Adaptive Management and Effective Implementation of Sediment TMDLs in the Lake Tahoe Basin, USA

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Abstract

Sediment is a common pollutant across the United States, and determinations of total maximum daily loads (TMDLs) for sediment are under development through enforcement of the Clean Water Act. In the Lake Tahoe basin, developing a TMDL for fine sediment particles (FSPs; <16 mm) is especially important as a part of efforts to improve declining lake clarity as well as to protect and restore other beneficial uses. Local regulatory agencies are crafting guidelines directed at the determination of implementable strategies that actually achieve measurable sediment load reductions. Concurrently, adaptive management (AM) in various forms is being proposed as a potential approach to achieving TMDLs or success in other projects having environmental impacts. Here, we describe an application of the AM process to the determination of daily sediment and FSP loads from an urban redevelopment project and a watershed restoration project currently underway in the Tahoe basin. Measured upland soil treatment effectiveness and measured urban stormwater quality information is used in relatively simple distributed models of runoff and sediment delivery from the two sites. Briefly, we demonstrate how monitoring can provide a critical, potentially overlooked linkage between predicted and measured sediment loads and how AM can be used to refine sediment reduction strategies to meet TMDL targets.

Introduction

Section 303(d) of the Clean Water Act requires states to establish total maximum daily loads (TMDLs) for impaired waters in an effort to restore and maintain their chemical, physical, biological, and aesthetic integrity. Perhaps the two most challenging dimensions of the TMDL process are (a) the establishment of scientifically credible water quality standards necessary to protect beneficial uses, fisheries, and riparian habitat and (b) the development of proven stormwater best management practices (BMPs) that achieve the load reductions deemed necessary to meet the targeted water quality goals. Herein, we focus on the latter challenge applied to the Lake Tahoe basin, where an effort is underway to develop a TMDL crediting and tracking program designed to assist implementers in achieving the sediment and fine sediment particle (FSP; < 16 mm) load reductions desired to restore the famed clarity of Lake Tahoe. FSPs in the Lake Tahoe basin are of particular concern because of their light-scattering effects while in suspension and their propensity to transport nutrients (e.g., total phosphorus).

TMDL implementation programs vary widely, but because of hydrologic variability and system complexity, hydrologic models are often used to predict possible load reductions associated with the different load reduction methods deployed. However, after the generation of model predictions and project implementation, robust follow-up monitoring to evaluate project effectiveness—or whether anticipated load reductions were actually achieved—may be lacking. Without such monitoring, TMDL credits granted for the project cannot be verified.

Every TMDL program is faced with the task of linking the performance of site-specific stormwater BMPs and erosion control BMPs (e.g., straw sediment basins or vaults, disturbed soils restoration, or bioswales) to local site- or watershed-scale daily load reductions such that regulatory agencies can apply the proper TMDL credits. For sediment or FSP TMDLs, this is especially difficult since the quantitative factors controlling soil erosion and hydrologic processes—as well as changes associated with treatment efforts necessary for the credible prediction of streamflows and loads—may be unavailable, or inadequately quantified. Because urban stormwater is more readily collected and likely represents one of the greatest opportunities to resolve the lake clarity problem, Nevada Division of Environmental Protection (NDEP) and the Lahontan Regional Water Quality Control Board (Lahontan Board) developed the Lake Clarity Crediting program. One core piece of this program is the Pollutant Load Reduction Model that can be used to estimate average annual decreased sediment loads associated with various BMPs deployed by local entities to obtain "clarity credits" towards meeting TMDL goals. Several rapid assessment tools have been developed to annually assess the condition of specific treatment BMPs as a proxy for BMP performance or load reduction effectiveness. These annual condition assessments for specific BMPs determine the number of clarity credits awarded for a project each year. Many explicit assumptions built into the Lake Clarity Crediting Program provide opportunities for hypothesis testing and the use of applied adaptive management (AM) in the TMDL program.

