United States
Environmental Protection
Agency

EPA/600/R-15/058 | September 2015
www.epa.gov/ord

WATERSHED MANAGEMENT OPTIMIZATION SUPPORT TOOL (WMOST) v2

Theoretical Documentation

Office of Research and Development
National Health and Environmental Effects Research Laboratory

EPA 600/R-15/058| September 2015
www.epa.gov

Watershed Management Optimization Support Tool (WMOST) v2

Theoretical Documentation

EPA Project Team

Naomi Detenbeck and Marilyn ten Brink
NHEERL, Atlantic Ecology Division
Narragansett, RI 02882

Alisa Morrison
Student Services Contractor at ORD, NHEERL,
Atlantic Ecology Division
Narragansett, RI 02882

Ralph Abele, Jackie LeClair, and Trish Garrigan
Region 1
Boston, MA 02109

Abt Associates Project Team

Viktoria Zoltay, Annie Brown, Brendan Small, and Isabelle Morin, Abt Associates, Inc.
Cambridge, MA 02138

National Health and Environmental Effects Research laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

Notice

The development of the tool described in this document has been funded by the U.S. Environmental Protection Agency (EPA), in part by EPA's Green Infrastructure Initiative, under EPA Contract No. EP-C-13-039/Work Assignment 07 to Abt Associates, Inc. Version 2 of WMOST was supported through funding to an EPA Region 1 RARE project. Versions 1 and 2 of this document have been subjected to the Agency's peer and administrative review and has been approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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 that is, accounting for the direct and indirect effects of decisions. The model considers water flows and does not consider water quality. It is spatially lumped with options for a daily or monthly modeling time step. The optimization of management options is solved using linear programming. WMOST is intended to be a screening tool used as part of an integrated watershed management process such as that described in EPA's watershed planning handbook (EPA 2008). WMOST serves as a public-domain, efficient, and user-friendly 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). Practices that can be evaluated include projects related to stormwater, water supply, wastewater, and land resources such as low-impact development (LID) and land conservation. WMOST can aid in evaluating LID and green infrastructure as alternative or complementary management options in projects proposed for State Revolving Funds (SRF). In addition, the tool can enable assessing the trade-offs and co-benefits of various practices. In WMOST v2, the Baseline Hydrology and Stormwater Hydrology modules assist users with input data acquisition and pre-processing. 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"[1]. IWRM has been promoted as an integral part of the "Water Utility of the Future"[2] 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.[3] The U.S. Environmental Protection Agency (EPA) has also endorsed the concept of IWRM, focusing on coordinated implementation of stormwater and wastewater management.[4]

Several states and river basin commissions have started to implement IWRM.[5] 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) regulations[6] 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 constructed stormwater best management practices [BMPs]), low-impact development (LID) and land conservation. In recent years, the EPA SRF funding guidelines have been broadened to include support for GI at local scales–e.g., stormwater BMPs to reduce runoff and increase infiltration–and watershed scales–e.g., conservation planning for source water protection. Despite this development, few applicants have taken advantage of these opportunities to try nontraditional approaches to water quality improvement.[7] In a few notable cases, local managers have evaluated the relative cost and benefit of preserving GI compared to traditional

---

[1] 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.

[2] 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.

[3] http://www.awra.org/policy/policy-statements--water-vision.html

[4] Nancy Stoner memo: http://water.epa.gov/infrastructure/greeninfrastructure/upload/memointegratedmunicipalplans.pdf

[5] AWRA. 2012. Case Studies in Integrated Water Resources Management: From Local Stewardship to National Vision. American Water Resources Association Policy Committee, Middleburg, VA.

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

[7] American Rivers. 2010. Putting Green to Work: Economic Recovery Investments for Clean and Reliable Water. American Rivers, Washington, D.C

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.[8]

Beginning with the American Recovery and Reinvestment Act (ARRA) and continued with 2010 Appropriations language, Congress mandated a 20% set-aside of SRF funding for a “Green Project Reserve (GPR)”, which includes GI and land conservation measures as eligible projects in meeting water quality goals. The utilization of the GPR for GI projects has been relatively limited, and responses have varied widely across states. According to a survey of 19 state allocations of Green Project Reserve funds, only 18% of funds were dedicated to GI projects, and none of these projects were categorized as conservation planning to promote source water protection.[8] The state of Virginia passed regulations banning the use of ARRA funds for GI projects until after wastewater treatment projects had been funded.[8] In New England, states exceeded the 20% GPR mandate and used 30% of their ARRA funds for the GPR but directed most of the funds (76%) to energy efficiency and renewables; other uses of ARRA funds included 12% for water efficiency, 9% for GI, and 3% for environmentally innovative projects.

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 Version 1 of the Watershed Management Optimization Support Tool (WMOST). Version 2 of WMOST has been developed with support from a RARE grant to EPA Region 1 and ORD collaborators, supplemented with funding from US EPA ORD’s Green Infrastructure Initiative research program. Enhancements to WMOST Version 2 include Baseline Hydrology and Stormwater Hydrology modules to facilitate populating WMOST with the necessary hydrologic input data pre- and post- stormwater BMP implementation and a Flood Damage module to allow consideration of flood-related costs into the optimization analysis.

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.[9] 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. The current version of WMOST focuses on management options for water quantity endpoints. Additional functionality to address water quality issues is one of the high priority enhancements identified for future versions.

Development of each version of the WMOST tool was overseen by an EPA Planning Team. Priorities for update and refinement of the original model[10] were established following review by a Technical Advisory Group comprised of water resource managers and modelers. Case studies for two communities were developed to illustrate the application of IWRM using WMOST v1. These case studies (Upper Ipswich River and Danvers/Middleton, MA) are available from the WMOST website. WMOST was presented to stakeholders in a workshop held at the EPA Region 1 Laboratory in

---

[8] http://www.crwa.org/blue.html, http://v3.mmsd.com/greenseamsvideo1.aspx

[9] 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.

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 Technical Advisory Group 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 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.

Acknowledgements

WMOST builds on research funded by the National Science Foundation Graduate Research Fellowship Program and published in “Integrated Watershed Management Modeling: Optimal Decision Making for Natural and Human Components.” Zoltay, V., Kirshen, P.H., Vogel, R.M., and Westphal, K.S. 2010. Journal of Water Resources Planning and Management, 136:5, 566-575.

EPA Project Team
Naomi Detenbeck[10] and Marilyn ten Brink[10], U.S. EPA ORD, NHEERL, Atlantic Ecology Division
Yusuf Mohamoud[11], U.S. EPA ORD, NERL, Ecosystems Research Division
Alisa Morrison[12], ORISE participant at U.S. EPA ORD, NHEERL, Atlantic Ecology Division
Ralph Abele[10], Jackie LeClair,[12] and Trish Garrigan[12], U.S. EPA Region 1

Technical Advisory Group for WMOST v1
Alan Cathcart, Concord, MA Water/Sewer Division
Greg Krom, Topsfield, MA Water Department
Dave Sharples, Somersworth, NH Planning and Community Development
Mark Clark, North Reading, MA Water Department
Peter Weiskel, U.S. Geological Survey, MA-RI Water Science Center
Kathy Baskin, Massachusetts Executive Office of Energy and Environmental Affairs
Steven Estes-Smargiassi, Massachusetts Water Resources Authority
Hale Thurston, U.S. EPA ORD, NRMRL, Sustainable Technology Division
Rosemary Monahan, U.S. EPA Region 1
Scott Horsley, Horsley Witten Group
Kirk Westphal, CDM Smith
James Limbrunner, Hydrologics, Inc.
Jay Lund, University of California, Davis

---

[10] Versions 1 and 2

[11] Version 1

[12] Version 2

Technical Advisory Group for WMOST v2
Bob Lent, U.S. Geological Survey
Darryl Davis and Chris Dunn, U.S. Army Corps of Engineers, Hydrologic Engineering Center
Matthew Bates, U.S. Army Corps of Engineers, Engineer Research and Development Center
Richard Zingarelli, Massachusetts Department of Conservation and Recreation
Steve Silva, former U.S. EPA and Taunton watershed stakeholder
Tom Johnson, U.S. EPA, ORD, Global Change Research Program
Marisa Mazzotta, U.S. EPA, ORD, NHERRL, Atlantic Ecology Division

Reviewers for WMOST v1
Theoretical Documentation
Marisa Mazzotta, U.S. EPA ORD, NHEERL, Atlantic Ecology Division
Mark Voorhees, U.S. EPA Region 1
Michael Tryby, U.S. EPA ORD, NERL, Ecosystems Research Division

WMOST Tool, User Guide and Case Studies
Daniel Campbell, U.S. EPA ORD, NHEERL, Atlantic Ecology Division
Alisa Richardson, Rhode Island Department of Environmental Management (partial review)
Alisa Morrison, Student Services Contractor at U.S. EPA ORD, NHEERL, Atlantic Ecology Division
Jason Berner, U.S. EPA OW, OST, Engineering Analysis Division

Reviewers for WMOST v2
Theoretical Documentation
Kristen Hychka, ORISE participant at U.S. EPA ORD, NHEERL, Atlantic Ecology Division
Mark Voorhees, U.S. EPA Region 1, Boston, MA
Thomas Johnson, U.S. EPA ORD, NCEA, Washington, D.C.

WMOST Tool, User Guide and Case Studies
Jason Berner, U.S. EPA OW, OST, Engineering Analysis Division
Yusuf Mohamoud, U.S. EPA ORD, NERL, Athens, GA
Steven Kraemer, U.S. EPA ORD, NERL, Athens, GA
Andrea Traviglia, U.S. EPA Region 1, Boston, MA

Previous Contributors
Yusuf Mohamoud, ORD, NERL, Ecosystems Research Division, Athens, GA 30605
Becky Wildner and Lauren Parker, Abt Associates, Inc.
Nigel Pickering, Horsley Witten Group under subcontract to Abt Associates Inc.
Richard M. Vogel, Tufts University under subcontract to Abt Associates Inc.

Table of Contents

Figures

Tables

1. Background

Objective of the Tool

The Watershed Management Optimization Support Tool (WMOST) is a public-domain software 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).

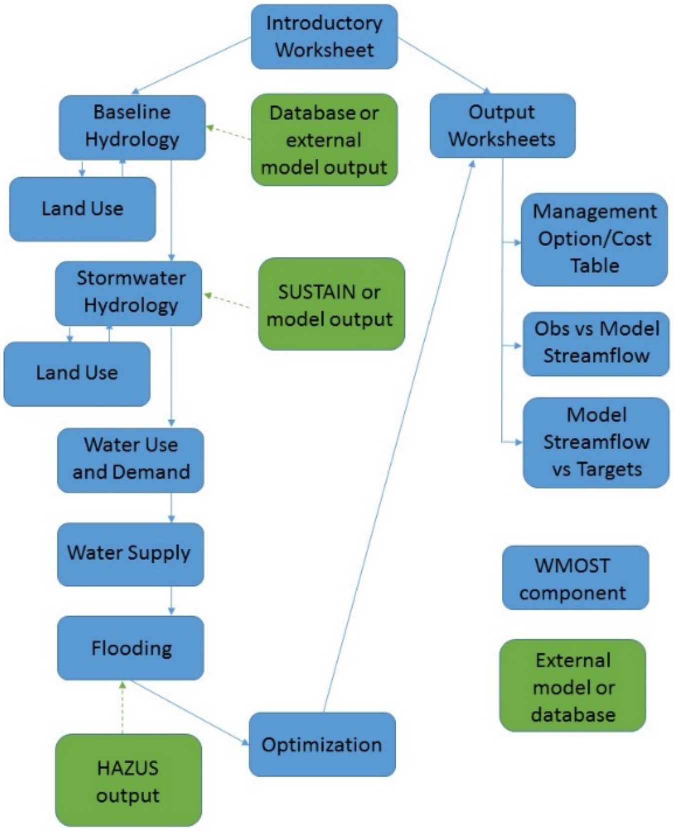
WMOST identifies the least-cost combination of management practices to meet the user specified management goals. Management goals may include meeting projected water supply demand, minimum and maximum in-stream flow targets, and reducing damages associated with flooding. The tool considers a range of management practices related to water supply, wastewater, nonpotable water reuse, aquifer storage and recharge, stormwater, low-impact development (LID), and land conservation, accounting for both the cost and performance of each practice. In addition, WMOST may be run for a range of values for management goals to perform a cost-benefit analysis and obtain a Pareto frontier or 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.

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. For example, results may demonstrate the potential cost-savings of coordinating or integrating the management of water supply, wastewater, and stormwater. In addition, the tool may facilitate the evaluation of LID and GI as alternative or complementary management options in projects proposed for State Revolving Funds (SRF). As of October 2010, SRF Sustainability Policy calls for integrated planning in the use of SRF resources as a means of improving the sustainability of infrastructure projects and the communities they serve. In addition, Congress mandated a 20% set-aside of SRF funding for a "Green Project Reserve" which includes GI and land conservation measures as eligible projects in meeting water quality goals.

About this Document

This document provides the theoretical background for WMOST, 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, physical limits on watershed components and management options, variable definitions, and internal configuration. Following an overview of the base model available in WMOST version 1, we describe three new modules available in version 2: 1) a baseline hydrology module, 2) a stormwater hydrology module, and 3) a flood damage module (Figure 1-1).

