notes
805	BMP Cost Functions	
Parameters	Parameter Definitions	Notes
BMPSITE	BMP site identifier in card 715	
LinearCost	Cost per unit length of the BMP structure (\$/ft)	
AreaCost	Cost per unit area of the BMP structure (\$/ft ²)	
TotalVolumeCost	Cost per unit total volume of the BMP structure (\$/ft ³)	
MediaVolumeCost	Cost per unit volume of the soil media (\$/ft ³)	
UnderDrainVolumeCost	Cost per unit volume of the under drain structure (\$/ft ³)	
ConstantCost	Constant cost (\$)	
PercentCost	Cost in percentage of all other cost (%)	
LengthExp	Exponent for linear unit	
AreaExp	Exponent for area unit	
TotalVolExp	Exponent for total volume unit	
MediaVolExp	Exponent for soil media volume unit	
UDVolExp	Exponent for underdrain volume unit	
Card No.	Card Name	Notes
810	BMP Site Adjustable Parameters	Sets range for decision variables [will not be used in WMOST setup because running SUSTAIN as simulation]
Card No.	Card Name	Notes
814	Pre-developed Timeseries at Assessment Point for Flow Duration Curve	[will not be used in WMOST setup because running SUSTAIN as simulation]
Card No.	Card Name	Notes
815	Assessment Point and Evaluation Factor	[required to obtain detailed output]
Card No.	Card Name	Notes
BMPSITE	BMP site identifier in card 715 if it is an assessment point	
FactorGroup	Flow or pollutant related evaluation factor group, -1 = flow related evaluation factor, # = pollutant ID in card 705	
FactorType	Evaluation Factor Type (negative number for flow related and positive number for pollutant related)	
	-1 = AAFV Annual Average Flow Volume (ft ³ /yr), -2 = PDF Peak Discharge Flow (cfs), -3 = FEF Flow Exceeding frequency (#times/year)	
	1 = AAL Annual Average Load (lb/yr), 2 = AAC Annual Average Concentration (mg/L), 3 = MAC Maximum #days Average Concentration (mg/L)	

Card No.	Card Name	Notes
FactorVal1	if FactorType = 3 (MAC): Maximum #Days; if FactorType = -3 (FEF): Threshold (cfs); all other FactorType: -99	
FactorVal2	if FactorType = -3 (FEF): Minimum inter-exceedance time (hr); if = 0 then daily running average flow exceeding frequency; if = -1 then daily average flow exceeding frequency; all other FactorType: -99	
CalcMode	Evaluation Factor Calculation Mode; -99 for Option 0 (card 800): no optimization; 1 = % percent of value under existing condition (0-100); 2 = S scale between pre-develop and existing condition (0-1); 3 = V absolute value in the unit as shown in FactorType (third block in this card)	
TargetVal1	Target value for evaluation factor calculation mode; -99 for Option 0 (card 800): no optimization; Target value for minimize cost Option 1 (card 800); Lower limit of target value for cost-effective curve Option 2 (card 800)	
TargetVal2	Target value for evaluation factor calculation mode; -99 for Option 0 (card 800): no optimization; -99 for Option 1 (card 800): minimize cost; Upper limit of target value for cost-effective curve Option 2 (card 800)	
Factor_Name	Evaluation factor name	(user specified without any space)

Appendix C – Variable Definitions

Page	Variable	Description and Units
Watershed Flow Balance		
Land Conservation and Stormwater Management		
12	$A_{l,s=1}$	= user specified HRU areas for each HRU, l , for HRU set 1, $s=1$, acres
	$bA_{l,s=1}$	= baseline HRU areas after reallocation for conservation, acres
	l	= HRU index, 1 to NLu
	s	= HRU set number
	NLu	= number of HRU types
	$bA_{l,s}$	= area allocated to ‘managed’ HRU in set s , acres
	$NLuSet$	= number of HRU sets
	$A_{Min,l,s}$	= minimum area possible for management for baseline HRU l and management set s , acres
	$A_{Max,l,s}$	= maximum area possible for management for baseline HRU l and management set s , acres
	$C_{C,l,s}$	= capital cost associated with land reallocation for each HRU in each set (e.g., purchasing forest land or bioretention basin), \$/acre
13	$Q_{Ru,t}$	= total runoff from all land areas, MG/time step
	$Q_{Ru,l,s,t}$	= runoff rate from HRU l in HRU set s for time step t , MG/time step
	$Q_{Re,t}$	= total recharge from all land areas, MG/time step
	$Q_{Re,l,s,t}$	= recharge rate from HRU l in HRU set s for time step t , MG/time step
Groundwater		
14	$V_{Gw,l}$	= initial volume of groundwater, MG
	$V_{Gw,t}$	= volume of groundwater at time t , MG
	$Q_{ExtGw,t}$	= inflow of external groundwater, MG/time step
	$Q_{PtGw,t}$	= private (point) groundwater discharges, MG/time step
	$Q_{WtpGw,t}$	= leakage from treated water distribution system, MG/time step
	$Q_{AsrGw,t}$	= recharge from ASR facility to groundwater, MG/time step
	$Q_{SepGw,t}$	= inflow from septic system, MG/time step
	$bQ_{GwMake,t}$	= flow of groundwater “make-up water” into the system, MG/time step
	$Q_{GwSw,t}$	= baseflow, MG/time step
	$bQ_{GwWtp,t}$	= withdrawal by water treatment plant, MG/time step
	$Q_{GwWwtp,t}$	= infiltration into wastewater collection system, MG/time step
	$bQ_{GwExt,t}$	= groundwater leaving the basin, MG/time step
	$Q_{GwPt,t}$	= private (point) groundwater withdrawals, MG/time step
	$Q_{WtpGw,t}$	= unaccounted-for-water flow from treated water distribution system to groundwater, MG/time step
	$Q_{Use1,u=1,t}$	= initial, unaccounted-for-water flow, MG/time step
	$bP_{WtpLeakFix}$	= percent of treated water distribution system leakage that is fixed, %
15	k_b	= groundwater recession coefficient
Storm Sewer		
	$Q_{StSSw,t}$	= flow from storm sewer system to surface water, MG/time step
	$Q_{UseNpStS,t}$	= municipal water use flow that goes directly to the storm sewer, MG/time step
	Q_{StSMax}	= storm sewer capacity, MG

Page	Variable	Description and Units
Surface Water		
	$Q_{ExtSw,t}$	= surface water inflow from outside of basin, MG/time step
	$Q_{PtSw,t}$	= discharge from surface water point sources, MG/time step
	$Q_{WwtpSw,t}$	= discharge from primary wastewater treatment plant, MG/time step
16	Q_{WrfSw}	= discharge from water reuse facility (advanced treatment), MG/time step
	$Q_{SwRes,t}$	= flow from surface water to reservoir, MG/time step
	$bQ_{SwWtp,t}$	= flow to water treatment plant, MG/time step
	$bQ_{SwASr,t}$	= flow to ASR facility, MG/time step
	$Q_{SwPt,t}$	= private surface water withdrawals, MG/time step
Reservoir		
	$V_{Res,I}$	= initial volume of reservoir, MG
	$V_{Res,t}$	= volume of reservoir at time t, MG
	$Q_{SwRes,t}$	= inflow to reservoir from surface water bodies, MG/time step
	$bQ_{SwExt,t}$	= flow to surface water bodies outside of basin; based on user input, this variable may be a decision variable or a user-specified time series, MG/time step
	$bQ_{ResWtp,t}$	= flow to water treatment plant, MG/time step
	$bQ_{ResASr,t}$	= flow to ASR facility, MG/time step
	$bQ_{WMake,t}$	= make-up water, MG/time step
	$Q_{ResPt,t}$	= direct, private withdrawal from reservoir, MG/time step
	$Q_{PtRes,t}$	= direct, private discharge to reservoir, MG/time step
Water Treatment Plant		
17	$Q_{WtpUseP,t}$	= flow from primary WTP to potable water use, MG/time step
	$bQ_{WtpUseNp,t}$	= flow from primary WTP to nonpotable water use, MG/time step
Potable Water Use		
	u	= water user
	$bQ_{IbtWUseP,t}$	= inflow of potable water to water treatment facility via interbasin transfer, MG/time step
	$P_{ConsUseP,u,t}$	= final percent consumptive use for potable water use, %
	$Fr_{PUse,u,t}$	= fraction of potable water use per time step per user type
	$bQ_{UsePSanS,t}$	= flow of potable water through the sanitary sewer to the wastewater treatment plant, MG/time step
	$Q_{UsePSep,t}$	= flow to septic systems within the study area, MG/time step
	$Q_{UsePSepExt,t}$	= flow to septic systems outside the study area, MG/time step
	$bQ_{UsePIbtWw,t}$	= wastewater flow from potable uses to interbasin transfer wastewater services, MG/time step
	$P_{ConsUsePI,u,t}$	= initial percent consumptive use of potable water
	$P_{UseNpMax,u}$	= maximum percent of potable demand that may be met by nonpotable water
	$P_{ConsUseNp,u,t}$	= percent consumptive use of nonpotable water
Nonpotable Water Use		
18	$bQ_{WrfUseNp,t}$	= inflow of nonpotable water from water reuse facility, MG/time step
	$bQ_{IbtWUseNp,t}$	= inflow of nonpotable water to water treatment facility via interbasin transfer, MG/time step
	$Fr_{NpUse,u,t}$	= fraction of nonpotable water use per time step per user type