While we have measured soil restoration or treatment effectiveness at the plot (1 m^2) and, to a lesser extent, hillslope (1 ha) scales in the Tahoe basin, these results are difficult to link directly to watershed-scale sediment-loading response without appropriate scaling (Grismer et al. 2008; Grismer, forthcoming [a]). Moreover, changes in daily loads are very difficult to attribute to specific land use conditions or treatment actions across the watershed because treated areas are often small relative to the overall watershed, and in-stream channel sediment transport variability can be large. Similarly, in urban settings, researchers often do not evaluate the performance of stormwater treatment *trains* (i.e., the use of BMPs in series) in terms of actual daily or annual sediment load reductions following implementation. In both cases, modeling efforts are required to organize the information, predict future performance (load reductions), and form testable hypotheses after project implementation. In practice, however, researchers often do not verify some of the model's critical assumptions and/or hydrologic and erosion factors with direct field measurements.

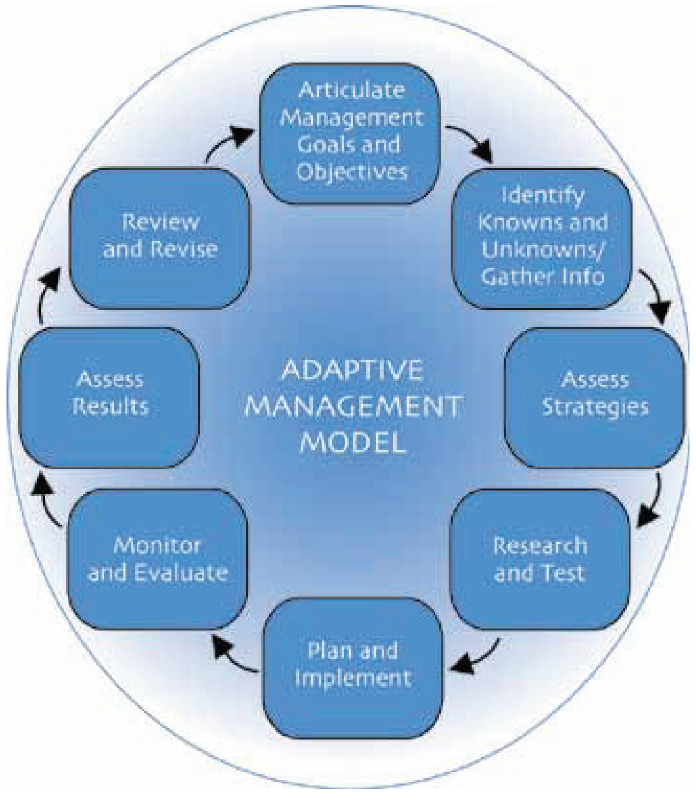

Figure 1. Illustration of the AM cycle as it may be applied to TMDL projects..

Nowhere is this observation truer than at Lake Tahoe, a subalpine lake whose basin straddles the border of California and Nevada in the Sierra Nevada. The lake is losing its famed clarity because of excess FSP and nutrient loading. Based on modeled estimates of historic lake loading rates, the NDEP and Lahontan Board have indicated that a 65% decrease in FSP loads will be needed to restore lake clarity (California Water Boards and Nevada Division of Environmental Protection, 2008). The Lake Tahoe TMDL program has also set an interim (20-year) transparency goal that will require a 32% reduction in FSP loads (California Water Boards and Nevada Division of Environmental Protection, 2010). We are in the process of evaluating critical assumptions about the sources and magnitudes of FSP loads and the load reduction effectiveness of various treatment approaches in the current TMDL program.

AM represents a promising framework for testing modeling assumptions and BMP effectiveness, addressing information gaps, and supporting effective TMDL implementation in conditions of substantial uncertainty, while simultaneously implementing these strategies to begin load reductions. The use of AM as a resource management technique began in the 1970s (Holling 1978), with various definitions evolving in the literature (e.g., Walters 1986; Parma et al. 1998; Shea et al. 1998; Callicott et al. 1999). Perhaps one of the most notable applications of AM was related to the successful maintenance of fisheries stocks in the Pacific Northwest (Gunderson, 1999).