Figure 1-1. WMOST Components and Interactions with External Databases or Models.



The rest of this document is organized as follows. The model's theoretical approach (i.e., equations) is described in detail in Section *2*. This section is organized according to the traditional description of an optimization model: first the objective function (Section *2.1*), and then the constraints (Section *2.2*). Readers interested in understanding the watershed system first may consider starting with Section *2.2* where flow balances are presented and then reading Section *2.1* which describes the management costs that constitute the objective function. Sections 3 through 5 describe the Baseline Hydrology, Stormwater Hydrology, and Flood-Damage modules, respectively. These modules assist users with input data acquisition and pre-processing and enable consideration of flood-damage costs in the optimization function. Section 6 describes the configuration of the software components. Section 7 summarizes the required input data to run the model. A series of appendices provides complementary information on common errors, parameter default values, user inputs, 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.

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 version 1 is shown in Figure 1-2. The figure shows the *possible* watershed system components and *potential* water flows among them.

The principal characteristics of WMOST include:

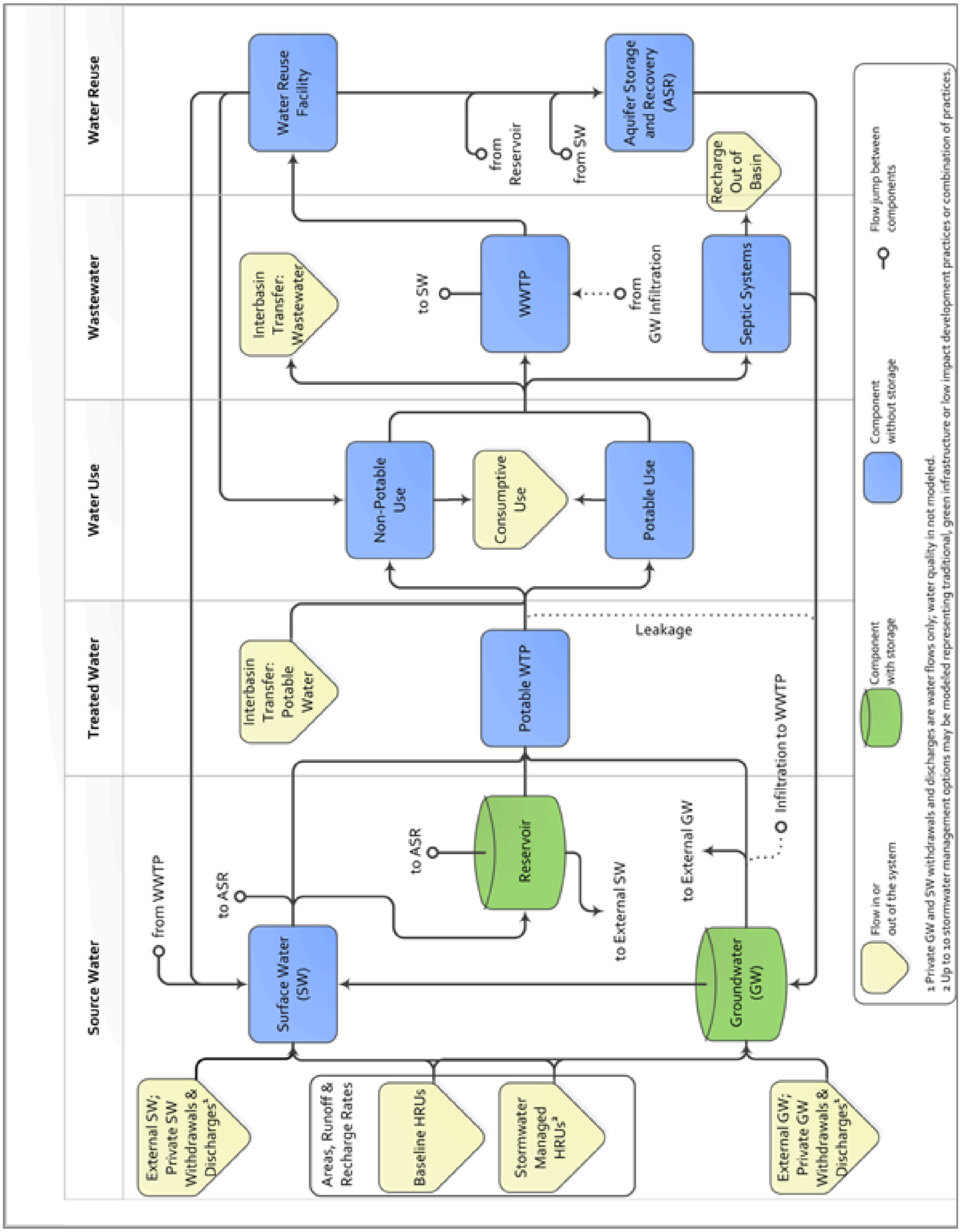
- Implementation in Microsoft Excel 2010© which is linked seamlessly with Visual Basic for Applications (VBA) and a free, linear programming (LP) optimization solver, eliminating the need for specialized software and using the familiar Excel platform for the user interface;
- User-specified inputs for 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 Lp_solve 5.5, a LP optimization solver, to determine the least-cost combination of practices that achieves the user-specified management goals (See *Section* 3 for details on Lp_solve 5.5, LP optimization, and the software configuration);
- Spatially lumped calculations modeling one basin and one reach but with flexibility in the number of hydrologic response units (HRUs),[13] each with an individual runoff and recharge rate;
- Modeling time step of a day or month without a limit on the length of the modeling period;[14]
- Solutions that account for both the direct and indirect effects of management practices. For example, the model will account for the fact 1) that implementing water conservation will reduce water revenue, wastewater flow and wastewater revenue if wastewater revenue is calculated based on water flow or 2) that 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 water supply demand from increased groundwater supply;
- Ability to specify up to ten stormwater management options, including traditional, GI or LID practices;
- Enforcement of physical constraints, such as the conservation of mass (i.e., water), within the watershed; and
- Consideration of water flows only (i.e., no water quality modeling yet).

---

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

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

Figure 1-2. Schematic of Potential Water Flows in the WMOST



1 Private GW and SW withdrawals and discharges are water flows only; water quality in not modeled.
2 Up to 10 stormwater management options may be modeled representing traditional, green infrastructure or low impact development practices or combination of practices.

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

Management Practice	Action	Model Component Affected	Impact
Land conservation	Increase area of land use type specified as 'conservable'	Land area allocation	Preserve runoff & recharge quantity & quality
Stormwater management via traditional, 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, treatment
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)
Potable water treatment capacity	Increase maximum treatment capacity	Potable water treatment plant	Treatment to standards, meet potable human demand
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 water quality of receiving water (or improve if sewer overflow events)
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

Management Practice	**Action**	**Model Component Affected**	**Impact**
Table 1-1 Continued			
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
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, and decrease loss of public and private assets due to flooding

2. Objective Function and Linear Programming

The objective function is defined as minimizing the total, annualized cost of all chosen management practices. The objective is minimized by selecting the optimal values for decision variables which are denoted with the prefix *b*. These decisions determine which management practices are selected to minimize the objective and meet all the constraints. This section provides the equations for the objective function and the constraints that define the linear programming (LP) optimization model.

In general, the following naming convention is followed in the equations.

- The first capital letter indicates the type of quantity (e.g., Q =flow, A=area) except for decision variables which 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 with 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 is 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 LP model).
    - Additional subscripts include *u* for different water uses (e.g., residential, commercial), *l* for different HRU types (e.g., residential/hydrologic soil group B/slope <5%), *s* for “sets” of HRU types which include the baseline HRU set and other sets that have the same HRUs but with management practices implemented such as stormwater management. The user specifies the number of water uses, HRU types, and sets of HRU types.

All variables are defined when they are first used in the text. Input variables, their units and definitions are summarized in *Section* 7. Units for input variables are based on the units expected to be used in the most-readily available data sources.

Objective Function

The objective function is defined as minimizing the total, annualized cost of all chosen management practices. The total, annualized cost includes annualized capital costs and annual operation and maintenance costs.

$$Z = (\sum_{i=1}^{n} C_{T,A_i}) \tag{1}$$

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

2.1.1 Costs

Total annual costs are calculated for all implemented management practices. In this section, we first we describe the generic form of cost equations, and then we provide all of the individual equations used in the model. 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 approaches with three different annualization factors, F, depending on the management practice.

$$C_{C,A} = F \times C_C \tag{2}$$

where

$C_{C,A}$ = unit annual capital cost, \$/year

C_C = unit capital cost, \$

Unit construction costs for new facilities or costs for expanding the capacity of an existing facility (i.e., capital costs) are annualized over the expected lifetime of the new construction (e.g., wastewater treatment plant, bioretention basin).

$$F_{New} = \frac{i \times (1+i)^{T_{New}}}{(1+i)^{T_{New}} - 1} \tag{3}$$

where

i = interest rate in percent/100, 0 - 1

T_{New} = lifetime of new construction, years

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

$$F_{Exist} = \frac{i \times (1+i)^{T_{New}}}{(1+i)^{T_{New}} - 1} \times \frac{T_{Plan} - T_{Exist}}{T_{Plan}} \tag{4}$$

where

T_{Plan} = the planning horizon, years

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.

$$F_{Plan} = \frac{i \times (1+i)^{T_{Plan}}}{(1+i)^{T_{Plan}} - 1} \tag{5}$$

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)[15] – 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 RRR 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 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. Recharge and runoff rates may be derived from a calibrated/validated simulation model such as Hydrological Simulation Program Fortran (HSPF),[16] Soil Water and Assessment Tool (SWAT)[17] and/or the Storm Water Management Model.[18] See *Section 2.2.1* for continuity equations defining total watershed runoff and recharge based on RRRs and 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 which may include projected increases in development.[19] 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

---

[15] 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.

[16] http://water.usgs.gov/software/HSPF/

[17] http://swat.tamu.edu/

[18] http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/

[19] 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).

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),

$$C_{ATb} = \sum_{l=1}^{nLu}\left((F_{Plan} \times C_{C,l,s=1} + C_{Om,l,s=1}) \times \left(bA_{l.s=1} - A_{l,s=1}\right)\right) \tag{6}$$

where

l = HRU index, 1 to nLu
s = number of HRU sets
C_{ATb} = total annual cost of reallocating areas among baseline HRUs from user-specified to model-chosen values, \$/year
nLu = number of HRU types
$C_{C,l,s=1}$ = 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/yr
$A_{l,s=1}$ = user specified areas for baseline HRU, acres
$bA_{l,s=1}$ = model-chosen, land area for baseline HRUs, acres

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 2.2.1*.

For s = 2 to $NLuSet$,

$$C_{ATm} = \sum_{s=2}^{NLuSet} \sum_{l=1}^{nLu}\left((F_{Plan} \times C_{C,l,s} + C_{Om,l,s}) \times bA_{l,s}\right) \tag{7}$$

where

$bA_{l,s=2to\ NLuSet}$ = model chosen land area for managed HRUs, acres
$NLuSet$ = number of HRU sets

Section 2.2 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 – via pricing and via 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.[20]

Pricing change: 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:

$$C_{ATPrice} = bPriceBin \times (F_{Plan} \times C_{C,Price} + C_{Om,Price}) \tag{8}$$

where

$C_{ATPrice}$ = annual cost to implement price changes, \$/year
$bPriceBin$ = a binary decision variable, 0 or 1
$C_{C,Price}$ = capital cost of price change, \$
$C_{Om,Price}$ = annual O&M costs for implementation of price change, \$/year

Direct demand reduction: The aggregate cost of various demand reduction practices may be specified and the initial demand will be reduced by the user specified percentage.

$$C_{ATDmd} = bDmdBin \times (F_{Plan} \times C_{CDm} + C_{OmDm}) \tag{9}$$

where

C_{ATDmd} = annual cost to implement direct demand management practices, \$/year
$bDmdBin$ = binary decision variable, 0 or 1
C_{CDm} = capital cost of direct demand management, \$
C_{OmDm} = annual O&M costs for direct demand management, \$/year

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.[21]

Infrastructure Capacity and Use: 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.

---

[20] 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.