Page	Variable	Description and Units
	$bQ_{UseNpSanS,t}$	= flow of nonpotable water through the sanitary sewer to the wastewater treatment plant, MG/time step
	$Q_{UseNpSep,t}$	= flow to septic systems within the study area, MG/time step
	$Q_{UseNpSepExt,t}$	= flow to septic systems outside the study area, MG/time step
	$bQ_{UseNpIbtWw,t}$	= flow of nonpotable water to wastewater collection system via interbasin transfer, MG/time step
	$Fr_{NpUseMunSewer,t}$	= fraction of municipal water flows that go directly to the storm sewer, %
19	$Q_{UseI,u,t}$	= initial specified water use, MG/time step
	$ElasPrice_u$	= price elasticity by water user, %
	$bPprice$	= percent change in price, %
	bQ_{Dm}	= model selected amount of demand reduction, MG/time step
	$Q_{UseP,u,t}$	= potable water demand by water user, MG/time step
	$Q_{UseNp,u,t}$	= nonpotable water demand by water user, MG/time step
Wastewater Treatment Plant and Sanitary Sewer		
	$bQ_{WwtpWrf}$	= outflow to water reuse facility from primary WWTP, MG/time step
20	$P_{WwtpLeakI}$	= percent leakage of groundwater into the wastewater collection system, as a percent of wastewater treatment plant inflow, %
	$bP_{WwtpLeakFix}$	= percent of leaks fixed in the wastewater collection system, %
	$P_{Sep,u}$	= percent of users serviced by septic systems recharging inside the study area, %
	$P_{SepExt,u}$	= percent of users serviced by septic systems draining outside the study area, %
Water Reuse Facility		
	$bQ_{WrfASr,t}$	= flow from the water reuse facility to the ASR facility, MG/time step
Watershed Constituent Loadings Balance		
Land Conservation and Stormwater Management		
21	$L_{Ru,l,s,t}$	= runoff loadings from HRU l in HRU set s for time step t , lbs/time step
	$L_{Ru,t}$	= loadings from runoff from all land areas, lbs/time step
22	$L_{Re,l,s,t}$	= recharge loadings from HRU l in HRU set s for time step t , lbs/time step
	$L_{Re,t}$	= loadings from recharge from all land areas, lbs/time step
Groundwater		
	$L_{Gw,t}$	= loadings within the groundwater system, lbs/time step
	$X_{Gw,l}$	= initial constituent concentration of groundwater, mg/L
	$L_{ExtGw,t}$	= loadings from external groundwater, lbs/time step
	$L_{PtGw,t}$	= loadings from private groundwater discharges lbs/time step
	$L_{ASrGw,t}$	= loadings from ASR facility to groundwater, lbs/time step
	$L_{SepGw,t}$	= loadings from septic system, lbs/time step
	$L_{WtpGw,t}$	= loadings from leakage of treated water distribution system from WTP, lbs/time step
	$L_{GwSw,t}$	= baseflow loadings, lbs/time step
	$L_{GwPt,t}$	= private groundwater withdrawal loadings, lbs/time step
	$L_{GwWtp,t}$	= loadings from withdrawal by water treatment plant lbs/time step
	$L_{GwWwtp,t}$	= loadings from infiltration into wastewater collection system, lbs/time step
	$L_{GwExt,t}$	= loadings from groundwater leaving the basin, lbs/time step

Page	Variable	Description and Units
23	$k_{Gw,0}$	= zero-order removal rate, mg/L/time step
	$X_{GwF,t}$	= final groundwater concentration after removal (if applicable), mg/L
	$k_{Gw,1}$	= first-order removal rate, 1/time step
Storm Sewer		
24	$L_{StSSw,t}$	= loadings from storm sewer system to surface water, lbs/time step
	$L_{UseNpSewer,t}$	= municipal water use loadings that goes directly to the sewer system, lbs/time step
Surface Water		
25	$L_{Sw,t}$	= surface water loadings before removal, lbs/time step
	$L_{ExtSw,t}$	= surface water loadings from outside of basin, lbs/time step
	$L_{PtSw,t}$	= loadings from surface water point sources, lbs/time step
	$L_{WwtpSw,t}$	= loadings from primary wastewater treatment plant, lbs/time step
	L_{WrfSw}	= loadings from water reuse facility (advanced treatment), lbs/time step
	$X_{SwF,t}$	= final surface water concentration, mg/L
	$L_{SwRes,t}$	= loadings from surface water to reservoir, lbs/time step
	$L_{SwWtp,t}$	= loadings to water treatment plant, lbs/time step
	$L_{SwAsr,t}$	= loadings to ASR facility, lbs/time step
	$L_{SwPt,t}$	= loadings of private surface water withdrawals, lbs/time step
	Reservoir	
26	$L_{Res,t}$	= reservoir loadings, lbs
	$X_{Res,I}$	= initial concentration of reservoir, mg/L
	$L_{SwRes,t}$	= loadings to reservoir from surface water, lbs/time step
	$L_{PtRes,t}$	= loadings from direct, private discharge to reservoir, lbs/time step
	$L_{SwExt,t}$	= loadings to surface water outside of basin, lbs/time step
	$L_{ResWtp,t}$	= loadings to water treatment plant, lbs/time step
	$L_{ResAsr,t}$	= loadings to ASR facility, lbs/time step
	$L_{ResPt,t}$	= loadings from direct, private withdrawal from reservoir, lbs/time step
	$k_{Res,0}$	= zero-order removal rate, mg/L/time step
	$X_{ResF,t}$	= final reservoir concentration after removal (if applicable), mg/L
	$k_{Res,1}$	= first-order removal rate, 1/time step
	$ResArea$	= area of the reservoir, acres
	V_{Res}	= volume of reservoir, MG
Water Treatment Plant		
27	$X_{WtpIn,t}$	= model calculated WTP influent concentration, mg/L
	$X_{WtpMaxIn}$	= user defined maximum influent concentration at WTP, mg/L
	$L_{WtpUseP,t}$	= loadings from primary WTP to potable water use, lbs/time step
	$L_{WtpUseNp,t}$	= loadings from primary WTP to nonpotable water use, lbs/time step
	$X_{WtpAvEff}$	= average effluent concentration leaving primary water treatment plant, mg/L
Potable Water Use		
28	$L_{UseP,t}$	= loadings after addition from potable water users, lbs/time step
	$X_{IbtWUse}$	= average interbasin transfer concentration for potable and nonpotable water, mg/L
	$L_{UsePAdd,u}$	= potable water user average loadings, lbs/time step
	$X_{UseP,t}$	= concentration after addition from potable water users, mg/L

Page	Variable	Description and Units
	$L_{UsePSanS,t}$	= loadings of potable water to wastewater treatment plant through the sanitary sewer, lbs/time step
	$L_{UsePSep,t}$	= loadings of potable water to septic systems within the study area, lbs/time step
	$L_{UsePSepExt,t}$	= loadings of potable water to septic systems outside the study area, lbs/time step
	$L_{UsePIbtWw,t}$	= wastewater loadings from potable users to interbasin transfer wastewater services, lbs/time step
Nonpotable Water Use		
29	$L_{UseNp,t}$	= loadings after addition from nonpotable water users, lbs/time step
	$L_{WrfUseNp,t}$	= loadings from nonpotable water from water reuse facility, lbs/time step
	$L_{UseNpAddl,u}$	= nonpotable water user average loadings, lbs/time step
	$X_{UseNp,t}$	= concentration after addition from nonpotable water users, mg/L
	$L_{UseNpSanS,t}$	= loadings of nonpotable water to wastewater treatment plant through the sanitary sewer, lbs/time step
	$L_{UseNpSep,t}$	= loadings of nonpotable water to septic systems within the study area, lbs/time step
	$L_{UseNpSepExt,t}$	= loadings of nonpotable water to septic systems outside the study area, lbs/time step
	$L_{UseNpIbtWw,t}$	= loadings of nonpotable water to wastewater collection system via interbasin transfer, lbs/time step
Wastewater Treatment Plant		
	$X_{WwtpIn,t}$	= model calculated WWTP influent concentration, mg/L
	$X_{WwtpMaxIn}$	= user defined maximum influent concentration at WWTP, mg/L
	$L_{WwtpWrf,t}$	= loadings to water reuse facility from primary WWTP, lbs/time step
30	$X_{WwtpAvEff}$	= average effluent concentration leaving primary wastewater treatment plant, mg/L
Water Reuse Facility		
	$L_{WrfAsr,t}$	= loadings from the water reuse facility to the ASR facility, lbs/time step
	$X_{WrfAvEff}$	= average effluent concentration leaving water reuse facility, mg/L
Septic Systems		
	$L_{SepGw,t}$	= loadings from primary septic system to groundwater system, lbs/time step
	$X_{SepAvEff}$	= average effluent concentration leaving septic system, mg/L
Aquifer Storage and Recovery		
31	$L_{AsrGw,t}$	= loadings from the ASR facility to groundwater, lbs/time step
	$X_{AsrAvEff}$	= average effluent concentration leaving ASR facility, mg/L
Objective Function		
32	Z	= total annual cost for all implemented management practices, \$
33	C_{T,A_i}	= total annualized cost for management option i, \$
	n	= total number of management options
	$C_{C,A}$	= unit annual capital cost, \$/year
	C_C	= unit capital cost, \$
	F	= annualization factors
	i	= interest rate in percent/100, 0 - 1

Page	Variable	Description and Units
	T_{New}	= lifetime of new construction, years
	F_{New}	= annualization factor for new construction or expansion of existing facility
	T_{Plan}	= planning horizon, years
	T_{Exist}	= remaining lifetime of existing facility, years
	F_{Exist}	= annualization factor for existing facilities
34	F_{Plan}	= annualization factor for planning horizon
	N_t	= total number of time steps in the modeling period
	$N_{LeapYrs}$	= number of leap years in the modeling period
Costs and Constraints Associated with Hydrology Management Options		
Land and Management		
35	C_{ATb}	= total annual cost of reallocating areas among baseline HRUs from user-specified to model-chosen values, \$/year
	$C_{C,l,s=1}$	= capital cost associated with land reallocation for each HRU in set 1 (e.g., purchasing forest land), \$/acre
	$C_{Om,l,s=1}$	= annual O&M cost associated with maintaining, for example, the land preservation, \$/acre/year
	C_{ATm}	= total annual cost of reallocating areas among managed HRUs from user-specified to model-chosen values, \$/year
Demand Management		
36	E_u	= price elasticity for water user, u
	$P_{PriceMax}$	= one time, maximum percent change in price, %
	bD_{price}	= a binary decision variable, 0 or 1
37	$C_{ATPrice}$	= total annual cost to implement price changes, \$/year
	$C_{C,Price}$	= capital cost of price change, \$
	$C_{Om,Price}$	= annual O&M costs for implementation of price change, \$/year
	C_{ATDmd}	= total annual cost to implement direct demand management practices, \$/year
	C_{CDm}	= capital cost of direct demand management, \$
	C_{OmDm}	= annual O&M costs for direct demand management, \$/year
	Q_{DmMax}	= maximum demand reduction available and associated with specified costs, MG/time step
Pumping		
38	$C_{ATGWPump}$	= total annual cost for groundwater pumping, \$/year
	$F_{GWPumpExist}$	= annualization factor based on remaining lifetime of existing facilities
	$C_{CGWPump}$	= capital costs of new/additional groundwater pumping capacity/facility, \$/MGD
	$C_{OmGWPump}$	= operation and maintenance costs for groundwater pumping, \$/MG
	$Q_{GWPumpI}$	= initial groundwater pumping capacity, MGD
	$F_{GWPumpNew}$	= annualization factor for new capacity or facilities
	$bQ_{GWPumpAddl}$	= additional groundwater pumping capacity, MGD
	$C_{ATSWPump}$	= total annual cost for surface water pumping, \$/year
	$F_{SWPumpExist}$	= annualization factor based on remaining lifetime of existing facilities
	$C_{CSWPump}$	= capital costs of new/additional surface water pumping capacity/facility, \$/MGD
	$C_{OmSWPump}$	= operation and maintenance costs for surface water pumping, \$/MG