Though definitions vary, the basic AM concepts remain simple and appealing (see Figure 1). AM begins with a clarification of goals and objectives, followed by the incorporation of all stakeholder and other available knowledge as well as the identification of knowledge gaps. Recognizing the information shortcomings, AM suggests the development of a project plan that includes monitoring designed to advance the information needed both to improve future modeling and implementation and to determine the relative success of the current implementation. Project goals and objectives (e.g., TMDL targets or fish stock quantities) are translated into measurable success criteria, which serve as triggers for possible corrective management actions (determined *a priori*) or project reevaluation. Success criteria and management responses are viewed not only as

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a means to achieve the initial objectives, but also as a process for learning more about the system(s) being managed and thereby improving future treatment efforts. Monitoring and development of applicable (quantitative) knowledge is included in project costs and is an inherent objective and foundational element of AM (Elzinga et al. 1998). In other words, the AM process represents a paradigm shift toward hypothesis-driven approaches in which initial outcomes affect future management actions and away from those that limit future inquiry by deploying unverified "solutions" on the basis of an assumed outcome.

To address the challenges inherent to both the determination and the implementation of sediment TMDLs, we advocate use of the AM model (see Hogan and Drake 2009, for sediment source control) for developing and evaluating load reduction methods at the project scale in the Tahoe basin. Herein, we follow the AM approach in describing two case studies, reflecting restoration projects currently underway, to discuss how monitoring can be used to help set TMDLs, evaluate relative success in achieving load reductions, and provide information that can guide the improvement of sediment reduction strategies and hydrologic model predictions.

Adaptive Management Case Studies: Modeling Approach and Linkage to Future Monitoring

Our objectives in this section are to: (a) demonstrate the use of a modeling approach that is based on several years of data collection to predict daily sediment loads and possible reductions from the Boulder Bay (BB) urban redevelopment area on Lake Tahoe's north shore and the Homewood Creek (HMR) watershed on the lake's west shore and (b) illustrate how AM can be applied on a site or program scale to measure, track, and support more effective implementation of sediment TMDLs. We will incorporate the modeling results from both projects into a field-based assessment whereby predictions are treated as hypotheses as well as targets for performance monitoring.

Part of the basic information needs in the AM process is the determination of existing and proposed land use type areas and related hydrologic conditions necessary for modeling. By way of example, Tables 1 and 2 summarize the pertinent land use information for the BB and HMR project areas, respectively. The largely forested HMR project involves the restoration of dirt roads and degraded ski runs, while the BB project involves the redevelopment and restoration of a combined impervious and degraded building site to be converted into a park area.

Table 1. Boulder Bay project area land uses (6.58 ha total on granitic soils)

LSPC Land Use	Area (m2)	Percentage of Project
Utility—Pervious	3,948	6.0
Utility— Impervious	30,270	46.0
Roads—Paved	9,344	14.2
Park	22,259	33.8

Note: LSPC, Loading Simulation Program in C++.

Table 2. Homewood Creek watershed characteristics and land uses (260.9 ha total, 89% volcanic soils).

Land Use Category	Area (m2)	Percentage of Basin	Slope (%)
Utility—Pervious	7,082	0.45	10.6
Utility—Impervious	4,768		17.9
Paved Roads	15,013	0.57	18.5
Dirt Roads	84,497	3.24	49.3
Ski Areas	439,173	21.2	49.6
Forests	19,130,000	73.3	47.3
Residential Areas	31,451	1.21	14.0

The modeling of watershed or stormwater runoff processes facilitates the organization of quantitative knowledge, the ready identification of information shortcomings, and the development of testable predictions. As suggested by Merritt et al. (2003), to inform land management decisions based on load (sediment and nutrient) allocations for the HMR watershed case study, we employed the US Environmental Protection Agency (USEPA) semi-distributed watershed model, Loading Simulation Program in C++ (LSPC; California Water Boards and Nevada Division of Environmental Protection 2008). Using annualized averaging from the 1994–2005 water year (WY) period, we first used LSPC to estimate appropriate TMDLs for each of the 182 catchments composing the Lake Tahoe basin. With precipitation (rain or snow) as the input driver and land use, soils, slope, and drainage channel network as the playing field, the model explicitly integrates the simulation of land and soil contaminant runoff with instream processes. That is, from the perspective of land allocation of sediment and nutrient loading, LSPC enables the linkage of instream water quality directly to point and nonpoint source loads.

