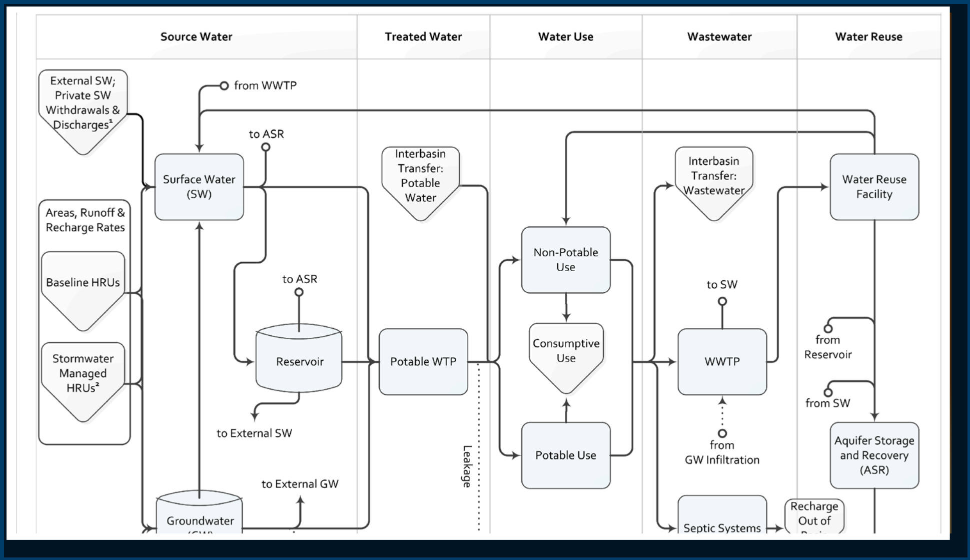
EPA
United States
Environmental Protection
Agency

EPA 600/R-13/151 | August 2013
www.epa.gov/ord

Watershed Management Optimization Support Tool (WMOST) v1

THEORETICAL DOCUMENTATION



Office of Research and Development
National Health and Environmental Effects Research Laboratory, Atlantic Ecology Division

EPA 600/R-13/151 | August 2013

Watershed Management Optimization Support Tool (WMOST) v1

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 and Jackie LeClair
Region 1
Boston, MA 02109

Yusuf Mohamoud
ORD, NERL, Ecosystems Research Division
Athens, GA 30605

Abt Associates Project Team

Viktoria Zoltay, Becky Wildner, Lauren Parker and Isabelle Morin, 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.

Notice

The information 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-07-023/ Work Assignment 32 to Abt Associates, Inc. It has been subjected to the Agency's peer and administrative review, and it has been approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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

Abstract

The Watershed Management Optimization Support Tool (WMOST) is a screening model that is spatially lumped with options for a daily or monthly time step. It is specifically focused on modeling the effect of management decisions on the watershed. The model considers water flows and does not consider water quality. The optimization of management options is solved using linear programming. The tool 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).[1] The objective of WMOST is to serve 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 watershed or jurisdiction for cost-effectiveness as well as environmental and economic sustainability (Zoltay et al., 2010). Examples of options that could be evaluated with the tool potentially include projects related to stormwater, water supply, wastewater and water-related resources such as low-impact development (LID) and land conservation. The tool is intended to aid in evaluating the environmental and economic costs, benefits, trade-offs and cobenefits of various management options. In addition, the tool is intended to facilitate the evaluation of LID and green infrastructure as alternative or complementary management options in projects proposed for State Revolving Funds (SRF). 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

[1] EPA. 2008. Handbook for Developing Watershed Plans to Restore and Protect Our Waters. March 2008. US Environmental Protection Agency. Office of Water. Nonpoint Source Control Branch, Washington, D.C. EPA 841-B-08-002.

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"[2]. IWRM has been promoted as an integral part of the "Water Utility of the Future"[3] 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.[4] The U.S. Environmental Protection Agency (EPA) has also endorsed the concept of IWRM, focusing on coordinated implementation of stormwater and wastewater management.[5]

Several states and river basin commissions have started to implement IWRM.[6] Even in EPA Region 1 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. The state of Massachusetts recently spearheaded the Sustainable Water Management Initiative (SWMI) process to allocate water among competing human and aquatic life uses in a consistent and sustainable fashion.[7]

Stormwater and land use management are two aspects of IWRM which include practices such as green infrastructure (GI, both natural GI and constructed stormwater BMPs), low-impact development (LID) and land conservation. In recent years, the EPA SRF funding guidelines have been broadened to include support for green infrastructure at local scales–e.g., stormwater best management practices (BMPs) to reduce runoff and increase infiltration–and watershed scales–e.g.,

---

[2] 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.

[3] 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.

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

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

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

[7] MA EAA. 2012. Massachusetts Sustainable Water Management Initiative Framework Summary (November 28, 2012); http://www.mass.gov/eea/agencies/massdep/water/watersheds/sustainable-water-management-initiative-swmi.html

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.[8] In a few notable cases, local managers have evaluated the relative cost and benefit of preserving green infrastructure compared to traditional approaches. In those cases, the managers have championed the use of green infrastructure as part of a sustainable solution for IWRM but these examples are rare.[9]

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 green infrastructure and land conservation measures as eligible projects in meeting water quality goals. The utilization of the GPR for green infrastructure 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 green infrastructure 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 green infrastructure 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 green infrastructure, 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 the Watershed Management Optimization Support Tool (WMOST). WMOST is based on a recent 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.[10] This model includes evaluation of conservation options for source water protection and infiltration of stormwater on forest lands, green infrastructure stormwater

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

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

[10] 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.

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 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 each of three communities were developed to illustrate the application of IWRM using WMOST; two of these case studies (Upper Ipswich River, and Danvers/Middleton, MA) are presented here. WMOST was presented to stakeholders in a workshop held at the EPA Region 1 Laboratory in Chelmsford, MA in April 2013, with a follow-up webinar on the Danvers/Middleton case study in May 2013. Feedback from the Technical Advisory Group and workshop participants has been incorporated into the user guide and theoretical documentation for WMOST.

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 and Marilyn ten Brink, U.S. EPA ORD, NHEERL, Atlantic Ecology Division
Alisa Morrison, Student Services Contractor at U.S. EPA ORD, NHEERL, Atlantic Ecology Division
Ralph Abele and Jackie LeClair, U.S. EPA Region 1
Yusuf Mohamoud, U.S. EPA ORD, NERL, Ecosystems Research Division

Technical Advisory Group

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

Reviewers

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

Table of Contents

Figures

Table

1. Background

1.1 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).