[21] http://www.epa.gov/watersense/our_water/start_saving.html#tabs-3

Groundwater pumping:

$$C_{ATGwPump} = (F_{GwPumpExist} \times C_{CGwPump} \times Q_{GwPumpI}) + (F_{GwPumpNew} \times C_{CGwPump} \times bQ_{GwPumpAddl}) + (C_{OmGwPump} \times \sum_{t} bQ_{GwWtp,t}) \tag{10}$$

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/year
$Q_{GwPumpI}$ = initial groundwater pumping capacity, MGD
$F_{GwPumpNew}$ = annualization factor for new capacity or facilities
$bQ_{GwPumpAddl}$ = additional groundwater pumping capacity, MGD
$bQ_{GwWtp,t}$ = flow from groundwater pump to water treatment plant, MGD

Surface water pumping:

$$C_{ATSwPump} = (F_{SwPumpExist} \times C_{CSwPump} \times Q_{SwPumpI}) + (F_{SwPumpNew} \times C_{CSwPump} \times bQ_{SwPumpAddl}) + (C_{OmSwPump} \times \textstyle\sum_{t}(bQ_{SwWtp,t} + bQ_{ResWtp,t})) \tag{11}$$

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/year
$Q_{SwPumpI}$ = initial surface water pumping capacity, MGD
$F_{SwPumpNew}$ = annualization factor for new capacity or facilities
$bQ_{SwPumpAddl}$ = additional surface water pumping capacity, MGD
$bQ_{SwWtp,t}$ = flow from surface water to water treatment plant, MGD
$bQ_{ResWtp,t}$ = flow from reservoir to water treatment plant, MGD

Water treatment facility (WTP):

$$C_{ATWtp} = (F_{WtpExist} \times C_{CWtp} \times Q_{WtpMaxI}) + (F_{WtpNew} \times C_{CWtp} \times bQ_{WtpAddl}) + (C_{OmWtp} \times \sum_{t}(bQ_{SwWtp,t} + bQ_{GwWtp,t} + bQ_{ResWtp,t})) \tag{12}$$

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} = annual O&M costs for water treatment, \$/MG/year

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

The cost for repairing unaccounted-for water in the potable distribution system is calculated as:

$$C_{ATUaw} = (F_{Plan} \times C_{CUaw} + C_{OmUaw}) \times \frac{bP_{WtpGwFix}}{100} \tag{13}$$

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} = annual O&M cost to maintain low Uaw rate, \$/year
$bP_{WtpGwFix}$ = percent of leakage that is fixed, %

Wastewater treatment plant (WWTP):

$$\begin{aligned} C_{ATWwtp} &= (F_{WwtpExist} \times C_{CWwtp} \times Q_{WwtpMaxI}) + (F_{WwtpNew} \times C_{CWwtp} \times bQ_{WwtpAddl}) \\ &\quad + (C_{OmWwtp} \times \sum_{t} (bQ_{UsePWwtp,t} + bQ_{UseNpWwtp,t} + Q_{GwWwtp,t})) \end{aligned} \tag{14}$$

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
$Q_{WwtpMaxI}$ = initial wastewater treatment capacity, MGD
$F_{WwtpNew}$ = annualization factor for new capacity or facilities
$bQ_{WwtpAddl}$ = additional wastewater treatment capacity, MGD
C_{OmWwtp} = annual O&M costs for wastewater treatment, \$/MG/year
$bQ_{UsePWwtp,t}$ = flow from potable water use to treatment plant, MGD
$bQ_{UseNpWwtp,t}$ = flow from nonpotable water use to treatment plant, MGD
$Q_{GwWwtp,t}$ = groundwater infiltration into collection system, MGD

Reducing infiltration into wastewater collection system:

$$C_{ATGwWwtp} = (F_{Plan} \times C_{CGwWwtp} + C_{OmGwWwtp}) \times \frac{bP_{GwWwtpFix}}{100} \tag{15}$$

where

$C_{ATGwWwtp}$ = total annualized capital 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, %

Water reuse facility (WRF):

$$C_{ATWrf} = (F_{WrfExist} \times C_{CWrf} \times Q_{WrfMaxI}) + (F_{WrfNew} \times C_{CWrf} \times bQ_{WrfAddl}) + (C_{OmWrf} \times \sum_{t} bQ_{WwtpWrf,t}) \tag{16}$$

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
$Q_{WrfMaxI}$ = existing maximum WRF capacity, MGD
F_{WrfNew} = annualization factor for new capacity or facilities
C_{OmWrf} = annual O&M costs for WRF, \$/MG/year
$bQ_{WrfAddl}$ = additional or new WRF capacity, MGD
$bQ_{WwtpWrf}$ = flow from WWTP to WRF, MGD

Nonpotable distribution system (Npdist):

$$C_{ATNpdist} = (F_{NpdistExist} \times C_{CNpdist} \times Q_{NpdistI}) + (F_{NpdistNew} \times C_{CNpdist} \times bQ_{NpdistAddl}) + (C_{OmNpdist} \times \sum_{t} bQ_{WrfUseNp,t}) \tag{17}$$

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 maximum capacity Npdist, \$/MGD
$C_{OmNpdist}$ = annual O&M costs for maximum capacity Npdist, \$/MG/year
$bQ_{WrfUseNp,t}$ = flow from WRF to nonpotable water use, MGD

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 WMOST v1, 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).

$$C_{ATAsr} = (F_{AsrExist} \times C_{CAsr} \times Q_{AsrMaxI}) + (F_{AsrNew} \times C_{CAsr} \times bQ_{AsrAddl}) + \left(C_{OmAsr} \times \sum_{t} \left(bQ_{WrfAsr,t} + bQ_{SwAsr,t} + bQ_{ResAsr,t}\right)\right) \tag{18}$$

where

C_{ATAsr} = total annual costs for ASR, $/year
$F_{AsrExist}$ = annualization factor based on remaining lifetime of existing facilities
C_{CAsr} = capital costs of existing facility annualized over the remaining lifetime, $/year
C_{OmAsr} = operation and maintenance costs of ASR, $/year
$Q_{AsrMaxI}$ = existing maximum capacity, MGD
F_{AsrNew} = annualization factor for new or additional capacity
$bQ_{AsrAddl}$ = capacity of new or additional capacity, MGD
$bQ_{WrfAsr,t}$ = flow from WRF to ASR, MGD
$bQ_{SwAsr,t}$ = flow from surface water to ASR, MGD
$bQ_{ResAsr,t}$ = flow from reservoir to ASR,MGD

Reservoir or surface storage (e.g., storage tank, pond):

$$C_{ATRes} = (F_{ResExist} \times C_{CRes} \times V_{ResMaxI}) + (F_{ResNew} \times C_{CRes} \times bV_{ResAddl}) + (C_{OmRes} \times (bV_{ResAddl} + V_{ResMaxI})) \tag{19}$$

where

C_{ATRes} = total annual costs for reservoir/surface storage, $/year
$F_{ResExist}$ = annualization factor based on remaining lifetime of existing facilities
C_{CRes} = capital costs of new or additional capacity, $
$V_{ResMaxI}$ = existing capacity, MG
F_{ResNew} = annualization factor based on lifetime of new facilities
$bV_{ResAddl}$ = additional or new capacity, MG
C_{OmRes} = annual O&M cost, $/year

Interbasin transfer (IBT) for water and wastewater: As shown in Figure 1-2, 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:

$$C_{ATIbtW} = F_{Plan} \times C_{CIbtW} \times bQ_{IbtWAddl} + C_{IbtW} \times \sum_{t} \left(bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t}\right) \tag{20}$$

where

C_{CIbtW} = initial cost of purchasing additional water rights for IBT and construction of necessary infrastructure, $/MGD
$bQ_{IbtWAddl}$ = additional water IBT capacity purchased, MGD
C_{IbtW} = cost of purchasing IBT water, $/MGD
$bQ_{IbtWUseP,t}$ = flow of IBT water to potable water use, MGD
$bQ_{IbtWUseNp,t}$ = flow of IBT water to nonpotable water use, 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:

$$C_{ATIbtWw} = F_{Plan} \times C_{CIbtWw} \times bQ_{IbtWwAddl} + C_{IbtWw} \times \sum_{t} (bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t}) \qquad (21)$$

where

C_{CIbtWw} = initial cost of purchasing additional wastewater transfer rights for IBT and construction of necessary infrastructure, \$/MGD
$bQ_{IbtWwAddl}$ = additional wastewater IBT capacity purchased, MGD
C_{IbtWw} = cost of IBT wastewater services, \$/MGD
$bQ_{UsePIbtWw,t}$ = flow of wastewater from potable use to IBT, MGD
$bQ_{UseNpIbtWw,t}$ = flow of wastewater from nonpotable use to IBT, 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:

$$C_{FAn} = C_{Fn} \times \frac{1}{T_n} \quad \textit{for } Qn \qquad (22)$$

where

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

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. Therefore, these equations are programmed in the linear programming solver as “special order sets” or SOS. The SOS function allows a piece-wise definition so that each equation applies only to the specific flow interval for which it is valid. 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:

$$C_{FA} = \sum_t m_{Fn12} \times Q_{SwRes,t} + b_{Fn12} \quad \textit{for flow between } Qn \textit{ and } Qn_{+1} \qquad (23)$$

where

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 Qn and Qn+1
$Q_{SwRes,t}$ = flow in the stream channel, ft^3/sec

Penalty for Insufficient Water: WMOST gives the user an option to allow “make up” of water shortfalls within the watershed system by adding a hypothetic flow of water to the reservoir located at the outlet of the watershed. This ensures that the system is able to meet the specified in-stream flow targets and inform the user that available water was insufficient. This option allows for feasible runs without iterative guessing about flow targets that are feasible.

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.

$$C_{ATMU} = \sum_{t} C_{MUW} \times bQ_{MUWt} \tag{24}$$

where

C_{ATMU} = annualized cost of make-up water, \$/year

C_{MUW} = penalty for make-up water, \$/MGD

$bQ_{MUW\,t}$ = Flow of “made-up” water into the system to balance mass *t*, MGD

Total costs:

Total annual costs for all services, C_{AT}, is calculated as the sum of all annualized capital and O&M costs as defined above:

$$\begin{aligned} C_{AT} = {} & C_{ATb} + C_{ATm} + C_{ATPrice} + C_{ATDmd} + C_{ATGwPump} + C_{ATSwPump} + C_{ATWtp} + C_{ATUaw} + \\ & C_{ATWwtp} + C_{ATGwWwtp} + C_{ATWrf} + C_{ATNpdist} + C_{ATAsr} + C_{ATRes} + C_{ATIbtW} + C_{ATIbtWw} + C_{ATMU} + \\ & C_{FA} + C_{FAn} \end{aligned} \tag{25}$$

2.1.2 Revenue

Revenue is calculated and provided for informational purposes. It is not part of the objective function because most municipalities minimize cost and calculate the rates necessary to cover those costs. Total revenue, R_T, is calculated as the sum of water and wastewater services.

$$R_T = \left(\left(R_{UsePT} + R_{UseNpT}\right) \times \left(1 + \frac{bP_{Price}}{100}\right)\right) + R_{WwT} \tag{26}$$

where

R_{UsePT} = revenue from delivered potable water, \$/year

R_{UseNpT} = revenue from delivered nonpotable water, \$/year

R_{WwT} = revenue from wastewater services, \$/year

bP_{Price} = percent price increase for potable and nonpotable water services, %

These quantities are further defined as follows.

$$R_{UsePT} = \sum_{m} R_{UsePF} + \left(R_{UseP} \times \sum_{t} \left(Q_{WtpUseP,t} + bQ_{IbtWUseP,t}\right)\right) \tag{27}$$

$$R_{UseNpT} = \sum_{m} R_{UseNpF} + (R_{UseNp} \times \sum_{t} bQ_{WrfUseNp,t}) + (R_{UseP} \sum_{t} (bQ_{WtpUseNp,t} + bQ_{IbtWUseNp,t})) \tag{28}$$

where

R_{UsePF} = fixed monthly fee for potable customers, \$/month
R_{UseNpF} = fixed monthly fee for nonpotable customers, \$/month
m = monthly time steps in period of analysis
R_{UseP} = original customer price per unit of water for potable water, \$/MG
R_{UseNp} = original customer price per unit of water for nonpotable water, \$/MG
$Q_{WtpUseP,t}$ = flow of water from water treatment plant to potable uses, MGD
$bQ_{WtpUseNp,t}$ = flow of water from water treatment plant to nonpotable uses, MGD
$bQ_{IbtWUseP,t}$ = flow of water from interbasin transfer to potable uses, MGD
$bQ_{IbtWUseNp,t}$ = flow of water from interbasin transfer to nonpotable uses, MGD
$bQ_{WrfUseNp,t}$ = flow of nonpotable water from water reuse facility to nonpotable uses, MGD

Wastewater revenue may be calculated based on water flow into a house or organization or based on separately metered sewer flow. The user specifies which situation exists in their system or which situation the user would like to model on the Infrastructure page under Wastewater Treatment Plant heading.

If wastewater fees are charged based on wastewater flow, then

$$R_{WwT} = \sum_{m} R_{WwF} + (R_{Ww} \times \sum_{t} \left(bQ_{UsePWwtp,t} + bQ_{UsePIbtWw,t} + bQ_{UseNpWwtp,t} + bQ_{UseNpIbtWw,t}\right)) \tag{29}$$

where

R_{WwF} = fixed monthly fee for all customers, \$/month
R_{Ww} = customer price for wastewater services per unit wastewater, \$/MG
$bQ_{UsePWwtp,t}$ = wastewater flow from potable uses to wastewater treatment plant, MGD
$bQ_{UseNpWwtp,t}$ = wastewater flow from nonpotable uses to wastewater treatment plant, MGD
$bQ_{UsePIbtWw,t}$ = wastewater flow from potable water uses exported to interbasin transfer, MGD
$bQ_{UseNpIbtWw,t}$ = wastewater flow from nonpotable water uses exported to interbasin transfer, MGD

If wastewater fees are charged based on water flow, then

$$R_{WwT} = \sum_{m} R_{WwF} + (R_{Ww} \times \sum_{t} (Q_{WtpUseP,t} + bQ_{IbtWUseP,t} + bQ_{WrfUseNp,t} + bQ_{WtpUseNp,t} + bQ_{IbtWUseNp,t})) \tag{30}$$

Constraints

The objective in Section 0 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. Any constraint or management option can be excluded by entering -9 instead of an input value as specified on the user interface pages.