We applied the LSPC model on a daily (rather than annualized) basis to determine the daily sediment loads for HMR based on the different land uses and associated runoff-dependent, upscaled sediment yield functions. These functions relate sediment load per unit runoff to soil type, slope, and FSP fraction at the 1-m^2 scale; we determined them from adaptively managed field rainfall simulation (RS) tests of progressively modified soil restoration strategies (Grismer and Hogan 2004, 2005a, 2005b; Grismer et al. 2008, 2009) across the basin. Use of the sediment yield functions reduced parameterization concerns because a daily time-step is deployed, upscaling factors were small, and plot-wise variability is averaged across the hillslope to watershed scales (Grismer, forthcoming [a]). For example, in the HMR watershed, the upscaling multiplier for 1 mm of runoff is 0.1917, indicating that RS plot-scale loads were approximately five times that needed to represent the watershed sediment loading.

A similar, though simpler, approach was used to model daily runoff and sediment loads from BB. For BB, the site drainage design routes all stormwater runoff after filling limited storage in low-impact development (LID) approaches, such as green roof and pervious pavement technologies, into tanks, infiltration galleries, and detention basins. In this case, the best available land use–dependent sediment yield information was determined from a recent stormwater runoff monitoring study (Heyvaert et al. 2008) at the existing site; we then used this information for the proposed BB project area.

Modeling uncertainties in both cases reflected a lack of field-derived knowledge of the actual performance of the various BMP, LID, or soil restoration strategies at the site or watershed scales. At HMR, uncertainty remains about the upscaling factors estimated from modeling comparisons with streamflow and loading data; these factors require further verification, which is currently underway. Similarly, at the BB site, factors that remain uncertain include the actual post-project BMP, LID, and soil restoration sediment yields as well as the performance parameters of the tanks, detention basins, and infiltration galleries with respect to sediment and FSP removal at the site scale.

AM Hypothesis Testing

Our approach to evaluating the successful achievement of TMDL targets (e.g., the overall 65% FSP load reduction at Tahoe) involves a determination of daily accumulated sediment loads from dry and wet year hydrology under existing and proposed project conditions followed by a reanalysis of this loading after project implementation (e.g., soil restoration and/or the installation of stormwater BMPs) and subsequent comparison. Though the original system designs were based in part on standard engineering design storms, the use of actual precipitation data to determine sediment loads enables (a) the incorporation of changing soil moisture conditions resulting from successive storms rather than a simple evaluation of possible loads from a single design storm, (b) load determination for actual runoff events that are likely to recur such that post-implementation performance can be evaluated, and (c) the determination of accumulated annual loading for the watershed or project area such that targeted reductions can be identified or determined for downstream water bodies.

Treating model predictions as hypotheses to be tested is a critical step toward developing an accurate understanding of actual treatment outcome

With the pre-project predicted and post-project measured accumulated load comparisons, we will test several hypotheses of concern to TMDL crediting; the specific hypotheses to be tested will continue to evolve as outlet (HMR, or BB site drainage culverts) monitoring data are developed. Possible hypotheses to be tested include the following:

- How critical is antecedent moisture (soil or rain) toward the evaluation of infiltration-type stormwater treatment performance?
- Must a minimum antecedent moisture threshold be exceeded prior to sediment discharge from infiltration-type systems?
- Are sediment and FSP removal rates in all systems rain intensity–dependent?
- Does upslope soil restoration actually increase site- or watershed-scale infiltration capacity and FSP capture while decreasing sediment yields from treated areas?

We underscore that the paradigm shift toward inquiry in the AM process is somewhat similar to the design, build, and testing process common to engineering practice. For stormwater runoff, real reductions in sediment, FSP, or nutrient loads from either the urban or forested land uses rely on a reduction in surface runoff (infiltration or capture), a reduction in sediment or nutrient yields per unit of runoff (soil restoration or stormwater treatment), or a combination thereof.

