EVALUATION OF MODELING TOOLS FOR TMDL DEVELOPMENT AND IMPLEMENTATION

R. Muñoz–Carpena, G. Vellidis, A. Shirmohammadi, W. W. Wallender

ABSTRACT. *The Total Maximum Daily Load (TMDL) program, established by U.S. federal law, drives U.S. water quality policy and management today. Mathematical models, in combination with field monitoring data, are widely used when developing TMDLs since they can potentially save time, reduce cost, and minimize the need for experimentally evaluating management alternatives. This article introduces the collective effort of a multidisciplinary panel of experts to evaluate the current status of TMDL modeling technology available for the most common waterbody impairment factors, along with issues of proper model use, uncertainty of modeling results, and economic tools to optimize the selection and application of these tools for TMDL development. Each of these topics is developed in individual articles within this collection. The review indicates that the status of TMDL modeling tools for the most common stream impairments is inconsistent. Research must continue to advance our understanding of many of the processes leading to stream impairment, and to address many of the existing model limitations. Reviews of case studies within this collection of articles show that users must be better trained to improve the application of TMDL models. In some cases, lack of adequate data sets limits model development and application. Existing computer models are considered capable of simulating sediment and nutrients, lacking for dissolved oxygen, and grossly insufficient for biological indicators. Quantification of modeling uncertainty, communication to end users, and economic optimization of the results are suggested as indispensable components to improve the success of the TMDL program.*

Keywords. *Biological indicators, Computer models, Dissolved oxygen, DO, Economics, Mathematical simulation, Modeling, Nutrients, Pathogens, Sediment, TMDL, Total Maximum Daily Loads, Uncertainty, Waterbody, Water quality, Watershed.*

Water pollution derives from point (direct and identifiable pollution discharges) and nonpoint (pollution from diffuse sources caused by rainfall or snowmelt moving over and through the ground) sources. A Total Maximum Daily Load (TMDL) is defined by the U.S. Environmental Protection Agency (USEPA) as the calculated maximum amount of a pollutant that a waterbody can receive and still meet applicable state water quality standards, and an allocation of that amount to the pollutant's sources. A TMDL comprises the sum of loads from point and nonpoint sources plus a margin of safety.

The U.S. Congress mandated the TMDL program in Section 303(d) of the original Clean Water Act of 1972 and charged the USEPA and the states to develop the program. Most of the early efforts by the USEPA and states (1972–1990s) focused on controlling point sources through National Pollutant Discharge Elimination System (NPDES) permits. The USEPA did not publish any guidelines for state implementation of Section 303(d) until 1991 (USEPA, 1991 and others) despite the fact that Section 208 of the 1972 Act had acknowledged the need. Active litigation from the states has brought this program to public attention, making it the cornerstone of U.S. water quality policy today. The validity of the TMDL process was reaffirmed in 2001 after the U.S. Congress requested a committee to assess the scientific basis of reducing water pollution.

To date, close to 60,000 types of impairments have been reported by the USEPA (2006) as violating different water quality standards such as drinking, swimming, fishing, etc. The top ten causes of waterbody impairments encompass nearly 80% of the 303(d) listed waterbody segments and include: (1) pathogens (14.6% of total segments listed); (2) heavy metals (mercury 14.3% and others 8.3%); (3) nutrients (8.8%); (4) sediment (8.2%); (5) oxygen depletion (6.7%); and (6) biological impairments (habitat alteration 4.4%, temperature 4.6%, pH 4.6%, and unknown causes 4.8%). These are responsible for close to 36,000 impaired waters listed so far, for which close to 20,000 TMDLs have been approved. The number of impaired waters, however, is expected to increase substantially as additional monitoring is performed and new and revised water quality standards are adopted. The average annual cost of the TMDL program to states and the USEPA over the period 2000–2015 is estimated to be between US$900 to US$3200 million per year nationwide, of which US$63 to US$69 million per year will be invested in developing

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  ISSN 0001–2351

TMDLs, US$17 million per year in monitoring to support the TMDLs, and the rest in implementation (USEPA, 2001).

