



Identification of Key Assumptions and Models for the Development of Total Maximum Daily Loads

Regulatory Analysis and Scientific Affairs

Publication Number 4736
November 2006

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Regulatory and Scientific Affairs

API PUBLICATION 4736
FIRST EDITION, NOVEMBER 2006

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ACKNOWLEDGMENTS

THE FOLLOWING PEOPLE ARE RECOGNIZED FOR THEIR CONTRIBUTIONS OF TIME AND EXPERTISE DURING THIS STUDY AND IN THE PREPARATION OF THIS REPORT:

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Abstract

This study identifies and reviews the most widely used, publicly available watershed and receiving water models used in total maximum daily load (TMDL) analysis. These models are the primary tool states and EPA use to establish TMDLs, the pollutant loading budgets required when a state determines that a surface water body does not achieve applicable surface water quality standards. Applicable models range from simple mass balances to highly sophisticated computer models that simulate dynamic water quality variations. Watershed models are used to predict point and nonpoint source pollutant loadings in runoff from different types of land use. Receiving water models are used to predict receiving water quality as a function of pollutant loadings and hydrologic conditions. The applicability of these models and their complexity, input data requirements, and prediction capabilities are described. The most important model input requirements for developing scientifically supported water quality simulations are identified and prioritized. In the case of watershed models, the most important variables are: (1) the physical characteristics of the watershed; (2) the land uses; and (3) the loading functions that relate pollutant loadings to land use. The key data requirements for receiving water models are: (1) the adequate characterization of hydraulics, which governs the transport of pollutants; (2) the pollutant transformation rates; and (3) the pollutant sources. The review of available TMDL models emphasizes that site-specific data must be available to calibrate and validate whichever model is selected to meet the TMDL objectives. An essential element of any TMDL is validation of water quality model predictive capability, using a field data set that is independent of the data used for model calibration. Also, a component of every TMDL should be sensitivity analyses of model predictions to allow probability analysis of uncertainty.

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Executive Summary

The American Petroleum Institute (API) commissioned this evaluation of models for developing total maximum daily loads (TMDL) as required by Section 303(d) of the Clean Water Act. TMDLs are required when a state determines that a surface water body does not achieve applicable surface water quality standards. The TMDL is designed to identify the pollutant sources causing and/or contributing to the impaired water quality, and to determine allowable point and nonpoint source pollutant loadings that will assure the water quality standard is achieved.

Water quality models are the primary tool states and EPA use to establish TMDLs. Applicable models range from simple mass balances to highly sophisticated computer models that simulate dynamic water quality variations. There are two basic categories of models used for TMDL studies: (1) watershed models, and (2) receiving water models. Watershed models are used to predict point and nonpoint source pollutant loadings in runoff from different types of land use. Receiving water models are used to predict receiving water quality as a function of pollutant loadings and hydrologic conditions. Some comprehensive models link watershed pollutant load prediction and receiving water quality effects analysis. Dynamic water quality models are available to simulate temporal variations in water quality. Ecological models are receiving water models that simulate chemical transport and transformation in aquatic food webs. Publicly available watershed and receiving water models are available for virtually every category of TMDL. Generally, a publicly available model that is well documented and has been demonstrated to generate scientifically acceptable predictions should be used for TMDLs.

The data requirements for watershed and receiving water models become increasingly demanding as the models become more complex and sophisticated. Model selection must consider the nature of the water quality impairment and the complexity of the model needed to adequately simulate the source-effect relationship. As a general rule of thumb, the entity performing the TMDL should select the least complex model that meets the TMDL objectives.

This study identifies and reviews the most widely used, publicly available watershed and receiving water models. The applicability of these models and their complexity, input data requirements, and prediction capabilities are described. The most important model input requirements for developing scientifically supported water quality simulations are identified and prioritized. In the case of watershed models, the most important variables are: (1) the physical characteristics of the watershed; (2) the land uses; and (3) the loading functions that relate pollutant loadings to land use. The key data requirements for receiving water models are: (1) the adequate characterization of hydraulics, which governs the transport of pollutants; (2) the pollutant transformation rates; and (3) the pollutant sources. Section 2 of the report summarizes the most important data for each type of watershed and water quality model described in this report.

The review of available TMDL models emphasizes that site-specific data must be available to calibrate and validate whichever model is selected to meet the TMDL objectives. An essential element of any TMDL is validation of water quality model predictive capability, using a field data set that is independent of the data used for model calibration. Also, a component of every TMDL should be sensitivity analyses of model predictions to allow probability analysis of uncertainty.

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This report is intended to provide the reader with an understanding of the use of models in the development and implementation of total maximum daily loading (TMDL) studies. The Clean Water Act (CWA, Section 303(d)) requires a TMDL when a surface water body does not achieve a surface water quality standard or designated use.¹ Regulations promulgated by the U.S.