In both case studies here, we consider daily loading results in the context of accumulated sediment load (kg) for an example wet (1995 WY) and dry water year (1994 WY) to illustrate how the AM approach can be used both to refine project design and to inform future monitoring results. Considering pre- and post-project sediment loads first for the BB site, Figure 2 illustrates the accumulated sediment loads determined for pre-project installation of 20-year design storm BMPs only and proposed project conditions during the 1994 and 1995 (dry and wet, respectively) water years. Based on very limited stormwater sampling, we anticipate that the FSP fraction of the sediment load will be about 90% of the total sediment load from this urban setting. Note that in Figure 2(a), the predicted sediment load from the proposed project during the dry water year is zero with only two events leading to sediment discharge from the minimum 20-year design BMPs, but considerable sediment loads from the site under current conditions are predicted. In Figure 2(b), sediment loads from current conditions are not shown as they are only slightly greater than that from the 20-year BMP design (13,300 vs. 10,060 kg/year) and far greater than the predicted project load of 2,610 kg/year. Overall, model predictions suggest that proposed project storage will be capable of containing all stormwater during low-precipitation years, and that from all but six storm events during a very wet water year. Such a conclusion will be tested with post-project monitoring and, if it is not achieved, additional treatments or BMPs will be installed to ensure that no discharge occurs during similar dry water years. In contrast, considerable sediment loading occurs under current conditions in dry and wet water years but could be contained by the 20-year BMP design in dry years and only partially contained during a very wet water year. Thus, regulators and project designers should then convene to determine whether such a "20-year" design capacity is adequate for project implementation, TMDL targets, and sufficient TMDL credits to proceed with project permitting.

For the HMR watershed, we developed sediment load graphs similar to those outlined here for the BB site (not shown). In the HMR example, we considered levels of sustained restoration efforts for the more disturbed, erodible land uses (e.g., dirt roads and ski runs) such that watershed soil functionality was improved. The RS test plot data used to develop the plot-scale sediment yield functions indicated that the FSP fraction of the sediment loads from the slightly disturbed soils of HMR are expected to range from 40% to 55% of the total compared to 90% from urban areas. However in this case, hydrologic variability casts hypothesis testing in terms of confidence levels (single-tailed *t*-distribution tests) by which streamflow and load measurements can indicate successful improvements in soil functionality that were registered at the watershed scale (Grismer, forthcoming [b]). At this point, we are measuring HMR flows and sediment concentrations during the spring snowmelt periods in 2009 and 2010, following partial watershed restoration in 2008 and 2009, as a means of determining soil restoration impacts at the watershed scale prior to full project implementation.

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Importance of Monitoring and Results Assessment to the AM Process

As described above, the AM process requires project performance monitoring after installation to test hypotheses and improve model parameters and, we hope, future implementations. In the case of Lake Tahoe, monitoring costs are largely shouldered by the developer as they are built into the permit process. Using the data in Figure 2, regulators can advise the redevelopment project as to the design level sufficient to meet TMDL goals. Moreover, if pre-project TMDL crediting for the achievement of load reductions is considered part of project implementation, monitoring should be required to verify model-predicted loads as well as possible redesign and implementation to ensure the attainment of prescribed load reductions. Similarly, in the HMR watershed, though complicated by hydrologic variability, substantial dirt road restoration (50% by area, or 1.6% of the HMR catchment) results in model-predicted reductions of mean daily sediment loads by 12–30 kg for average daily flows of 99–804 L/second (3.5–28.4 ft^3/second) in the 1994–2005 water years. Such reductions require further verification with monitoring data that are currently being collected. Other model results suggest that monitoring for specific time periods (spring snowmelt) and flowrates may enable the detection of load reductions associated with restoration in less than five years (Grismer, forthcoming [b]). At this time, proponents of both project (and local government entities, such as counties installing new stormwater treatment or BMP projects) will be committed to monitoring for several years so as to be able to include dry and wet year effects on system performance. Such monitoring information is necessary to (a) allow appropriate project crediting by the Tahoe Regional Planning Agency, the bi-state regulatory agency charged with TMDL implementation for the Lake Tahoe basin; (b) determine whether such predicted load reductions are even possible; and (c) improve the knowledge base needed for the site or watershed modeling required to estimate loads under the range of conditions found across the basin.

