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


## 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.

## Table of Contents

Page

# List of Tables

Page

# List of Figures

# 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

# Introduction Section 1

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.

# Summary of TMDL Modeling — Section 2

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 (1st, 2nd, and 3rd 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.

**Table 2-5**
**Key Receiving Water Model Variables**

| Input Variable | Importance of Site-Specific Data | Comments |
|---|---|---|
| Hydraulic characteristics — depth, cross-sectional areas, bottom slope in rivers and streams, velocities, time of travel | Essential | Hydrodynamics of a receiving water body determine the spatial (and temporal) distribution of all water quality constituents |
| | | The level of hydraulic detail required will be dependent upon the model selected and the TMDL objectives. Time-varying hydrodynamics require refined model hydraulic characteristics |
| | | Modeling of water quality constituents that are important on an annual or seasonal time frame (e.g., bioaccumulation, nutrient enrichment), does not usually require refined model hydraulic parameters |
| | | Usually one of the model variable sets with readily available, accurate information. |
| | | Confirm that appropriate data sources and detail are included in the model to model hydrodynamics |
| Pollutant transformation coefficients — biodegradation rates, volatilization rates, chemical reaction rates, sedimentation and suspension rates | Moderate | Equations and coefficients that simulate the transformation (fate) of constituents |
| | | Control the model predictions of the spatial and temporal concentrations of the constituents |
| | | Models have default coefficients for the constituents simulated |
| | | Default coefficients are rarely applicable to a specific receiving water |
| | | Site-specific transformation coefficients are established by model calibration using field data |
| Pollutant sources and loading rates | Essential | All point and nonpoint sources of TMDL target pollutants must be identified. |
| | | Locations where each point and nonpoint source enters the receiving water must be accurately identified |
| | | Loadings for each source must be accurately defined for model calibration and validation |
| | | Point source identification and data are typically readily available; non-point source data are not |
| Hydrologic inputs — flows, tides | Essential | Hydrologic inputs represent the simulation conditions that determine the “critical” condition(s) for the TMDL |
| | | Hydrology is site-specific and based on historic meteorological and stream flow records — records are usually readily available |
| | | Hydrologic inputs should be associated with a probability of occurrence (e.g., 7-day average flow with a 1-in-10 year recurrence interval). |

The objective of the TMDL is to allocate allowable pollutant loadings to point and non-point sources, thereby assuring that a surface water body complies with a water quality criterion and its designated uses. To satisfy this objective, a method is required to predict water quality resulting from pollutant loadings and the physical, chemical, and biological characteristics of the surface water body. The methodology for making such predictions is a cause-effect "model" of the surface water body. The term "model" can be interpreted broadly — a model may be as simple as a mass balance performed by hand or as complex as a multi-dimensional fate and transport model that simulates multiple interrelated water quality constituents. The simplest definition of a model is that it is a mathematical formulation of a physical, chemical, and/or biological surface water system that can be used to predict the responses (effects) of the system to an actual, assumed or predicted set of inputs (causes).

The TMDL approach assumes that specific water quality constituents with numeric values determine if a designated use is impaired, either directly as a water quality criterion (e.g., a toxicity-derived criterion for a metal) or indirectly as a causal variable (e.g., phosphorus for nutrient enrichment). States also have narrative water quality criteria such as "no toxics in toxic amounts" or "nutrients that cause nuisance growth of aquatic plants." A narrative criterion cannot be addressed by a TMDL unless and until an appropriate numerical translator for the criterion is developed by the state.[4] Most states have not developed the necessary numeric translators for their narrative criteria. This fact means that before a TMDL can be developed for a receiving water that is identified as having an impairment of a narrative criterion, causal water quality constituents that can be defined by numeric values must be identified as the first step of a TMDL.

[4] EPA's 2004 listing guidance (Office of Water, July 21, 2003) requires that states identify specific pollutants to perform TMDLs, as required by 40 *CFR* 130.7L(d), to address impairments of narrative criteria and biological criteria and any other impairment that is not specifically linked to a pollutant(s).

The Texas Commission on Environmental Quality (TCEQ)[5] has prepared an excellent description of the TMDL process, which addresses model selection, calibration, validation and application. This guidance manual is available for free in Adobe portable document format (PDF) from the TCEQ's web site at: www.tnrcc.state.tx.us/water/quality/tmdl/index.html.

### *Modeling fundamentals*

There are two general categories of water quality model that are typically used for conducting TMDLs[6]:

1. Watershed models, which typically are used to predict non-point source pollutant loadings; and
2. Receiving water models that simulate the transport and fate of water quality constituents.

Ecosystem or ecological models are a form of receiving water model that simulates the relationship between the biology of aquatic organisms and their physical and chemical environment. They can be linked to or are a functional component of a receiving water quality model, but may also be a completely separate analytical procedure that uses water quality model output data and physical system descriptions as inputs.

Both categories of models require simulation of the surface water system hydrodynamics, which is the fundamental transport mechanism for pollutants in surface water bodies. Hydrodynamics may be incorporated directly into the models or modeled separately and then used as inputs to the loading or receiving water model.

Simulation models may also be "steady-state" or "dynamic" with respect to surface water hydrology. A steady-state model simulates water quality or pollutant loadings under a set of specified, invariant hydrologic (stream flow, tides, and/or precipitation) input conditions. Historically, most receiving water modeling for constituents such as dissolved oxygen has been done with steady-state hydrologic models, with the input assumptions typically representing some form of critical hydrologic condition (e.g., low stream flow). Dynamic models simulate the varying response of water quality to variable input conditions including physical factors such as rainfall, sunlight and temperature, variable source

[5] TNRCC, June 1999, *Developing Total Maximum Daily Load Projects in Texas: A Guide for Lead Organizations*, GI-250, Austin, Texas. TCEQ was formerly called the Texas Natural Resource Conservation Commission (TNRCC).
[6] Ibid., EPA, 1997

loadings of pollutants, and variable hydrodynamics caused by tides and changes in stream flows.

There is also a distinction within the dynamic modeling approach between those model formulations that assume equilibrium conditions between phases (i.e., mass transfer resistance between solids, water, and atmosphere is negligible) and those that assume that resistance to mass transfer between phases is significant. Dynamic models that simulate changing point and non-point source loads, hydrology, and hydrodynamics and equilibrium between solid, aqueous, and atmospheric phases are acceptable for pollutants with physical and chemical properties that are consistent with this assumption. If mass transfer resistance is important for a pollutant, then a model incorporating non-equilibrium conditions should be used for water quality simulations.

Models may also be characterized as deterministic or empirical. A deterministic model uses theoretical mathematical constructions of the physical, chemical, and biological processes in a surface water to develop the cause-effect relationships that it simulates. An empirical model is a mathematical formulation that does not attempt to directly describe the underlying physical, chemical, or biological processes, but instead uses statistical methods or observed relationships to develop cause-effect relations between system inputs and outputs. It is common for deterministic models to incorporate empirical relationships for some of the internal functional relationships required to simulate receiving water quality and ecosystems. Similarly, most empirical models are based on an evaluation of the theoretical cause-effect relationships among the variables that are used as inputs and the predicted outputs. Thus, most of the models described in this report are based on a mix of deterministic and empirical relationships.

