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Timothy Stagnitta
U.S. EPA (ORISE), stagnitta.timothy@epa.gov

Naomi Detenbeck
U.S. EPA, detenbeck.naomi@epa.gov

Amy Piscopo
U.S. EPA, piscopo.amy@epa.gov

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An Overview of the U.S. EPA's Watershed Management Optimization Support Tool (WMOST): A case study in Taunton, Massachusetts

Tim Stagnitta[a], Naomi Detenbeck[b], and Amy Piscopo[c]
a- ORISE Research Participant at the U.S. EPA/ORD/NHEERL Atlantic Ecology Division (Stagnitta.Timothy@epa.gov)
b- U.S. EPA/ORD/NHEERL Atlantic Ecology Division (Detenbeck.Naomi@epa.gov)
c- U.S. EPA/ORD/NHEERL Atlantic Ecology Division (Piscopo.Amy@epa.gov)

Abstract: Integrated water resources management (IWRM) is a planning framework to balance tradeoffs between competing water uses within a watershed. One tool available to aid planners with IWRM is the Watershed Management Optimization Support Tool (WMOST), an Excel-based tool that supports decision-making by optimizing for cost effective solutions that meet water quantity and quality regulations. In this case study, WMOST was used to assess multiple management options for the nutrient-impaired Taunton River basin in Massachusetts, United States. Nitrogen water quality targets were determined from regional Total Maximum Daily Loads, which suggest that a 20% reduction in non-point sources (NPS) is necessary to protect the downstream estuary of Mt. Hope Bay. To meet these goals WMOST was used to model the implementation of stormwater best management practices and riparian restoration. Preliminary results show implementing a combination of infiltration basins and restoration of riparian areas that receive high nutrient loads is the most cost-effective solution for reducing nitrogen loadings in the upper Taunton River basin. This paper outlines required input data, highlights the capabilities of WMOST, and provides preliminary analyses and solutions to a real-world problem.

Keywords: Watershed Resources Management, Decision Support Tools, Water Quality, Best Management Practices, Riparian Buffers

1 INTRODUCTION

Water managers face many decisions related to water demand, maintaining healthy aquatic habitats, reservoir operations, pollutant reduction requirements, and other water quantity and quality needs that are interconnected, with competing goals to meet specific requirements (Pahl-Wostl, 2007). The Global Water Partnership, an international network of water resources organizations defines integrated water resources management (IRWM) as a planning strategy to enable sustainable water resources development, by establishing policies, strategies and legislation through management and sustainable practices (UNEP-DHI Centre for Water and Environment, 2009). IWRM enables water resources managers to systematically assess tradeoffs among competing goals within a watershed. A recent report introduced a collaborative strategic approach to reduce nutrient pollution in waters across the U.S. (US Water Alliance et al., 2017). This report outlines the need for a statewide institution that could support strategies to reduce nutrients for stakeholders with competing interests by offering financing, governance, and operational functions (US Water Alliance et al., 2017). Furthermore, the report highlights that IWRM is difficult to incorporate in practice because the "American system of water management is fragmented, which constrains water users". Decision-support tools can alleviate this challenge by providing stakeholders with information on the tradeoffs between different management options.

Decision-support tools are adaptable and can filter through numerous alternative planning strategies and goals to reach a user-specified objective (Matthies, Giupponi, and Ostendorf, 2007). A simple decision-support tool was created for watershed scale analyses to screen tradeoffs between structural and non-structural management options to understand competing benefits for water quantity goals (Zoltay et al., 2010). Building on this model, the United States Environmental Protection Agency (EPA) created the

Watershed Management Optimization Support Tool (WMOST). The first version of WMOST incorporated water quantity management options, the second version provided users with options to input default databases, a stormwater management module, and a flood module to evaluate flood related damages. The most current version of WMOST v3, adds water quality components to the model. This report will focus on a case study in Taunton, MA to highlight the capabilities of WMOST v3. See Detenbeck et al. (2018a) in this proceedings for a summary of WMOST components.

2 Case Study

Freshwater ecosystems across the Northeast have been severely degraded through years of pollution from wastewater effluent, stormwater, agriculture runoff, and various other pollutants (U.S. EPA, 2000a, 2000b). This study focuses on the 220km^2 Wading – Threemile River Watershed in the Upper Taunton basin in lower Massachusetts, USA, where nearly 50% of the basin is developed or agricultural land (Figure 1). The basin is subject to both nonpoint and point source loadings, with multiple water bodies listed on the Massachusetts state 303(d) list as impaired due to eutrophication, pathogens, or other pollutants. The basin includes nine towns with both groundwater extraction and surface sources for drinking water. Towns also buy and sell water to make-up for deficiencies during low flow periods. The EPA and a consortium of interest groups identified goals to protect undeveloped areas which provide environmental benefits to the watershed and to protect the downstream estuary of Mt. Hope Bay. WMOST is being applied to identify management strategies to reduce non-point sources (NPS) water pollution within the watershed, among other goals.