The point and nonpoint components of TMDL loads can be evaluated via monitoring and computer modeling. Although monitoring is potentially the most desirable method, its use is limited due to high cost and extreme spatial and temporal ecosystem variability. Mathematical models, in combination with field monitoring data, can potentially save time, reduce cost, and minimize the need for experimentally evaluating management alternatives. The role of mathematical models in the TMDL process was recognized early in the initial USEPA (1991) guidelines as a way "to evaluate alternative pollutant loading scenarios." The document identified three guidelines for selecting an appropriate model for calculating numerical TMDLs, i.e., the model must: (1) be applicable to the specific situation, (2) provide appropriate level of analysis, and (3) incorporate practical constraints into the selection criteria. The National Research Council's Committee to Assess the Scientific Basis of the TMDL Approach to Water Pollution Reduction (NRC, 2001) has issued specific recommendations related to the use of models in this context. First, the USEPA should promote the development of models that effectively integrate environmental stressors (or control actions) with biological responses in the watershed. Second, monitoring and data collection should be coordinated with the TMDL modeling requirements. Last, modeling (and other components of the TMDL program) must explicitly recognize and evaluate uncertainty. Reckhow (2003) further discusses the issue of model uncertainty in the TMDL process and the need to assess it in an adaptive management context in order to make better decisions and increase the chances of success of the TMDL program.

In October 2005, a panel of experts from USDA–CSREES Regional Project S–1004 (entitled "Development and Evaluation of TMDL Planning and Assessment Tools and Processes") discussed the application and use of mathematical models in the TMDL process. The conclusions of this meeting pointed to the need for an in–depth critical study of the current modeling practices used in the TMDL program in three main areas: the role of models, model selection, and model application. The group expressed concerns that the role and power of models is often overstated by users and developers. Model users need to acknowledge that modeling is only a component in a complex process. Model developers need to better clarify the proper use and limitations of their models in the user documentation to prevent misuse or abuse of these tools. Although in general terms models are better at simulating relative changes in a watershed, the panel found that they are often used as absolute value predictors. The S–1004 group accepted that although the merging of geographical information systems (GIS) with mathematical process–based models has made model application to watersheds easier, most models are based on "old" science even though improved technology exists.

Regarding model selection, the S–1004 experts found that although model selection should be objective–dependent and specific to each case, often this is not the case. The selection of the model should be part of an adaptive management process and subject to revision as more information is developed for each TMDL–specific study. Model selection is sometimes limited due to low expectations that can impede model development. It was also pointed out that often the "free market" does not select the best model for a specific application, but often the endorsement of models by public agencies increases the chances of the model being used. The selection and application of different models in the same study was recommended as a means to assess uncertainty in the TMDL results. The panel recommended that the terms "more accurate" and "less accurate" be preferred over "complex" and "simple" models, since the latter can be misleading. The additional effort involved in selecting and applying a more detailed and potentially more accurate model can be cost–effective for TMDLs.

In spite of existing recommendations, model application was considered lacking, and it is advised that quality control for TMDL modeling match that of monitoring standards. The committee pointed out that although graphical user interfaces (GUIs) can help the user in selecting proper parameter values and processing results efficiently, they can also lead to a greater misuse of models since they allow potentially less qualified users to use the models. Issues related to temporal and spatial scales of model inputs are important and often not handled properly, especially when scales differ between calibration or evaluation and application. Although sensitivity analysis is useful in selecting proper parameters and models, and model uncertainty analysis provides much–needed assessment of results, these analyses are rarely used in most TMDL applications to date. It is suggested that sensitivity and uncertainty analysis be formally quantified in all TMDL modeling efforts. Finally, modelers were urged to synthesize modeling results for policy makers in a useful format.

Given the interest of this topic to a wider audience, since in fact TMDLs are currently driving U.S. water quality policy and management, the S–1004 Project participants agreed to prepare a collection of technical articles on the topic of modeling tools used in the assessment and implementation of TMDLs. The objective of the collection presented here is to provide a critical review of the models and modeling techniques currently used to simulate the most common waterbody impairment factors, and emphasize the current strengths and limitations of the existing models. A discussion of the uncertainty and economic assessment of TMDL modeling results wraps up the collection.