2.1.3 Continuity Equations

Land Management - Land Conservation and Stormwater Management: Land area in the watershed can be reallocated among baseline and managed HRU sets as described in *Section 2.1.1*. 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),[22] Soil Water and Assessment Tool (SWAT)[23] and/or the Storm Water Management Model (SWMM).[24]

Based on the optimization model's final allocation of area among HRUs, 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 preserved 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.

$$\sum_{l=1\ to\ NLu} A_{l,s=1} = \sum_{l=1\ to\ NLu} bA_{l,s=1} = \sum_{s=2\ to\ NLuSet}\ \sum_{l=1\ to\ NLu} bA_{l,s} \tag{31}$$

where

$A_{l,s=1}$ = user specified HRU areas

$bA_{l,s=1}$ = baseline HRU areas after reallocation for conservation

$bA_{l,s=2\ to\ NLuSet}$ = HRU areas under management

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

$$bA_{l,s} \geq A_{Min,l,s} \quad \text{for } l = 1 \text{ to } NLu \text{ and } s = 1 \tag{32}$$

where $A_{Min,l,s}$ = minimum area possible for baseline HRUs

$$bA_{l,s} \leq A_{Max,l,s} \quad \text{for } l = 1 \text{ to } NLu \text{ and } s = 1 \tag{33}$$

---

[22] http://water.usgs.gov/software/HSPF/

[23] http://swat.tamu.edu/

[24] http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/

where $A_{Max,l,s}$ = maximum area possible for baseline HRUs

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 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.

$$\text{where } C_{C,s,l} <> -9, \qquad bA_{l,s=1} - A_{l,s=1} \geq 0 \tag{34}$$

$$\text{else}, \qquad bA_{l,s=1} - A_{l,s=1} \leq 0 \tag{35}$$

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.

$$\sum_{s=2}^{nLuSet} bA_{l,s} \leq bA_{l,s=1} \text{ for each } l \tag{36}$$

where $bA_{l,s}$ = area allocated to ‘managed’ HRU in set *s*

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.

$$bA_{l,s} \geq A_{Min,l,s} \qquad \text{for } l = 1 \text{ to } nLu \text{ and } s = 2 \text{ to } NLuSet \tag{37}$$

where $A_{Min,l,s}$ = minimum area possible for management for HRU l and management set *s*

$$bA_{l,s} \leq A_{Max,l,s} \qquad \text{for } l = 1 \text{ to } nLu \text{ and } s = 2 \text{ to } NLuSet \tag{38}$$

where $A_{Max,l,s}$= maximum area possible for management for baseline HRU l 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.

$$Q_{Ru,t} = \sum_{l=1}^{NLu} (bA_{l,s=1} \times Q_{Ru,l,s=1,t}) + \sum_{s=2}^{NLuSet} \sum_{l=1}^{NLu} ((Q_{Ru,l,s,t} - Q_{Ru,l,s=1,t}) \times bA_{l,s}) \tag{39}$$

where $Q_{Ru,l,s,t}$ = runoff rate[25] from HRU l in HRU set s for time step *t*.

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

where $Q_{Re,l,s,t}$= recharge rate from HRU l in HRU set s for time step *t*.

Groundwater (Gw): The groundwater system, or aquifer, has storage. It may receive inflow from recharge, groundwater from outside of the watershed, point sources, leakage from the potable water distribution system, recharge from the aquifer storage and recharge (ASR) facility, and septic systems. Outflow from the groundwater system may discharge to surface water via baseflow, be withdrawn by the potable water treatment plant via groundwater wells, infiltrate into the wastewater collection system, and discharge to a groundwater system outside of the basin.

$$V_{Gw,t} = V_{Gw,t-1} + \big(Q_{Re,t} + Q_{ExtGwIn,t} + Q_{PtGw,t} + Q_{WtpGw,t} + Q_{AsrGw,t-1} + Q_{SepGw,t-1} - Q_{GwSw,t} - bQ_{GwWtp,t} - Q_{GwWwtp,t} - bQ_{GwExt,t} - Q_{GwPt,t}\big) \times \Delta t \tag{41}$$

where $V_{Gw,t}$= volume of groundwater, $Q_{Re,t}$ = recharge from all land areas, $Q_{ExtGwIn,t}$ = inflow of external groundwater, $Q_{PtGw,t}$ = private groundwater discharges, $Q_{WtpGw,t}$ = leakage from potable water from distribution system, $Q_{AsrGw,t}$ = recharge from ASR facility to groundwater, $Q_{SepGw,t}$ = inflow from septic systems, $Q_{GwSw,t}$= baseflow, $bQ_{GwWtp,t}$= withdrawal by water treatment plant, $Q_{GwWwtp,t}$ = infiltration into wastewater collection system, $bQ_{GwExt,t}$ = groundwater leaving the basin, $Q_{GwPt,t}$ = private groundwater withdrawals, and Δt = time step=1.

Two variables are further defined as

$$Q_{WtpGw,t} = Q_{UsePI,u=1,t} \times (1 - \frac{bP_{WtpLeakFix}}{100}) \tag{42}$$

where

$Q_{WtpGw,t}$ = unaccounted-for-water flow from distribution system to groundwater
$Q_{UsePI,u=1,t}$ = initial, unaccounted-for-water flow
$bP_{WtpLeakFix}$ = percent of distribution system leakage that is fixed

and

$$Q_{GwSw,t} = k_b \cdot V_{Gw,t-1} \tag{43}$$

where $Q_{GwSw,t}$ is baseflow and k_b is the groundwater recession coefficient.

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

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 as described in the next section below.

---

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

The surface water component may receive inflow from runoff, external surface water sources (i.e., an upstream reach), point sources, wastewater treatment plant, and a water reuse facility. 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.

$$\begin{aligned} Q_{Ru,t} + Q_{ExtSwIn,t} + Q_{PtSw,t} + Q_{GwSw,t} + Q_{WwtpSw,t} + Q_{WrfSw,t} \\ = Q_{SwRes,t} + bQ_{SwWtp,t} + bQ_{SwAsr,t} + Q_{SwPt,t} \end{aligned} \tag{44}$$

where

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

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 only from the surface 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. The reservoir is at the downstream portion of the watershed, so off-stream surface storage may be added to the reservoir storage.[26]

$$V_{Res,t} = V_{Res,t-1} + \left(Q_{SwRes,t} - bQ_{SwExt,t} - bQ_{ResWtp,t} - bQ_{ResAsr,t} + bQ_{WMake,t}\right) \times \Delta t \tag{45}$$

where

$V_{Res,t}$ = volume of reservoir
$Q_{SwRes,t}$ = inflow to reservoir from surface water bodies
$bQ_{SwExt,t}$ = flow to surface water bodies outside of basin
$bQ_{ResWtp,t}$ = flow to water treatment plant
$bQ_{ResAsr,t}$ = flow to ASR facility
$bQ_{WMake,t}$ = "make-up" water as needed to compensate for water shortfalls within the watershed system

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

---

[26] 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.

may be used to meet potable and nonpotable water use demand. In addition, some water is lost to the groundwater through leaks in the potable distribution system.

$$bQ_{ResWtp,t} + bQ_{SwWtp,t} + bQ_{GwWtp,t} = Q_{WtpUseP,t} + bQ_{WtpUseNp,t} + Q_{WtpGw,t} \tag{46}$$

where

$Q_{WtpUseP,t}$ = flow to potable water use
$bQ_{WtpUseNp,t}$ = flow to nonpotable water use

Potable Water Use (UseP):

$$\begin{aligned}(Q_{WtpUseP,t} + bQ_{IbtWUseP,t}) \times \left(1 - \frac{P_{ConsUsePAvg}}{100}\right) \\ = bQ_{UsePWwtp,t} + Q_{UsePSep,t} + Q_{UsePSepExt,t} + bQ_{UsePIbtWw,t}\end{aligned} \tag{47}$$

where

$bQ_{IbtWUseP,t}$ = inflow of potable water to water treatment facility via interbasin transfer
$P_{ConsUsePAvg,t}$ = flow weighted average of percent consumptive use for potable water uses
$bQ_{UsePWwtp,t}$ = flow to wastewater treatment plant
$Q_{UsePSep,t}$ = flow to septic systems within the study area
$Q_{UsePSepExt,t}$ = flow to septic systems outside the study area
$bQ_{UsePIbtWw,t}$ = wastewater flow from potable uses to interbasin transfer wastewater services

Nonpotable Water Use (UseNp):

$$\begin{aligned}(bQ_{WtpUseNp,t} + bQ_{WrfUseNp,t} + bQ_{IbtWUseNp,t}) \times \left(1 - \frac{P_{ConsUseNpAvg}}{100}\right) \\ = bQ_{UseNpWwtp,t} + Q_{UseNpSep,t} + Q_{UseNpSepExt,t} + bQ_{UseNpIbtWw,t}\end{aligned} \tag{48}$$

where

$bQ_{WrfUseNp,t}$ = inflow of nonpotable water from water reuse facility
$bQ_{IbtWUseNp,t}$ = inflow of nonpotable water to water treatment facility via interbasin transfer
$P_{ConsUseNpAvg,t}$ = flow weighted average of percent consumptive use for nonpotable water uses
$bQ_{UseNpWwtp,t}$ = flow of nonpotable water to wastewater treatment plant
$Q_{UseNpSep,t}$ = flow to septic systems within the study area
$Q_{UseNpSepExt,t}$ = flow to septic systems outside the study area
$bQ_{UseNpIbtWw,t}$ = flow of nonpotable water to wastewater collection system via interbasin transfer

Wastewater Treatment Plant (Wwtp):

$$bQ_{UsePWwtp,t} + bQ_{UseNpWwtp,t} + Q_{GwWwtp,t} = Q_{WwtpSw,t} + bQ_{WwtpWrf,t} \tag{49}$$

where $bQ_{WwtpWrf}$ = outflow to water reuse facility.

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

$$Q_{GwWwtp,t} = (1 - \frac{bP_{WwtpLeakFix}}{100}) \times \frac{P_{WwtpLeakI}}{100} \times \frac{\sum_{u=2}^{NWuser} Q_{UsePI,u,t} \times \left(1 - \frac{P_{ConsUsePI,u,t}}{100}\right) \times \left(1 - \frac{P_{Sep,u} + P_{SepExt,u}}{100}\right)}{\left(1 - \frac{P_{WwtpLeakI}}{100}\right)} \tag{50}$$

where

$P_{WwtpLeakI}$ = 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 distribution system,

$Q_{UsePI,u,t}$ = initial specified water use (total demand for potable and nonpotable water)

$P_{ConsUsePI,u,t}$ = initial percent consumptive use of potable water uses

$P_{Sep,u}$ = 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):

$$bQ_{WwtpWrf,t} = bQ_{WrfUseNp,t} + bQ_{WrfAsr,t} + Q_{WrfSw,t} \tag{51}$$

where $bQ_{WrfAsr,t}$= flow from the water reuse facility to the ASR facility.

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 may 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

$$Q_{UsePSep,t} = (\sum_{u} Q_{UsePI,u,t} \times \left(1 - \frac{P_{ConsUsePI,u,t}}{100}\right) \times \frac{P_{Sep,u}}{100}) \times \left(1 + ElasPrice \times \frac{bPprice}{100}\right) \times (1 - \frac{bP_{Dmd}}{100}) \times \left(1 - \frac{P_{UseNpMax,u,t}}{100}\right) \tag{52}$$

$$Q_{UseNpSep,t} = \left(\sum_{u} Q_{UsePI,u,t} \times \left(1 - \frac{P_{ConsUseNpI,u,t}}{100}\right) \times \frac{P_{Sep,u}}{100}\right) \times \left(1 + ElasPrice \times \frac{bPprice}{100}\right) \times (1 - \frac{bP_{Dmd}}{100}) \times \left(\frac{P_{UseNpMax,u,t}}{100}\right) \tag{53}$$

where

$Q_{UsePI,u,t}$ = initial potable water use/demand
$P_{Sep,u}$ = percent of users serviced by septic systems draining within the study area
bP_{Dmd} = percent demand reduction from direct demand management
$P_{UseNpMax,u,t}$ = maximum percent of water demand that can be met by nonpotable water
$ElasPrice$ = flow-weighted average of price elasticities for water user types
$bPprice$ = percent change in price

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

Flows to septic systems outside the study area are calculated as

$$Q_{UsePSepExt,t} = (\sum_{u} Q_{UsePI,u,t} \times \left(1 - \frac{P_{ConsUsePI,u,t}}{100}\right) \times \frac{P_{SepExt,u}}{100}) \times \left(1 + ElasPrice \times \frac{bPprice}{100}\right) \times (1 - \frac{bP_{Dmd}}{100}) \times \left(1 - \frac{P_{UseNpMax,u,t}}{100}\right) \tag{54}$$

$$Q_{UseNpSepExt,t} = \left(\sum_{u} Q_{UsePI,u,t} \times \left(1 - \frac{P_{ConsUseNpI,u,t}}{100}\right) \times \frac{P_{SepExt,u}}{100}\right) \times \left(1 + ElasPrice \times \frac{bPprice}{100}\right) \times (1 - \frac{bP_{Dmd}}{100}) \times \left(\frac{P_{UseNpMax,u,t}}{100}\right) \tag{55}$$

Septic flows enter the groundwater system:

$$Q_{UsePSep,t} + Q_{UseNpSep,t} = Q_{SepGw,t} \tag{56}$$

where $Q_{SepGw,t}$ = flow from septic systems to groundwater.