Selection of a model for a TMDL effort cannot be intelligently done until the water quality impairment is properly defined and the scope of the required effort to remedy the impairment is fully understood. Therefore, the first step in any TMDL study is to thoroughly evaluate the extent and probable causes of the impairment. This task will often include collecting additional receiving water and source data to verify that the surface water was correctly identified as impaired and to provide the data required for modeling. This preliminary evaluation should also include a review of the appropriateness and scientific foundation of the water quality criteria and designated uses that are identified as impaired.

Each state, tribe, commonwealth and territory[7] has its own unique method for designating surface waters as impaired and listing them on its CWA Section 303(d) list. EPA's 2002 and 2004 listing guidance documents[8] are designed to make the listing procedures more consistent, but the individual state listing procedures will still remain distinct. The most important distinction between state listing programs is the amount of quality-assured data upon which a state bases its listing decisions.

States that require an extensive database consisting of quality-assured field data for 303(d) listing may have sufficient data available to define the scope (geographic extent and types of sources and conditions contributing to the impairment) of the required TMDL modeling to remedy the impairment. In other states, the first step in the TMDL process may be developing and implementing a sampling program to collect the data to adequately characterize the extent of the water quality impairment (including verifying that an impairment actually exists and that the water quality criteria and designated uses are appropriate).

The geographic scope of a TMDL should encompass all portions of the upstream drainage area that contribute significant amounts of the constituent(s) that cause or contribute to the impaired water quality in the listed surface water segment. It may be practical and justified to limit the upstream drainage area included in the analysis. For example, if the constituent causing the impairment is absent, or is present in *de minimis* quantities in the water entering the impaired segment from upstream, and projections indicate that it is unlikely that future activities will contribute significant amounts of the constituent, it is acceptable to model only the impaired segment. Another way to state this condition is that if the "background" or "ambient" concentration of a constituent at a location upstream of the impaired surface water is a small fraction of the amount of the constituent that would cause or contribute to the impairment, and that background or ambient concentration is not projected to increase significantly in the future, it is acceptable to use that location as the upstream model boundary. Unless those conditions are satisfied, the upper boundary of the modeled watershed must be moved until the condition is satisfied.

Location of potentially controllable pollutant sources is also a factor in the selection of the geographical scope of the TMDL. A

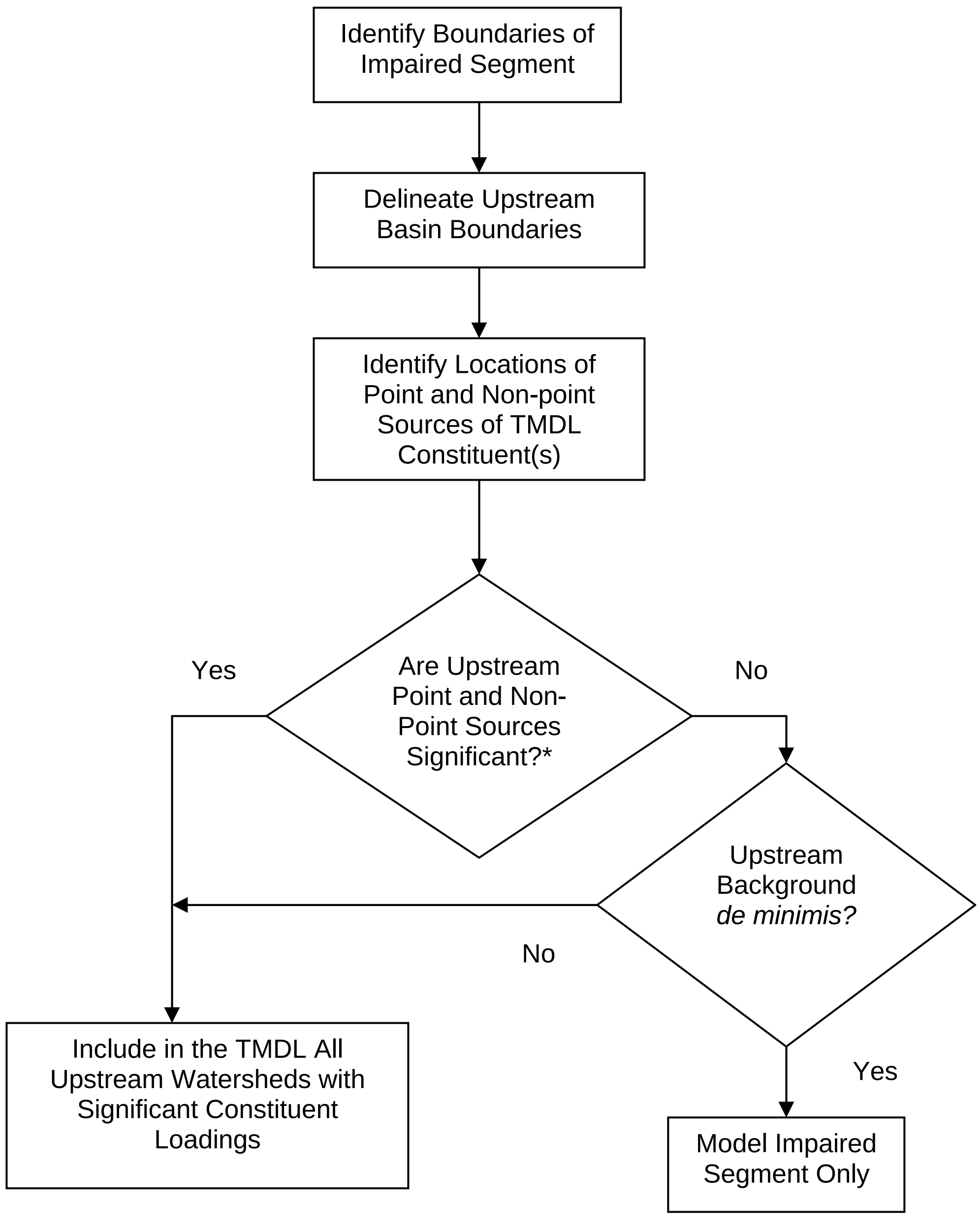
[7] The term "state" will be used herein to refer to states, tribes, territories, and commonwealths of the United States.
[8] www.epa.gov/owow/tmdl/policy.html

preliminary assessment of the sources of the constituents of concern and their location within the drainage basin of the impaired segment is a required element of the evaluation of the geographical extent of the TMDL modeling.

> Example: A river segment is designated as impaired because of low dissolved oxygen (DO) concentrations. The river and its tributaries upstream of the segment meet the DO criterion and have no major point or non-point sources of oxygen-demanding constituents that may otherwise affect downstream DO concentrations. In addition, the upstream segment is subject to Tier 2 antidegradation requirements and therefore no significant decreases in upstream DO can occur in future years. Therefore, the TMDL project team determines that the upstream boundary for the TMDL can be the upstream end of the impaired segment.

Each impaired surface water body must be evaluated based on its specific characteristics to determine the extent of the upstream drainage basin that should be included in the TMDL analysis. However, in many cases a substantial portion of the upstream drainage basin area will have to be included in the TMDL modeling of an impaired surface water. This is particularly true for water quality constituents that are contributed by both natural and anthropogenic sources, such as nutrients. The example given above is probably the exception, rather than the rule.

The factors that should go into selection of the geographic extent of the TMDL analysis are shown graphically in Figure 3-1.