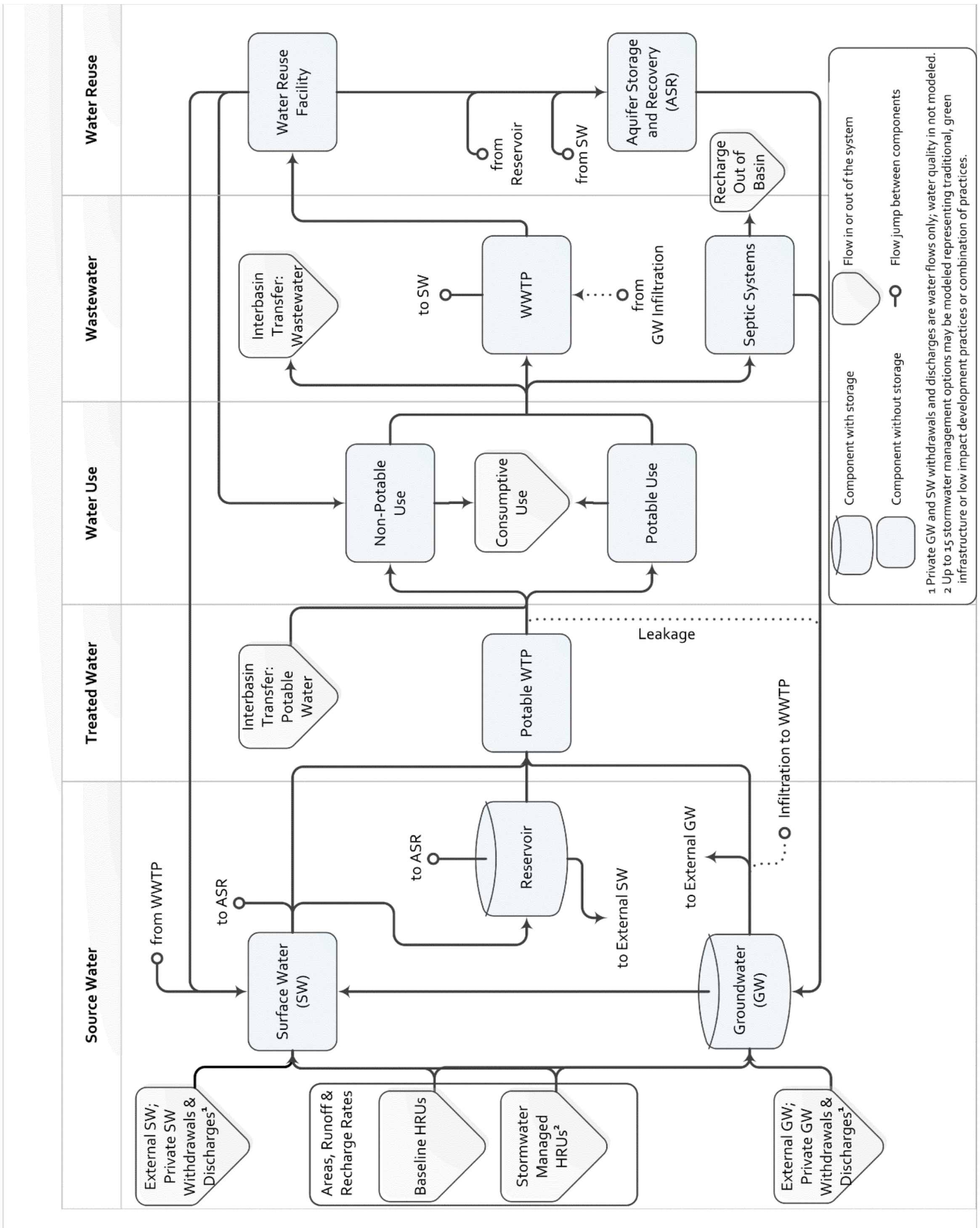
WMOST identifies the least-cost combination of management practices to meet the user specified management goals. Management goals may include meeting projected water supply demand and minimum and maximum in-stream flow targets. The tool considers a range of management practices related to water supply, wastewater, nonpotable water reuse, aquifer storage and recharge, stormwater, low-impact development (LID) and land conservation, accounting for the 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 green infrastructure 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 green infrastructure and land conservation measures as eligible projects in meeting water quality goals.

1.2 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 1-1*. The figure shows the *possible* watershed system components and *potential* water flows among them.

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



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),[11] 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;[12]
- Solutions that account for both the direct and indirect effects of management practices (e.g., since optimization is performed within the watershed system context, 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 fifteen stormwater management options, including traditional, green infrastructure or LID practices;
- A sustainability constraint that forces the groundwater and reservoir volumes at the start and end of the modeling period to be equal;
- 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).

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. *Section 3* describes the configuration of the software components. *Section 4* summarizes the required input data to run the model. We list considerations for future model development in *Section 5*.

[11] 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.

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

A *separate* User Guide document provides detailed direction on using WMOST and performing sensitivity and trade-off analyses, and includes two case studies. 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.

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

Management Practice	Action	Model Component Affected	Impact
Water reuse facility (advanced treatment) capacity	Increase MGD	Water reuse facility	Produce water for nonpotable demand, ASR, and/or improve water quality of receiving water
Nonpotable distribution system	Increase MGD	Nonpotable water use	Reduce demand for potable water
Aquifer storage & recharge (ASR) facility capacity	Increase MGD	ASR facility	Increase recharge, treatment, and/or supply
Demand management by price increase	Increase % of price	Potable and nonpotable water and wastewater	Reduce demand
Direct demand management	Percent decrease in MGD	Potable and nonpotable water and wastewater	Reduce demand
Interbasin transfer – potable water import capacity	Increase or decrease MGD	Interbasin transfer – potable water import	Increase potable water supply or reduce reliance on out of basin sources
Interbasin transfer – wastewater export capacity	Increase or decrease MGD	Interbasin transfer – wastewater export	Reduce need for wastewater treatment plant capacity or reduce reliance on out of basin services
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. Mathematical Description

This section provides the equations for the objective function and the constraints that define the linear programming (LP) optimization model. 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.

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 baseline HRU set and other sets that have the same HRUs but with management practice 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 4.* Units for input variables are based on the units expected to be used in the most-readily available data sources.

2.1 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. First, we describe the generic form of cost equations, and then we provide all of the individual equations 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
C_C	=	unit capital cost

Unit construction costs for new facilities or expanding the capacity of an existing facility with new construction 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
T_{New}	=	lifetime of new construction in years

Replacement costs for existing facility are calculated as $C_{C,A}$ adjusted for the remaining years in the facility's lifetime, T_{Exist}.

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

where

T_{Plan} = the planning horizon

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)[13] – 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),[14] Soil Water and Assessment Tool (SWAT)[15] and/or Storm Water Management Model.[16] 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.[17] At the same time, the user can specify the cost to purchase existing,

[13] 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.