Page	Variable	Description and Units
	$Q_{SwPumpI}$	= initial surface water pumping capacity, MGD
	$F_{SwPumpNew}$	= annualization factor for new capacity or facilities
	$bQ_{SwPumpAddl}$	= additional surface water pumping capacity, MGD
Water Treatment Plant		
39	C_{ATWtp}	= total annual costs for water treatment, \$/year
	$F_{WtpExist}$	= annualization factor based on remaining lifetime of existing facilities
	C_{CWtp}	= capital costs of new or additional water treatment capacity or facility, \$/MGD
	$Q_{WtpMaxI}$	= initial water treatment capacity, MGD
	F_{WtpNew}	= annualization factor for new capacity or facilities
	$bQ_{WtpAddl}$	= additional water treatment capacity, MGD
	C_{OmWtp}	= O&M costs for water treatment, \$/MG
	C_{CATUaw}	= total annualized capital cost of reducing unaccounted-for water, \$/year
	C_{CUaw}	= capital cost of fixing Uaw such as initial survey and initial work to lower Uaw rate, \$
	C_{OmUaw}	= O&M cost to maintain low Uaw rate, \$/year
	$bP_{WtpGwFix}$	= percent of leakage that is fixed, %
	$P_{WtpLeakFixMax}$	= maximum physical limit of leakage reduction in treated water distribution system (e.g., given age of system and the repair costs specified), %
Wastewater Treatment Plant		
	C_{ATWwtp}	= total annual costs for wastewater treatment, \$/year
	$F_{WwtpExist}$	= annualization factor based on remaining lifetime of existing facilities
	C_{CWwtp}	= capital costs of new or additional wastewater treatment capacity or facility, \$/MGD
	$Q_{WwtpMaxI}$	= initial wastewater treatment capacity, MGD
	$F_{WwtpNew}$	= annualization factor for new capacity or facilities
	$bQ_{WwtpAddl}$	= additional wastewater treatment capacity, MGD
	C_{OmWwtp}	= O&M costs for wastewater treatment, \$/MG
40	$C_{ATGwWwtp}$	= total annualized cost of reducing groundwater infiltration into the wastewater collection system, \$/year
	$C_{CGwWwtp}$	= capital cost of fixing infiltration such as initial survey and initial repairs to lower infiltration rate, \$
	$C_{OmGwWwtp}$	= annual O&M cost to maintain low infiltration rate, \$/year
	$bP_{WwtpGwFix}$	= percent of groundwater infiltration that is fixed, %
	$P_{WwtpLeakFixMax}$	= maximum physical limit of repairing infiltration into the wastewater collection system (e.g., given age of system and the repair costs specified), %
Water Reuse Facility		
	C_{ATWrf}	= total annual costs for water reuse, \$/year
	$F_{WrfExist}$	= annualization factor based on remaining lifetime of existing facilities
	C_{CWrf}	= capital costs of new or additional WRF capacity, \$/MGD
	$Q_{WrfMaxI}$	= existing maximum WRF capacity, MGD
	F_{WrfNew}	= annualization factor for new capacity or facilities
	C_{OmWrf}	= O&M costs for WRF, \$/MG
	$bQ_{WrfAddl}$	= additional or new WRF capacity, MGD

Nonpotable distribution system

Page	Variable	Description and Units
41	$C_{ATNpdist}$	= total annual costs for nonpotable water distribution, \$/year
	$F_{NpdistExist}$	= annualization factor for existing capacity or facilities
	$Q_{NpdistI}$	= existing capacity of nonpotable distribution system, MGD
	$F_{NpdistNew}$	= annualization factor for new capacity or facilities
	$bQ_{NpdistAddl}$	= new or additional capacity, MGD
	$C_{CNpdist}$	= capital costs for Npdist, \$/MGD
	$C_{OmNpdist}$	= O&M costs for Npdist, \$/MG
Aquifer Storage and Recovery		
	C_{ATAsr}	= total annual costs for ASR, \$/year
	$F_{AsrExist}$	= annualization factor based on remaining lifetime of existing facilities
	C_{CAsr}	= capital costs for ASR, \$/MGD
	C_{OmAsr}	= operation and maintenance costs of ASR, \$/MG
	$Q_{AsrMaxI}$	= existing maximum capacity for ASR, MGD
	F_{AsrNew}	= annualization factor for new or additional capacity
	$bQ_{AsrAddl}$	= new or additional capacity, MGD
Groundwater Storage and Discharge		
	$V_{Gw,Max}$	= maximum groundwater storage volume, MG
	$V_{Gw,Min}$	= minimum groundwater storage volume, MG
42	$Q_{GwExtMin,t}$	= minimum groundwater outflow from the basin, MG/time step
	C_{ATMUGw}	= total annualized cost of make-up water, \$/year
	C_{GwMake}	= penalty for make-up water, \$/MG
Reservoir or Surface Storage		
	$V_{Res,MaxI}$	= maximum reservoir volume, MG
	$bV_{Res,Addl}$	= additional surface water storage capacity, MG
	$V_{Res,Min}$	= minimum reservoir storage volume (i.e., “dead storage”), MG
43	C_{ATRes}	= total annual costs for reservoir/surface storage, \$/year
	C_{CRes}	= capital costs of new or additional reservoir capacity, \$/MG
	C_{OmRes}	= annual O&M cost for reservoir, \$/MG/year
	C_{ATMUW}	= total annualized cost of make-up water, \$/year
	C_{WMake}	= penalty for make-up water, \$/MG
In-stream Flow and Surface water Discharges		
	$Q_{SwMin,t}$	= minimum in-stream flow for basin reach, ft ³ /sec
	$Q_{SwMax,t}$	= maximum in-stream flow for basin reach, ft ³ /sec
	$Q_{SwExtMin,t}$	= minimum flow exiting the reservoir and basin, ft ³ /sec
	$Q_{SwExtMax,t}$	= maximum flow exiting the reservoir and basin, ft ³ /sec
Interbasin Transfer		
44	C_{IbtW}	= cost of purchasing IBT water, \$/MG
	C_{ATIbtW}	= total annualized cost of interbasin transfer of water, \$/year
	C_{IbtWw}	= cost of IBT wastewater services, \$/MG
	$C_{ATIbtWw}$	= total annualized cost of interbasin transfer of wastewater, \$/year
45	$Q_{IbtWAddlMax}$	= maximum additional IBT water capacity, MGD
	$bQ_{IbtWAddl}$	= additional IBT water capacity, MGD
	$Q_{IbtWwAddlMax}$	= maximum additional IBT wastewater capacity, MGD
	$bQ_{IbtWwAddl}$	= additional IBT wastewater capacity, MGD

Page	Variable	Description and Units
	$Q_{IbtWMaxDay}$	= maximum potable water transfers from/to outside the basin for each day in the optimization period, MGD
46	$Q_{IbtWwMaxDay}$	= maximum potable wastewater transfers from/to outside the basin for each day in the optimization period, MGD
	$NDay(month(t))$	= number of days in the month
	$Q_{IbtWMaxMonth,m}$	= maximum potable water transfers from/to outside the basin for each month, m, MG/month
	$Q_{IbtWwMaxMonth,m}$	= maximum potable wastewater transfers from/to outside the basin for each month, m, MG/month
	$NdtM$	= number of time steps in the month
47	$Q_{IbtWMaxYr}$	= maximum potable water transfers from/to outside the basin for a given year in the optimization period, MG/year
	$Q_{IbtWwMaxYr}$	= maximum potable wastewater transfers from/to outside the basin for a given year in the optimization period, MG/year
48	$NdtYr$	= number of time steps in the year
	$NDay(year(t))$	= number of days in the year
	C_{CibtW}	= initial cost of purchasing additional water rights for IBT and construction of necessary infrastructure, \$/MGD
	C_{CibtWw}	= initial cost of purchasing additional wastewater transfer rights for IBT and construction of necessary infrastructure, \$/MGD
Flood Damages		
	C_{FAn}	= annualized cost of damage caused by flood flow n , \$/year
	C_{Fn}	= cost of damage caused by flood flow n , \$
	T_n	= recurrence interval of flood flow n , years
	Q_n	= flood flow n , ft ³ /sec
	n	= one element of the sets of flood flow data entered by user
49	C_{FA}	= annualized cost of damage caused by flood flows over the modeling time period, \$/year
	m_{Fn12}, b_{Fn12}	= constants of equation resulting from linear interpolation between Q_n and Q_{n+1}
	$Q_{SwRes,t}$	= flow in the stream channel, ft ³ /sec
Combined Sewer Overflow Management		
	bP_{CS}	= percentage of sewer system that is combined, %
	$Q_{sansMax}$	= maximum sanitary sewer capacity, MGD
	Q_{StsMax}	= maximum storm sewer capacity, MGD
	$C_{ATCSewSep}$	= total annual costs for sewer separation, \$/year
	$F_{CSewSepNew}$	= annualization factor for new facilities
	$C_{CCSewSep}$	= capital costs for sewer separation, \$/MGD
50	$V_{OSTotal,t}$	= total volume in offline storage, MG (initial offline storage volume is 0)
	$bD_{OS,t}$	= binary decision variable for use of offline storage, 0 or 1
	C_{ATOS}	= total annual costs for offline storage, \$/year
	k_{VC}	= virtual daily charge, \$
	C_{omOS}	= O&M costs for use of offline storage, \$/MG
	$bQ_{CSOS,t}$	= flow from combined sewer to offline storage, MG/time step
	$bQ_{OSWwtp,t}$	= flow from offline storage to WWTP, MG/time step
	V_{OSMax}	= maximum offline storage capacity, MG