*Significant in this context means a source that contributes measurably to the total pollutant loading

**Figure 3-1. Selecting the Geographic Area for the TMDL**

## *Selecting a Model*

The model or models used for a TMDL should be selected based on the following factors:

1. The water quality constituent(s) causing and/or contributing to the impairment in the listed surface water;
2. The category of constituent sources and conditions causing the impairment — point sources, non-point sources (including sediments and atmospheric deposition), physical conditions, hydrologic conditions;
3. The geographical scope of the water quality impairment and the factors believed to be causing it;
4. The public availability of a suitable model(s);
5. A successful history of past applications of the model including validation and acceptance by regulatory agencies and the public;
6. The experience of the project team that will apply the model;
7. The data available to calibrate and validate the model, and the ability (time and budget) to collect additional data if required; and
8. The time and budget allotted to the model development phase of the TMDL.

The principle that is usually followed for model selection is to select the simplest model that will meet the principal TMDL objective — to control pollutant sources to the extent necessary to eliminate the impairment. To properly apply this principle the causes and effects of the water quality impairment must be well understood. Ultimately, the selected model must be capable of predicting the water quality effects of the selected control options with sufficient accuracy to assure that the impairment is eliminated and to justify implementation of the selected controls. For some surface waters identified as impaired, the sources of pollutants causing the impairment may not be well-defined and additional field sampling and analysis will be required before a model can be selected.[9]

[9] Surface waters listed as impaired based on a narrative standard, such as those listed based on a biological assessment or toxicity measured by a whole effluent toxicity (WET) test, cannot be modeled until the causative pollutant(s) or other stressors (habitat) are identified. EPA has emphasized this principle in its 2004 listing guidance (Office of Water, July 21, 2003).

The physical, chemical, and biological factors that are principal considerations in model selection are summarized in Tables 3-1 and 3-2 for watershed models and receiving water models, respectively.

**Table 3-1**
**Watershed Model Simulation Capability**

| Ambient Characteristic | Model Capabilities |
|---|---|
| Temporal variation | Steady-state – can include multiple scenarios representing changes in hydrologic conditions |
| | Dynamic –needed when the temporal variations of water quality are significant with respect to the identified impairment |
| Pollutants simulated | Sediment |
| | Specific Nutrients (N, P) |
| | Other chemicals (e.g., specific pesticides, metals) |
| Hydrology | Runoff |
| | Base flow |
| Land use | Urban |
| | Rural |
| | Combination |
| Pollutant transport | Conservative[10] |
| | Transformations (physical, chemical, biological) |

There are several generalizations applicable to both waste load models and receiving water models:

- Dynamic models require much more input data and computational power than steady-state models.[11] The resources required to simulate a watershed or receiving waters with a dynamic model are often an order of magnitude greater than required for a steady-state model.
- Increasing model complexity results in an increased number of model parameters such as biological, physical, and chemical kinetic and mass transfer coefficients, hydrologic coefficients, and similar model parameters. In many cases these parameters cannot be directly measured and must be assigned by default or calibration with field data. This can result in a model that is more of a curve-fitting exercise than it is a true simulation of the system that it is intended to represent.
- There is often an advantage to using a model that is more complex than the minimum needed, because as future

[10] The term "conservative" when used to refer to water quality constituents means that they are assumed to not be reduced or removed from the water column by any physical, chemical, or biological reactions.
[11] This is especially true for simulation of non-equilibrium conditions, where mass transfer coefficients are required; and/or where transformations must be considered and rate constants are needed.

data become available it may be possible to improve on the model parameterization and thus on its predictive capability. However, a more complex model will not necessarily give more accurate results when input data are limited and require the use of default values and assumptions.

- The only useful simulation model is one that has been calibrated and validated[12] with field data. The calibration and validation process allows the calculation of statistical measures to determine how well the model predicts measured conditions. This statistical information is essential for determining if the model is adequate for predicting the water quality cause and effect relationships required to develop an adequate TMDL.

### *Boundary conditions (pollutant loads)*

An issue that always is present in any water quality modeling effort is how to set the model boundary conditions. Boundary conditions are the inputs to a watershed or receiving water model that originate from outside the boundaries of the system (watershed, basin) that is being modeled. Pollutant loadings or concentrations are a component of the boundary conditions of a water quality model.[13] As described in the preceding section on selection of the geographic scope of a TMDL study, the geographic area simulated should include all potentially controllable point and non-point sources of the constituents that are contributing to the impairment.[14] If this definition is adhered to, then any loadings of the target constituents entering the geographic area simulated for the TMDL should, by definition, be boundary conditions.

[12] Validation, which is called verification by some modelers, is the simulation of water quality or loading with a set of field data that is independent of the field data set(s) used for model calibration (collected as a separate sampling event with no potential for serial correlation with the calibration set). The ability of the model to predict the measured response variables from the independent event is used as a measure of the validity of the model predictions.

[13] Boundary conditions are more completely described in Section 4 of this report.

[14] The identification of potentially controllable sources will depend upon the specific pollutant and watershed being studied. At the beginning of a TMDL, it may not be possible to identify controllable sources, in which case all sources that contribute quantifiable amounts of the pollutant causing the impairment should be incorporated in the model.

**Table 3-2**
**Receiving Water Model Simulation Capability**

| Ambient Characteristic | Model Attributes |
|---|---|
| Temporal variation – hydraulics/hydrology | Steady-state – can include multiple scenarios representing changes in meteorological conditions |
| | Dynamic – typically needed when the temporal variations of water quality are significant with respect to impairment |
| Temporal variation – water quality parameters | Steady-state |
| | Dynamic |
| Pollutants simulated | Oxygen demand |
| | Specific nutrients |
| | Specific organic chemicals |
| | Specific metals |
| | Specific bioaccumulative chemicals (organics, metals) |
| | Thermal |
| | Sediment |
| Spatial variation | 1 dimension |
| | 2 dimensions |
| | 3 dimensions |
| Ecological components | Aquatic plants |
| | Higher species (e.g., zooplankton, fish) |
| Pollutant transformations | Conservative pollutants |
| | Physical, chemical, biological reactions |
| Sources/sinks | Point sources |
| | Non-point sources |
| | Sediments |
| | Volatilization |
| | Advection, sediment transport from upstream |
| | Advection, sediment transport downstream |
| | Atmospheric deposition |
| Water body | Rivers/streams |
| | Lakes/reservoirs |
| | Estuaries |
| | Coastal waters |

As a general rule, boundary condition loadings for water quality constituents included in a TMDL should always be based on field measurements. There is no justification for using default assumptions for boundary condition concentrations, which must be known to achieve a reliable simulation of watershed pollutant loadings or receiving water quality for a TMDL.

In the case of a watershed where the land and surface waters have been affected by human activity at or near the boundaries and it is difficult or impossible to collect data that is not affected by controllable sources, boundary condition data may have to be transferred from a watershed with similar hydrology and geology that is not similarly affected. Transfer of boundary conditions data from one watershed to another must be done with great care, however, because in the case of constituents such as metals, sediments, and nutrients, naturally-occurring variations of these constituents in undisturbed areas can result in large differences in ambient boundary conditions. The only justification for transferring boundary conditions data for target pollutants from a similar watershed to the watershed that is the subject of the TMDL is when collection of site-specific data is impractical because of physical or resource limitations.