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

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

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

[17] 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).

undeveloped forest land. With this information provided, the model can decide whether it is cost effective to reallocate land from projected developed HRUs to undeveloped forest HRUs. The cost to reallocate land area among baseline HRUs is defined below.

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

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

where

s	=	number of HRU sets
C_{ATb}	=	total annual cost of reallocating areas among baseline HRUs from user-specified to model-chosen values
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)
$C_{Om,l,s=1}$	=	annual O&M cost associated with maintaining, for example, the land preservation
$A_{l,s=1}$	=	user specified areas for baseline HRU
$bA_{l,s=1}$	=	model-chosen, land area for baseline HRUs

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

When the model chooses to place land area under a management practice, additional costs specified by the equation below are incurred. In addition, the runoff and recharge rates corresponding to that HRU set are used to calculate total runoff and recharge as shown by equations in *Section 2.1.1*.

For s = 2 to $NLuSet$, where $C_{C,l,s=1} \neq -9$,

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

where

$bA_{l,s=2to\ NLuSet}$	=	model chosen land area for managed HRUs
$NLuSet$	=	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 practice 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.[18]

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 equals 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:

$$C_{ATPrice} = bPriceBin \times (F_{Plan} \times C_{CDmPrice} + C_{OmDmPrice}) \tag{8}$$

where

$C_{ATPrice}$	=	annual cost to implement price changes
$bPriceBin$	=	a binary decision variable
$C_{CDmPrice}$	=	capital cost of price change
$C_{OMDmPrice}$	=	annual O&M costs for implementation of price change

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.

$$C_{ATDmd} = \frac{bQ_{DmRed}}{Q_{DmRedMax}} \times (F_{Plan} \times C_{CDm} + C_{OmDm}) \tag{9}$$

where

C_{ATDmd}	=	annual cost to implement direct demand management practices
bQ_{DmRed}	=	quantity of direct demand reduction
$Q_{DmRedMax}$	=	maximum demand reduction available
$C_{CDmPrice}$	=	capital cost of direct demand management
$C_{OMDmPrice}$	=	annual O&M costs for direct demand management

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.[19]

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 system follow similar forms for total annual costs.

[18] 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.

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

Groundwater pumping:

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

where

$C_{ATGwPump}$	=	total annual cost for groundwater pumping
$F_{GwPumpExist}$	=	annualization factor based on remaining lifetime of existing facilities
$C_{CGwPump}$	=	capital costs of new/additional groundwater pumping capacity/facility
$Q_{GwPumpI}$	=	initial groundwater pumping capacity
$F_{GwPumpNew}$	=	annualization factor for new capacity or facilities
$bQ_{GwPumpAddl}$	=	additional groundwater pumping capacity
F_{Yrs}	=	factor to maintain annual value for O&M costs
$bQ_{GwWtp,t}$	=	flow from groundwater pump to water treatment plant

where one variable, F_{Yrs}, is further defined as inverse of the number of days or months in the modeling period divided by the total number of days or months in all years modeled even if the modeling period includes only part of a year. Therefore, it is the inverse of the fraction of years, or partial year(s) modeled which allows the scaling of the O&M costs accrued over the modeling period to an average annual cost.

$$F_{Yrs} = 1/\frac{number\ of\ time\ steps\ modeled}{total\ number\ of\ time\ steps\ in\ all\ years\ modeled} \tag{11}$$

Surface water pumping:

$$C_{ATSwPump} = (F_{SwPumpExist} \times C_{CSwPump} \times Q_{SwPumpI}) + (F_{SwPumpNew} \times C_{CSwPump} \times bQ_{SwPumpAddl}) + (C_{OmSwPump} \times F_{Yrs} \times \sum_t (bQ_{SwWtp,t} + bQ_{ResWtp,t})) \tag{12}$$

where

$C_{ATSwPump}$	=	total annual cost for surface water pumping
$F_{WtpExist}$	=	annualization factor based on remaining lifetime of existing facilities
$C_{CSwPump}$	=	capital costs of new/additional surface water pumping capacity/facility
$Q_{SwPumpI}$	=	initial surface water pumping capacity
$F_{SwPumpNew}$	=	annualization factor for new capacity or facilities
$bQ_{SwPumpAddl}$	=	additional surface water pumping capacity
$bQ_{SwWtp,t}$	=	flow from surface water to water treatment plant
$bQ_{ResWtp,t}$	=	flow from reservoir to water treatment plant

Water treatment facility (WTP):

$$C_{ATWtp} = (F_{WtpExist} \times C_{CWtp} \times Q_{WtpMaxI}) + (F_{WtpNew} \times C_{CWtp} \times bQ_{WtpAddl}) + (C_{OmWtp} \times F_{Yrs} \times \sum_t (bQ_{SwWtp,t} + bQ_{GwWtp,t} + bQ_{ResWtp,t})) \tag{13}$$

where

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

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:

$$C_{ATUaw} = \left(F_{Plan} \times C_{CUaw} + C_{OmUaw}\right) \times \frac{bP_{WtpGwFix}}{100} \tag{14}$$

where

C_{CAUaw}	=	total annualized capital cost of reducing unaccounted-for water
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
$bP_{WtpGwFix}$	=	percent of leakage that is fixed

Wastewater treatment plant (WWTP):

$$\begin{aligned} C_{ATWwtp} = {} & \left(F_{WwtpExist} \times C_{CWwtp} \times Q_{WwtpMaxI}\right) + \left(F_{WwtpNew} \times C_{CWwtp} \times bQ_{WwtpAddl}\right) \\ & + \left(C_{OmWwtp} \times F_{Yrs} \times \sum_{t} \left(bQ_{UsePWwtp,t} + bQ_{UseNpWwtp,t} + Q_{GwWwtp,t}\right)\right) \end{aligned} \tag{15}$$

where

C_{ATWwtp}	=	total annual costs for wastewater treatment
$F_{WwtpExist}$	=	annualization factor based on remaining lifetime of existing facilities
C_{CWwtp}	=	capital costs of new or additional wastewater treatment capacity or facility
$Q_{WwtpMaxI}$	=	initial wastewater treatment capacity
$F_{WwtpNew}$	=	annualization factor for new capacity or facilities
$bQ_{WwtpAddl}$	=	additional wastewater treatment capacity
C_{OmWtp}	=	annual O&M costs for wastewater treatment
$bQ_{UsePWwtp,t}$	=	flow from potable water use to treatment plant
$bQ_{UseNpWwtp,t}$	=	flow from nonpotable water use to treatment plant
$Q_{GwWwtp,t}$	=	groundwater infiltration into collection system