Environmental Protection Agency (EPA) require states and tribes to perform TMDLs for all water bodies under their jurisdiction that they have identified as impaired waters pursuant to the provisions of Section 303(d)(1) of the CWA. Section 303(d)(2) requires EPA to approve or disapprove state lists of impaired waters and TMDLs developed by states to eliminate the impairments. If a TMDL is approved, the TMDL is to be incorporated into the state's continuing planning process required by Section 303(e). If EPA disapproves a state's TMDL, then EPA is required to develop the TMDL and the state must include the EPA-derived TMDL into its continuing planning process.

Water quality models, which simulate the fate and transport of pollutants, are the principal tools that are used to develop and implement a TMDL. These models are designed to be predictive tools that will allow the regulatory agency to determine the amount of reductions in pollutant loading that will be required of each contributing source in order to assure that the surface water achieves the relevant water quality criterion and/or designated use.

Because models are central to the development and implementation of TMDLs, the American Petroleum Institute (API) Clean Water Issues Task Force commissioned this review of the types of models used for TMDL studies and the assumptions underlying their development and use.

¹ Section 303(d)(1)(A) identifies these as surface waters where technology-based effluent standards promulgated pursuant to Sections 301(b)(1)(A) and (B) are not stringent enough to implement any applicable water quality standard. Such surface waters are referred to as "impaired."

Objective

This report focuses on the types of models used for TMDLs, the key assumptions underlying the models, how models are selected for specific surface waters and impairments, the data required to apply the models to a specific surface water and impairment, and how the predictive capability of the models is assessed.

EPA has published a report entitled *Compendium of Tools for Watershed Assessment and TMDL Development*.² EPA's *Compendium* provides detailed descriptions of most of the models that are included in this review. The Water Environment Research Foundation (WERF) has also published a survey and assessment of water quality models that is available as a CD-ROM.³ This API review is not intended to be a substitute for EPA's *Compendium*, other EPA guidance, the WERF assessment, and published technical references on water quality modeling. The reader should refer to the EPA compendium and WERF report for more detailed descriptions of watershed and water quality models. A list of published references on modeling is included in this report.

Scope

This review covers different types of water quality models applied to TMDLs performed to date. It also includes models recommended for, but not necessarily applied to, TMDLs. Because there are literally dozens of water quality models, both public and proprietary, this review focuses on well-documented models that are in the public domain and most commonly recommended for TMDL use. A range of model complexity is represented in this review. Models that are applicable to a wide range of surface water constituents were evaluated for this study.

This report is designed to inform users about the application of models to specific types of TMDL problems, with emphasis on assuring that predictions of water quality are as reliable and accurate as practical, given the time and resources available to conduct the TMDL. This review does not recommend any specific model for any particular application.

² EPA, 1997, *Compendium of Tools for Watershed Assessment and TMDL Development*, EPA 841-B-97-006, Office of Water, Washington, D.C.

³ WERF, 2001, *Water Quality Models: A Survey and Assessment*, Order No. D13209TC (CD-ROM), Washington, D.C.

Organization

This report is organized into the following sections:

1. Introduction;
2. Summary of TMDL modeling;
3. TMDL Fundamentals;
4. Watershed Models; and
5. Receiving Water Models.

A list of websites for downloading the publicly available models described in this report is presented at the end of the report. A list of references on TMDLs and models is also provided following the website list.

The objective of this study was to review federal, state, and regional TMDL methodologies and guidance to identify key assumptions, variables, and input data required to develop waste load allocations (WLA) for point sources and load allocations (LA) for non-point sources that, when implemented, will restore water quality in an impaired water body so that it meets applicable water quality criteria and designated uses. The review focused on the models available to federal, state, regional, and local regulatory authorities to perform TMDL studies. The term “models” is used in its broadest sense, ranging from simple desktop calculations to complex mathematical models that must be run on powerful computers.

The review is broken into 3 categories:

- (1) an overview of TMDL modeling including how models are selected and how the boundaries of the water body to be modeled are specified;
- (2) watershed models used to predict point and non-point source pollutant loadings from sub-watersheds and watershed; and
- (3) receiving water quality models that are used to predict the transport and fate of specific water quality constituents in a surface water body.

The conclusions drawn from this review are presented in this summary section.

TMDL Fundamentals

Fundamental steps in the TMDL process are: identifying water quality constituents causing the impairment, determination of the geographic boundaries, selection of the modeling approach for developing quantitative WLAs and LAs, selecting the appropriate critical hydrologic conditions, and calibrating and validating the selected model(s). The principal considerations in these steps are summarized in Table 2-1.