Selection of boundary condition pollutant loadings is also complicated for persistent chemical constituents that are subject to atmospheric transport. Examples are mercury, polychlorinated biphenyls (PCBs), and polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). In these cases, atmospheric transport can result in elevated “boundary conditions” in areas of a watershed that have essentially no anthropogenic activities that can contribute such constituents. Atmospheric transport of certain pollutants from outside the boundaries of a watershed will be important in such cases and the boundary condition for this source of pollutants will have to be considered as a variable in the TMDL analysis that can change if air emissions of the pollutant, both within the watershed and outside the watershed boundaries, are controlled in the future.

The objective of watershed models is to simulate the entrainment of pollutants (including sediment) from ground surfaces by precipitation and subsequent surface water runoff and pollutant transport 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. Ground water models are not usually considered as watershed models, but in specific instances where ground water contributions to surface waters may be important pollutant sources, ground water models may also serve as watershed models. Some watershed models also include the ability to simulate ground water pollutant contributions in a watershed.

These models are referred to as watershed models because they are intended to predict runoff volumes and pollutant loadings from the surface areas that are tributary to a receiving water body[15]. The geographical size of the watershed can range from very small tributaries (which may be referred to as sub-watersheds) to entire river basins.[16]

These models have the following attributes in common:

- They use land use data, soils data, and surface slopes as the basic foundation for estimating pollutant loadings; and
- They calculate the pollutant loadings as a function of the volume of pollutant runoff that is estimated from precipitation-runoff correlations.

The models differ in the degree of detail in predicting the entrainment and transport of pollutants into surface waters. The time scales used for pollutant loading predictions can be in years (e.g., annual averages), days, or even minutes. The temporal scale

[15] Watershed models can be applied to land areas as small as a fraction of an acre.
[16] Watershed models typically predict both non-point and point source loadings. Pollutant loadings from urban areas are, for the most part, point sources. Pollutant loadings from rural land may be either point sources or non-point sources. In either event, the models described in this section are intended to estimate waste loads from watershed surface areas, whether they enter surface water as point or non-point sources.

of the model should be based on the needs of the study — if short-term variations in water quality are important, watershed analysis time scale must be short enough to be useful to the TMDL analysis. Conversely, in other cases (e.g., nutrient loadings) predictions on a seasonal or annual basis will be adequate for a TMDL.

The following sections describe generic categories of watershed models available for TMDLs, ranging from the simplest loading equations to complex watershed models capable of simulating large watersheds, multiple pollutants, and receiving water impacts.

### *Loading equations*

The simplest methods for pollutant load predictions are equations relating pollutant loadings to land use. EPA's *Compendium* refers to these as "simple models." These models use empirical equations to correlate pollutant loadings to land-use and runoff volumes. Table 4-1 lists a few examples of loading equations used for watershed pollutant load predictions. EPA's *Compendium* lists additional watershed models and summarizes their predictive capabilities in more detail.

**Table 4-1**
**Example Watershed Load Equations**

| Model | Reference | Model Capabilities |
|---|---|---|
| EPA Screening | *Compendium*, May 1997, Appendix A | Urban, rural sites, nutrients, sediments |
| | | Not a computer program |
| USGS Regression | *Compendium*, May 1997, Appendix A | Urban, nutrients, sediments |
| | | Not a computer program |
| Federal Highway Administration Model (FHWA) | *Compendium*, May 1997, Appendix A | Highways, urban and rural drainage |
| | | Statistical computer model |
| | | Rudimentary transport analysis |
| | | Nutrients, metals |
| Watershed | *Compendium*, May 1997, Appendix A | Rural, nutrients |
| | | Spreadsheet, valid only for certain geographic areas |
| Sediment and phosphorus prediction (SLOSS) | *Compendium*, May 1997, Appendix A | Rural, sediment, phosphorus |
| | | Computer model using Universal Soil Loss Equation (USLE) |

Some of these methods are used with spreadsheets and/or calculators; others are computer-based algorithms. These methods do not typically simulate the rainfall-runoff-pollutant transport process as a function of time and precipitation intensity and short-term variability in pollutant loadings (hours, days, weeks, and months) is not predicted by these loading equations. The FHWA and SLOSS models are more complex and more sophisticated than the other models shown in Table 4-1 and consequently require more detailed input data than the simple spreadsheets or equations. Also, the prediction capability of any of these methods is directly related to the amount of site-specific data that are used in the analysis.

The input information required for the watershed equations typically consists of the data shown in Table 4-2.

**Table 4-2**
**Input Data for Watershed Equations**

| Category | Description |
|---|---|
| Geographic | Watershed drainage area<br>Topography (slope)<br>Soil types |
| Land use | Disaggregated into urban, rural land use types and subtypes, percent impervious cover, management practices for agriculture and urban areas |
| Precipitation | Local records of annual, monthly or daily precipitation |

These models are considered as appropriate for screening applications; i.e., to determine the relative importance of point and non-point source contributions to water quality impairment and to determine which areas of a watershed are the most important contributors of selected pollutants. In screening applications, the model default parameters are typically used for predictions of pollutant generation.

These models have been used for TMDLs, when long-term (e.g., annual average) contributions of pollutants are sought (such as nutrient discharges to a lake). When these simple approaches are used for TMDLs, site-specific data on pollutant loadings and more detailed land use and management data are used to in order to improve the prediction capability of the methods.

Watershed equations are useful for scoping TMDL projects and determining data collection needs. As a general rule, however, they are too simplistic to adequately predict watershed pollutant contributions suitable for TMDL evaluations and development of implementation plans.

### *Comprehensive watershed modeling*

EPA’s *Compendium* separates watershed models that are more complex than the watershed equations into three categories: (1) mid-range models, (2) detailed models, and (3) field models. The difference between these two categories of model is principally related to the time and geographic scales used for the simulations of runoff pollutant loads and the level of detail of soil types and land use simulated. Comprehensive models simulate fate and transport of pollutants in small tributaries and, in some models, rivers. The most important difference between watershed models used for “screening” runoff as a contributing source to an impairment and use of comprehensive watershed models for prediction of pollutant loading is the level of site-specific detail considered.

Comprehensive watershed modeling is needed for TMDLs when watershed runoff pollutant loadings contribute significantly to surface water quality impairment. The required temporal scale of water quality predictions also determines the complexity of simulation models. For example, if surface water quality variations associated with single storm events are important, then a comprehensive, detailed watershed model is needed. These models will generate short-term waste load estimates used in dynamic receiving water quality models (or the waste load model may perform this impact analysis) to predict responses to short-term events.

Conversely, if evaluation of seasonal or annual variations in surface water quality is the objective of a TMDL (which will often be the case for nutrient enriched waters), less complex models can be used. It may even be possible to use a watershed loading equation with site-specific data to satisfy the TMDL evaluation needs. In such cases, the receiving water quality modeling can often be performed with a steady-state water quality model using the seasonal or annual waste loads predicted by the watershed model.

Table 4-3 lists some examples of comprehensive watershed pollutant loading models used for prediction of watershed runoff for evaluations that are consistent with the requirements of a TMDL.

All of these models have extensive site-specific data requirements that must be satisfied for them to function as adequate simulation models. All require calibration and validation before they can be considered as suitable for predicting pollutant loadings for TMDLs.