Reducing infiltration into wastewater collection system:

$$C_{ATGwWwtp} = \left(F_{Plan} \times C_{CGwWwtp} + C_{OmGwWwtp}\right) \times \frac{bP_{GwWwtpFix}}{100} \tag{16}$$

where

$C_{CATGwWwtp}$	=	total annualized capital cost of reducing groundwater infiltration into the wastewater
$C_{CGwWwtp}$	=	capital cost of fixing infiltration such as initial survey and initial repairs to lower infiltration
C_{OmUaw}	=	annual O&M cost to maintain low infiltration rate
$bP_{WwtpGwFix}$	=	percent of groundwater infiltration that is fixed

Water reuse facility (WRF):

$$C_{ATWrf} = (F_{WrfExist} \times C_{CWrf} \times Q_{WrfMaxI}) + (F_{WrfNew} \times C_{CWrf} \times bQ_{WrfAddl}) + (C_{OmWrf} \times F_{Yrs} \times \sum_t bQ_{WwtpWrf,t}) \tag{17}$$

where

C_{ATWrf}	=	total annual costs for water reuse
$F_{WrfExist}$	=	annualization factor based on remaining lifetime of existing facilities
C_{CWrf}	=	capital costs of new or additional WRF capacity
$Q_{WrfMaxI}$	=	existing maximum WRF capacity
F_{WrfNew}	=	annualization factor for new capacity or facilities
C_{OmWrf}	=	annual O&M costs for WRF
$bQ_{WrfAddl}$	=	additional or new WRF capacity
$bQ_{WwtpWrf}$	=	flow from WWTP to WRF

Nonpotable distribution system (Npdist):

$$C_{ATNpdist} = (F_{NpDistExist} \times C_{CNpDist} \times Q_{NpDistMaxI}) + (F_{NpdistNew} \times C_{CNpdist} \times Q_{NpDistAddl}) + (C_{OmNpdist} \times F_{Yrs} \times \sum_t bQ_{WrfUseNp,t}) \tag{18}$$

where

$C_{ATNpdist}$	=	total annual costs for nonpotable water distribution
$F_{NpdistNew}$	=	annualization factor for new capacity or facilities
$bQ_{NpdistAddl}$	=	new or additional capacity
$C_{CNpdist}$	=	capital costs for maximum capacity Npdist
$C_{OmNpdist}$	=	annual O&M costs for maximum capacity Npdist
$Q_{NpdistMaxPotential}$	=	total maximum potential capacity need for nonpotable distribution system

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 injection well and/or aquifer and/or to meet permit requirements).

$$C_{ATAsr} = (F_{AsrExist} \times C_{CAsr} \times Q_{AsrMaxI}) + (F_{AsrNew} \times C_{CAsr} \times bQ_{AsrAddl}) + (C_{OmAsr} \times F_{Yrs} \times \sum_t (bQ_{WrfAsr,t} + bQ_{SwAsr,t} + bQ_{ResAsr,t})) \tag{19}$$

where

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

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

$$C_{ATRes} = (F_{ResExist} \times C_{CRes} \times V_{ResMaxI}) + (F_{ResNew} \times C_{CRes} \times bV_{ResAddl}) + (C_{OmRes} \times (bV_{ResAddl} + V_{ResMaxI})) \tag{20}$$

where

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

Interbasin transfer (IBT) for water and wastewater:

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

$$C_{ATIbtW} = F_{Plan} \times C_{CIbtW} \times bQ_{IbtWAddl} + C_{IbtW} \times F_{Yrs} \times \sum_t \left(bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t}\right) \tag{21}$$

where

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

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:

$$C_{ATIbtWw} = F_{Plan} \times C_{CIbtWw} \times bQ_{IbtWwAddl} + C_{IbtWw} \times F_{Yrs} \times \sum_{t} (bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t}) \tag{22}$$

where

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

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:

$$C_{AT} = C_{ATb} + C_{ATm} + C_{ATPrice} + C_{ATDmd} + C_{ATGwPump} + C_{ATSwPump} + C_{ATWtp} + C_{ATUaw} + C_{ATWwtp} + C_{ATGwWwtp} + C_{ATWrf} + C_{ATNpdist} + C_{ATAsr} + C_{ATRes} + C_{ATIbtW} + C_{ATIbtWw} \tag{23}$$

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.

$$R_T = ((R_{UsePT} + R_{UseNpT}) \times \left(1 + \frac{bP_{Price}}{100}\right)) + R_{WwT} \tag{24}$$

where

R_{UsePT}	=	revenue from delivered potable water
R_{UseNpT}	=	revenue from delivered nonpotable water
R_{WwT}	=	revenue from wastewater services
bP_{Price}	=	percent price increase for potable and nonpotable water services

These quantities are further defined as follows.

$$R_{UsePT} = F_{Yrs} \times \sum_{m} R_{UsePF} + (R_{UseP} \times F_{Yrs} \times \sum_{t} (Q_{WtpUseP,t} + bQ_{IbtWUseP,t})) \tag{25}$$

$$R_{UseNpT} = F_{Yrs} \times \sum_{m} R_{UseNpF} + (R_{UseNp} \times F_{Yrs} \times \sum_{t} bQ_{WrfUseNp,t}) + (R_{UseP} \times F_{Yrs} \times \sum_{t} (bQ_{WtpUseNp,t} + bQ_{IbtWUseNp,t})) \tag{26}$$

where

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

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

$$R_{WwT} = F_{Yrs} \times \sum_{m} R_{WwF} + (R_{Ww} \times F_{Yrs} \times \sum_{t} (bQ_{UsePWwtp,t} + bQ_{UsePIbtWw,t} + bQ_{UseNpWwtp,t} + bQ_{UseNpIbtWw,t})) \tag{27}$$

where

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

If wastewater fees are charged based on water flow, then

$$R_{WwT} = F_{Yrs} \times \sum_{m} R_{WwF} + (R_{Ww} \times F_{Yrs} \times \sum_{t} (Q_{WtpUseP,t} + bQ_{IbtWUseP,t} + bQ_{WrfUseNp,t} + bQ_{WtpUseNp,t} + bQ_{IbtWUseNp,t})) \tag{28}$$

2.2 Constraints

The objective in *Section 2.1* 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.