Table 2-1
Fundamental Requirements of TMDL Development

Consideration	Requirements
Criteria to protect designated uses (i.e., cause of impairment)	Must be numeric and for a specific constituent(s) — either a water quality standard or a causal variable
	Narrative standards (e.g., “no toxics in toxic amounts”) must be addressed with a numeric translator
	TMDLs cannot be developed until causal water quality variables are identified
Geographic boundaries	Must encompass all significant pollutant sources
	Exclusion of sub-watersheds that do not and will not contribute to impairment is cost-effective
Model selection basis	Physical characteristics of the watershed and/or water body
	Constituents to be simulated
	Temporal variation in water quality (e.g., seasonal, annual, event-related)
	Sources of pollutants
	Hydrologic regime(s) associated with impairment
	Data availability and resources to generate adequate database
	Simple model appropriate if default data must be used for many parameters
Data requirements	Field data for model calibration and validation
	Background conditions based on field data at un-impacted locations
Uncertainty analysis	Uncertainty of model predictions must be included in the TMDL
	Sensitivity analysis of key model variables must be conducted and presented

Watershed Models

Watershed models are used to simulate the entrainment of pollutants (including sediment) from ground surfaces by precipitation and subsequent surface water runoff and transport of the pollutants to surface waters. Watershed models may be used to generate inputs to receiving water quality models or may include their own receiving water modeling capability. Important considerations in the selection and use of watershed models are identified in Table 2-2.

Table 2-2
Watershed Model Selection Considerations

Consideration	Comments
Model complexity	Simple models and equations are only appropriate for screening purposes (i.e., importance of non-point sources)
	Accommodate sufficient site-specific detail for reliable cause-effect predictions
	Temporal variations in water quality to be evaluated (i.e., hourly, daily, seasonal, annual)
	Receiving water simulation capability built-in or linked?
	Evaluate required inputs for associated receiving water model(s)
Data needs	Model requirements are determined by model complexity: more complex = more data
	Data must represent full range of hydrologic conditions to be considered
	Sufficient site-specific data for model calibration and validation

Table 2-3 summarizes the most important watershed model input variables, in order of their relative importance. When using this table it should be understood that for any specific watershed and TMDL study, the relative importance of some of the variables shown in Table 2-3 to achieving the study objectives may change. Also, although they are very important variables to reliable model simulations, watershed physical characteristics and land uses are also generally the easiest variables to obtain accurate data on. Therefore, a great deal of effort is not usually required to assure that these important variables are adequately represented in a watershed model.

**Table 2-3
Key Watershed Model Variables**

Variable	Importance of Site-Specific Data	Comments
Physical characteristics — soil types, slopes, streams (1 st , 2 nd , and 3 rd order)	Essential	Physiographic characteristics of the watershed are single most important component
		Required watershed physical detail is dependent upon the model selected and the TMDL objectives
		Storm event modeling (short-term predictions of runoff) requires most detailed physiographic characterization
		Usually readily available with accurate information
		Confirm that appropriate data sources and detail are included in the model
Land use	Essential	Land uses determine the runoff rates and pollutant loadings generated the model
		Detail required is based on the model and TMDL objectives.
		Requirements and data availability for land use are similar to those of physical characteristics.
		Confirm that appropriate data sources and degree of detail are appropriate for model and objectives
Pollutant loading rates	Moderate	Empirical coefficients or factors that are used to calculate pollutant loadings as a function of land use
		Pollutant loading rates must account for antecedent rainfall-runoff events In complex models that predict runoff event loadings
		Loading rate coefficients must allow evaluation of land management practices.
Precipitation-runoff rate coefficients	Moderate	Rates are a function of land use and physical characteristics (slope, soil type)
		Must allow adjustments to represent various land management practices
		Should account for antecedent rainfall events in complex models that predict runoff event loadings
Pollutant transformation coefficients (e.g., sedimentation rates, biological or chemical removal)	Low	Typically are only important when a watershed model is linked to a receiving water model
		Transformations (physical, chemical, biological) included are based on pollutants simulated

Receiving Water Models

Receiving water models of some form will be at the heart of all TMDLs. These models will be used to predict the WLAs and LAs that are necessary to assure that an existing water quality impairment will be eliminated and that water quality and uses will be protected in the future. Therefore, selection and application of receiving water models will be one of the most important, if not the most important, aspects of TMDL development and implementation. There are a number of publicly available receiving water models that can be used for TMDLs. Any of the models reviewed for this project will give acceptable simulation results provided that the model is appropriate for the surface water body modeled and sufficient site-specific data are available for calibration and validation. Table 2-4 summarizes the principal considerations in the selection of receiving water models.

Table 2-4
Receiving Water Model Selection Considerations

Consideration	Comments
Model complexity	Need for simulating temporal variations in water quality is a fundamental consideration
	Models that simulate steady-state hydrodynamic transport of pollutants will suffice for many (most?) TMDLs
	Steady-state hydrodynamic models can simulate time-variable water quality for selected pollutants
	Dynamic modeling of hydrodynamic transport of pollutants is necessary if transient variability of water quality is important
	Linkage to watershed model is necessary if transient runoff events must be modeled
Data needs	Physical description of surface waters
	Data must represent full range of hydrologic conditions to be considered
	Time-variable hydrologic and hydraulic data are required for dynamic modeling of pollutant transport
	Sufficient site-specific data for model calibration and validation

The key variables in receiving water models are identified in Table 2-5. They are shown in approximate order of importance. However, it must be understood that the specific receiving water, target pollutants, and TMDL objectives are important determinants of the relative importance of the model variables.