Page	Variable	Description and Units
Costs and Constraints Associated with Loadings Management Options		
Water Treatment Plant		
	bP_{UWtp}	= portion of flows receiving upgraded treatment at WTP, %
	C_{ATUWtp}	= total annual costs for upgraded water treatment, \$/year
	C_{CUWtp}	= capital costs of upgraded water treatment capacity, \$/MGD
	$F_{UWtpNew}$	= annualization factor for new upgraded water treatment capacity
51	$X_{UWtpOut}$	= average effluent concentration achieved by upgraded water treatment, mg/L.
Wastewater Treatment Plant		
	bP_{UWwtp}	= portion of flows receiving upgraded treatment at WWTP, %
	$C_{ATUWwtp}$	= total annual costs for upgraded wastewater treatment, \$/year
	C_{CUWwtp}	= capital costs of upgraded wastewater treatment capacity, \$/MGD
	$F_{UWwtpNew}$	= annualization factor for new upgraded wastewater treatment capacity
52	$X_{UWwtpOut}$	= average effluent concentration achieved by upgraded wastewater treatment, mg/L
Enhanced Septic		
	C_{ATEsep}	= total annual costs for enhanced septic system, \$/year
	C_{OmEsep}	= O&M costs for enhanced septic system, \$/MG
	bP_{Esep}	= portion of flows routed for enhanced treatment within the septic system, %
	$Q_{EsepMax}$	= maximum enhanced septic system capacity, MGD
Surface water and Reservoir		
53	$X_{SwTarget}$	= surface water target concentration, mg/L
	$X_{ResTarget}$	= reservoir target concentration, mg/L
	$L_{SwTarget}$	= surface water target loadings, lbs/time step
	$L_{ResTarget}$	= reservoir target loadings, lbs/time step
Runoff Loadings Direct Reduction		
55	C_{ATRB}	= total annual costs for riparian buffer implementation, \$/year
	c	= land use conversion number
	$NRipConv$	= total number of possible land use conversions
	g	= relative loads group
	$NRipLoads$	= total number of relative loads groups
	$C_{CCRB,c}$	= initial cost to convert riparian land area, \$/acre
	$C_{OmRB,c}$	= O&M cost for riparian land area conversion, \$/acre/year
	$A_{RB,c,g}$	= riparian land area for each land use conversion and relative loads group, acres
	$bD_{RB,c,g}$	= binary decision variable for each land use conversion and relative loads group, 0 or 1
	$L_{RuAdjUp,t}$	= loadings from HRUs upgradient to a buffer area that have a loadings adjustment, lbs/time step
56	$F_{RBArea,l,g}$	= fraction of HRU land use area that is upgradient from the riparian buffer for each land use and relative loads group
	$P_{RBAAdj,c}$	= load adjustment efficiency for each land use conversion, %
	$L_{RuAdd,t}$	= loadings changes from converted HRU land areas, lbs/time step
57	$C_{ATDR,d}$	= total annual costs for direct reduction set, d , \$/year

Page	Variable	Description and Units
	$C_{DR,l,d}$	= capital cost for direct reduction on HRU, l , in direct reduction set, d , \$/acre
	$C_{OmDR,l,d}$	= O&M cost for direct reduction on HRU, l , in direct reduction set, d , \$/acre/year
	$A_{DR,l,d}$	= area receiving treatment within HRU, l , from direct reduction set, d , acres
	N_{DRSet}	= number of runoff loadings direct reduction sets
	$P_{DR,l,d}$	= direct reduction for each land use, c , in direct reduction set, d , %
	$bD_{DR,d}$	= binary decision variable for direct reduction set, d , 0 or 1
Loadings Target Adjustment		
58	C_{ATSR}	= total annual cost for streambank restoration loadings target adjustments, \$/year
	C_{CSR}	= capital cost for loadings target adjustment BMP, \$/stream feet restored
	bFt_{Str}	= number of stream feet restored or number of outfalls stabilized or enhanced
	$L_{RR,SR}$	= loading removal rate due to streambank restoration, lb/ft/time step
	Ft_{StrMax}	= maximum number of linear stream length that can be stabilized or restored, feet
59	C_{ATOut}	= total annual costs for outfall enhancement or stabilization loadings target adjustments, \$/year
	C_{COut}	= capital cost for loadings target adjustment BMP, \$/outfalls stabilized or enhanced
	bN_{Out}	= number of outfalls stabilized or enhanced
	$L_{RR,Out}$	= loading removal rate due to outfall enhancement or stabilization, lb/outfall/time step
	N_{OutMax}	= maximum number of outfalls than can be stabilized or enhanced
Combined Sewer Overflow Module		
Runoff		
62	$Fr_{CSS,l}$	= fraction of HRU area that is serviced by the CSS
	$Q_{RuCS,t}$	= total runoff from land areas serviced by the CSS, MG/time step
	$Q_{RuStS,t}$	= total runoff from land areas previously serviced by the CSS and currently serviced by a separate storm/sanitary sewer system, MG/time step
Potable Water Use		
	$bQ_{UsePCS,t}$	= flow of potable user flows through the combined sewer to the wastewater treatment plant, MG/time step
Nonpotable Water Use		
63	$bQ_{UseNpCS,t}$	= flow of nonpotable user flows through the combined sewer to the wastewater treatment plant, MG/time step
Sanitary Sewer		
	$Q_{SansWwtp,t}$	= sanitary sewer flows to the wastewater treatment plant, MG/time step
Combined Sewer		
64	$Q_{CSWwtp,t}$	= combined sewer flows to the wastewater treatment plant, MG/time step
	Q_{CSMax}	= combined sewer maximum, MG
CSO Events		
65	$Q_{CSWwtpMax}$	= hydraulic capacity of interceptor sewer that flows to the WWTP, MG/time step
	k	= large constant (e.g., 100,000)

Page	Variable	Description and Units
	$bD_{CSWwtp,t}$	= binary decision variable used to count hydraulic capacity exceedances for the interceptor sewer, 0 or 1
	$Q_{RuCSMax}$	= hydraulic capacity of flows to the interceptor sewer, MG/time step
	$bD_{RuCS,t}$	= binary decision variable used to count hydraulic capacity exceedances for the fraction of runoff routed to the combined sewer, 0 or 1
	N_{CSOmax}	= maximum number of allowable CSO events

Appendix D - Future Development

The following model enhancements may be implemented in future development efforts. These suggestions are based on reviewer and stakeholder feedback.

D.1 Model Components and Functionality

- Enhanced detail in modeling watershed components and processes
 - Adding a deep aquifer/groundwater storage component
 - Building in a time step independent delay between groundwater and septic recharge and baseflow to stream reach (e.g., as derived from detailed runoff-rainfall model or calibrated internally)
 - Adding stormwater utility – additional watershed component where stormwater system is separate from wastewater system fees and associated costs and revenues (user can specify percent of HRU's runoff that drains to stormwater utility)
 - Reservoirs
 - Subtracting evaporative losses from reservoir
 - Providing option for reservoir to be located at top of reach rather than at outlet
 - Modeling of infiltration/inflow and its management even if all wastewater is handled via interbasin transfer
 - Modeling of increased inflow associated with management actions through the analysis of precipitation time series and an explicit relationship between groundwater volume and infiltration rate.
 - Additional options for specifying pricing structure for water and wastewater services (e.g., increasing price blocks for water).
- Enhanced or additional management practices
 - Drought management program where demand reductions are triggered by low-flows in the stream reach.
 - Individual limits on withdrawals from each surface and groundwater source (e.g., ability to limit withdrawals to sustainable yield, if known).
 - Increased leakage over time in water distribution and sewer collection systems when funds have not been allocated to their management
 - Non-linear cost function for management of leakage from water distribution system and infiltration/inflow into sewer collection system
 - Non-linear price elasticities for demand management via pricing
 - Option for interbasin transfer of raw water to water treatment plant (WMOST v3 assumes direct transfer of potable water to the user)
 - Option to specify maximum outflow to downstream reach (i.e., maximum “Sw outflow to external Sw”)
 - Achievement of pre-development hydrology as management goal by adding ability to specify constraints for total basin runoff and recharge rates that mimic pre-development hydrology
 - Routing out of basin wastewater to the wastewater treatment plant

- Additional modules/functionality
 - Sensitivity and uncertainty analysis module which identifies most critical input data (i.e., greatest effect on results), most limiting resource, or most impacting human activity
 - Linking the model with climate data from CREAT⁶⁰ or other climate projections to facilitate sensitivity and uncertainty analyses
 - Demand management module as a pre-processing step to facilitate calculating one estimate for potential user demand reductions and the associated cost (e.g., rebates for water efficient appliances, monthly metering and billing, water rate changes, outdoor watering policies)
 - Enhanced spatial modeling by optimizing multiple reaches (e.g., running the model for multiple study areas/subbasins, routing between them and potentially optimizing for all areas/subbasins not just individually). This option would allow for an optimal solution across a region without creating ‘hot spot’ problems in any one basin.
 - Option for objective function
 - Alternative objective function such as maximizing in-stream flow for a user-specified budget
 - Multi-objective function such as minimizing cost, meeting human demand and achieving minimum in-stream flow targets with the ability to weight each objective for their relative priority/importance. The ability to weight different objectives would also allow prioritization based on social or political factors/costs.
 - Automated generation of trade-off curve between objective and user selected constraint.
 - User ability to define a generic constraint that is not pre-programmed
 - Ability to model more than three direct reduction management options
 - Ability to model more than one riparian buffer set (e.g., riparian buffer width)
 - Calculation of co-benefits of solutions
 - Avoided costs (e.g., system capacity expansion)
 - Savings in compliance costs for stormwater, drinking water and water quality standards
 - Changes in ecosystem services based on changes in-stream flow and land use (e.g., additional forest area) and their monetized value
 - Addition of payment values for flow trading
 - Allow for two constituents to be modeled at once
 - CSO module use when modeling hydrology and loadings
 - Incorporation of LTCP-EZ’s methodology for affordability analysis as an analysis of the cost estimates provided by WMOST for the lowest-cost solution

⁶⁰ <http://water.epa.gov/infrastructure/watersecurity/climate/creat.cfm>

- Flood module enhancement to minimize overestimation of flooding costs for floods that persist over consecutive days

D.2 User Interface and User Support

- Input features
 - Ability to specify additional IBT initial cost as one time fixed cost (\$) or based on capacity (\$/MGD)
 - Provide alternate setting for entering input using metric units
 - Only allow optimization when all check boxes next to input data buttons are checked
- Output features
 - Provide capital and O&M costs for management practices separately in results table
 - Provide time series for all flows among components and for storage volumes for groundwater and reservoir/surface storage as an advanced user option
 - Provide initial values for infrastructure capacities and other management practices
- Testing and guidance on appropriate spatial and temporal scales for modeling
- Create a tutorial to teach about optimization (e.g., a simple optimization problem in Excel to demonstrate optimization concepts).