Aquifer Storage and Recovery Facility (Asr):

$$bQ_{SwAsr,t} + bQ_{ResAsr,t} + bQ_{WrfAsr,t} = Q_{AsrGw,t} \tag{57}$$

where $Q_{AsrGw,t}$ = flow from the ASR facility to groundwater.

2.1.4 Physical Limits on Watershed Components

Facility capacity: Flow through a facility must not 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, see Table 1-1). This constraint applies to surface water pumping, groundwater pumping, water treatment, wastewater treatment, water reuse, and aquifer storage facilities.

$$bQ_{SwWtp,t} + bQ_{ResWtp,t} \leq Q_{SwPumpI} + bQ_{SwPumpAddl} \tag{58}$$

$$bQ_{GwWtp,t} \leq Q_{GwPumpI} + bQ_{GwPumpAddl} \tag{59}$$

$$bQ_{ResWtp,t} + bQ_{SwWtp,t} + bQ_{GwWtp,t} \leq Q_{Wtp,MaxI} + bQ_{Wtp,Addl} \tag{60}$$

$$bQ_{UsePWwtp,t} + bQ_{UseNpWwtp,t} + Q_{GwWwtp,t} \leq Q_{Wwtp,MaxI} + bQ_{Wwtp,Addl} \tag{61}$$

$$bQ_{WwtpWrf,t} \leq Q_{Wrf,MaxI} + bQ_{Wrf,Addl} \tag{62}$$

$$bQ_{SwAsr,t} + bQ_{ResAsr,t} + Q_{WrfAsr,t} \leq Q_{Asr,MaxI} + bQ_{Asr,Addl} \tag{63}$$

$$bQ_{WrfUseNp,t} \leq Q_{Npdist,MaxI} + bQ_{Npdist,Addl} \tag{64}$$

where

$Q_{SwPumpI}$ = initial surface water pumping capacity
$bQ_{SwPumpAddl}$ = additional surface water pumping capacity
$Q_{GwPumpI}$ = initial groundwater pumping capacity
$bQ_{GwPumpAddl}$ = additional groundwater pumping capacity
$Q_{Wtp,MaxI}$ = initial water treatment plant capacity
$bQ_{Wtp,Addl}$ = additional water treatment plant capacity
$Q_{Wwtp,MaxI}$ = initial wastewater treatment plant capacity
$bQ_{Wwtp,Addl}$ = additional wastewater treatment plant capacity
$Q_{Wrf,MaxI}$ = initial water reuse facility capacity
$bQ_{Wrf,Addl}$ = additional water reuse facility capacity
$Q_{Asr,MaxI}$ = initial ASR facility capacity
$bQ_{Asr,Addl}$ = additional ASR facility capacity

Limits for groundwater and reservoir storage volumes: For groundwater, the minimum storage volume, $\boldsymbol{V_{Gw,Min}}$, may be specified to reflect the maximum desired drawdown (e.g., to avert land subsidence). The maximum volume, $\boldsymbol{V_{Gw,Max}}$, may also be specified to reflect the size of the aquifer and the maximum storage capacity. For the reservoir, the minimum storage volume, $\boldsymbol{V_{Res,Min}}$, may be specified to reflect "dead storage" (i.e., what can not be released from the reservoir) or the quantity that is required to be maintained for emergencies. The maximum volume, $\boldsymbol{V_{Res,MaxI}}$, may be specified to reflect the physical size of the reservoir (note that additional surface water storage capacity, $\boldsymbol{bV_{Res,Addl}}$, is one of the management options in *Table 1-1*).

$$V_{Gw,t} \leq V_{Gw,Max} \tag{65}$$

$$V_{Gw,t} \geq V_{Gw,Min} \tag{66}$$

$$V_{Res,t} \leq V_{Res,Max} + bV_{Res,Addl} \tag{67}$$

$$V_{Res,t} \geq V_{Res,Min} \tag{68}$$

2.1.5 Constraints Associated with Management Options

Human demand and demand management: The user may specify the number of water use categories; however, the first water use category is always unaccounted water. The user only specifies demand data, $Q_{UsePI,u=1,t}$ for this water use category; therefore *unaccounted water is not affected by demand management or consumptive use and is assumed to entirely drain to the groundwater*.

Initial demand, $Q_{UsePI,u,t}$, 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.

$$ElasPrice = \frac{\sum_u \left(E_u * \sum_t Q_{UsePI,u,t}\right)}{\sum_u \sum_t Q_{UsePI,u,t}} \quad (69)$$

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.

In addition, water demand is divided into potable and nonpotable demand based on the percent of demand that can be met by nonpotable water, $P_{UseNpMax,u}$.

$$Q_{UsePMin,t} = (1 - \frac{bP_{Dmd}}{100}) \times (\sum_{u=2\ to\ NUse} Q_{UsePI,u,t} \times (1 - \frac{P_{UseNpMax,u,t}}{100})) \times (1 + ElasPrice \times \frac{bPprice}{100}) \quad (70)$$

$$Q_{UseNpMin,t} = (1 - \frac{bP_{Dmd}}{100}) \times (\sum_{u=2\ to\ NUse} Q_{UsePI,u,t} \times \frac{P_{UseNpMax,u}}{100}) \times (1 + ElasPrice \times \frac{bPprice}{100}) \quad (71)$$

Minimum demand for potable and nonpotable water uses is set as:

$$Q_{WtpUseP,t} + bQ_{IbtWUseP,t} \geq Q_{UsePMin,t} \quad (72)$$

$$bQ_{WtpUseNp,t} + bQ_{IbtWUseNp,t} + bQ_{WrfUseNp,t} \geq Q_{UseNpMin,t} \quad (73)$$

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.

$$P_{ConsUseP,u,t} = \frac{P_{ConsUsePI,u,t} - P_{UseNpMax,u} \times P_{ConsUseNp,u,t}}{100 - P_{UseNpMax,u}} \quad (74)$$

In-stream flow: Minimum and maximum in-stream flows may be specified for the surface water reach,$Q_{SwRes,t}$, and for minimum flows exiting the basin, $Q_{ExtSwOut,t}$. These constraints can be used to ensure that minimum flow targets are met or that peak flows are reduced.

$Q_{SwMin,t} \leq Q_{SwRes,t}$ where $Q_{SwMin,t}$= minimum in-stream flow for subbasin reach (75)

$Q_{SwMax,t} \geq Q_{SwRes,t}$ where $Q_{SwMax,t}$= maximum in-stream flow for subbasin reach (76)

$Q_{SwExtMin,t} \leq Q_{ResExt,t}$ where $Q_{SwExtMin,t}$= minimum flow exiting subbasin (77)

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

$$Q_{GwExtMin,t} \leq bQ_{GwExt,t} \tag{78}$$

Management limits: The model user may specify limits on the social and/or physical limits of implementing four management options–increasing water price, fixing leaks in the water distribution and wastewater collection systems, and inter-basin transfer.

$$bP_{Price} \leq P_{PriceMax} * D_{price} \tag{79}$$

where

$P_{PriceMax}$ = one time, maximum percent change in price
D_{price} = a binary decision variable

$$bP_{WtpLeakFix} \leq P_{WtpLeakFixMax} \tag{80}$$

Where

$P_{WtpLeakFixMax}$ = maximum physical limit of leakage reduction in distribution system (e.g., given age of system and the repair costs specified)

$$bP_{WwtpLeakFix} \leq P_{WwtpLeakFixMax} \tag{81}$$

Where

$P_{WwtpLeakFixMax}$ = maximum physical limit of repairing infiltration into the wastewater collection system (e.g., given age of system and the repair costs specified).

Maximum IBT flows can be specified as daily, monthly, and/or annual limits.

For the daily limit, if the time step is daily, then, *for each timestep in the period of analysis,*

$$bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq Q_{IbtWMaxDay} \tag{82}$$

$$bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq Q_{IbtWwMaxDay} \tag{83}$$

For the daily limit, if the time step is monthly, then the limits are multiplied up to a monthly value; therefore, *for each time step in the period of analysis,*

$$bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq Q_{IbtWMaxDay} \times NDay(month(t)) \tag{84}$$

$$bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq Q_{IbtWwMaxDay} \times NDay(month(t)) \tag{85}$$

where

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

Since the period of analysis may start and/or end on a day other than the start or end of a month or year, limits are prorated to keep the limits accurate for partial months or years. For daily time steps, monthly limits are prorated for the number of days in the month within the period of analysis. Annual limits are prorated for the number of days or months in the year within the period of analysis.

For the monthly limit, if the time step is daily, then *for each month in the period of analysis,*

$$\sum_{t=1\ to\ NdtM} bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq Q_{IbtWMaxMonth,m} \times \frac{NdtM}{NDay\big(month(t)\big)} \tag{86}$$

$$\sum_{t=1\ to\ NdtM} bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq Q_{IbtWwMaxMonth,m} \times \frac{NdtM}{NDay\big(month(t)\big)} \tag{87}$$

where

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

For the monthly limit, if the time step is monthly, then *for each month in the period of analysis,*

$$bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq Q_{IbtWMaxMonth,m} \tag{88}$$

$$bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq Q_{IbtWwMaxMonth,m} \tag{89}$$

For the annual limit, *for each year in the period of analysis,*

$$\sum_{t=1\ to\ Ndt} bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq Q_{IbtWMaxYr} \times \frac{Ndt}{NdtYr} \tag{90}$$

$$\sum_{t=1\ to\ Ndt} bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq Q_{IbtWwMaxYr} \times \frac{Ndt}{NdtYr} \tag{91}$$

where

$Q_{IbtWMaxYr}$ = maximum potable water transfers from/to outside the basin for a given year in the optimization period

$Q_{IbtWwMaxYr}$ = maximum potable wastewater transfers from/to outside the basin for a given year in the optimization period

Ndt = number of time steps in the year

$NdtYr$ = potential number of time steps in the full year (i.e., 365 or 366 for daily and 12 for monthly time step)

3. Baseline Hydrology Module

WMOST v2 includes three modules that assist users with retrieving and processing required input data for baseline hydrology, stormwater hydrology, and flood-damage costs. These modules are described in the next three chapters. The Baseline Hydrology module provides users with pre-processed hydrology databases and automated functionality to retrieve and process the data and populate the appropriate WMOST input fields. WMOST requires time series of runoff and recharge for the hydrologic response units (HRUs)[27] in the study area and a groundwater recession coefficient. Previous applications of WMOST version 1 required obtaining these data from a calibrated/validated simulation model such as Hydrological Simulation Program--Fortran (HSPF)[28], Soil Water Assessment Tool, or the Storm Water Management Model (SWMM). In version 2 of WMOST, we provide a database of selected model outputs that the user can select from via the user interface rather than cutting and pasting model output from an external source. Currently the model library includes model output from HSPF models but other model types such as SWAT will be included in future versions.

The pre-processed hydrology databases in WMOST version 2 are comprised of regional data from calibrated HSPF models from which the user will select the watershed most similar to their study watershed. Each HSPF model has two associated datasets – one for 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)[29], and infiltration data for each HRU. Metadata are compiled for all the HSPF models 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 from the HSPF documentation, time period for available time series, and calibration time period.

The user downloads a zip file called “SupportFiles” which contains a folder by the same name with database files (.csv files). The user must save this folder in the same folder as the WMOST Excel file. The hydrology module shows the user the HRUs that exist in the selected HSPF watershed model and the available time period. The user 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 WMOST 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

---

[27] In WMOST, an HRU is a land area with characteristics (e.g., land cover, soil type) that responds similarly to precipitation.

[28] 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/

[29] 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

coefficient for the study area by averaging the HRU specific recession coefficients weighted by their respective areas and annual flows.

Databases are available for the following HSPF models in New England: Ipswich, Taunton, Blackstone North, Blackstone South, Sudbury, and Pawcatuck. 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). The derivation of the hydrology databases are described in the following subsections. Model output for other regions of the country will be included in future releases.

Hydrology Time Series Database

Here we describe the process of extracting data from HSPF model output to provide the pre-packaged inputs to WMOST in the Baseline Hydrology module. As we add time series from other model types (e.g., SWAT), we will provide similar processing information for those models. HSPF defines HRUs and represents subsurface flow differently from WMOST. In addition, HSPF models are detailed simulation models run at the hourly time step while WMOST is a screening, optimization tool run at the daily or monthly time step. As such the following considerations and assumptions are important to note about the derivation of the hydrology databases.