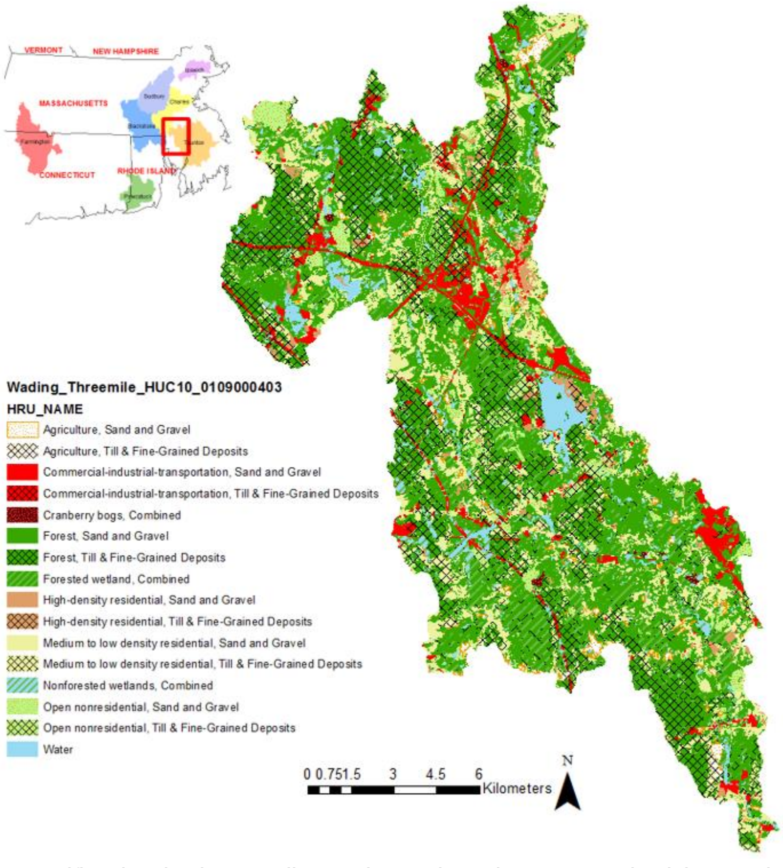

Figure 1. Land use classification in the Wading - Threemile River Watershed in Southern Massachusetts. Soil classes Sand/Gravel are open and Till/Fine-Grained are cross-hatched

2.1 Model Set-up

WMOST has a Microsoft ® Excel interface that guides users through each input required by the optimization program. This outline highlights a few components of WMOST, while the manual provides an in-depth guide and description of WMOST (Detenbeck et al., 2018b). Below, numbered items name specific WMOST components, letter items are descriptions of watershed components, and bullet items are the case study data descriptions and sources.