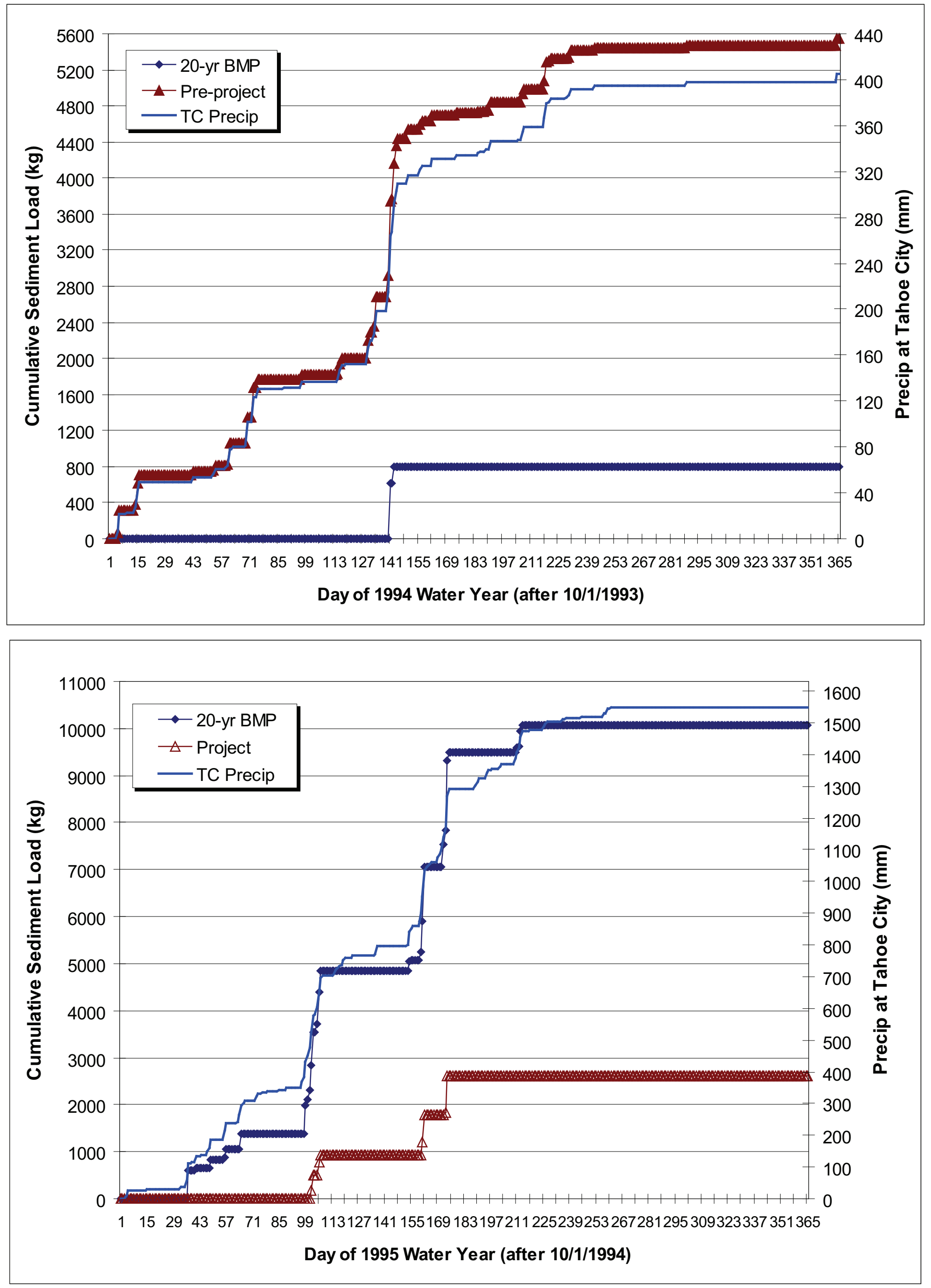

Figure 2. Predicted accumulated sediment loads from the Boulder Bay site under pre-project and 20-year BMP design (flow/load is zero under project design) in 1994 WY (a) and under 20-year BMP and project conditions in 1995 WY (b). TC, Tahoe City.

Closure

To effectively implement and accurately assess the progress and outcomes of TMDL efforts, we suggest that it is necessary to base initial modeling efforts on directly measured runoff, water quality, and climate data and to link modeling assumptions to a clearly articulated AM implementation process supported by this quantitative performance monitoring. Treating model predictions as hypotheses to be tested is a critical step toward developing an accurate understanding of actual treatment outcomes.