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 series[30]. 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 effective impervious area (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 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 3-1). 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 3-1shows the schematic for HSPF storage components and flows and their corresponding variables’ names.

---

[30] 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.

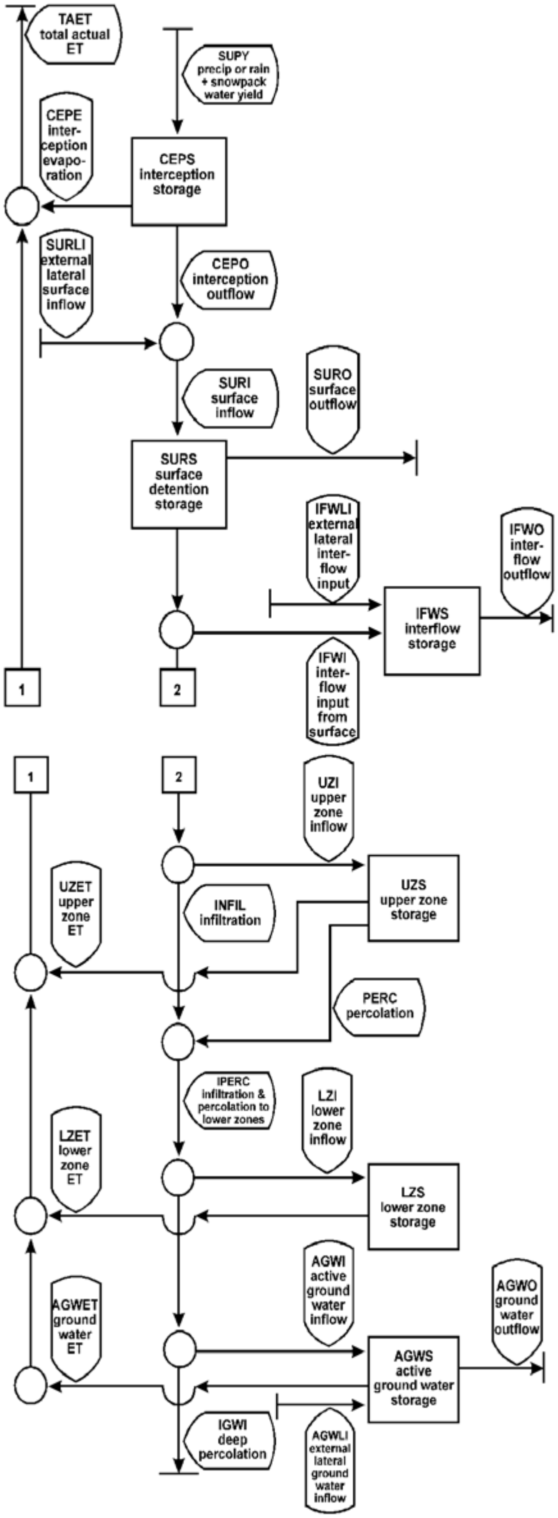


Figure 3-1. HSPF Schematic (EPA 2005)

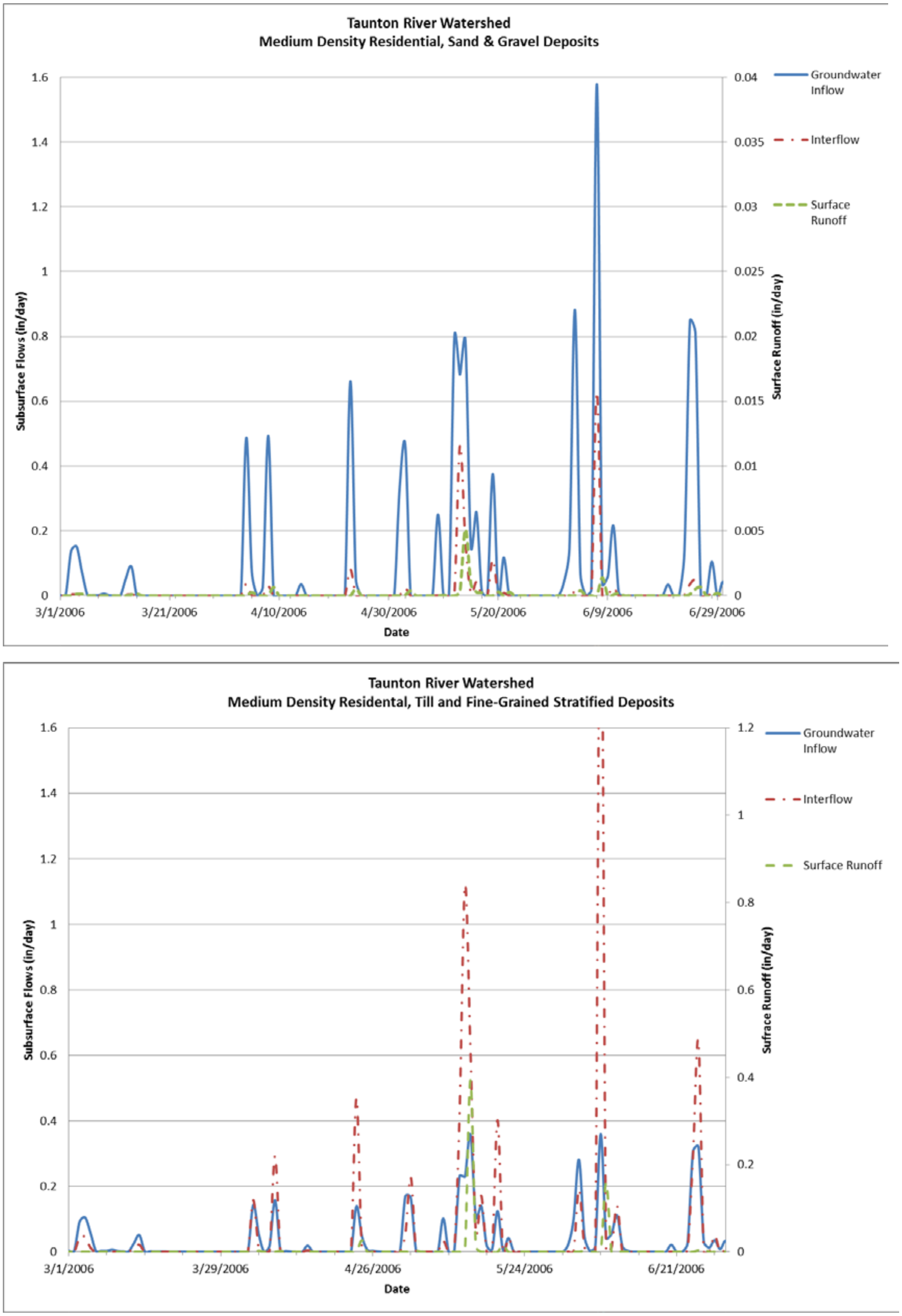
To develop WMOST input data from HSPF data, we summed subsurface flows to derive one subsurface flow time series. This process follows methods used by DeSimone et al. (2002) and EPA's System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN; EPA 2014) where interflow and active groundwater 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 above methodology required confirmation to ensure its applicability given: 1) the change in variables (subsurface inflow rather than subsurface outflow) and 2) the timing of interflow can resemble 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 3-2). 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.

Subsurface Flow Adjustments

All time series are at an hourly time step. At this scale, five of the six watersheds had negative recharge values in their recharge time series; the Blackstone watershed has all positive values. When evapotranspiration is greater than infiltration, negative net flow is the result. However, the linear solver in WMOST can not 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 value is maintained.

Figure 3-2. HSPF Time Series for Two Pervious HRUs



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 sewered 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.

Overview of Variables in the Hydrology Database

Table 3-1 below shows the time series that we extracted from HSPF. We used these data to:
1) provide metadata to the user when selecting the appropriate watershed and modeling time period for their analysis, 2) simulate evapotranspiration in SUSTAIN runs as part of the Stormwater Module, and 3) provide input to future potential climate change and sensitivity modules.

Table 3-1. Raw HSPF Time Series

Variable Type	HSPF Variable	Description
Calculated Water Flows	TAET	Total Actual Evapotranspiration
	AGWI	Active Groundwater Inflow
	AGWET	Active Groundwater Evapotranspiration
	IFWI	Interflow Input from Surface
	SURO	Surface Outflow
Measured Data	PET	Potential Evapotranspiration
	PREC	Precipitation
	TEMP	Air Temperature

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

The time series data were extracted, processed and compiled into one .csv file per watershed. The final times series databases contain the data elements shown in Table 3-2 below. The files are named according to the watershed name with a suffix of "Timeseries."

Table 3-2. Hydrology Database for WMOST v2

Purpose	WMOST Variable	HSPF Variable
For use in WMOST calculations (hydrology module)	Runoff	SURO
	Recharge	IFWI + AGWI - AGWET
For use in SUSTAIN calculations (stormwater module) and metadata to aid user with watershed and time period selection (hydrology module)	Air Temperature	TEMP
For user's reference	Precipitation	PREC
	Potential Evapotranspiration	PET

HRU Characteristics Database

The second hydrology database for a watershed contains information on the following HRU characteristics: groundwater recession coefficients, percent effective impervious area (EIA), and infiltration rate. EIA values are provided in the HSPF documentation.

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.

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).[31] 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.

---

[31] http://water.epa.gov/scitech/datait/models/basins/upload/2000_08_14_BASINS_tecnote6.pdf

4. Stormwater Hydrology Module

The Stormwater Hydrology module transforms baseline runoff and recharge 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 Module automates this process by dynamically linking with EPA's SUSTAIN model to derive the necessary input data for WMOST (EPA 2014a).

BMP Selection and Sizing

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 module, the user selects the type(s) of BMP to consider and specifies the desired design size(s). If the Baseline Hydrology module is not used, the user must also provide the percent impervious area and infiltration rate of developed HRUs. 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 (e.g., pervious pavement plus bioretention basin for remaining impervious areas), the user may still run a stormwater model outside of WMOST and manually input those results.

WMOST version 2 has the capability to simulate three of the BMPs included in SUSTAIN; future versions will include more options. We selected three BMPs from the following BMPs that are available in SUSTAIN and for which we have default design parameters from the Performance Analysis study for New England and SUSTAIN case studies (EPA 2010, EPA 2014a). 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.[32]

---

[32] HSPF BMP Web Toolkit (http://www.epa.gov/athens/research/HSPFWebTools/) 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").

SUSTAIN BMP Options

- Bioretention Area: Depressed area with porous backfill under a vegetated surface. It provides groundwater recharge and runoff detention. May include an underdrain with subsurface outflow.
- Gravel Wetland/ Constructed Wetland: Potentially up to three parts to the system - a sediment forebay and two wetland cells with subsurface discharge.
- Wet Pond: Excavated area that is designed to permanently retain some volume of water at all times. Wet ponds provide storage detention, infiltration, and biological uptake of nutrients.
- Dry Pond: Excavated area that stores stormwater runoff for a limited amount of time, providing water storage detention and improved infiltration of runoff.
- Infiltration Basin: Excavated area with gravel backfill and no outlets. Infiltration basins collect runoff during a storm event and release it into the soil by infiltration.
- Infiltration Trench: Rock-filled ditches with no outlets. Infiltration trenches collect runoff during a storm event and release it into the soil by infiltration.
- Porous Pavement: Pavement that is an alternative to asphalt or concrete surfaces that allows stormwater to drain through the porous surface to a stone reservoir underneath. The pavement’s reservoir temporarily stores surface runoff before allowing the runoff to infiltrate the soil.
- Water Quality Swale/ Grassed Swale: Shallow grass-covered hydraulic conveyance channels that help facilitate infiltration and slow runoff by providing storage detention.

In selecting the initial set of BMPs to incorporate into WMOST version 2, we considered the appropriate hydrological soil groups, land use types, hydrologic treatment processes, and unit costs. We selected the BMPs shown in Table 4-1 for 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 applications[33].

---

[33] http://www.epa.gov/region1/soakuptherain/index.html, http://www.seattle.gov/util/MyServices/DrainageSewer/Projects/GreenStormwaterInfrastructure/RainWise/

Table 4-1. Selected BMPs for WMOST v2 (EPA and MassDEP 2009, EPA 2011a)

BMPs	Land Use	Hydrologic Soil Group	Hydrologic Treatment	New Development Unit Cost
Rain garden/ Bioretention basin with underdrain	Any	Any	Infiltration, Evapotranspiration, Detention	\$8.64/ft^3 treated
Infiltration trench	Any	A, B	Infiltration, Evapotranspiration, Detention	\$7.78/ft^3 treated
Detention pond	Any	Any	Evapotranspiration, Detention	\$4.24/ft^3 treated

BMP unit costs originate from EPA and MassDEP (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.) The final BMP cost is calculated as follows:

BMP Cost = Volume of Runoff to Manage (ft3) x Retrofit Cost (\$/treated ft3)

Design parameters shown in Table 4-2 below are used for BMP specifications and originate from several sources (MPCA 2014, EPA 2014b, EPA 2011a, EPA 2010, EPA 2009, EPA and MassDEP 2009).