**Table 4-3**
**Examples of Comprehensive Watershed Models**

| Model and Reference | Pollutants | Model Capabilities |
|---|---|---|
| Soil and Water Assessment Tool (SWAT) — component of U.S. EPA's BASINS 3.0 system.<br><br>*Compendium*, May 1997, Appendix A; USDA-Agricultural Resource Service, Temple, TX | Nitrogen<br>Phosphorus<br>Sediment<br>Specific pesticides (Limit of 10, including sediment) | Rural sites |
| | | Replaces USDA-ARS SWRRBWQ model |
| | | Evaluates management methods such as fertilizer and pesticide application rates |
| | | Predicts daily estimates of runoff and pollutant loads |
| Storm Water Management Model (SWMM)<br><br>*Compendium*, May 1997, Appendix A; U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | Nitrogen<br>Phosphorus<br>Sediment<br>Specific pesticides (Limit of 10, including sediment) | Urban sites |
| | | Continuous and storm event simulation |
| | | Evaluates management methods |
| | | Time series of flow and pollutant concentrations at user-specified intervals, seasonal and annual summaries |
| Storage, Treatment, Overflow, Runoff Model (STORM)<br><br>*Compendium*, May 1997, Appendix A; U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA. | Total suspended solids<br>Biochemical oxygen demand<br>Settleable Solids<br>Total coliforms<br>Ortho-phosphate<br>Total nitrogen | Urban sites |
| | | Evaluates storage of storm water |
| | | Hourly hydrographs and pollutographs, storm event summaries |
| Hydrological Simulation Program-Fortran (HSPF) — component of U.S. EPA's BASINS 3.0 system.<br><br>*Compendium*, May 1997, Appendix A; U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | Sediment (three types — clay, sand, silt)<br>One pesticide or other specific organic pollutant<br>Biochemical oxygen demand<br>Ortho-phosphate<br>Ammonia or nitrate | Urban and rural sites, includes ground water flow contributions |
| | | Evaluation of BMPs and development design criteria |
| | | HSPF has the ability to simulate water quality in tributary rivers and streams |
| | | Time series of runoff flow, sediment loads and pollutant concentrations, water quality at points in the watershed |

These comprehensive watershed models use different approaches for predicting runoff and pollutant contributions from watersheds with varying land uses and cover. Most combine empirical and theoretical formulations to predict pollutant entrainment and transport as a function of rainfall and physical properties of the watershed.

Our review of the simulation approaches used in these models does not support a conclusion that any specific modeling approach is superior to the others. Model selection should be based on an assessment of the TMDL project's requirements for watershed runoff predictions, and the availability of site-specific data for model parameters and for validating model predictions.

The mathematical relationships used in the models to relate runoff rate and pollutant loadings to precipitation, land use, surface cover and land management practices have the most effect on predictive capability. The runoff rates and pollutant loadings as a function of land use, cover, and management practices are usually based on default values in the models, supplemented by technical references. These will be the weakest links in the watershed loading estimates and in the absence of site-specific validation data, such estimates may be so inaccurate as to seriously compromise a TMDL when watershed runoff contributions are important. This is particularly a concern when "untraditional" watershed pollutants such as mercury are the pollutants causing the surface water quality impairment.

Geophysical data including watershed boundaries, slopes, tributary channel properties, and precipitation are essential to the model but are usually easy to obtain. When seasonal or annual watershed modeling is sufficient to satisfy the TMDL objectives, published precipitation data from the National Weather Service or locally-operated rain gauges with a sufficiently long record to provide statistically-based rainfall estimates is satisfactory. When storm-event or similar short-term modeling is necessary, estimating precipitation on a sub-watershed scale may be necessary, but even these data can generally be estimated from available records without too much effort.

### *Selecting a watershed modeling approach*

The data requirements for comprehensive watershed pollutant loading models are extensive. This is especially true when it is necessary to model short-term temporal variations in water quality in response to runoff pollutant loadings. Therefore, the first determination that must be made in a TMDL project is the importance of watershed pollutant contributions to the surface water quality impairment. This determination should be made based on consideration of the following factors:

- The type of impairment and the pollutant causing it, e.g., watershed runoff sources will typically be significant contributors to surface waters impaired by excessive sediment and/or nutrient loadings. Conversely, watershed sources would typically not be major contributors to low dissolved oxygen concentrations or elevated heavy metals concentrations during critical, low-stream flow conditions.

- The type of land uses in a watershed. Confined animal feeding operations and dairy farms may be significant contributors of nutrients and coliform organisms, for example. Urban runoff will contain heavy metals and polynuclear aromatic hydrocarbons.

The relatively simple waste load equations described in this section are useful for assessing the importance of watershed pollutant loading contributions compared to point source contributions. These models can be used with default assumptions for most input data to generate approximations of the pollutant loadings from the watershed, which can be compared to loadings from point sources, sediments, and background. If watershed contributions are a significant portion of the total receiving water loading of the target pollutant, then a comprehensive watershed model can be selected for the TMDL.

Factors that should be considered in selecting a comprehensive watershed loading model are identified in Table 4-4.

**Table 4-4**
**Selecting a Comprehensive Watershed Loading Model**

| Factor | Considerations |
|---|---|
| Pollutants | Must simulate all pollutants causing impairment, including causal constituents that do not have numeric criteria |
| Land use | Must address all important land uses in the watershed |
| Time scale | Short-term or long-term predictions: determine if dynamic or steady-state model is needed |
| Groundwater | Include if groundwater is a potentially significant contributor to impairment |
| Compatibility w/ receiving water models | Ability of model to provide input to appropriate receiving water models |
| Data availability and data collection resources | Are site-specific data available, or can they be collected, to satisfy most of the model input requirements |
| Model output | Adequacy for uncertainty and sensitivity analyses |
| Experience of users | Experience and capability of the TMDL staff to use a complex model |

The level of effort, time, and cost that can be devoted to watershed modeling is an important consideration in selection of a model. Dynamic simulation of runoff and pollutant loadings is extremely data intensive and is thus time-consuming and expensive. Thus, it is important to determine, before the modeling approach and model are selected, the time scale of simulation that is necessary for the specific TMDL.

It is not always the best approach to select the most comprehensive watershed model available, if this means having to use default data and parameters for many input variables. The uncertainty introduced into the model predictions if a complex model with numerous default model parameters is used for a TMDL evaluation could be a significant component of total prediction uncertainty. Thus, selection of a watershed model should consider the data and technical resources available to adequately calibrate and validate the model, using site-specific data.

An advantage of mathematical models is that sensitivity analyses of model predictions can identify the data inputs and model parameters that are most important to the predictions. Statistical evaluation of sensitivity analyses is an important tool to characterize the uncertainty in the model predictions as a function of the uncertainty in the input variables. Sensitivity analysis is an essential step of any modeling analysis and will identify model inputs that require the most attention in site-specific data collection.

Validation of the selected watershed model with site-specific data should be a required component of every TMDL. Validation[17] means comparison of model predictions to field data that correspond to known input conditions. For example, to demonstrate that a watershed model can adequately predict the relationship between runoff, land use, and phosphorus loading at a specified downstream location with available phosphorus data, the model should be run using the annual precipitation data for one or more years for which tributary total phosphorus concentrations are available. The model predictions should be statistically compared to the measured data to assess model validation.

Statistical evaluation of the validation runs (i.e., statistical comparison between predicted and measured loadings, concentrations, and flows) should always be performed. This will provide an estimate of model prediction accuracy and supplements the sensitivity analyses.