Content of the TMDL Modeling Collection

The TMDL collection contained in the companion technical articles is the product of the collective effort of a multidisciplinary team of 42 engineers, scientists, economists, regulators, managers, and consultants. Eighteen institutions (universities, state and federal agencies, and industry) from 18 different states in the U.S. and abroad have collaborated in this effort. The collection is divided into two distinct groups of articles (fig. 1). The first group of four articles reviews models and modeling techniques currently used to simulate the most common waterbody impairment factors reported by the USEPA (2006), with the exception of heavy metals. These factors are sediment and nutrients (Borah et al., 2006), pathogens (Benham et al., 2006), dissolved oxygen (Vellidis et al., 2006), and biological indicators (Yagow et al., 2006). The second group of articles discusses the assessment of modeling results from an uncertainty perspective (Shirmohammadi et al., 2006) and the economic evaluation of these results to optimize the TMDL selection and application (Bosch et al., 2006).

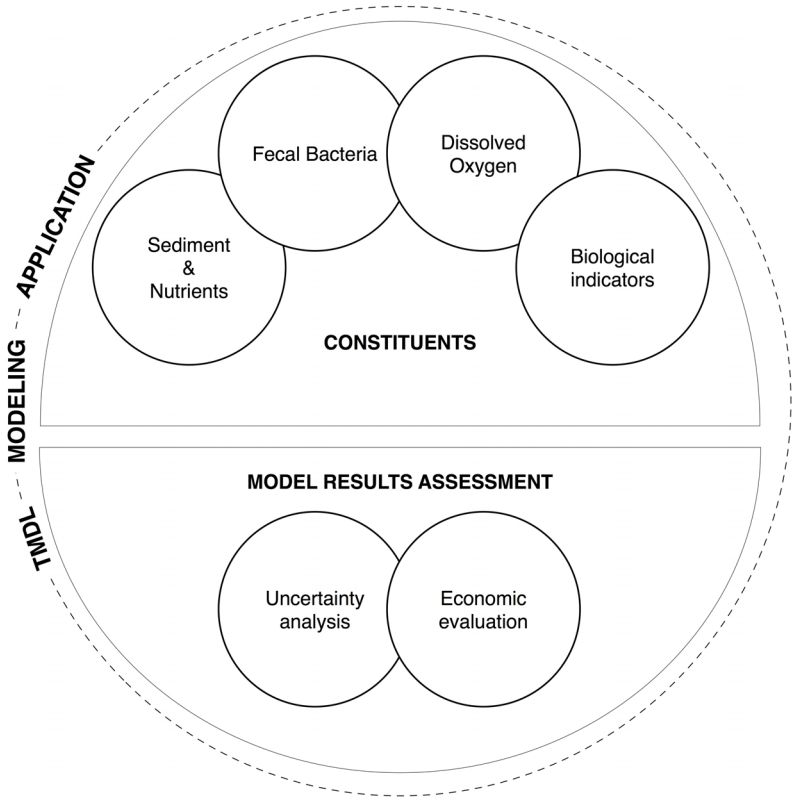

Figure 1. The TMDL modeling application.

Constituents

A detailed discussion on the status of TMDL modeling of sediment and nutrients is presented by Borah et al. (2006). The authors review 17 different water quality models classified according to their intended use, i.e.: (1) estimation of source loading inputs, (2) evaluation of receiving water quality, (3) establishment of load allocations in the watershed, and (4) design and implementation of BMPs. A desirable list of model characteristics is suggested for sediment and nutrient TMDL studies, including that the model: (1) be watershed−based, (2) run on a continuous−simulation basis, (3) provide adequate pollutant source representation (i.e., point source and nonpoint sources, surface and ground waters, dissolved and particulate components), and (4) represent the major watershed and land use characteristics that influence the pollutant(s) of concern. The uneven application of models for these pollutants to date is showcased in the discussion of two recent TMDL applications for nutrient−impaired watersheds. Major differences were found in the TMDL (loads vs. concentrations), model calibration requirements, and the role of the model as presented in the TMDL reports (explicit vs. implicit, load quantification vs. study of alternatives). Several model development needs were identified. Developers must provide improved user support and documentation, and focus on physically based models vs. some of the empirically based algorithms commonly used today. Some of the common components needed (or requiring improvement) in these models are: debris flow, stream bank erosion, BMP simulation, and improvements in the model user interfaces. User training and understanding of model limitations is deemed essential, as is the need to use models in conjunction with other local data sources and expertise to achieve good TMDL outcomes.