Appendix E – SWMM Input File Example

[TITLE]

[OPTIONS]

```

FLOW_UNITS          CFS
INFILTRATION        MODIFIED_HORTON
FLOW_ROUTING        KINWAVE
START_DATE          01/01/1960
START_TIME          00:00:00
REPORT_START_DATE   01/01/1960
REPORT_START_TIME   00:00:00
END_DATE            12/31/2015
END_TIME            23:00:00
SWEEP_START         01/01
SWEEP_END           01/01
DRY_DAYS            0
REPORT_STEP         01:00:00
WET_STEP            00:05:00
DRY_STEP            00:05:00
ROUTING_STEP        0:05:00
ALLOW_PONDING      NO
INERTIAL_DAMPING    PARTIAL
VARIABLE_STEP       0.75
LENGTHENING_STEP   0
MIN_SURFAREA        0
NORMAL_FLOW_LIMITED BOTH
SKIP_STEADY_STATE   NO
FORCE_MAIN_EQUATION H-W
LINK_OFFSETS        DEPTH
MIN_SLOPE           0

```

[EVAPORATION]

```

;;Type      Parameters
;;-----
FILE         1.0    1.0    1.0    1.0    1.0    1.0    1.0    1.0    1.0    1.0    1.0    1.0
DRY_ONLY     NO

```

[TEMPERATURE]

```

FILE         "taunton_final.swm"    01/01/1960
WINDSPEED    FILE
SNOWMELT     34      0.5    0.6    0.0    50.0    0.0
ADC          IMPERVIOUS  1.0    1.0    1.0    1.0    1.0    1.0    1.0    1.0    1.0    1.0
ADC          PERVIOUS   1.0    1.0    1.0    1.0    1.0    1.0    1.0    1.0    1.0    1.0

```

[RAINGAGES]

```

;;          Rain      Time   Snow   Data
;;Name      Type      Intrvl Catch  Source
;;-----

```

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1 VOLUME 1:00 1.0 FILE "taunton_final.dat" TFgreen IN

[SUBCATCHMENTS]

```

;;
;;Name          Raingage      Outlet          Total   Pcnt.   Pcnt.   Curb   Snow
;;              Raingage      Outlet          Area   Imperv  Width  Slope  Length Pack
;;-----
PervASoil       1              PA              2.471   0       0       328.084 1      0
PervBSoil       1              PB              2.471   0       0       328.084 1      0
PervCSoil       1              PC              2.471   0       0       328.084 1      0
PervCDSoil      1              PCD             2.471   0       0       328.084 1      0
PervDSoil       1              PD              2.471   0       0       328.084 1      0
ForPervASoil    1              FPA             2.471   0       0       328.084 1      0
ForPervBSoil    1              FPB             2.471   0       0       328.084 1      0
ForPervCSoil    1              FPC             2.471   0       0       328.084 1      0
ForPervDSoil    1              FPD             2.471   0       0       328.084 1      0
AgPervASoil     1              APA             2.471   0       0       328.084 1      0
AgPervBSoil     1              APB             2.471   0       0       328.084 1      0
AgPervCSoil     1              APC             2.471   0       0       328.084 1      0
AgPervDSoil     1              APD             2.471   0       0       328.084 1      0
ComImp          1              ComI            2.471   100     0       328.084 1      0
HDRImp          1              HDRI            2.471   100     0       328.084 1      0
MDRImp          1              MDRI            2.471   100     0       328.084 1      0
LDRImp          1              LDRI            2.471   100     0       328.084 1      0
HWYImp          1              HWYI            2.471   100     0       328.084 1      0
FORImp          1              FORI            2.471   100     0       328.084 1      0
OPNImp          1              OPNI            2.471   100     0       328.084 1      0
AGImp           1              AGI             2.471   100     0       328.084 1      0
ComPervA        1              ComA            2.471   0       0       328.084 1      0
ComPervC        1              ComC            2.471   0       0       328.084 1      0
HDRPervA        1              HDRA            2.471   0       0       328.084 1      0
HDRPervC        1              HDRC            2.471   0       0       328.084 1      0
MDRPervA        1              MDRA            2.471   0       0       328.084 1      0
MDRPervC        1              MDRC            2.471   0       0       328.084 1      0
OPNPervA        1              OPNA            2.471   0       0       328.084 1      0
OPNPervC        1              OPNC            2.471   0       0       328.084 1      0
WETFORPervASoil 1              WETA            2.471   0       0       328.084 1      0

```

[SUBAREAS]

```

;;Subcatchment  N-Imperv      N-Perv          S-Imperv      S-Perv          PctZero      RouteTo      PctRouted
;;-----
PervASoil       0.01          0.1             0.01          0.05            0            OUTLET
PervBSoil       0.01          0.1             0.01          0.05            0            OUTLET
PervCSoil       0.01          0.1             0.01          0.05            0            OUTLET
PervCDSoil      0.01          0.1             0.01          0.05            0            OUTLET
PervDSoil       0.01          0.1             0.01          0.05            0            OUTLET
ForPervASoil    0.01          0.1             0.01          0.05            0            OUTLET
ForPervBSoil    0.01          0.1             0.01          0.05            0            OUTLET
ForPervCSoil    0.01          0.1             0.01          0.05            0            OUTLET
ForPervDSoil    0.01          0.1             0.01          0.05            0            OUTLET
AgPervASoil     0.01          0.1             0.01          0.05            0            OUTLET
AgPervBSoil     0.01          0.1             0.01          0.05            0            OUTLET

```

AgPervCSoil	0.01	0.1	0.01	0.05	0	OUTLET
AgPervDSoil	0.01	0.1	0.01	0.05	0	OUTLET
ComImp	0.01	0.1	0.01	0.05	0	OUTLET
HDRImp	0.01	0.1	0.01	0.05	0	OUTLET
MDRImp	0.01	0.1	0.01	0.05	0	OUTLET
LDRImp	0.01	0.1	0.01	0.05	0	OUTLET
HWYImp	0.01	0.1	0.01	0.05	0	OUTLET
FORImp	0.01	0.1	0.01	0.05	0	OUTLET
OPNImp	0.01	0.1	0.01	0.05	0	OUTLET
AGImp	0.01	0.1	0.01	0.05	0	OUTLET
ComPervA	0.01	0.1	0.01	0.05	0	OUTLET
ComPervC	0.01	0.1	0.01	0.05	0	OUTLET
HDRPervA	0.01	0.1	0.01	0.05	0	OUTLET
HDRPervC	0.01	0.1	0.01	0.05	0	OUTLET
MDRPervA	0.01	0.1	0.01	0.05	0	OUTLET
MDRPervC	0.01	0.1	0.01	0.05	0	OUTLET
OPNPervA	0.01	0.1	0.01	0.05	0	OUTLET
OPNPervC	0.01	0.1	0.01	0.05	0	OUTLET
WETFORPervASoil	0.01	0.1	0.01	0.05	0	OUTLET

[INFILTRATION]

;;Subcatchment	MaxRate	MinRate	Decay	DryTime	MaxInfil
;;-----	-----	-----	-----	-----	-----
PervASoil	6	0.25	3.24	7	0
PervBSoil	4	0.1	3.24	7	0
PervCSoil	3	0.05	3.24	7	0
PervCDSoil	2.5	0.04	3.24	7	0
PervDSoil	2	0.03	3.24	7	0
ForPervASoil	9.5	9.5	3.24	7	0
ForPervBSoil	4	0.1	3.24	7	0
ForPervCSoil	0.938	0.938	3.24	7	0
ForPervDSoil	2	0.03	3.24	7	0
AgPervASoil	8.01	8.01	3.24	7	0
AgPervBSoil	4	0.1	3.24	7	0
AgPervCSoil	0.768	0.768	3.24	7	0
AgPervDSoil	2	0.03	3.24	7	0
ComImp	3.0	0.5	4	7	0
HDRImp	3.0	0.5	4	7	0
MDRImp	3.0	0.5	4	7	0
LDRImp	3.0	0.5	4	7	0
HWYImp	3.0	0.5	4	7	0
FORImp	3.0	0.5	4	7	0
OPNImp	3.0	0.5	4	7	0
AGImp	3.0	0.5	4	7	0
ComPervA	3.8	3.8	3.24	7	0
ComPervC	0.336	0.336	3.24	7	0
HDRPervA	5.95	5.95	3.24	7	0
HDRPervC	0.605	0.605	3.24	7	0
MDRPervA	8.075	8.075	3.24	7	0
MDRPervC	0.806	0.806	3.24	7	0
OPNPervA	8.455	8.455	3.24	7	0

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```

OPNPervC      0.832      0.832      3.24      7      0
WETFORPervASoil  0.2      0.2      3.24      7      0
    
```

[AQUIFERS]

```

;;Name      Por      WP      FC      KS      Kslp      Tslp      ETu      ETs      Seep      Ebot      Egw      Umc
-----
SoilAaqu    0.453    0.085    0.19    0.43    48      15      0.35    6      0      0      0      0.4
SoilBaqu    0.463    0.116    0.232   0.13    35      15      0.35    12     0      0      0      0.4
SoilCaqu    0.398    0.136    0.244   0.06    53      15      0.35    10     0      0      0      0.3
SoilCDaqu   0.464    0.187    0.310   0.04    45      15      0.35    17     0      0      0      0.3
SoilDaqu    0.430    0.221    0.321   0.02    61      15      0.35    10     0      0      0      0.3
    