Figure 4-1 is a flow chart showing the major steps in selecting and applying a watershed loading model to a TMDL. Note that if atmospheric deposition is a significant source of a targeted pollutant (e.g., mercury, dioxins), a watershed model is generally required for predicting entrainment and transport of the pollutant to a receiving water. However, few watershed models have

[17] Validation is also called "verification" in some references.

provisions for incorporating atmospheric (wet or dry) deposition into the pollutant source terms, and such models will have to be modified to incorporate this source.[18]

### *Data sources for watershed models*

Much of the input data required for watershed models is site-specific and publicly available. Table 4-5 summarizes the principal data requirements and sources for these models.

**Table 4-5**
**Data Sources for Watershed Models**

| Category | Importance of Site-specific Data | Data Sources |
|---|---|---|
| Topographic | Essential | Most information can be obtained from topographic maps and stream gauge records. Field data for channel cross-sections may be needed. |
| Soil types | Essential | USDA Natural Resources Conservation Service, local and state cooperating agencies |
| Land Use | Essential | USGS maps, aerial photos, state and local governments (planning offices) |
| Precipitation | Essential | National Weather Service, state and local weather networks (including TV stations), privately-operated weather networks |

[18] None of the watershed models described in this report have an explicit atmospheric source input. EPA Region IV developed a watershed model for the Savannah River mercury TMDL that does include atmospheric deposition as a source (EPA, 2001). This EPA model is an example of how atmospheric deposition can be included as specific type of source in a watershed model.

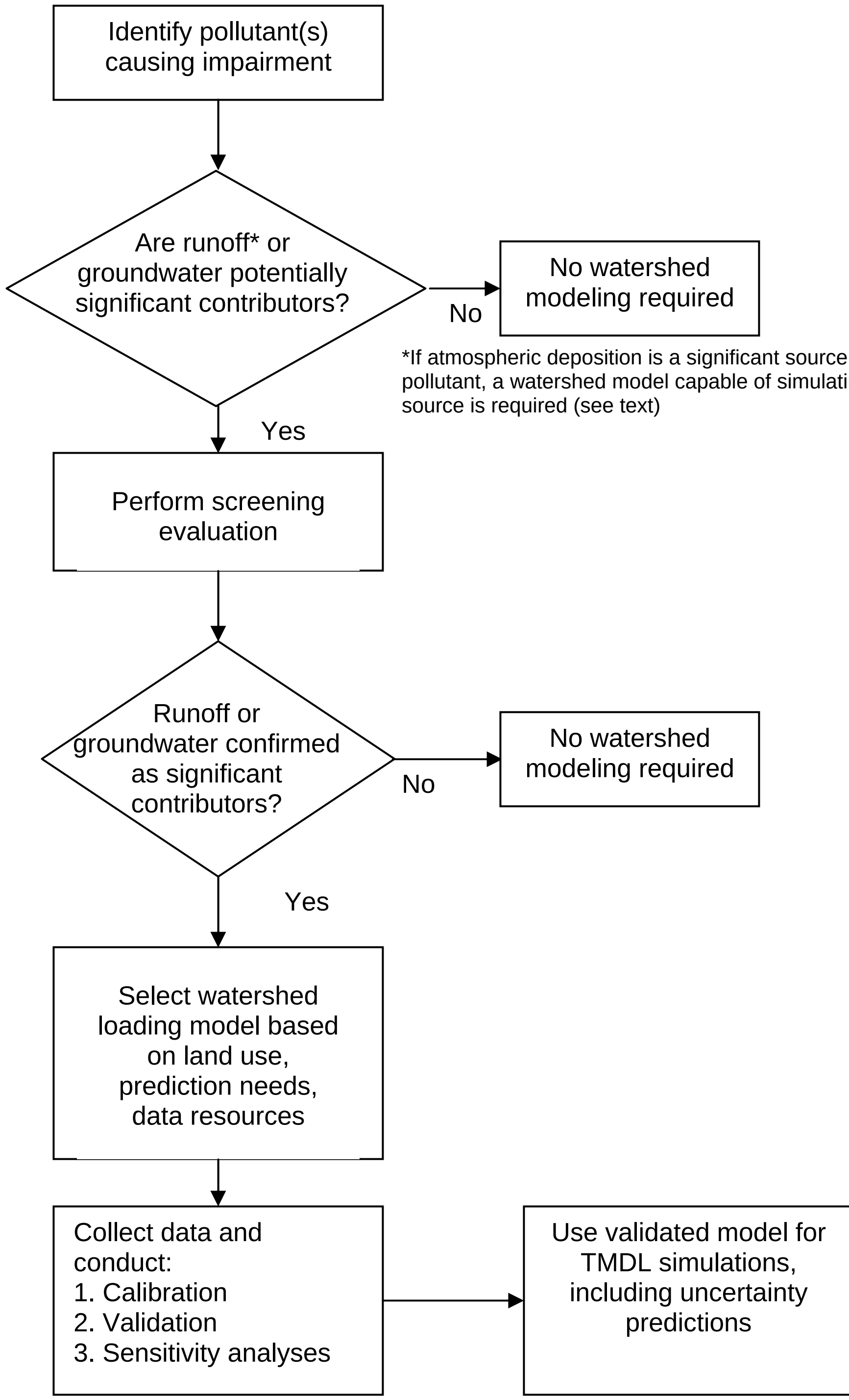



**Figure 4-1**
**Selection and application of watershed models**

Receiving water models are the principal tools used in the TMDL process, because they predict the cause-effect relationship between pollutant loadings and water quality. If properly selected, calibrated, and validated a model should be capable of evaluating alternative TMDL implementation scenarios, including pollutant tradeoffs between point and non-point sources and among point sources. Therefore, selection and proper implementation of a receiving water model is an essential component of a TMDL study.

Section 2 of this report discussed the considerations for selecting a receiving water model for a specific TMDL study. This section describes the different types of models available and identifies the input requirements for each type of model.

Receiving water modeling requires simulating multiple environmental processes:

(1) transport of the pollutants within the water body;

(2) physical pollutant transformations (settling, suspension, volatilization);

(3) biological and chemical pollutant transformations; and

(4) inputs or withdrawals of water and pollutants by point and non-point sources, including exit from the system being modeled (i.e., flow into a downstream water body).

A receiving water model must maintain a mass balance on all simulated water quality constituents; therefore, correct simulation of the hydrodynamics of the receiving water is an essential model component. Thomann and Mueller have written a good reference for the details of surface water quality modeling.[19]

The most convenient approach to describing receiving water models is through two categories of time-variation simulations: (1) steady-state, and (2) dynamic (or time-variable). It should be noted that this categorization is an over-simplification; some “steady-state” water quality models predict temporal variations in water

[19] Thomann, R.V. and Mueller, J.A., 1987, *Principles of Surface Water Quality Modeling and Control*, HarperCollins Publishers, Inc., New York, N.Y.

quality parameters although the hydrodynamics are simulated as steady state. In this section, the distinction between steady state and dynamic receiving water models is based on the simulation of hydrodynamics that affect pollutant transport.

### *Steady-state models*

The assumption of steady-state hydrodynamics is a common simplification used in receiving water modeling. Typically, the model is used to simulate water quality at a critical hydrologic condition specified by the user. Modeling pollutant loadings and water quality responses in a river at the 7-day, 1-in-10 year recurrence low stream flow (7Q10) (or a similar low flow specification) is the most common example of this approach. The steady-state hydrodynamics assumption can also be used for tidally affected surface waters, by using an assumed tidal dispersion input as a model boundary condition.