1. Baseline Hydrology Module
    a. WMOST has options to either manually import baseline data or to automatically retrieve these time series from a server using menu selections in the tool. These data can also be accessed interactively using the EPA's Estuary Data Mapper (EDM; www.epa.gov/edm). EDM has a database of input WMOST hydrology and loading time series for a select number of watersheds across the Northeastern U.S. These time series are generated from hydrologic models such as the Hydrologic Simulation Program Fortran (HSPF; Bicknell et al., 2001), Stormwater Management Model (SWMM; U.S. EPA, 2008), and the Soil Water and Assessment Tool (SWAT; Arnold et al., 1998 and Arnold and Fohrer, 2005). Data inputs for time series and watershed characteristics, such as % effective imperviousness and infiltration rates, are organized by Hydrologic Response Units (HRU; i.e., unique combination of landuse and soil class).
        - Wading – Threemile is separated into ten land-use classes and three soil groups (sand/gravel, till/fine-grained, and combined). We uploaded SWMM-generated hydrology and loading time series. The SWMM model hydrology parameters and loading build-up\wash-off coefficients were calibrated for New England during development of EPA's OPTI-TOOL, a tool to evaluate watershed or site-specific stormwater management options (Tetra Tech, 2015a, 2015b).
2. Stormwater Management
    a. WMOST interacts with the EPA's System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN), which generates managed hydrology and loading time series for each HRU by Best Management Practice (BMP) combination. BMPs require design depths (a design parameter to meet certain water quantity and/or quality targets)
        - This model tested nine structural BMPs: bioretention basin, enhanced biofiltration with internal storage reservoir, extended dry detention basin, grass swale with underdrain, gravel wetland, infiltration basin, infiltration chamber, infiltration trench, and wet pond. Each BMP was modeled with a 5.08cm design depth, and using default SUSTAIN values for capital and maintenance costs, 1st order pollutant lost rates, and BMP parameters (U.S. EPA, 2009).
    b. Riparian buffers are forested areas that border water bodies and provide benefits such as pollutant removal and reduction in runoff to streams and lakes (Klapproth and Johnson, 2009). We used the Riparian Analysis Toolbox, an ArcGIS add-on, to identify riparian areas for potential conservation or restoration, as well as the upland zones that produce runoff and loadings to downslope riparian segments (Baker and Van Appledorn, 2010). This tool has been modified to delineate 30m buffers using fine-resolution National Hydrography Dataset Plus version 2 and 10m digital elevation models. Output from this tool is used to rank riparian segments by up-gradient loads and then categorize these segments into high, medium, and low relative load groups. For either restoration or conservation scenarios, each relative load riparian group is assigned pollutant load adjustment efficiencies in WMOST, as well as capital and maintenance costs. WMOST models riparian areas as a binary decision where it can only choose all or none of the riparian area in a specific HRU and relative load group to restore or conserve.
        - In the Wading – Threemile basin there is approximately 190.6 hectares of riparian area that could be restored to forested area.

3. Water Use and Demand Management
    a. Potable water demand is categorized by users within the watershed such as; unaccounted water (leaks), residential, residential institutions, commercial, agricultural, industrial, municipal, or other. There are several data sources for water demand information such as the United States Geological Survey (USGS) county level data or town water use information.

    - Massachusetts requires towns to report water use information through Annual Statistic Reports (ASR). These reports include monthly water demand, groundwater or surface water withdrawals by pumping station, and interbasin transfer of water to or from other towns. This model included wastewater nitrogen loadings associated with residential users based on 2010 CENSUS and 2.66 kg/capita/day of nitrogen produced (U.S. EPA and MA EOAE, 1991).
  b. Potential non-potable water use such as outdoor irrigation and toilet flushing is accounted for by assigning a maximum percentage of demand to non-potable uses and recalculating total potable use.
    - The default maximum non-potable use for all users is 45% and average non-potable seasonality values were derived from the Massachusetts Water Management Act.
  c. Septic systems on public water and discharging outside of the basin do not recharge groundwater and do not contribute to baseflow within the watershed; thus, accounting for septic systems discharging inside or outside of the basin is necessary (Detenbeck et al., 2018b).
    - Based on utility boundaries for sewered and nonsewered areas and CENSUS population estimates, 62% of public water users have septic systems within the Wading – Threemile watershed. Septic systems also discharge nutrients to groundwater systems. A default value was provided for daily average septic effluent concentrations and then adjusted as part of the calibration process as needed.

4. Water Supply Sources and Infrastructure
  a. Surface Water System:
    - The maximum storage volume of the most downstream lake in the basin, Sheppard's Factory Pond, was obtained from a database of modeled lake morphology for the Northeastern U.S. (Hollister et al., 2011). Surface water withdrawals were derived from ASR pumping information. Surface water pollutant discharges were calculated from point sources, from EPA's Discharge Monitoring Database (DMR; https://echo.epa.gov) of monthly flow and pollutant concentration values. Calibrated values include an initial lake volume with minimum and maximum bounds, as well as initial pollutant concentration and 1st order loss rates for nitrogen.
  b. Groundwater:
    - The maximum groundwater storage volume was estimated from aquifer information. Initial and minimum groundwater volumes were established during calibration. ASR reports supplied groundwater withdrawals from pumping wells. Groundwater discharges included septic systems discharging inside the basin but receiving public water supplies from outside the basin, and other private discharges. Private well withdrawals were also incorporated within the basin. Calibrated values and time series included the groundwater recession coefficient, groundwater pollutant discharge time series (due to uncertainties in source data), initial pollutant concentration, and discharge loss rates.
  c. Interbasin Transfer of water and wastewater:
    - Towns across New England often sell or buy water from other towns to account for surplus or deficiencies within a respective town. Interbasin transfer of water or wastewater with the associated costs were derived from ASRs.
  d. Water Infrastructure: Infrastructure components such as: facility capacity, costs, pollutant effluent, management data for water treatment plants (WTP), potable distribution system, and the wastewater treatment plant (WWTP). Data were obtained from utility websites and regional data.
  e. Measured streamflow data was obtained at the outlet of the watershed from the USGS gauge 01109060 on Threemile River near North Dighton, MA. Monitoring data were very limited; thus, measured pollutant concentration values were calculated from 2002 SPARROW (Spatially Referenced Regressions on Watershed attributes) modeled total yearly load at the outlet of the river. These measured values were used to calibrate the model.