We have attempted to show how an AM approach and post-project performance monitoring can be used to assess actual project outcomes and refine treatment strategies. Employing such an approach provides a real-time feedback loop that will enable land managers, regulatory personnel, and other stakeholders to develop an increasing understanding of sediment and FSP reduction strategies related to TMDL crediting in the Tahoe basin. We suggest that the most cost-effective approach to TMDL implementation is based on the development of an accurate understanding of treatment and BMP effectiveness through field measurements at the project scale, rather than a reliance solely on modeled predictions. Those field measurements should be used to further calibrate and/or parameterize the models employed so that their predictive power is increased and load reduction technologies improved. This monitoring effort is included as part of the project permitting process to ensure that future monitoring costs are considered in the initial planning.

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Monroe County, New York, Field Tests the Watershed Treatment Model 2010 Beta Edition

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The Center for Watershed Protection is continually seeking to test new tools or new applications of tools and incorporate them into our watershed analysis and planning process. We also encourage partner organizations and communities to test the tools that we develop. In this issue of the Bulletin, our first brave volunteers, Andy Sansone and Paula Smith of the Monroe County Stormwater Coalition, tested the Watershed Treatment Model (WTM) in Shipbuilders Creek (SC), a small watershed draining directly to Lake Ontario. Originally released in 2003, we recently updated the WTM, and Andy and Paula have tested the revised version, referred to as the WTM 2010 beta edition. This article describes the WTM 2010 beta edition, details Paula and Andy's bold adventure, and recounts some important lessons learned.

What Is the WTM and How Can I Use It in My (Total Maximum Daily) Life?

The WTM (Caraco, 2002) is a spreadsheet-based, decision-making and pollutant-accounting tool that calculates annual runoff volumes and pollutant loads (including total suspended solids, total nitrogen, bacteria, and total phosphorus) in small watersheds. Since the WTM is a simple modeling tool (i.e., it is not physically based and it calculates on an annual basis), watershed practitioners need to consider when to apply it in a total maximum daily load (TMDL) watershed, and when other, more complex, models may be appropriate.

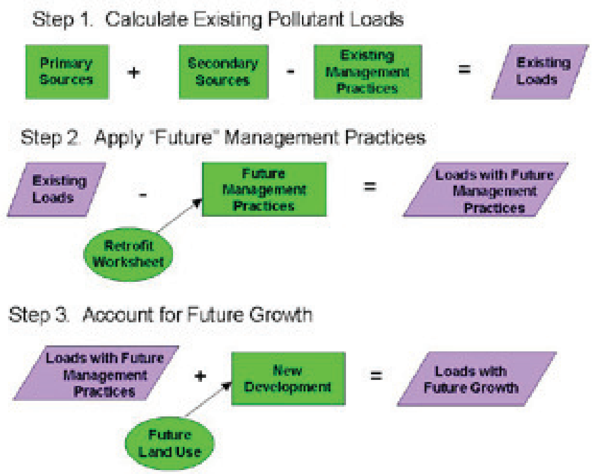

Figure 1. Model structure of the WTM. Note that the purple boxes refer to loads, including both pollutant loads and runoff volumes. The oval shapes are "support" worksheets of the WTM that provide input to another calculation sheet.

When the practices needed to meet the requirements of a TMDL will be costly or widespread, an intense modeling and monitoring effort may save money in the long term. Since the WTM is not a physically based model, it does not have the ability to produce hydrographs that reflect watershed processes and does not reflect seasonal variability. As a result, the WTM may not be the best tool for *developing* TMDLs in these cases. On the other hand, TMDLs increasingly must be developed and implemented rapidly, particularly in small urban or urbanizing watersheds where changing land use requires immediate action. In some cases, even simple surrogates, such as impervious cover (see Arnold et al., this issue), have been used to develop TMDLs. The WTM offers another alternative in these watersheds, allowing the watershed manager to focus in some detail on particular pollutants and to compare a range of treatment options quickly.

Another role for the WTM is as a *tracking tool.* Even for TMDLs that warrant more complex modeling, implementation ultimately happens at the local level. For example, the requirements of a TMDL may be integrated into a municipal separate storm sewer system (MS4) permit. With rare exceptions, local governments are facing tight budgets and need tools that they can implement with existing staff resources. Since the WTM is a spreadsheet, local government staff can maintain it and can update it over time without hiring an outside consultant. One potential application is to populate the WTM with data from an initial monitoring effort, such as pollutant loads and practice efficiencies, then use the WTM to track practice implementation over time.

Some Details about the WTM

The WTM is structured to answer three questions (Figure 1):

- What is the current pollutant load and runoff volume in

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