```

[GROUNDWATER]

```

;;Subcat    Aquifer    Node      Esurf    A1      B1      A2      B2      A3      DSW      Egwt
-----
PervASoil   SoilAaqu   PA        1.0      0.9     1.0     0.9     1.0     0      0      0.2
PervBSoil   SoilBaqu   PB        1.0      0.9     1.0     0.9     1.0     0      0      0.25
PervCSoil   SoilCaqu   PC        1.0      0.9     1.0     0.9     1.0     0      0      0.3
PervCDSoil  SoilCDaqu  PCD       1.0      0.9     1.0     0.9     1.0     0      0      0.35
PervDSoil   SoilDaqu   PD        1.0      0.9     1.0     0.9     1.0     0      0      0.4
ForPervASoil SoilAaqu   FPA       1.0      0.9     1.0     0.9     1.0     0      0      0.2
ForPervBSoil SoilBaqu   FPB       1.0      0.9     1.0     0.9     1.0     0      0      0.25
ForPervCSoil SoilCaqu   FPC       1.0      0.9     1.0     0.9     1.0     0      0      0.3
ForPervDSoil SoilDaqu   FPD       1.0      0.9     1.0     0.9     1.0     0      0      0.35
AgPervASoil SoilAaqu   APA       1.0      0.9     1.0     0.9     1.0     0      0      0.2
AgPervBSoil SoilBaqu   APB       1.0      0.9     1.0     0.9     1.0     0      0      0.25
AgPervCSoil SoilCaqu   APC       1.0      0.9     1.0     0.9     1.0     0      0      0.3
AgPervDSoil SoilDaqu   APD       1.0      0.9     1.0     0.9     1.0     0      0      0.35
ComPervA    SoilAaqu   ComA      1.0      0.9     1.0     0.9     1.0     0      0      0.2
ComPervC    SoilCaqu   ComC      1.0      0.9     1.0     0.9     1.0     0      0      0.3
HDRPervA    SoilAaqu   HDRA      1.0      0.9     1.0     0.9     1.0     0      0      0.2
HDRPervC    SoilCaqu   HDRC      1.0      0.9     1.0     0.9     1.0     0      0      0.3
MDRPervA    SoilAaqu   MDRA      1.0      0.9     1.0     0.9     1.0     0      0      0.2
MDRPervC    SoilCaqu   MDRC      1.0      0.9     1.0     0.9     1.0     0      0      0.3
OPNPervA    SoilAaqu   OPNA      1.0      0.9     1.0     0.9     1.0     0      0      0.2
OPNPervC    SoilCaqu   OPNC      1.0      0.9     1.0     0.9     1.0     0      0      0.3
WETFORPervASoil SoilAaqu   WETA      1.0      0.9     1.0     0.9     1.0     0      0      0.2
    
```

[JUNCTIONS]

```

;;
;;Name      Invert      Max.      Init.      Surcharge      Pounded
;;Name      Elev.      Depth      Depth      Depth      Area
-----
PA          0          0          0          0          0
PB          0          0          0          0          0
PC          0          0          0          0          0
PCD         0          0          0          0          0
PD          0          0          0          0          0
FPA         0          0          0          0          0
FPB         0          0          0          0          0
FPC         0          0          0          0          0
FPD         0          0          0          0          0
    
```

APA	0	0	0	0	0
APB	0	0	0	0	0
APC	0	0	0	0	0
APD	0	0	0	0	0
ComI	0	0	0	0	0
HDRI	0	0	0	0	0
MDRI	0	0	0	0	0
LDRI	0	0	0	0	0
HWYI	0	0	0	0	0
FORI	0	0	0	0	0
OPNI	0	0	0	0	0
AGI	0	0	0	0	0
ComA	0	0	0	0	0
ComC	0	0	0	0	0
HDRA	0	0	0	0	0
HDRC	0	0	0	0	0
MDRA	0	0	0	0	0
MDRC	0	0	0	0	0
OPNA	0	0	0	0	0
OPNC	0	0	0	0	0
WETA	0	0	0	0	0

[POLLUTANTS]

;;Name	Mass Units	Rain Concen.	GW Concen.	I&I Concen.	Decay Coeff.	Snow Only	Co-Pollut. Name	Co-Pollut. Fraction	DWF Concen.
TP	MG/L	0.017	0.0	0.0	0.00	NO *	0.0	0	

[LANDUSES]

;;Name	Cleaning Interval	Fraction Available	Last Cleaned
Perv_A_Soil	0	0	0
Perv_B_Soil	0	0	0
Perv_C_Soil	0	0	0
Perv_CD_Soil	0	0	0
Perv_D_Soil	0	0	0
For_Perv_ASoil	0	0	0
For_Perv_BSoil	0	0	0
For_Perv_CSoil	0	0	0
For_Perv_DSoil	0	0	0
Ag_Perv_ASoil	0	0	0
Ag_Perv_BSoil	0	0	0
Ag_Perv_CSoil	0	0	0
Ag_Perv_DSoil	0	0	0
Com_Imp	0	0	0
HDR_Imp	0	0	0
MDR_Imp	0	0	0
LDR_Imp	0	0	0
HWY_Imp	0	0	0
FOR_Imp	0	0	0

WMOST v2 Theoretical Documentation

```
OPN_Imp      0      0      0
AG_Imp       0      0      0
```

```
[COVERAGES]
;;Subcatchment  Land Use      Percent
;;-----
ComPervA      Perv_A_Soil    100
ComPervC      Perv_C_Soil    100
HDRPervA      Perv_A_Soil    100
HDRPervC      Perv_C_Soil    100
MDRPervA      Perv_A_Soil    100
MDRPervC      Perv_C_Soil    100
OPNPervA      Perv_A_Soil    100
OPNPervC      Perv_C_Soil    100
WETFORPervASoil  For_Perv_ASoil  100
PervASoil     Perv_A_Soil    100
PervASoil     Perv_B_Soil     0
PervASoil     Perv_C_Soil     0
PervASoil     Perv_CD_Soil    0
PervASoil     Perv_D_Soil     0
PervASoil     For_Perv_ASoil  0
PervASoil     For_Perv_BSoil  0
PervASoil     For_Perv_CSoil  0
PervASoil     For_Perv_DSoil  0
PervASoil     Ag_Perv_ASoil  0
PervASoil     Ag_Perv_BSoil  0
PervASoil     Ag_Perv_CSoil  0
PervASoil     Ag_Perv_DSoil  0
PervASoil     Com_Imp      0
PervASoil     HDR_Imp      0
PervASoil     MDR_Imp      0
PervASoil     LDR_Imp      0
PervASoil     HWY_Imp      0
PervASoil     FOR_Imp      0
PervASoil     OPN_Imp      0
PervASoil     AG_Imp       0
PervBSoil     Perv_A_Soil    0
PervBSoil     Perv_B_Soil    100
PervBSoil     Perv_C_Soil     0
PervBSoil     Perv_CD_Soil    0
PervBSoil     Perv_D_Soil     0
PervBSoil     For_Perv_ASoil  0
PervBSoil     For_Perv_BSoil  0
PervBSoil     For_Perv_CSoil  0
PervBSoil     For_Perv_DSoil  0
PervBSoil     Ag_Perv_ASoil  0
PervBSoil     Ag_Perv_BSoil  0
PervBSoil     Ag_Perv_CSoil  0
PervBSoil     Ag_Perv_DSoil  0
PervBSoil     Com_Imp      0
PervBSoil     HDR_Imp      0
```

PervBSoil	MDR_Imp	0
PervBSoil	LDR_Imp	0
PervBSoil	HWY_Imp	0
PervBSoil	FOR_Imp	0
PervBSoil	OPN_Imp	0
PervBSoil	AG_Imp	0
PervCSoil	Perv_A_Soil	0
PervCSoil	Perv_B_Soil	0
PervCSoil	Perv_C_Soil	100
PervCSoil	Perv_CD_Soil	0
PervCSoil	Perv_D_Soil	0
PervCSoil	For_Perv_ASoil	0
PervCSoil	For_Perv_BSoil	0
PervCSoil	For_Perv_CSoil	0
PervCSoil	For_Perv_DSoil	0
PervCSoil	Ag_Perv_ASoil	0
PervCSoil	Ag_Perv_BSoil	0
PervCSoil	Ag_Perv_CSoil	0
PervCSoil	Ag_Perv_DSoil	0
PervCSoil	Com_Imp	0
PervCSoil	HDR_Imp	0
PervCSoil	MDR_Imp	0
PervCSoil	LDR_Imp	0
PervCSoil	HWY_Imp	0
PervCSoil	FOR_Imp	0
PervCSoil	OPN_Imp	0
PervCSoil	AG_Imp	0
PervCDSoil	Perv_A_Soil	0
PervCDSoil	Perv_B_Soil	0
PervCDSoil	Perv_C_Soil	0
PervCDSoil	Perv_CD_Soil	100
PervCDSoil	Perv_D_Soil	0
PervCDSoil	For_Perv_ASoil	0
PervCDSoil	For_Perv_BSoil	0
PervCDSoil	For_Perv_CSoil	0
PervCDSoil	For_Perv_DSoil	0
PervCDSoil	Ag_Perv_ASoil	0
PervCDSoil	Ag_Perv_BSoil	0
PervCDSoil	Ag_Perv_CSoil	0
PervCDSoil	Ag_Perv_DSoil	0
PervCDSoil	Com_Imp	0
PervCDSoil	HDR_Imp	0
PervCDSoil	MDR_Imp	0
PervCDSoil	LDR_Imp	0
PervCDSoil	HWY_Imp	0
PervCDSoil	FOR_Imp	0
PervCDSoil	OPN_Imp	0
PervCDSoil	AG_Imp	0
PervDSoil	Perv_A_Soil	0
PervDSoil	Perv_B_Soil	0
PervDSoil	Perv_C_Soil	0