2.2 NEOS Online Server

After required data is entered into WMOST spreadsheets, WMOST creates optimization files for use with the NEOS online server (https://neos-server.org/neos/). NEOS is a free numerical optimization program service. For WMOST, users have the option to choose between two non-linear algorithms that are part of the Basic Open-source Nonlinear Mixed Integer program (Bonmin) (Bonami et al., 2008). The optimization set-up files are then uploaded to the NEOS server to run on the online servers to terminate at an optimal solution and results are returned showing if a model reaches an optimal solution successfully or if there was an infeasibility within the model. Infeasibilities occur in the model for several reasons, such as inability to meet target constraints, the model could run out of water if demand and withdrawals information is not accurate, or inaccurate starting values.

2.3 Calibration

The calibration period for the Wading – Threemile case study was 2002-2006 which includes both a relatively dry year (2002) and a wet year (2005). At the local climatological rain gauge (WBAN14765), the median yearly precipitation between 1960 and 2014 was 113.74cm, where 2002 and 2005 yearly precipitation was 106.81cm and 142.88cm respectfully. The modeled streamflow hydrology has a Nash-Sutcliffe Efficiency (NSE) of 0.34, R^2 of 0.50, relative percent error of 50.1%, and a median bias of 0.45 m^3/sec. The model tended to overestimate lower flows in the fall months and underestimate larger flows in the spring months. The modeled baseflow was overestimated, which could be due to inaccurate groundwater parameters in the SWMM input time series. This is an acceptable fit, given the complexity of real-world conditions, the lack of measured water quality data available, and the intended use of this model for screening purposes. There was one outlier on October 15, 2005, where the model predicts a streamflow of 101 m^3/sec and the measured streamflow is 26 m^3/sec.

After the model was calibrated to the best fit possible, WMOST was run to assess trade-offs between use of structural BMPs and riparian buffer restoration to reduce NPS nitrogen by 20%. While the downstream Mt. Hope Bay within the Narragansett Bay estuary does not yet have an established Total Maximum Daily Load (TMDL) for nitrogen, permits for wastewater treatment plants in the Taunton watershed refer to regional goals for reducing NPS nitrogen by 20%, so we adopted this as a target for the current case study. We conducted a progression of optimization runs described as follows:

I. The first optimization run considered nine different BMPs of equal design depths (5.08cm) to determine which BMP was most cost-effective for meeting the nitrogen load reduction target.
II. For the BMP identified in (I), two additional design depths (2.54cm and 1.5cm) were considered in a second optimization to narrow in on a cost-effective depth given that across New England, smaller sized storms are more frequent. The median storm event between 1960 – 2014 was 0.41cm and 80% of all daily precipitation events were 1.5cm or smaller (NCDC Local Climatological Data, WBAN14765).
III. The third optimization considered only riparian buffer restoration.
IV. The fourth optimization considered a combination of riparian buffer restoration and the BMP identified in (I) with the design depth identified in (II).
V. Model runs III-IV were repeated for a wetter year, 2005, to assess the effect of weather variability on the robustness of management decisions.

3 Discussion and Results

Of the nine BMPs modeled with 5.08cm design depths, WMOST identified infiltration basins as the most cost-effective structural BMP to meet the nitrogen load reduction target. Thus, infiltration basins with design depths of 2.54cm and 1.5cm were also modeled. Of these options, infiltrations basins with design depths of 1.5cm were determined to be the most cost-effective. Baseline scenario runs were compared to model runs with management options that implemented 1.5cm infiltration basins across developed HRU classes, implemented restoration of developed and agriculture riparian areas, or implemented a combination of the two management options (Table 1).