2.2.1 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, ft^3/acre/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),[20] Soil Water and Assessment Tool (SWAT)[21] and/or Storm Water Management Model.[22]

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.

$$\sum_{l=1\ to\ NLu} A_{l,s=1} = \sum_{l=1\ to\ NLu} bA_{l,s=1} = \sum_{s=2\ to\ NLuSet} \sum_{l=1\ to\ NLu} bA_{l,s} \tag{29}$$

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

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

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

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

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

$$bA_{l,s} \geq A_{Min,l,s} \quad \text{for } l = 1 \text{ to } NLu \text{ and } s = 1 \tag{30}$$

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

$$bA_{l,s} \leq A_{Max,l,s} \quad \text{for } l = 1 \text{ to } NLu \text{ and } s = 1 \tag{31}$$

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 can not 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.

$$\text{where } C_{C,s,l} <> -9, \qquad bA_{l,s=1} - A_{l,s=1} \geq 0 \tag{32}$$

$$\text{else}, \qquad bA_{l,s=1} - A_{l,s=1} \leq 0 \tag{33}$$

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 can not be greater than the area allocated to the corresponding baseline land use chosen under conservation, $bA_{l,s=1}$ (e.g., 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 green infrastructure practices to meet a specific stormwater standard.

$$\sum_{s=2}^{nLuSet} bA_{l,s} \leq bA_{l,s=1} \quad \text{for each } l \tag{34}$$

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.

$$bA_{l,s} \geq A_{Min,l,s} \qquad \text{for } l = 1 \text{ to } nLu \text{ and } s = 2 \text{ to } NLuSet \tag{35}$$

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

$$bA_{l,s} \leq A_{Max,l,s} \qquad \text{for } l = 1 \text{ to } nLu \text{ and } s = 2 \text{ to } NLuSet \tag{36}$$

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

The total runoff and recharge for each time step are calculated based on the final area allocations for all HRUs and HRU sets.

$$Q_{Ru,t} = \sum_{l=1}^{NLu}(bA_{l,s=1} \times Q_{Ru,l,s=1,t}) + \sum_{s=2}^{NLuSet}\sum_{l=1}^{NLu}((Q_{Ru,l,s,t} - Q_{Ru,l,s=1,t}) \times bA_{l,s}) \tag{37}$$

where $Q_{Ru,l,s,t}$[23] = runoff rate from HRU l in HRU set s for time step *t*.

$$Q_{Re,t} = \sum_{l=1}^{NLu}(bA_{l,s=1} \times Q_{Re,l,s=1,t}) + \sum_{s=2}^{NLuSet}\sum_{l=1}^{NLu}((Q_{Re,l,s,t} - Q_{Re,l,s=1,t}) \times bA_{l,s}) \tag{38}$$

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.

$$\begin{aligned} V_{Gw,t} = V_{Gw,t-1} + \big(&Q_{Re,t} + Q_{ExtGwIn,t} + Q_{PtGw,t} + Q_{WtpGw,t} + Q_{AsrGw,t-1} + Q_{SepGw,t-1} - Q_{GwSw,t} \\ &- bQ_{GwWtp,t} - Q_{GwWwtp,t} - bQ_{GwExt,t} - Q_{GwPt,t}\big) \times \Delta t \end{aligned} \tag{39}$$

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

Two variables are further defined as

$$Q_{WtpGw,t} = Q_{UsePI,u=1,t} \times \left(1 - \frac{bP_{WtpLeakFix}}{100}\right) \tag{40}$$

where

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

and

$$Q_{GwSw,t} = k_b \cdot V_{Gw,t-1} \tag{41}$$

where 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.

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

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

$$Q_{Ru,t} + Q_{ExtSwIn,t} + Q_{PtSw,t} + Q_{GwSw,t} + Q_{WwtpSw,t} + Q_{WrfSw,t} = Q_{SwRes,t} + bQ_{SwWtp,t} + bQ_{SwAsr,t} + Q_{SwPt,t} \quad (42)$$

where

$Q_{ExtSwIn}$	=	surface water inflow from outside of basin
Q_{PtSw}	=	discharge from surface water point sources
Q_{WwtpSw}	=	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}	=	flow to water treatment plant
bQ_{SwAsr}	=	flow to ASR facility
Q_{SwPt}	=	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.[24]

$$V_{Res,t} = V_{Res,t-1} + \left(Q_{SwRes,t} - bQ_{SwExt,t} - bQ_{ResWtp,t} - bQ_{ResAsr,t}\right) \times \Delta t \quad (43)$$

where

V_{Res}	=	volume of reservoir
Q_{SwRes}	=	inflow to reservoir from surface water bodies
bQ_{SwExt}	=	flow to surface water bodies outside of basin
bQ_{ResWtp}	=	flow to water treatment plant
bQ_{ResAsr}	=	flow to ASR facility

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

Water Treatment Plant (Wtp):

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

$$bQ_{ResWtp,t} + bQ_{SwWtp,t} + bQ_{GwWtp,t} = Q_{WtpUseP,t} + bQ_{WtpUseNp,t} + Q_{WtpGw,t} \tag{44}$$

where

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

Potable Water Use (UseP):

$$\sum_u ((Q_{WtpUseP,t} + bQ_{IbtWUseP,t}) \times \left(1 - \frac{P_{ConsUseP,u,t}}{100}\right) \times F_{UseP,u,t}) = bQ_{UsePWwtp,t} + Q_{UsePSep,t} + Q_{UsePSepExt,t} + bQ_{UsePIbtWw,t} \tag{45}$$

where

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

One variable is further defined as

$$F_{UseP,u,t} = \frac{Q_{UseP,u,t}}{\sum_u Q_{UseP,u,t}} \tag{46}$$

where

$Q_{UseP,u,t}$	=	potable water use by user u at time t

Nonpotable Water Use (UseNp):

$$\sum_u ((bQ_{WtpUseNp,t} + bQ_{WrfUseNp,t} + bQ_{IbtWUseNp,t}) \times \left(1 - \frac{P_{ConsUseNp,u,t}}{100}\right) \times F_{UseNp,u,t}) = bQ_{UseNpWwtp,t} + Q_{UseNpSep,t} + Q_{UseNpSepExt,t} + bQ_{UseNpIbtWw,t} \tag{47}$$

where

One variable is further defined as

$$F_{UseNp,u,t} = \frac{Q_{UseNp,u,t}}{\sum_u Q_{UseNp,u,t}} \tag{48}$$

where

$Q_{UseNp,u,t}$ = nonpotable water use by user u at time t

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 of are calculated as

$$Q_{UsePSep,t} = \sum_{n=2}^{NWuser} (Q_{UsePI,u,t} \times \left(1 - \frac{P_{UseNpMax,u,t}}{100}\right) \times \left(1 - \frac{P_{ConsUseP,u,t}}{100}\right) \times \frac{P_{Sep,u}}{100} \times \left(1 + ElasPrice_u \times \frac{bP_{Price}}{100}\right) - \left(1 - \frac{P_{UseNpMax,u,t}}{100}\right) \times \left(1 - \frac{P_{ConsUseP,u,t}}{100}\right) \times \frac{P_{Sep,u}}{100} \times F_{UseP,u,t} \times bQ_{DmRed}) \tag{52}$$