Steady-state water quality modeling requires substantially less input data than is required to simulate time-varying hydrodynamics. For this reason, most agencies and modelers will use the steady-state hydrodynamic assumption whenever it will satisfy the study objectives. Also, the steady-state modeling assumption does not have to be limited to simulation of critical low-stream flow conditions. High flow conditions, different periods in a tidal cycle, and similar “snapshots” of a time-variable water quality constituent may be used to simulate the probable range of values for the constituent, and this approach may be sufficient to adequately address a water quality impairment. However, when surface water impairment is time-variable (e.g., fecal coliform counts in response to point and non-point source inputs during and after a runoff event), then dynamic solutions are generally required for accurate cause and effect predictions.

There are a number of available steady-state receiving water quality models. Examples of the more widely used and comprehensive steady-state models are shown in Table 5-1. There are also several forms of the Streeter-Phelps dissolved oxygen models that are often used by state agencies for waste load allocations. Many of these have been extended to include nitrogenous oxygen demand (ammonia and organic nitrogen), but in general they are less flexible than the models shown in Table 5-1 and are typically only applicable to waste load allocations to meet dissolved oxygen criteria.

**Table 5-1**
**Examples of Steady-state Water Quality Models**

| Model/Reference | Pollutants | Model Capabilities |
|---|---|---|
| Enhanced Stream Water Quality Model (QUAL2E) — component of U.S. EPA's BASINS 3.0 system.<br><br>*Compendium*, May 1997, Appendix A; U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | Dissolved oxygen-BOD<br>Nitrogen cycle<br>Phosphorus cycle<br>Temperature<br>Salinity<br>Chlorophyll-*a*<br>User-specified conservative and non-conservative pollutants | Branching stream and river systems in one dimension (assumes complete vertical and lateral mixing)<br>Point and non-point sources<br>Includes a statistical uncertainty analysis package |
| Simplified Method Program — Variable-Complexity Stream Toxics Model (SMPTOX4)<br><br>*Compendium*, May 1997, Appendix A; U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | Suspended solids<br>Dissolved pollutants<br>Particulate pollutants | Single stream segments in one dimension<br>Point sources only<br>Has three tiers of increasing complexity<br>Includes sediment-water column transfers in most complex tier<br>Includes a database for a number of specific chemicals |
| Exposure Analysis Modeling System (EXAMS II)<br><br>*Compendium*, May 1997, Appendix A; U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | User-specified organic and inorganic chemicals<br>Suspended solids | Streams, rivers, lakes, and reservoirs in 1, 2, or 3 dimensions<br>Models photolysis, hydrolysis, biotransformation, oxidation, and sorption to sediments and biota of user-specified constituents<br>Summary tables of pollutant fate and distribution, longitudinal and vertical concentration profiles<br>Intended to evaluate long-term, time-averaged loadings |
| Methods for Description and Prediction of Eutrophication-related Processes in Reservoirs (FLUX, PROFILE, BATHTUB)<br><br>*Compendium*, May 1997, Appendix A; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. | Nitrogen cycle<br>Phosphorus cycle<br>Chlorophyll-*a*<br>Dissolved oxygen | Nutrient and water balances on lakes and reservoirs, hypolimnetic oxygen depletion, algal response to nutrients<br>Evaluation of spatially-segmented water bodies of complex morphology<br>Graphics and tabular displays of nutrient, algae, and dissolved oxygen concentrations, statistical evaluation of predictions compared to measured values |

There are versions of steady-state models that can simulate transport in tidal rivers (estuaries). For example, the Texas Commission on Environmental Quality has a publicly available version of the QUAL2 model (called QUAL-TX) that has been successfully applied to the Houston Ship Channel and several other narrow estuaries. This model and others like it use a tidal dispersion term in the transport equations to account for tidal mixing. They do not simulate tidal movement directly.

The models identified in Table 5-1 are suitable for simulating a wide range of water quality constituents and processes.[20] They are generally suitable for any TMDLs that can be calculated using the steady-state hydrodynamics assumption. It is probable that most states will attempt to perform their TMDLs using this type of model, because they are familiar with the approach and the dynamic modeling approaches will often require data collection that will exceed the resources of the regulatory agency.

The input data categories for the models listed in Table 5-1, as well as those for other steady-state water quality models, are similar although specific formats may differ. Table 5-2 summarizes the input data categories for steady-state models and also shows the relative importance of site-specific data for each category of data.

Data identified as essential in Table 5-2 are the minimum requirements for a water quality model used for a TMDL. The amount of detail that is required for each category of data identified in Table 5-2 is a function of the specific problem being addressed — the surface water body, the pollutant or pollutants concerned, and the model selected to simulate the cause-effect water quality relationships.

The critical flows used in the models for calculating TMDLs are typically based on statistical analyses of stream flow data. Historically, most water quality modeling for waste load allocations has been done for a critical low flow condition (e.g., the 7-day average low flow with a recurrence interval of 10 years). However, there is no reason that critical conditions cannot represent a more frequent flow event, if the purpose of the TMDL is to protect water quality from adverse conditions that occur at higher stream flows. For example, seasonal flows or annual average flows may be satisfactory for simulating seasonal algal growth in rivers and lakes. The important consideration is whether or not the flow condition being modeled is transient; i.e., only occurs for a short period of time and this transient condition must be simulated to adequately calculate a TMDL. When transient conditions are the principal focus of a TMDL, and temporal variations in water quality must be predicted to address the TMDL objectives, then dynamic modeling of hydrodynamics is necessary.

EPA's *Compendium* provides a summary of the input and output data for a number of steady state water quality models.

[20] Note: some of the dynamic water quality models described in the next section can be used in a steady-state mode and are thus also suitable for steady-state modeling.

**Table 5-2**
**Data Requirements for Steady-state Water Quality Models**

| Category | Importance of Site-specific Data | Data Sources |
|---|---|---|
| Geometry — width, depth, slope, and channel length for streams, rivers, and tidal rivers; surface area and bathymetry for lakes and reservoirs | Essential | Most information can be obtained from topographic maps and stream gauge records. Field data for channel cross-sections may be needed. |
| Hydrology/hydraulics — design flows; depth-cross-sectional area-velocity correlations; tidal range and dispersion (tidal rivers only); vertical and horizontal density variations (for reservoirs and estuaries). | Essential | Stream gauging records supply both flow and depth-area-velocity relationships. Time of travel studies will improve hydraulic transport estimates. Temperature and salinity data for vertical or horizontal density distributions can be obtained from water quality records or must be measured in the field. |
| Point sources — location, flows, and pollutant discharges | Essential | State/EPA discharge monitoring reports (PCS system); special data collection efforts for water quality studies (e.g., TMDL) |
| Non-point sources — location, flows, and pollutant discharges | Essential (if non-point sources are significant) | Usually must be estimated using watershed models. Special data collection efforts for the water quality study. |
| Biodegradation/transformation rates of pollutants — includes benthic transformations | Moderate | Site-specific rates are usually estimated by model calibration and validation using water quality data collected for that purpose |
| Reaeration rates | Low | Models have one or more default reaeration rate equations; selection of appropriate equations is done during calibration and validation. |
| Sedimentation rates | Low | Site-specific rates are usually obtained by model calibration and validation using water quality data collected for that purpose |
| Chemical/physical transformation rates for pollutants | Low | Default rates in models/literature are usually used for volatilization and chemical reactions |
| Calibration and validation water quality data sets | Essential | Requires field-collected data for all target pollutants. Data collected at known hydrologic and transport conditions (measured during the study), at a sufficient number of locations to provide for model calibration and validation. Minimum of two independent data sets is necessary. |

The importance of the site-specific data sets for water quality model calibration and validation cannot be overemphasized. Calibration with site data is used to set the biological, chemical, and physical transformation rates for the pollutant(s) being modeled. Validation with an independent site data set[21] is required

[21] An independent data set must represent a separate monitoring event so that there is no possibility that the data are serially correlated. An independent event is not, for example, data from the second or third day of a 3-day monitoring event.

to confirm the accuracy and precision of the model. These data sets are usually generated by short-term, intensive field studies specifically designed to collect data for this purpose. Occasionally, state or federal water quality monitoring stations with long-term records are available for the TMDL study area and can be used to supplement a calibration/validation data collection effort. Because the data are collected under widely varying conditions and/or are too limited, only rarely do existing sampling stations provide sufficient coverage and frequency to completely satisfy model calibration and validation requirements.