Table 4-2. BMP Specifications

Parameter	Bioretention Area	Infiltration Trench	Detention Basin
Orifice Height (ft)	0	0	4
Orifice Diameter (in)	6	0	Sized[34]
Weir Height (ft)	0.5	0.5	4
Soil Depth (ft)	2.5	0.5	1
Soil Porosity (0-1)	0.4	0.4	0.4
Soil Field Capacity (ft/ft)	0.3	0.3	0.3
Soil Wilting Point (ft/ft)	0.15	0.15	0.15
Vegetative Parameter A (0.1-1.0)	0.9	1	1
Soil layer infiltration rate (in/hr)	4	0.8	Native soil rate
Underdrain switch (0-off, 1-on)	1	1	0
Depth of storage media below underdrain (ft)	0.67	6	0
Underdrain void space (0-1)	0.4	0.45	0
Background infiltration rate (in/hr)	Native soil rate	Native soil rate	Native soil rate

---

[34] Sized based on 24-hour drainage of runoff through the ponding basin and using the orifice equation $Q = C \times A \times \sqrt{2gh}$

Based on the user-specified depth, the module calculates the required storage volume for the BMP following the Massachusetts example for the static method[35]:

Required storage volume = Impervious area x 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:

BMP unit storage volume = Sum of (Depth x 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.

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 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 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 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.

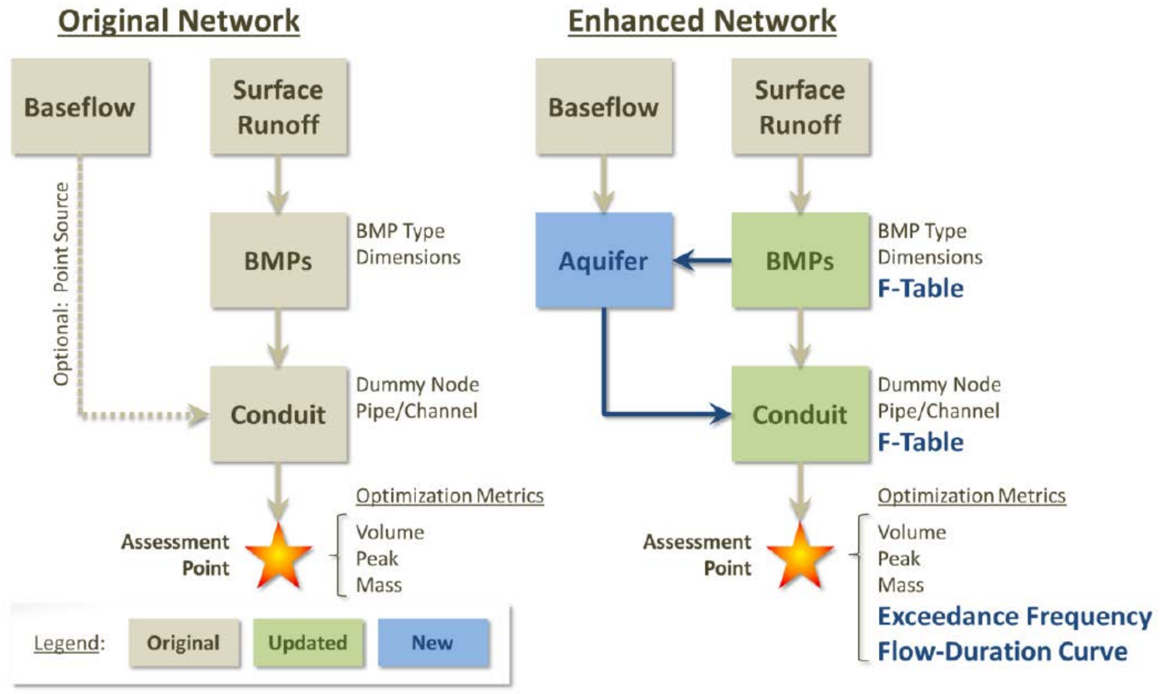
The aquifer component in SUSTAIN tracks water infiltrated through BMPs to the aquifer. The aquifer does not affect the BMP function or performance. Only the aquifer is affected by inflow from the BMP (Figure 4-1). WMOST has a component that tracks aquifer inflow and storage as well as baseflow to the 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.

---

[35] 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)."

Figure 4-1. SUSTAIN Flows With and Without an Aquifer Component (EPA 2014b)



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

- Runoff 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 time series database, user specifications, appropriate default BMP characteristics, and HRU infiltration rates/soil types. If the user does not use the hydrology module, the stormwater 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 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. 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.
- “ “ = selection solutions to run if strScenario = run for select solutions. In this case, we will leave this blank.

SUSTAIN outputs results into separate files for each subbasin, in this case a combination of HRU and BMPs. The WMOST Stormwater Hydrology 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:

- Runoff = Weir outflow + Orifice or channel outflow + Untreated outflow
- Recharge = Underdrain + 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.

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.

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.

Considerations for the Flood-Damage Module

The general methodology for modeling flood damages in risk assessments includes the following steps:

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 HEC-HMS[36] or values obtained from existing statistical analyses (e.g., USGS PeakFQ[37]).
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 HEC-RAS[38].
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 MH[39].

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. Data for one or more of these steps may be available from an existing flood insurance study.

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) linear representation of flood-damages in the calculation of total management costs which is a requirement of the linear programming solver used to solve the optimization problem; 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 determine the relative cost-effectiveness of management actions; and 5) usability without extensive effort or flood modeling expertise.

---

[36] http://www.hec.usace.army.mil/software/hec-hms/

[37] http://water.usgs.gov/software/PeakFQ/

[38] http://www.hec.usace.army.mil/software/hec-ras/

[39] https://www.fema.gov/hazus

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 programing effort. Therefore, we considered two main approaches for the flood module. The first approach would accept results from flood-damage modeling, that is 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 flow and watershed characteristics to flood damages. The regression could be programmed in 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 consistently emphasized that at the local scale, infrastructure (e.g., culverts and impoundments) has a significant impact on flooding. 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 2011/Atkins 2013) found that the explanatory variables did not include 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. Discussion 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.

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 stormwater management which are facilitated by the Baseline Hydrology and Stormwater Hydrology modules in WMOST v2. 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.[40] 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 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

---

[40] Appendix C documents the approaches evaluated for incorporating flood damages in the optimization module and rationale for the selected approach.

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 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 damages[41]. In addition, one can not 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). The model provides a warning to the user if any flows are above the highest flow data point provided by the user. This will inform the user that some damages and benefit of avoiding those damages may not be counted.
- ➢ Adding to the Objective Function: The linear equations are programmed in the linear 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 if 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

---

[41] 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.

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 cost of flood damages are 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. 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,

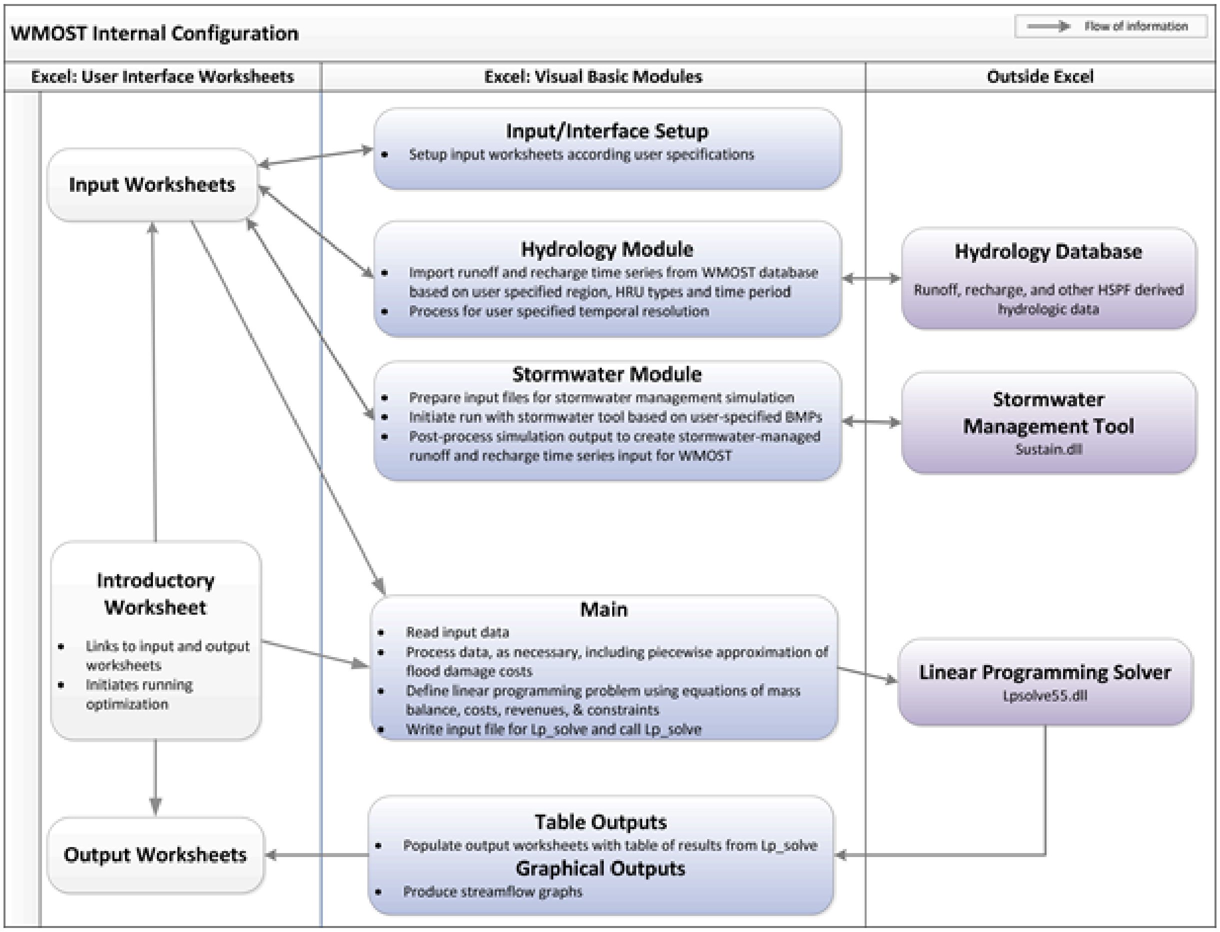
3) Access and pre-process input data via the Baseline Hydrology, Stormwater Hydrology and Flood-Damage modules and

4) Initiate optimization runs.

VBA also reads the input data from worksheets and generates a custom linear programming (LP) optimization model by creating equations based on the input data. Finally, VBA calls the LP solver called Lp_solve and returns the results to the Excel interface for the user. Figure 6-1 shows the flow of information and process links between components of WMOST

Lp_solve 5.5 is freely available at http://lpsolve.sourceforge.net/. It is a mixed integer linear programming solver. The website provides background on LP (e.g "What is Linear Programming?", "Linear programming basics", and detailed description of the solver and its use with various software.

Figure 6-1. WMOST Internal Configuration



7. Summary of Input Data

Variables	Units	Description
General		
$TPlan$	*yrs*	Planning horizon
i	*%*	Interest rate
Runoff and Recharge Rates		
$Q_{Ru,s,l,t}$	*inches/time step*	Unit runoff for each HRU in each set of baseline and managed set of HRUs for each time step
$Q_{Re,s,l,t}$	*inches/time step*	Unit recharge for each HRU in each set of baseline and managed set of HRUs for each time step
Point Sources		
$Q_{PtSw,t}$	*MGD per time step*	Flow from private point source to surface water, i.e., discharge
$Q_{SwPt,t}$	*MGD per time step*	Flow from surface water to private point source, i.e., withdrawal
$Q_{PtGw,t}$	*MGD per time step*	Flow from private point source to groundwater, i.e., discharge
$Q_{GwPt,t}$	*MGD per time step*	Flow from groundwater to private point source, i.e., withdrawal
Land Use: Conservation and Stormwater Management		
$A_{s,l}$	*Acres*	Baseline or scenario land areas
$A_{min_{s,l}}$	*Acres*	Minimum area for each HRU
$A_{max_{s,l}}$	*Acres*	Maximum area for each HRU
$C_{CA_{s,l}}$	*$/Acre*	Capital cost to conserve or manage HRU *l* in land use set *s*
$C_{OmA_{s,l}}$	*$/Acre/yr*	O&M cost to conserve or manage HRU *l* in land use set *s*
Groundwater Storage		
k_b	*1/time step*	Groundwater recession coefficient
$V_{Gw,I}$	*MG*	Initial groundwater volume
$V_{Gw,Min}$	*MG*	Minimum volume
$V_{Gw,Max}$	*MG*	Maximum volume
$Q_{GwExt,t}$	*MG/time step*	Flow from study area groundwater to external groundwater
$Q_{GwExtMin,t}$	*MG/time step*	Minimum flow from study area groundwater to external groundwater
$Q_{ExtGw,t}$	*MG/time step*	Flow from external groundwater into study area groundwater