$$Q_{UseNpSep,t} = \sum_{n=2}^{NWuser} (Q_{UsePI,u,t} \times \left(\frac{P_{UseNpMax,u,t}}{100}\right) \times \left(1 - \frac{P_{ConsUseNp,u,t}}{100}\right) \times \frac{P_{Sep,u}}{100} \times \left(1 + ElasPrice_u \times \frac{bP_{Price}}{100}\right) - \left(\frac{P_{UseNpMax,u,t}}{100}\right) \times \left(1 - \frac{P_{ConsUseNp,u,t}}{100}\right) \times \frac{P_{Sep,u}}{100} \times F_{UseNp,u,t} \times bQ_{DmRed}) \tag{53}$$

where

$Q_{UsePI,u,t}$	=	initial potable water use/demand
$P_{UseNpMax,u,t}$	=	maximum percent of water demand that can be met by nonpotable water
$P_{Sep,u}$	=	percent of users serviced by septic systems draining within the study area
$ElasPrice_u$	=	price elasticity for water user type, u,
bP_{Price}	=	percent price change

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

$$Q_{UsePSepExt,t} = \sum_{n=2}^{NWusesr} (Q_{UsePI,u,t} \times \left(1 - \frac{P_{UseNpMax,u,t}}{100}\right) \times \left(1 - \frac{P_{ConsUseP,u,t}}{100}\right) \times \frac{P_{SepExt,u}}{100} \times \left(1 + ElasPrice_u \times \frac{bPprice}{100}\right) - \left(1 - \frac{P_{UseNpMax,u,t}}{100}\right) \times \left(1 - \frac{P_{ConsUseP,u,t}}{100}\right) \times \frac{P_{SepExt,u}}{100} \times F_{UseP,u,t} \times bQ_{DmRed}) \tag{54}$$

$$Q_{UseNpSepExt,t} = \sum_{u=2}^{NWUser} (Q_{UsePI,u,t} \times \left(\frac{P_{UseNpMax,u,t}}{100}\right) \times \left(1 - \frac{P_{ConsUseNp,u,t}}{100}\right) \times \frac{P_{SepExt,u}}{100} \times \left(1 + ElasPrice_u \times \frac{bPprice}{100}\right) - \left(\frac{P_{UseNpMax,u,t}}{100}\right) \times \left(1 - \frac{P_{ConsUseNp,u,t}}{100}\right) \times \frac{P_{SepExt,u}}{100} \times F_{UseNp,u,t} \times bQ_{DmRed}) \tag{55}$$

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.

2.2.2 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, $V_{Gw,Min}$, may be specified to reflect the maximum desired drawdown (e.g., to avert land subsidence). The maximum volume, $V_{Gw,Max}$, may also be specified to reflect the size of the aquifer and the maximum storage capacity. For the reservoir, the minimum storage volume, $V_{Res,Min}$, 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, $V_{Res,MaxI}$, may be specified to reflect the physical size of the reservoir (note that additional surface water storage capacity, $bV_{Res,Addl}$, is one of the management options in *Table 1-1*).

$$V_{Gw,t} \leq V_{Gw,Max} \quad (65)$$

$$V_{Gw,t} \geq V_{Gw,Min} \quad (66)$$

$$V_{Res,t} \leq V_{Res,Max} + bV_{Res,Addl} \quad (67)$$

$$V_{Res,t} \geq V_{Res,Min} \quad (68)$$

Sustainable system: The final volume of the reservoir and groundwater are constrained to be equal to their respective initial volumes. Therefore, no deficit can build up over the modeling time period. New England, for example, is a region where many systems are within-year. However, the longer time period that is modeled, the constraints become less binding because only the initial and final volumes are forced to be equal.

$$V_{Res,t=1} = V_{Res,t=tf} \quad (69)$$

$$V_{Gw,t=1} = V_{Gw,t=tf} \quad (70)$$

where *tf* is the last day in the time period optimized.

2.2.3 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.

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, $P_{UseNpMax,u}$.

$$Q_{UsePMin,t} = \sum_{u=2\ to\ NUser} (Q_{UsePI,u,t} \times (1 - \frac{P_{UseNpMax,u,t}}{100})) \times (1 + ElasPrice_u \times \frac{bPprice}{100}) - \left(1 - \frac{P_{UseNpMax,u,t}}{100}\right) \times F_{UseP,u,t} \times bQ_{DmRed}) \quad (71)$$

$$Q_{UseNpMin,t} = \sum_{u=2\ to\ NUser} (Q_{UsePI,u,t} \times \frac{P_{UseNpMax,u}}{100}) \times (1 + ElasPrice_u \times \frac{bPprice}{100}) - \frac{P_{UseNpMax,u,t}}{100} \times F_{UseNp,u,t} \times bQ_{DmRed}) \quad (72)$$

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

$$Q_{WtpUseP,t} + bQ_{IbtWUseP,t} \geq Q_{UsePMin,t} \tag{73}$$

$$bQ_{WtpUseNp,t} + bQ_{IbtWUseNp,t} + bQ_{WrfUseNp,t} \geq Q_{UseNpMin,t} \tag{74}$$

Consumptive water use

The final or adjusted percent consumptive use for potable water use, $P_{ConsUseP,u,t}$, is calculated based on the initial percent consumptive use of potable water, $P_{ConsUsePI,u,t}$, $P_{UseNpMax,u}$, 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.

$$P_{ConsUseP,u,t} = \frac{P_{ConsUsePI,u,t} - P_{UseNpMax,u} \times P_{ConsUseNp,u,t}/100}{100 - P_{UseNpMax,u}} \tag{75}$$

It is possible to enter input data for potable and nonpotable percent consumptive use and maximum percent nonpotable use in a combination that result in an adjusted percent potable consumptive use value being outside of the feasible range of 0-100%. Therefore, a third table in the “Nonpotable Demand” input data worksheet pre-calculates the adjusted percent potable consumptive use values and is highlighted red if the value is outside of the feasible range. The model will not run if any of these values are outside of the feasible range and the user is provided with an error message to change one or more of the input values.