Table 1. Optimization results for Wading - Threemile River basin with a least cost objective and imposed constraint of 20% annual nitrogen load reduction for the dry year of 2002 and wet year of 2005. The *italics* text refers to results for 1.5cm infiltration basins and the **bold** text refers to riparian buffer restoration

Year	Model Run	Max Daily Load (kg)	Annual Load (kg)	Daily Reduction (%)	Implementation/ Restoration (Hectares)	Total Cost (Millions $)
2005 (wet)	Baseline	2625	85,503	--	--	2.255
	1.5 cm Infiltration Basin (II)	2100	82,952	20	*1374*	2.648
	Riparian Buffer Restoration (III)	2346	78,559	11	**191**	3.939
	1.5 cm Infiltration Basin + **Riparian Buffer Restoration (IV)**	2100	82,952	20	*1374*	2.648
2002 (dry)	Baseline	655	73,567	--	--	2.261
	1.5 cm Infiltration Basin (II)	524	67,331	20	*440*	4.164
	Riparian Buffer Restoration (III)	524	67,030	20	**111**	3.223
	1.5 cm Infiltration Basin + **Riparian Buffer Restoration (IV)**	524	67,106	20	*37* + **106**	3.271

The baseline scenario for 2002 with no target nitrogen constraint had a maximum daily load of 655 kg N and a total annual load of 73,567 kg N, at a total cost of $2.261 million for existing management practices to supply water demand and wastewater treatment needs. These included costs to operate and maintain the WTP, WWTP, pumping to meet demand, and the interbasin transfer of water and wastewater. The optimization with 1.5cm infiltration basins treated stormwater runoff from 440 hectares of the commercial/till HRU to produce an annual load of 67,331 kg N at a total cost of $4.164 million. Infiltration basins were implemented on an HRU with a large percent effective imperviousness because by treating this HRU with a BMP, the reduction in load would be larger than other HRUs with less impervious area. The next optimization (III) restored 111 hectares of riparian area with high and medium loads, producing an annual load of 67,030 kg N at a total cost of $3.223 million. This was the least cost management option to reduce nitrogen loads during 2002. The combination optimization (IV) with an upper limit of 20 hectares treated by infiltration basins on a single HRU, modeled 20 hectares treated with infiltration basins on low density-residential/till and 17 hectares treated of commercial/till, and 106 hectares of riparian restoration to forested area, with an annual load of 67,106 kg N at a total cost of $3.271 million.

The baseline scenario for 2005 with no target constraint had a maximum daily load of 2625 kg N and an annual load of 85,503 kg N, at a total cost of $2.255 million. 2005 was an overall wet year which also included a major tropical storm on October 15, 2005, which had large influence on the results for the wet year. The optimization with 1.5cm infiltration basins treated 1374 hectares of open/till and low-density residential/till HRUs with an annual load of 82,952 kg N at a total cost of $2.648 million. Compared to 2002 results, the solver implemented on cheaper HRUs with less impervious area, although 2005 results implemented more acres treated with infiltration basins. Restoring all riparian area to forested area was not effective in reaching the 20% load reduction for nitrogen, because of the large maximum daily load associated with the tropical storm. The combination optimization indicated that the cheapest and most effective option to implement was low cost infiltration basins on HRUs with less impervious area.

Overall conclusions to reduce non-point source nitrogen are described below:

- Infiltration basins with smaller design depths are the most cost effective structural BMP
- Riparian buffers are generally more cost-effective at reducing annual nitrogen loads than infiltration basins but alone provide insufficient treatment capacity during wet years
- Infiltration basins are generally more effective at reducing large daily loads than riparian buffer restoration during wet periods
- With a changing climate the magnitude, frequency, and duration of wet and dry periods will increase (IPCC, 2014). Preliminary results indicate that a combination of management practices would be best suited to handle the variation of future climatic conditions. These results could vary in different climatic regions and under future scenarios

4 Limitations and Future Work

WMOST is a decision support tool to aid water managers in finding solutions to complex water quantity and quality issues. WMOST is meant to provide users with tangible results to incorporate in future grants and give stakeholders the opportunity to present the benefits of different management options.

One limitation of WMOST is that it’s a single objective optimization model, where targets or goals can only be modeled as constraints or as one objective. For example, by setting a goal to reduce nitrogen as a constraint, the model can only produce one solution. To provide more flexibility in exploring options, a multi-objective version of WMOST is in development, which would allow a user to analyse decisions with objectives that minimize cost and minimize the pollutant load simultaneously (Piscopo et al., 2018). This gives users the ability to observe solutions across a tradeoff curve, which enables stakeholders to make more informed decisions within a watershed.

In addition to improving the capabilities of WMOST, this case study will be expanded. We will assess additional management options and targets such as enhancing groundwater recharge and reducing flooding across different climate scenarios. We will also model and assess the effect of different climate scenarios and future development projections on water quality and quantity within the basin.

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