Benham et al. (2006) present an overview of the concepts, tools, and methods currently used to develop bacteria impairment TMDLs. This article focuses on the two computer models most widely used for this purpose. While both models permit spatial watershed discretization and allow temporal variations in bacteria loading, model flexibility is limited. The main limitations were found in the representation of bacterial life cycles and the ability to adequately simulate bacteria concentrations during extreme conditions. As an alternative to traditional water quality models, the load−duration method is shown to provide good representation of overall water quality and needed pathogen load reductions. However, load contributions within the watershed must be determined through inventorying, supplemental sampling, and subsequent modeling relating land use and hydrologic response to bacterial concentrations. Research needs identified for these models include improved source characterization of both animal (behavior patterns, habitat and population density, and accurate estimations of bacteria production types and variability) and human sources (reliable surveys of sewage locations and bacteria productions for different populations). Additional improvements are needed in the representation of pathogen transport and reactive processes in these models, as well as the ability to simulate catastrophic or rare events. Finally, the need to incorporate modeling tools into risk−based analysis and decision support systems is presented. In spite of these limitations, models are found to be beneficial in helping develop TMDLs and as educational tools for the watershed and source characterization process for both stakeholders and modelers.

Low dissolved oxygen (DO) levels are the most common cause of stream impairment in the southern U.S. In southern Georgia, for example, low DO is responsible for more than

90% of the listed impairments. Vellidis et al. (2006) state that one of the most daunting problems associated with developing DO TMDLs is the fact that it is sometimes not possible to distinguish between natural and anthropogenic causes of low DO. These authors reviewed 13 constituent transport or flow and constituent transport models that are used in the U.S. for simulating DO concentrations in lotic systems. Of these, four are the most widely used and are described in detail. DO modeling in streams is a complex problem since many physical, chemical, and biological sources and sinks must be considered. Despite advancements, many DO models are still not capable of simulating some of the most complex drivers of DO dynamics, partly because the scientific community does not yet fully understand these processes, and the models continue to require user−estimated inputs for these processes. Although most models rely on the Streeter−Phelps oxygen−sag curve to predict DO, it is implemented at different levels of complexity and data requirements. One limitation of this algorithm is that it was derived for point source and plug flow, conditions that are not met in most applications. In addition, basic data to test these models for specific applications is often not available or lacking at best. Because of these limitations, the authors strongly recommend that uncertainty in the DO model results be explicitly quantified in the margin of safety (MOS) of the TMDL. To overcome these limitations, future research must focus on understanding DO dynamics and creating comprehensive and easily accessible databases of DO parameters.

From a water quality modeling perspective, the major difficulty in using biological indicators for TMDL development is that these indicators generally do not establish a direct link with the pollutant(s) responsible for the impairment. Yagow et al. (2006) critically review available methods currently used for biological impairment studies. Field sampling and habitat assessment are the basic techniques used in these types of TMDLs. The metrics resulting from sampling and assessment are usually compiled into aggregated indexes. These indexes can be based on any of three main types of biological communities (algae, macroinvertebrates, and fish), and assessment of each community provides different information on the nature of the impairment. In most cases, biological indicators can provide a more responsive and broader detection of pollutants than chemical or physical monitoring. The fact that different biological communities may respond contradictorily to increases in a given pollutant complicates the interpretation and modeling of the biological indexes, but this could also be a key to strengthening the link between TMDL implementation and water quality recovery. As a result, the authors recommend that more than one biological community be sampled for better reliability, and that the USEPA and the states jointly develop guidelines or procedures for interpreting multi−community assessments. Research efforts are needed to directly link biology with specific pollutants and to improve procedures to factor lag−time into the water−quality recovery process.

Model Results Assessment

The issue of model uncertainty has important policy, regulatory, and management implications, but the source and magnitude of uncertainty and its impact on TMDL assessment have not been studied in depth. Shirmohammadi et al. (2006) review sources of uncertainty (e.g., input variability, model algorithms, model calibration data, and scale) and methods of uncertainty evaluation and strategies for communicating uncertainty in TMDL models to users. The uncertainty evaluation methods studied are: (1) first−order approximation, (2) mean value first−order reliability method, (3) Monte Carlo, (4) Latin hypercube sampling with constrained Monte Carlo, and (5) generalized likelihood uncertainty estimation). Four case studies are presented to highlight uncertainty quantification in TMDL models. Results indicate that uncertainty in TMDL models is a real issue and should be taken into consideration not only during the TMDL development phase, but also in the design of BMPs during the TMDL implementation phase. First−order error (FOE) analysis and Monte Carlo simulation (MCS) or any modified versions of these two basic methods may be used to assess uncertainty. This collective study concludes that the best method to account for uncertainty would be to develop uncertainty probability distribution functions and incorporate such uncertainties into TMDL load allocation through the margin of safety, the magnitude of which is generally selected arbitrarily at the present time. It is proposed that explicit quantification of uncertainty be made an integral part of the TMDL process. This will benefit private industry, the scientific community, regulatory agencies, and action agencies involved with TMDL development and implementation.