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.

$$Q_{SwMin,t} \leq Q_{SwRes,t} \tag{76}$$
where $Q_{SwMin,t}$= minimum in-stream flow for subbasin reach

$$Q_{SwMax,t} \geq Q_{SwRes,t} \tag{77}$$
where $Q_{SwMax,t}$= maximum in-stream flow for subbasin reach

$$Q_{SwExtMin,t} \leq Q_{ResExt,t} \tag{78}$$
where $Q_{SwExtMin,t}$= minimum flow exiting subbasin

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.

$$Q_{GwExtMin,t} \leq bQ_{GwExt,t} \tag{79}$$

Management limits:

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

$$bP_{Price} \leq P_{PriceMax} * bPriceBin \tag{80}$$

where

$P_{PriceMax}$ = one time, maximum percent change in price

$$bQ_{DmRed} \leq Q_{DmRedMax} \tag{81}$$

$$bP_{WtpLeakFix} \leq P_{WtpLeakFixMax} \tag{82}$$

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

$$bP_{WwtpLeakFix} \leq P_{WwtpLeakFixMax} \tag{83}$$

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,*

$$bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq \; Q_{IbtWMaxDay} + bQ_{IbtWAddl} \tag{84}$$

$$bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq Q_{IbtWwMaxDay} + bQ_{IbtWwAddl} \tag{85}$$

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,*

$$bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq \; (Q_{IbtWMaxDay} + bQ_{IbtWAddl}) \times NDay(month(t)) \tag{86}$$

$$bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq (Q_{IbtWwMaxDay} + bQ_{IbtWwAddl}) \times NDay(month(t)) \tag{87}$$

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

$NDay(month(t))$ = 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 monthly limit, if the time step is daily, then *for each month in the period of analysis,*

$$\sum_{t=1 \; to \; NdtM} bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq \; Q_{IbtWMaxMonth,m} \times \frac{NdtM}{NDay(month(t))} + bQ_{IbtWAddl} \tag{88}$$

$$\sum_{t=1 \ to \ NdtM} bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq Q_{IbtWwMaxMonth,m} \times \frac{NdtM}{NDay(month(t))} + bQ_{IbtWwAddl} \tag{89}$$

where

$Q_{IbtWwMaxMonth,m}$	=	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 monthly limit, if the time step is monthly, then *for each month in the period of analysis,*

$$bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq \ Q_{IbtWMaxMonth,m} + NdtM \times bQ_{IbtWAddl} \tag{90}$$

$$bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq Q_{IbtWwMaxMonth,m} + NdtM \times bQ_{IbtWwAddl} \tag{91}$$

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

$$\sum_{t=1 \ to \ Ndt} bQ_{IbtWUseP,t} + bQ_{IbtWUseNp,t} \leq \ Q_{IbtWMaxYr} \times \frac{Ndt}{NdtYr} + NDaysYr \times bQ_{IbtWAddl} \tag{92}$$

$$\sum_{t=1 \ to \ Ndt} bQ_{UsePIbtWw,t} + bQ_{UseNpIbtWw,t} \leq Q_{IbtWwMaxYr} \times \frac{Ndt}{NdtYr} + NDaysYr \times bQ_{IbtWwAddl} \tag{93}$$

where

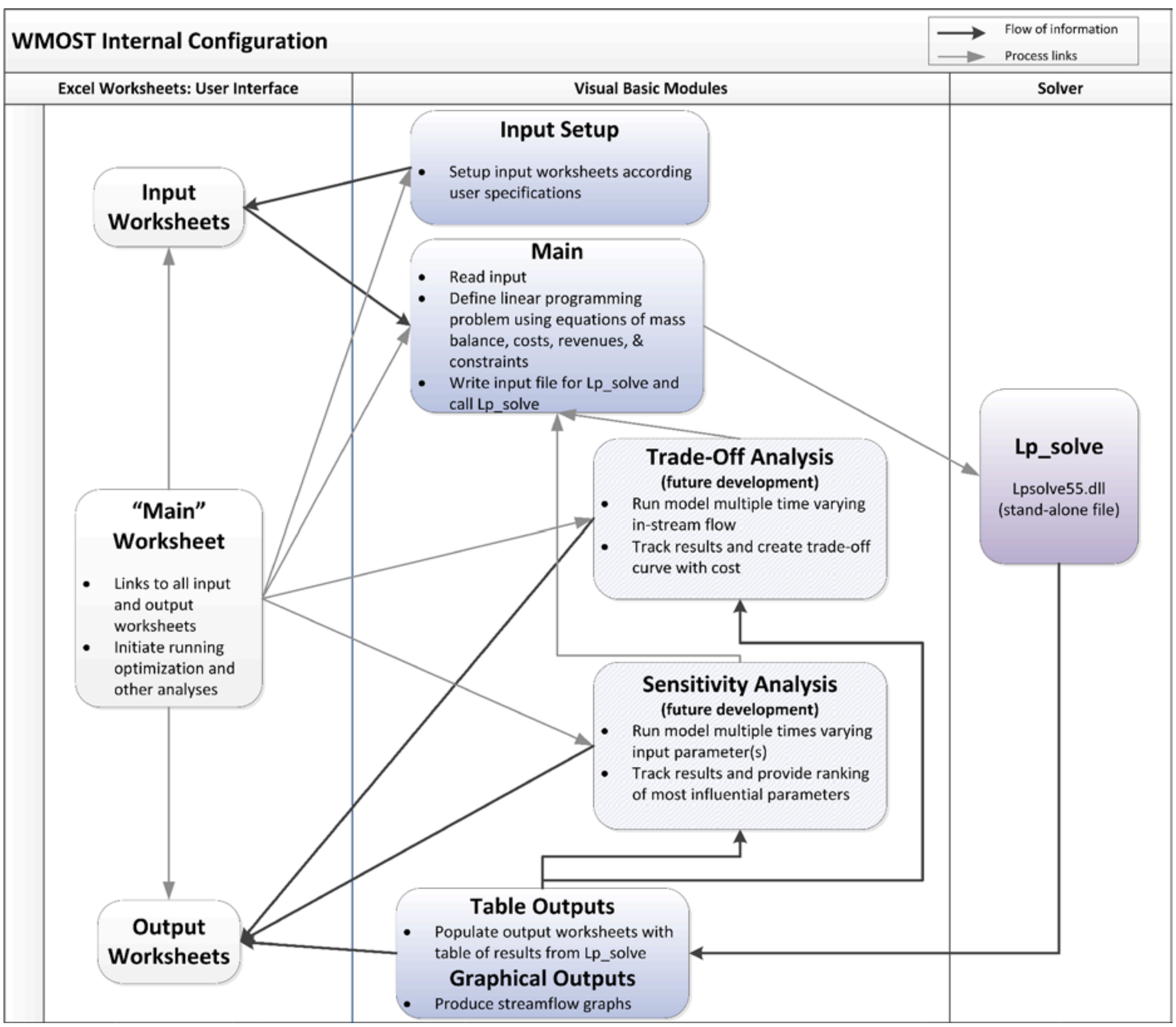
$Q_{IbtWMaxYr}$	=	maximum potable water transfers from/to outside the basin for a given year in the optimization period
$Q_{IbtWwMaxYr}$	=	maximum potable wastewater transfers from/to outside the basin for a given year in the optimization period
Ndt	=	number of time steps in the year
NdtYr	=	potential number of time steps in the full year (i.e., 365 or 366 for daily and 12 for monthly time step)
NDaysYr	=	number of days in the year that are modeled

3. 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 and 3) 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 3-1* shows the flow of information and process links between components of WMOST. Two modules are noted for future development – Sensitivity Analysis and Trade-Off Analysis. These analyses can be performed manually as described in the User Guide.