```

PervDSoil      Perv_CD_Soil      0
PervDSoil      Perv_D_Soil       100
PervDSoil      For_Perv_ASoil    0
PervDSoil      For_Perv_BSoil    0
PervDSoil      For_Perv_CSoil    0
PervDSoil      For_Perv_DSoil    0
PervDSoil      Ag_Perv_ASoil     0
PervDSoil      Ag_Perv_BSoil     0
PervDSoil      Ag_Perv_CSoil     0
PervDSoil      Ag_Perv_DSoil     0
PervDSoil      Com_Imp           0
PervDSoil      HDR_Imp           0
PervDSoil      MDR_Imp           0
PervDSoil      LDR_Imp           0
PervDSoil      HWY_Imp           0
PervDSoil      FOR_Imp           0
PervDSoil      OPN_Imp           0
PervDSoil      AG_Imp            0
ForPervASoil   Perv_A_Soil       0
ForPervASoil   Perv_B_Soil       0
ForPervASoil   Perv_C_Soil       0
ForPervASoil   Perv_CD_Soil      0
ForPervASoil   Perv_D_Soil       0
ForPervASoil   For_Perv_ASoil    100
ForPervASoil   For_Perv_BSoil    0
ForPervASoil   For_Perv_CSoil    0
ForPervASoil   For_Perv_DSoil    0
ForPervASoil   Ag_Perv_ASoil     0
ForPervASoil   Ag_Perv_BSoil     0
ForPervASoil   Ag_Perv_CSoil     0
ForPervASoil   Ag_Perv_DSoil     0
ForPervASoil   Com_Imp           0
ForPervASoil   HDR_Imp           0
ForPervASoil   MDR_Imp           0
ForPervASoil   LDR_Imp           0
ForPervASoil   HWY_Imp           0
ForPervASoil   FOR_Imp           0
ForPervASoil   OPN_Imp           0
ForPervASoil   AG_Imp            0
ForPervBSoil   Perv_A_Soil       0
ForPervBSoil   Perv_B_Soil       0
ForPervBSoil   Perv_C_Soil       0
ForPervBSoil   Perv_CD_Soil      0
ForPervBSoil   Perv_D_Soil       0
ForPervBSoil   For_Perv_ASoil    0
ForPervBSoil   For_Perv_BSoil    100
ForPervBSoil   For_Perv_CSoil    0
ForPervBSoil   For_Perv_DSoil    0
ForPervBSoil   Ag_Perv_ASoil     0
ForPervBSoil   Ag_Perv_BSoil     0
ForPervBSoil   Ag_Perv_CSoil     0

```

ForPervBSoil	Ag_Perv_DSoil	0
ForPervBSoil	Com_Imp	0
ForPervBSoil	HDR_Imp	0
ForPervBSoil	MDR_Imp	0
ForPervBSoil	LDR_Imp	0
ForPervBSoil	HWY_Imp	0
ForPervBSoil	FOR_Imp	0
ForPervBSoil	OPN_Imp	0
ForPervBSoil	AG_Imp	0
ForPervCSoil	Perv_A_Soil	0
ForPervCSoil	Perv_B_Soil	0
ForPervCSoil	Perv_C_Soil	0
ForPervCSoil	Perv_CD_Soil	0
ForPervCSoil	Perv_D_Soil	0
ForPervCSoil	For_Perv_ASoil	0
ForPervCSoil	For_Perv_BSoil	0
ForPervCSoil	For_Perv_CSoil	100
ForPervCSoil	For_Perv_DSoil	0
ForPervCSoil	Ag_Perv_ASoil	0
ForPervCSoil	Ag_Perv_BSoil	0
ForPervCSoil	Ag_Perv_CSoil	0
ForPervCSoil	Ag_Perv_DSoil	0
ForPervCSoil	Com_Imp	0
ForPervCSoil	HDR_Imp	0
ForPervCSoil	MDR_Imp	0
ForPervCSoil	LDR_Imp	0
ForPervCSoil	HWY_Imp	0
ForPervCSoil	FOR_Imp	0
ForPervCSoil	OPN_Imp	0
ForPervCSoil	AG_Imp	0
ForPervDSoil	Perv_A_Soil	0
ForPervDSoil	Perv_B_Soil	0
ForPervDSoil	Perv_C_Soil	0
ForPervDSoil	Perv_CD_Soil	0
ForPervDSoil	Perv_D_Soil	0
ForPervDSoil	For_Perv_ASoil	0
ForPervDSoil	For_Perv_BSoil	0
ForPervDSoil	For_Perv_CSoil	0
ForPervDSoil	For_Perv_DSoil	100
ForPervDSoil	Ag_Perv_ASoil	0
ForPervDSoil	Ag_Perv_BSoil	0
ForPervDSoil	Ag_Perv_CSoil	0
ForPervDSoil	Ag_Perv_DSoil	0
ForPervDSoil	Com_Imp	0
ForPervDSoil	HDR_Imp	0
ForPervDSoil	MDR_Imp	0
ForPervDSoil	LDR_Imp	0
ForPervDSoil	HWY_Imp	0
ForPervDSoil	FOR_Imp	0
ForPervDSoil	OPN_Imp	0
ForPervDSoil	AG_Imp	0

```

AgPervASoil      Perv_A_Soil      0
AgPervASoil      Perv_B_Soil      0
AgPervASoil      Perv_C_Soil      0
AgPervASoil      Perv_CD_Soil     0
AgPervASoil      Perv_D_Soil      0
AgPervASoil      For_Perv_ASoil   0
AgPervASoil      For_Perv_BSoil   0
AgPervASoil      For_Perv_CSoil   0
AgPervASoil      For_Perv_DSoil   0
AgPervASoil      Ag_Perv_ASoil    100
AgPervASoil      Ag_Perv_BSoil    0
AgPervASoil      Ag_Perv_CSoil    0
AgPervASoil      Ag_Perv_DSoil    0
AgPervASoil      Com_Imp          0
AgPervASoil      HDR_Imp          0
AgPervASoil      MDR_Imp          0
AgPervASoil      LDR_Imp          0
AgPervASoil      HWY_Imp          0
AgPervASoil      FOR_Imp          0
AgPervASoil      OPN_Imp          0
AgPervASoil      AG_Imp           0
AgPervBSoil      Perv_A_Soil      0
AgPervBSoil      Perv_B_Soil      0
AgPervBSoil      Perv_C_Soil      0
AgPervBSoil      Perv_CD_Soil     0
AgPervBSoil      Perv_D_Soil      0
AgPervBSoil      For_Perv_ASoil   0
AgPervBSoil      For_Perv_BSoil   0
AgPervBSoil      For_Perv_CSoil   0
AgPervBSoil      For_Perv_DSoil   0
AgPervBSoil      Ag_Perv_ASoil    0
AgPervBSoil      Ag_Perv_BSoil    100
AgPervBSoil      Ag_Perv_CSoil    0
AgPervBSoil      Ag_Perv_DSoil    0
AgPervBSoil      Com_Imp          0
AgPervBSoil      HDR_Imp          0
AgPervBSoil      MDR_Imp          0
AgPervBSoil      LDR_Imp          0
AgPervBSoil      HWY_Imp          0
AgPervBSoil      FOR_Imp          0
AgPervBSoil      OPN_Imp          0
AgPervBSoil      AG_Imp           0
AgPervCSoil      Perv_A_Soil      0
AgPervCSoil      Perv_B_Soil      0
AgPervCSoil      Perv_C_Soil      0
AgPervCSoil      Perv_CD_Soil     0
AgPervCSoil      Perv_D_Soil      0
AgPervCSoil      For_Perv_ASoil   0
AgPervCSoil      For_Perv_BSoil   0
AgPervCSoil      For_Perv_CSoil   0
AgPervCSoil      For_Perv_DSoil   0

```

AgPervCSoil	Ag_Perv_ASoil	0
AgPervCSoil	Ag_Perv_BSoil	0
AgPervCSoil	Ag_Perv_CSoil	100
AgPervCSoil	Ag_Perv_DSoil	0
AgPervCSoil	Com_Imp	0
AgPervCSoil	HDR_Imp	0
AgPervCSoil	MDR_Imp	0
AgPervCSoil	LDR_Imp	0
AgPervCSoil	HWY_Imp	0
AgPervCSoil	FOR_Imp	0
AgPervCSoil	OPN_Imp	0
AgPervCSoil	AG_Imp	0
AgPervDSoil	Perv_A_Soil	0
AgPervDSoil	Perv_B_Soil	0
AgPervDSoil	Perv_C_Soil	0
AgPervDSoil	Perv_CD_Soil	0
AgPervDSoil	Perv_D_Soil	0
AgPervDSoil	For_Perv_ASoil	0
AgPervDSoil	For_Perv_BSoil	0
AgPervDSoil	For_Perv_CSoil	0
AgPervDSoil	For_Perv_DSoil	0
AgPervDSoil	Ag_Perv_ASoil	0
AgPervDSoil	Ag_Perv_BSoil	0
AgPervDSoil	Ag_Perv_CSoil	0
AgPervDSoil	Ag_Perv_DSoil	100
AgPervDSoil	Com_Imp	0
AgPervDSoil	HDR_Imp	0
AgPervDSoil	MDR_Imp	0
AgPervDSoil	LDR_Imp	0
AgPervDSoil	HWY_Imp	0
AgPervDSoil	FOR_Imp	0
AgPervDSoil	OPN_Imp	0
AgPervDSoil	AG_Imp	0
ComImp	Perv_A_Soil	0
ComImp	Perv_B_Soil	0
ComImp	Perv_C_Soil	0
ComImp	Perv_CD_Soil	0
ComImp	Perv_D_Soil	0
ComImp	For_Perv_ASoil	0
ComImp	For_Perv_BSoil	0
ComImp	For_Perv_CSoil	0
ComImp	For_Perv_DSoil	0
ComImp	Ag_Perv_ASoil	0
ComImp	Ag_Perv_BSoil	0
ComImp	Ag_Perv_CSoil	0
ComImp	Ag_Perv_DSoil	0
ComImp	Com_Imp	100
ComImp	HDR_Imp	0
ComImp	MDR_Imp	0
ComImp	LDR_Imp	0
ComImp	HWY_Imp	0