Bosch et al. (2006) present the role of economics in TMDL development and implementation, with special emphasis on economic underpinnings of optimal TMDLs, synthesis of economic models and tools available, case studies of applications of economic models in related water quality improvement studies, and recommendations on how economic analyses can best be integrated into multidisciplinary watershed planning efforts. The authors make the case that appropriate use of economic principles and models will benefit society. They indicate that TMDL programs can be improved by: (1) using economic analysis of costs and benefits to set and implement TMDL goals and standards, (2) using pollution targeting and trading programs to minimize costs of reducing pollution, and (3) considering multi−media impacts of pollution. The ability of economic and environmental models to estimate the benefits of pollution reduction can be improved by collecting better monitoring data on pollution levels and associated environmental damages. Collecting more data on stakeholder responses to water quality improvement programs, including TMDL programs, will improve the ability of economic models to estimate stakeholder costs of implementing TMDL programs. Extending economic and environmental models to consider multi−media impacts of pollution will assist in more accurately estimating the costs and benefits of pollution reduction. Economic models in combination with environmental models can be used to assist in pollution targeting and trading programs to minimize the costs of achieving water quality goals, while distributing costs equitably among stakeholders.

Summary and Conclusions

A collection of articles focused on a critical evaluation of current water quality modeling technology for TMDL development and application is introduced. This compilation is the result of the collective effort of a large multidisciplinary group of experts from academic, regulatory, and consulting organizations.

The outcome of this review indicates that the status of tools for assessment and implementation of TMDLs for four of the most common stream impairments is inconsistent. In spite of their limitations, nutrient, sediment, and pathogen transport models are considered suitable for current modeling efforts, although efforts to update them should continue to address their existing limitations. In addition, it is essential that users be better trained to improve the application of these models for specific combinations of pollutants and watershed conditions. Despite advancements, many DO models are still not capable of simulating some of the most complex drivers of DO dynamics, partly because the scientific community does not yet fully understand these processes, and the models continue to require user−estimated inputs for these processes. Further research is needed to understand and quantify DO processes and gather data sets for calibration and validation. Meanwhile, an explicit quantification of model uncertainty through the margin of safety in the TMDL is strongly recommended. While biological indicators are widely used to detect stream impairments, models do not currently exist that link the biology with specific pollutants. The fact that each of the biological communities responds differently to increases in a given pollutant complicates the interpretation and modeling of the biological indexes, but this also provides more information about the source of an impairment and could be key to understanding the pathways between individual pollutants and biological responses. Research is needed to link pollutant loadings and biological responses so that useful models can be developed. Quantification of modeling uncertainty, communication to end users, and economic optimization of the results are suggested as indispensable components to improve the success of the TMDL program.

The desired outcome of this collective effort is to prompt model users involved in the TMDL process to a broader, more philosophical discussion of the status of modeling capabilities and applications, and also to help other modelers, regulators, and action agencies when dealing with TMDL issues for water bodies.

Acknowledgements

This article is one of a collection of seven TMDL modeling−related articles in this volume of the *Transactions of ASABE*. These articles are a product of the multi−state USDA−CSREES Hatch Southern Region Project S−1004 "Development and Evaluation of TMDL Planning and Assessment Tools and Processes." The authors participating in the collection wish to acknowledge partial support from the USEPA (Region 5). The authors also wish to thank D. Borah, B. L. Benham, G. Yagow, D. J. Bosch, and co−authors for their leadership in developing the articles for this TMDL modeling collection. This article is dedicated to the memory of our mentor and friend Dr. John E. Parsons (1951−2005), who enriched the life of many and contributed to this and numerous other efforts in the hydrology community.

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