Variables	Units	Description
Surface Water/Stream Reach		
$Q_{ExtSw,t}$	*ft³/sec*	Inflow from external surface water to study area stream reach
$Q_{SwRes,t}$	*ft³/sec*	Flow from stream reach to reservoir
$Q_{SwResMin,t}$	*ft³/sec*	Minimum in-stream flow in reach
$Q_{SwResMax,t}$	*ft³/sec*	Maximum in-stream flow in reach
$Q_{SwExtMin,t}$	*ft³/sec*	Minimum surface water flow out of study area
Reservoir/Surface Storage		
$V_{Res,I}$	*MG*	Reservoir volume
$V_{Res,Min}$	*MG*	Minimum reservoir volume
$V_{Res,Max}$	*MG*	Current maximum reservoir volume
$Q_{ExtSwOutMin,t}$	*ft³/sec*	Minimum flow
$C_{C,Res}$	*$/MG*	Capital construction cost
$C_{Om,Res}$	*$/MG/yr*	O&M costs
Water Users		
$Q_{UsePI,u,t}$	*MGD*	Demand for each user per time step
$P_{ConsUseI,u,t}$	*%*	Percent consumptive use for each water user for an average month for each month
$P_{UseNpMax,u,t}$	*%*	Maximum percent demand that can be met by nonpotable water for each user for an average month for each month
$P_{ConsUseNp,u,t}$	*%*	Percent consumptive use for nonpotable water for each user for an average month for each month
R_{UseP}	*$/100 ft³*	Customer's price for potable water
R_{UseNp}	*$/100 ft³*	Customer's price for nonpotable water
R_{Ww}	*$/100 ft³*	Customer's price for wastewater
$P_{Sep,u}$	*%*	Percent septic use for each user
Demand Management		
E_u	*% demand reduction / % price increase*	Price elasticity for each user
$C_{C,Price}$	*$*	Capital cost to implement price increase
$C_{Om,Price}$	*$/yr*	O&M cost to administer price increase (e.g., resurvey for appropriate price etc.)
C_{CDm}	*$*	Capital cost of direct demand management
C_{OmDm}	*$/yr*	Annual O&M costs for direct demand management
Interbasin Transfer		
C_{CIbtW}	*$/MGD*	Initial cost for obtaining rights to and building infrastructure for interbasin transfer of potable water

Variables	Units	Description
Interbasin Transfer	**Interbasin Transfer**	**Interbasin Transfer**
C_{CIbtWw}	*$/MGD*	Initial cost for obtaining rights to and building infrastructure for interbasin transfer of wastewater
C_{IbtW}	*$/MGD*	Service cost for water interbasin transfer
C_{IbtWw}	*$/MGD*	Service cost for wastewater interbasin transfer
$Q_{IbtWMaxDay,t}$ $Q_{IbtWwMaxDay,t}$	*MGD*	Maximum interbasin transfer flow for water and wastewater on a daily limit
$Q_{IbtWMaxMonth,t}$ $Q_{IbtWwMaxMonth,t}$	*MGD*	Maximum interbasin transfer flow for water and wastewater on a monthly limit
$Q_{IbtWMaxYr,t}$ $Q_{IbtWwMaxYr,t}$	*MGD*	Maximum interbasin transfer flow for water and wastewater on an annual limit
Nonpotable water distribution system (NpDist)		
$C_{C,Npdist}$	*$/MGD*	Capital construction cost for nonpotable distribution system
$C_{Om,Npdist}$	*$/MGD/yr*	O&M cost for nonpotable distribution system
$Q_{NpdistI}$	*MGD*	Nonpotable distribution system: Current max capacity
$T_{Npdist,Exist}$	*yrs*	Lifetime remaining on existing construction of nonpotable distribution system
$T_{Npdist,New}$	*yrs*	Lifetime for new construction of nonpotable distribution system
Water Treatment Plant		
$C_{C,GwPump}$	*$/MGD*	Gw pumping: Capital construction cost
$C_{Om,GwPump}$	*$/MGD/yr*	Gw pumping: O&M costs
$Q_{GwPumpI}$	*MGD*	Gw pumping: Current max capacity
$T_{GwPump,Exist}$	*yrs*	Gw pumping lifetime remaining on existing construction
$T_{GwPump,New}$	*yrs*	Gw pumping lifetime of new construction
$C_{C,SwPump}$	*$/MGD*	Sw pumping: Capital construction cost
$C_{Om,SwPump}$	*$/MGD/yr*	Sw pumping: O&M costs
$Q_{SwPumpI}$	*MGD*	Sw pumping: Current max capacity
$T_{SwPump,Exist}$	*yrs*	Sw pumping lifetime remaining on existing construction
$T_{SwPump,New}$	*yrs*	Sw pumping lifetime of new construction
$C_{C,Wtp}$	*$/MGD*	Wtp: Capital construction cost
$C_{Om,Wtp}$	*$/MGD/yr*	Wtp: O&M costs
$T_{Wtp,Exist}$	*yrs*	Wtp lifetime remaining on existing construction
$T_{Wtp,New}$	*yrs*	Wtp lifetime of new construction
$Q_{Wtp,Max}$	*MGD*	Wtp: Current max capacity
$C_{C,WtpLeak}$	*$*	Capital cost of survey & repair

Variables	Units	Description
Water Treatment Plant		
$C_{Om,WtpLeak}$	*$/yr*	O&M costs for continued leak repair
$P_{WtpLeakFixMax}$	*%*	Maximum percent of leaks that can be fixed
Wastewater treatment plant		
$C_{C,Wwtp}$	*$/MGD*	Capital construction cost
$C_{Om,Wwtp}$	*$/MGD/yr*	O&M costs
$T_{Exist,Wwtp}$	*yrs*	Lifetime remaining on existing construction
$T_{New,Wwtp}$	*yrs*	Lifetime of new construction
$Q_{Wwtp,Max}$	*MGD*	Current maximum capacity
$P_{WwtpLeakFixMax}$	*%*	Maximum percent of leakage that can be fixed
$P_{WwtpLeakI}$	*% of WW Inflow*	Initial groundwater infiltration into WW collection system
$C_{C,WwtpLeak}$	*$*	Initial cost of repairs
$C_{Om,WwtpLeak}$	*$/yr*	O&M costs of repairs
Water reuse facility		
$C_{C,Wrf}$	*$/MGD*	Capital construction cost
$C_{Om,Wrf}$	*$/MGD/yr*	O&M costs
$T_{Exist,Wrf}$	*yrs*	Lifetime remaining on existing construction
$T_{New,Wrf}$	*yrs*	Lifetime of new construction
$Q_{Wrf,Max}$	*MGD*	Current maximum capacity
Aquifer Storage and Recovery		
$C_{C,Asr}$	*$/MGD*	Capital construction cost
$C_{Om,Asr}$	*$/MGD/yr*	O&M costs
$T_{Exist,Asr}$	*yrs*	Lifetime remaining on existing construction
$T_{New,Asr}$	*yrs*	Lifetime of new construction
$Q_{Asr,Max}$	*MGD*	Current maximum capacity
Flood Flows and Damage		
Q_T	*ft^3/sec*	Flood flow of recurrence interval T
T	*Years*	Recurrence interval of flood flow
C_{Q_T}	*$*	Damage associated with a flood flow

8. 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.

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.

Burkham, D.E. 1977. A Technique for Determining Depths for T-year Discharges in Rigid Boundary Channels. pp. 77-83, USGS Water-Resources Investigations Report.

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.

Fill, H.D. and A.A. Steiner. 2003. “Estimating Instantaneous Peak Flow from Mean Daily Flow Data”, Journal of Hydrologic Engineering 8(6): 365-369,
doi: http://dx.doi.org/10.1061/(ASCE)1084-0699(2003)8:6(365)

Lund, J.R. 2002. Floodplain Planning with Risk-Based Optimization. Journal of Water Resources Planning and Management. 128:3. May/June 2002, pp. 202-207.

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.

Prettenthaler, 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.

U.S. Army Corps of Engineers (USACE). 2013. Flood Risk Management, IWR Report 2013-R-05.

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). 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

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.

Vogel, R.M., C. Yaindl, and M. Walter. 2011. Nonstationarity: Flood Magnification and Recurrence Reduction Factors in the United States. Journal of the American Water Resources Association. 47:3. Pp. 464-474.

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

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:

- number of HRU types, HRU sets or water users is less than or equal to zero
- warning to user that data will be deleted if new setup is requested for input data tables
- price elasticity values are not negative
- minimum in-stream flow is greater than maximum in-stream flow,
- time series data, that is runoff (and therefore recharge, water demand, point sources) dates, are not daily or monthly
- 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 and data, such as the time series data and watershed map files, are not found
- stormwater simulation is attempted to be run prior to generating the input files
- when calculating runoff and recharge, dates or watershed have not been selected
- when calculating the groundwater recession coefficient,
    - the area in the baseline HRUs is empty,
    - data is missing from the recharge table, and
    - modeling dates have not been entered.
- user attempts to enter less than 0 or greater than 50 land use sets or water user types

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 data for 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.

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 timestep (Min)	
	BMP simulation timestep (Min)	
	CRAAT (The ratio of max velocity to mean velocity under typical flow conditions)	
	Model output control (0-the same timestep 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

Parameters	Parameter Definitions	Notes
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	*[specify time series input files associated with each WMOST HRU]*
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	*[will not be used in WMOST setup, subsurface dynamic modeled in WMOST]*[42]
Card No.	**Card Name**	**Notes**
713	Aquifer Pollutant Background Concentration	*[will not be used in WMOST setup, subsurface dynamic modeled in WMOST]*
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

---

[42] 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.

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	
Card No.	**Card Name**	**Notes**
715	BMP Site Information	(BIORETENTION,WETPOND,CISTERN,DRYPOND,INFILTRATIONTRENCH,GREENROOF,POROUSPAVEMENT,RAINBARREL,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	*[will not be used in WMOST setup, accounted for within WMOST]*
Card No.	**Card Name**	**Notes**
721	Tier-1 Watershed Outlets Definition	*[will not be used in WMOST setup]*
Card No.	**Card Name**	**Notes**
722	Tier-1 Watershed Timeseries Definition	*[will not be used in WMOST setup]*

Card No.	**Card Name**	**Notes**
723	Pump Curve	(applies if PUMP_FLG is ON in card 725) *[not applicable to BMPs in WMOST v2]*
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)	
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)	
UNDVOID	Fraction of underdrain storage depth that is void space (0-1)	
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	
GIi	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) *[not applicable to BMPs in WMOST v2]*
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 (ft2)	
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 = NSGAII	
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 ($))
MaxRuns	Maximum number of iterations	(for Option 2)
NumBest	Number of best solutions for output	(for Option 1)
Card No.	**Card Name**	**Notes**
805	BMP Cost Functions	
Parameters	**Parameter Definitions**	**Notes**
BMPSITE	BMP site identifier in card 715	
LinearCost	Cost per unit length of the BMP structure ($/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]*
Parameters	**Parameter Definitions**	**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 (ft3/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)	
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 - Future Development

The following model enhancements may be implemented in future development efforts. These suggestions are based on reviewer and stakeholder feedback.

C.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 option for combined sewer–stormwater collection system (user could specify percent of each HRU’s runoff that drains to sewer system)
    - 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
    - Additional options for specifying pricing structure for water and wastewater services (e.g., increasing price blocks for water).
- Enhanced or additional management practices
    - Construction of a separate stormwater system where combined sewer system exists or no stormwater collection system exists
    - 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 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 [43]
    - Non-linear price elasticities for demand management via pricing
    - Option for interbasin transfer of raw water to water treatment plant (WMOST version 1 assumes direct transfer of potable water to the user)

---

[43] Non-linear functions can be approximated by a set of linear equations to keep the model a linear programming optimization problem.

    - 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 CREAT[44] or other climate projections to facilitate sensitivity and uncertainty analyses
    - Setting or module to assist running a 'simulation' scenario without new management options implemented to assess model performance prior to optimization; this may include automated calculation and reporting of performance metrics comparing measured and modeled streamflow
    - Provide guidance when the solution is infeasible, e.g., specify which constraint(s) made the solution infeasible. This can be determined using output from Lp_solve.
    - 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.
    - Development of a water quality module to allow for optimization with water quality and/or water quantity management goals
        - The water quality module would allow for the use of WMOST in EPA's Integrated Municipal Stormwater and Wastewater Planning[45] by screening

---

[44] http://water.epa.gov/infrastructure/watersecurity/climate/creat.cfm

[45] http://cfpub.epa.gov/npdes/integratedplans.cfm

        stormwater and wastewater management practices for the most cost-effective combination to meet water quality standards.
    - User ability to define a generic constraint that is not pre-programmed
    - 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

C.2 User Interface and User Support

- Input features
    - Direct linking and interoperability with simulation models for importing baseline runoff and recharge rate time series (e.g., Hydrological Simulation Program Fortran (HSPF),[46] Soil Water and Assessment Tool (SWAT)[47]
    - 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
    - When Setup 1 is clicked and the tables are emptied, change the buttons for land use, recharge and runoff back to blue and uncheck them.
    - Only allow optimization when input data boxes 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 with simple, idealized example to teach about WMOST and decision making in a watershed context
- Create a tutorial to teach about optimization (e.g., a simple optimization problem in Excel to demonstrate optimization concepts).

---

[46] http://water.usgs.gov/software/HSPF/

[47] http://swat.tamu.edu/