```

ComImp FOR_Imp 0
ComImp OPN_Imp 0
ComImp AG_Imp 0
HDRImp Perv_A_Soil 0
HDRImp Perv_B_Soil 0
HDRImp Perv_C_Soil 0
HDRImp Perv_CD_Soil 0
HDRImp Perv_D_Soil 0
HDRImp For_Perv_ASoil 0
HDRImp For_Perv_BSoil 0
HDRImp For_Perv_CSoil 0
HDRImp For_Perv_DSoil 0
HDRImp Ag_Perv_ASoil 0
HDRImp Ag_Perv_BSoil 0
HDRImp Ag_Perv_CSoil 0
HDRImp Ag_Perv_DSoil 0
HDRImp Com_Imp 0
HDRImp HDR_Imp 100
HDRImp MDR_Imp 0
HDRImp LDR_Imp 0
HDRImp HWY_Imp 0
HDRImp FOR_Imp 0
HDRImp OPN_Imp 0
HDRImp AG_Imp 0
MDRImp Perv_A_Soil 0
MDRImp Perv_B_Soil 0
MDRImp Perv_C_Soil 0
MDRImp Perv_CD_Soil 0
MDRImp Perv_D_Soil 0
MDRImp For_Perv_ASoil 0
MDRImp For_Perv_BSoil 0
MDRImp For_Perv_CSoil 0
MDRImp For_Perv_DSoil 0
MDRImp Ag_Perv_ASoil 0
MDRImp Ag_Perv_BSoil 0
MDRImp Ag_Perv_CSoil 0
MDRImp Ag_Perv_DSoil 0
MDRImp Com_Imp 0
MDRImp HDR_Imp 0
MDRImp MDR_Imp 100
MDRImp LDR_Imp 0
MDRImp HWY_Imp 0
MDRImp FOR_Imp 0
MDRImp OPN_Imp 0
MDRImp AG_Imp 0
LDRImp Perv_A_Soil 0
LDRImp Perv_B_Soil 0
LDRImp Perv_C_Soil 0
LDRImp Perv_CD_Soil 0
LDRImp Perv_D_Soil 0
LDRImp For_Perv_ASoil 0

```

LDRImp	For_Perv_BSoil	0
LDRImp	For_Perv_CSoil	0
LDRImp	For_Perv_DSoil	0
LDRImp	Ag_Perv_ASoil	0
LDRImp	Ag_Perv_BSoil	0
LDRImp	Ag_Perv_CSoil	0
LDRImp	Ag_Perv_DSoil	0
LDRImp	Com_Imp	0
LDRImp	HDR_Imp	0
LDRImp	MDR_Imp	0
LDRImp	LDR_Imp	100
LDRImp	HWY_Imp	0
LDRImp	FOR_Imp	0
LDRImp	OPN_Imp	0
LDRImp	AG_Imp	0
HWYImp	Perv_A_Soil	0
HWYImp	Perv_B_Soil	0
HWYImp	Perv_C_Soil	0
HWYImp	Perv_CD_Soil	0
HWYImp	Perv_D_Soil	0
HWYImp	For_Perv_ASoil	0
HWYImp	For_Perv_BSoil	0
HWYImp	For_Perv_CSoil	0
HWYImp	For_Perv_DSoil	0
HWYImp	Ag_Perv_ASoil	0
HWYImp	Ag_Perv_BSoil	0
HWYImp	Ag_Perv_CSoil	0
HWYImp	Ag_Perv_DSoil	0
HWYImp	Com_Imp	0
HWYImp	HDR_Imp	0
HWYImp	MDR_Imp	0
HWYImp	LDR_Imp	0
HWYImp	HWY_Imp	100
HWYImp	FOR_Imp	0
HWYImp	OPN_Imp	0
HWYImp	AG_Imp	0
FORImp	Perv_A_Soil	0
FORImp	Perv_B_Soil	0
FORImp	Perv_C_Soil	0
FORImp	Perv_CD_Soil	0
FORImp	Perv_D_Soil	0
FORImp	For_Perv_ASoil	0
FORImp	For_Perv_BSoil	0
FORImp	For_Perv_CSoil	0
FORImp	For_Perv_DSoil	0
FORImp	Ag_Perv_ASoil	0
FORImp	Ag_Perv_BSoil	0
FORImp	Ag_Perv_CSoil	0
FORImp	Ag_Perv_DSoil	0
FORImp	Com_Imp	0
FORImp	HDR_Imp	0

```

FORImp MDR_Imp 0
FORImp LDR_Imp 0
FORImp HWY_Imp 0
FORImp FOR_Imp 100
FORImp OPN_Imp 0
FORImp AG_Imp 0
OPNImp Perv_A_Soil 0
OPNImp Perv_B_Soil 0
OPNImp Perv_C_Soil 0
OPNImp Perv_CD_Soil 0
OPNImp Perv_D_Soil 0
OPNImp For_Perv_ASoil 0
OPNImp For_Perv_BSoil 0
OPNImp For_Perv_CSoil 0
OPNImp For_Perv_DSoil 0
OPNImp Ag_Perv_ASoil 0
OPNImp Ag_Perv_BSoil 0
OPNImp Ag_Perv_CSoil 0
OPNImp Ag_Perv_DSoil 0
OPNImp Com_Imp 0
OPNImp HDR_Imp 0
OPNImp MDR_Imp 0
OPNImp LDR_Imp 0
OPNImp HWY_Imp 0
OPNImp FOR_Imp 0
OPNImp OPN_Imp 100
OPNImp AG_Imp 0
AGImp Perv_A_Soil 0
AGImp Perv_B_Soil 0
AGImp Perv_C_Soil 0
AGImp Perv_CD_Soil 0
AGImp Perv_D_Soil 0
AGImp For_Perv_ASoil 0
AGImp For_Perv_BSoil 0
AGImp For_Perv_CSoil 0
AGImp For_Perv_DSoil 0
AGImp Ag_Perv_ASoil 0
AGImp Ag_Perv_BSoil 0
AGImp Ag_Perv_CSoil 0
AGImp Ag_Perv_DSoil 0
AGImp Com_Imp 0
AGImp HDR_Imp 0
AGImp MDR_Imp 0
AGImp LDR_Imp 0
AGImp HWY_Imp 0
AGImp FOR_Imp 0
AGImp OPN_Imp 0
AGImp AG_Imp 100

```

[LOADINGS]

```
;;Subcatchment Pollutant Loading
```

```

;;-----
[BUILDDUP]
;;LandUse      Pollutant      Function      Coeff1      Coeff2      Coeff3      Normalizer
;;-----
Perv_A_Soil    TP          EXP          0.173733   0.100      1.000      AREA
Perv_B_Soil    TP          EXP          0.194073   0.100      1.000      AREA
Perv_C_Soil    TP          EXP          0.169932   0.100      1.000      AREA
Perv_CD_Soil   TP          EXP          0.184957   0.100      1.000      AREA
Perv_D_Soil    TP          EXP          0.175145   0.100      1.000      AREA
For_Perv_ASoil TP          EXP          0.000      0.100      1.000      AREA
For_Perv_BSoil TP          EXP          0.194073   0.100      1.000      AREA
For_Perv_CSoil TP          EXP          0.000      0.100      1.000      AREA
For_Perv_DSoil TP          EXP          0.000      0.100      1.000      AREA
Ag_Perv_ASoil  TP          EXP          0.000      0.100      1.000      AREA
Ag_Perv_BSoil  TP          EXP          0.7980286  0.100      1.000      AREA
Ag_Perv_CSoil  TP          EXP          0.000      0.100      1.000      AREA
Ag_Perv_DSoil  TP          EXP          0.000      0.100      1.000      AREA
Com_Imp        TP          EXP          0.0685     0.200      1.000      AREA
HDR_Imp        TP          EXP          0.0926     0.200      1.000      AREA
MDR_Imp        TP          EXP          0.0754     0.200      1.000      AREA
LDR_Imp        TP          EXP          0.056      0.200      1.000      AREA
HWY_Imp        TP          EXP          0.0515     0.200      1.000      AREA
FOR_Imp        TP          EXP          0.056      0.200      1.000      AREA
OPN_Imp        TP          EXP          0.056      0.200      1.000      AREA
AG_Imp         TP          EXP          0.056      0.200      1.000      AREA

[WASHOFF]
;;
;;Land Use      Pollutant      Function      Coeff1      Coeff2      Cleaning      BMP
;;-----      Eff.          Effic.
Perv_A_Soil    TP          EXP          1.000      2.00      0.0          0.0
Perv_B_Soil    TP          EXP          1.000      2.00      0.0          0.0
Perv_C_Soil    TP          EXP          1.000      2.00      0.0          0.0
Perv_CD_Soil   TP          EXP          1.000      2.00      0.0          0.0
Perv_D_Soil    TP          EXP          1.000      2.00      0.0          0.0
For_Perv_ASoil TP          EXP          1.000      2.00      0.0          0.0
For_Perv_BSoil TP          EXP          1.000      2.00      0.0          0.0
For_Perv_CSoil TP          EXP          1.000      2.00      0.0          0.0
For_Perv_DSoil TP          EXP          1.000      2.00      0.0          0.0
Ag_Perv_ASoil  TP          EXP          1.000      2.00      0.0          0.0
Ag_Perv_BSoil  TP          EXP          1.000      2.00      0.0          0.0
Ag_Perv_CSoil  TP          EXP          1.000      2.00      0.0          0.0
Ag_Perv_DSoil  TP          EXP          1.000      2.00      0.0          0.0
Com_Imp        TP          EXP          2.000      1.00      0.0          0.0
HDR_Imp        TP          EXP          2.000      1.00      0.0          0.0
MDR_Imp        TP          EXP          2.000      1.00      0.0          0.0
LDR_Imp        TP          EXP          2.000      1.00      0.0          0.0
HWY_Imp        TP          EXP          2.000      1.00      0.0          0.0
FOR_Imp        TP          EXP          2.000      1.00      0.0          0.0
OPN_Imp        TP          EXP          2.000      1.00      0.0          0.0

```

AG_Imp TP EXP 2.000 1.00 0.0 0.0

[REPORT]

INPUT NO

CONTROLS NO

SUBCATCHMENTS ComPervA ComPervC HDRPervA HDRPervC MDRPervA MDRPervC OPNPervA OPNPervC

SUBCATCHMENTS ForPervASoil ForPervCSoil AgPervASoil AgPervCSoil WETFORPervASoil ComImp HDRImp MDRImp OPNImp

NODES None

LINKS None