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 3-1. WMOST Internal Configuration



4. Summary of Input Data

Variables	Units	Description
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*
Runoff and Recharge Rates[25]		
$Q_{Ru,s,l,t}$	*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
Potable Demand		
$Q_{UsePI,u,t}$	*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
Nonpotable Demand		
$P_{ConsUseNp,u,t}$	*%*	Percent consumptive use for nonpotable water for each user for an average month for each month
Demand Management		
E_u	*% demand reduction / % price increase*	Price elasticity for each user
$C_{C,Price}$	*$*	Capital cost to implement price increase

[25] Recharge and runoff rates may be derived from a calibrated/validated simulation model such as Soil Water Assessment Tool, Hydrological Simulation Program--Fortran or Storm Water Management Model.

Variables	Units	Description
$C_{Om,Price}$	*$/yr*	O&M cost to administer price increase (e.g., resurvey for appropriate price etc.)
$P_{PriceMax}$	*%*	Maximum percent price change
$\mathrm{Q}_{\mathrm{DmRedMax}}$	*MGD*	Maximum/total direct demand reduction
C_{CDm}	*$*	Initial cost for direct demand reduction
C_{OmDm}	*$/yr*	O&M cost for direct demand reduction
Septic System Users		
$P_{Sep,u}$	*%*	Percent septic use for each public water user that drains within modeled watershed
$P_{SepExt,u}$	*%*	Percent septic use for each public water user that drains outside modeled watershed
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
$Q_{PtGw,t}$	*MG per time step*	Flow from private point source to groundwater, i.e., discharge
$Q_{GwPt,t}$	*MG per time step*	Flow from groundwater to private point source, i.e., withdrawal
Surface Water/Stream Reach and Reservoir/Surface Storage		
$Q_{ExtSw,t}$	*ft^3/sec*	Inflow from external surface water to study area stream reach
$Q_{SwResMin,t}$	*ft^3/sec*	Minimum in-stream flow in reach
$Q_{SwResMax,t}$	*ft^3/sec*	Maximum in-stream flow in reach
$Q_{SwExtMin,t}$	*ft^3/sec*	Minimum surface water flow out of study area
$Q_{PtSw,t}$	*MG per time step*	Flow from private point source to surface water, i.e., discharge

Variables	Units	Description
$Q_{SwPt,t}$	*MG per time step*	Flow from surface water to private point source, i.e., withdrawal
$V_{Res,I}$	*MG*	Reservoir volume
$V_{Res,Min}$	*MG*	Minimum reservoir volume
$V_{Res,Max}$	*MG*	Current maximum reservoir volume
$Q_{ExtSwOutMin,t}$	*ft^3/sec*	Minimum flow out of study area
$C_{C,Res}$	*$/MG*	Capital construction cost
$C_{Om,Res}$	*$/MG*	O&M costs
R_{UseP}	*$/100 ft^3*	Customer's price for potable water
R_{UseNp}	*$/100 ft^3*	Customer's price for nonpotable water
R_{Ww}	*$/100 ft^3*	Customer's price for wastewater
Interbasin Transfer		
C_{CIbtW}	*$/MGD*	Initial cost for obtaining rights to and building infrastructure for interbasin transfer of potable water
C_{CIbtWw}	*$/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
$Q_{IbtWAddlMax}$ $Q_{IbtWwAddlMax}$	*MGD*	Maximum *additional* interbasin transfer flow for water and wastewater on a daily basis
General		
TPlan	*yrs*	Planning horizon
i	*%*	Interest rate
Water Treatment Plant		
R_{UsePF}	*$/month*	Consumer's price for potable water: Fixed monthly fee

Variables	Units	Description
R_{UseP}	*$/HCF*	Consumer's price for potable water: Variable, volume-based fee
$C_{C,GwPump}$	*$/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
$C_{Om,WtpLeak}$	*$/yr*	O&M costs for continued leak repair
$P_{WtpLeakFixMax}$	*%*	Maximum percent of leaks that can be fixed
Wastewater treatment plant		
R_{WwF}	*$/month*	Consumer's price for wastewater: Fixed monthly fee
R_{Ww}	*$/HCF*	Consumer's price for wastewater: Variable, volume-based fee
$C_{C,Wwtp}$	*$/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

Variables	Units	Description
$P_{WwtpLeakFixMax}$	%	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
Nonpotable water distribution system (NpDist)		
R_{UseNpF}	*$/month*	Consumer’s price for nonpotable water: Fixed monthly fee
R_{UseNp}	*$/HCF*	Consumer’s price for nonpotable water: Variable, volume-based fee
$C_{C,Npdist}$	*$/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
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

5. Future Development

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

5.1 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 [26]

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

- 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)
- 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[27] or other climate projections to facilitate sensitivity and uncertainty analyses
  - 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.
  - Stormwater module that is run as a pre-processor for generating managed runoff and recharge rate time series
  - 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.

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

- 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[28] by screening 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
- 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

5.2 User Interface and User Support

- Input features
  - Provide generic runoff and recharge rates for various combinations of land cover/land use, soil, and slope HRUs (i.e., for various precipitation/weather regions) so that user does not need an existing, detailed simulation model to derive input values for runoff and recharge rates
  - Direct linking and interoperability with simulation models for importing baseline runoff and recharge rate time series (e.g., Hydrological Simulation Program Fortran (HSPF),[29] Soil Water and Assessment Tool (SWAT)[30]
  - 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

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

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

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

        - 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)

6. 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 with case studies as a source of default data.

6.1 User Error Checks

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

- 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, and
- adjusted percent consumptive use for potable water values are between 0-100%.

6.2 User Manual, Case Studies and Default Data

Two case studies are provided with the model user guide 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% depending on the infrastructure or management practice.

Many federal and state websites provide data for geographic information systems 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.

United States
Environmental Protection
Agency

PRESORTED STANDARD
POSTAGE & FEES PAID
EPA
PERMIT NO. G-35

Office of Research and Development
National Health and Environmental
Effects Research Laboratory
Atlantic Ecology Division
Narragansett, RI 02882

Official Business
Penalty for Private Use
$300

Recycled/Recyclable
Printed with vegetable-based ink on paper that
contains a minimum of 50% post-consumer fiber
and is processed chlorine free.