### *Dynamic models*

When transient water quality conditions are the principal focus of a TMDL, and temporal variations in water quality must be predicted to achieve the TMDL objectives, then dynamic water quality modeling will usually be required. The data requirements for dynamic modeling are typically more than an order of magnitude beyond that required for steady-state modeling. Temporal data for all parameters affecting time-variable mass transport must be collected and entered into the dynamic model. In addition, the physical relationships between stream flow and water depth, velocity, surface area, and cross-sectional area must be validated for the range of flows to be simulated. Additional model input parameters (e.g., sediment transport including sediment suspension) usually not required for a steady-state model may be required for a dynamic model. Martin and McCutcheon have written a good reference on hydrodynamics and transport for water quality modeling.[22]

Dynamic water quality modeling requires simulation of the time-variable mass transport of water quality constituents. This mass transport is driven by hydrodynamics of the surface water being modeled. Therefore, the first step in dynamic water quality modeling is simulation of the hydrodynamics (velocities, current directions, depths). This is accomplished with hydrodynamic models that may be either completely separate models generating time variable hydrodynamic inputs for a water quality model, or may be a component of an integrated hydrodynamic-water quality model.

Examples of available dynamic water quality models are shown in Table 5-3. Separate hydrodynamic models that generate input data for water quality models are also included in this table.

[22] Martin, J.L. and McCutcheon, S.C., 1999, *Hydrodynamics and Transport for Water Quality Modeling*, CRC Press, Inc. Boca Raton, FLA.

**Table 5-3**
**Examples of Dynamic Water Quality Models**

| Model/Reference | Simulated Variables | Model Capabilities |
|---|---|---|
| DYNHYD5 — Link-node tidal hydrodynamic model<br><br>*Compendium*, May 1997, Appendix A; U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | Velocities<br>Depths | Branching stream, river, and estuary systems in one dimension (assumes complete vertical and lateral mixing)<br>Part of WASP5 water quality modeling system<br>Assumes channels have a constant top width and variable depth<br>Generates time-variable velocities and depths at time intervals of 1 to 24 hours |
| RIVMOD-H — River hydrodynamics model<br><br>*Compendium*, May 1997, Appendix A; U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | Velocities<br>Depths | Branching stream, river, and estuary systems in one dimension (assumes complete vertical and lateral mixing)<br>Distributed with WASP5<br>Model can use natural cross-sections<br>Generates time-variable depths and discharges for unsteady flow conditions |
| CH3D-WES — Curvilinear hydrodynamics in three dimensions<br><br>*Compendium*, May 1997, Appendix A; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. | Velocities<br>Depths<br>Current Direction | 2-D and 3-D hydrodynamic model developed for the Chesapeake Bay Program<br>Predicts velocities, directions, and depths in 2- or 3-D for each specified cell of the model<br>Requires a workstation or supercomputer and considerable expertise in hydrodynamic analysis. |
| CE-QUAL-RIV1 — Hydrodynamic and water quality model for streams.<br><br>*Compendium*, May 1997, Appendix A; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. | Temperature, salinity, dissolved oxygen, nitrogen cycle, phosphorus cycle, phytoplankton, benthic algae and macrophytes, bacteria, and first order decay of a user-specified constituent | Integrated hydrodynamic and water quality model. Branching stream, river, and estuary systems in one dimension (assumes complete vertical and lateral mixing)<br>Tabular displays of nutrient, algae, and dissolved oxygen concentrations. |

Continued on next page

**Table 5-3 (Continued)**
**Examples of Dynamic Water Quality Models**

| Model | Simulated Variables | Model Capabilities |
|---|---|---|
| CE-QUAL-W2 — Two-dimensional, laterally-averaged, hydrodynamic and water quality model<br><br>*Compendium*, May 1997, Appendix A; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. | Temperature, salinity, dissolved oxygen, nitrogen cycle, phosphorus cycle, phytoplankton, bacteria, and first order decay of user-specified constituents | Branching stream, river, and estuary systems in one or two dimensions (laterally averaged when used in two dimensions)<br>Different time steps can be used for hydrodynamic and water quality modules, thus reducing the computational burden for complex systems.<br>Predicts time-varying concentrations of water quality constituents as a function of depth and distance downstream. |
| WASP5 — Water quality analysis simulation program<br><br>*Compendium*, May 1997, Appendix A; U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | Temperature, salinity, sediment, dissolved oxygen, nitrogen cycle, phosphorus cycle, phytoplankton, benthic algae and macrophytes, bacteria, and first order decay of user-specified constituents | Branching streams and estuary systems in one, two, or three dimensions<br>Models sediment deposition and suspension, daughter products of specified degradable chemicals.<br>Generates time-variable constituent concentrations at user-specified output intervals. |
| Hydrological Simulation Program-Fortran (HSPF) — component of U.S. EPA's BASINS 3.0 system<br><br>*Compendium*, May 1997, Appendix A; U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | Sediment (three components – clay, silt, sand), one user-specified organic pollutant, BOD, ammonia or nitrate, ortho-phosphate | Branching rivers and reservoirs in one-dimension (well-mixed)<br>Continuous or storm-event simulation<br>Watershed model that simulates time-varying pollutant transport and fate of sediment, nutrients, metals and hydrocarbons. |
| CE-QUAL-ICM — Three-dimensional, time-variable integrated compartment eutrophication model<br><br>*Compendium*, May 1997, Appendix A; U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. | Temperature, salinity, dissolved oxygen, carbon cycle, nitrogen cycle, phosphorus cycle, phytoplankton, zooplankton, silica, bacteria, sediments | 1-D, 2-D and 3-D hydrodynamic model developed for the Chesapeake Bay Program. Uses hydrodynamics from CH3D-WES.<br>Considers benthic pollutant exchange<br>Generates time-variable constituent concentrations. |
| Environmental Fluid Dynamics Code (EFDC)<br><br>U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | Dissolved oxygen, chemical oxygen demand, organic carbon, algae, fecal coliform, nitrogen, phosphorus, silica, metals | Near and far-field mixing in streams, rivers, lakes, reservoirs, estuaries, and bays; 1-D, 2-D<br>Can simulate periodic inundation and dewatering of wetlands<br>Combines mixing zone and far-field modeling; can provide hydrodynamic input to WASP5 |

With a few exceptions, input data categories for dynamic models are similar to those of the steady-state models — the difference is that for each time-variable parameter, the input data consists of values of that parameter for every time step required by the model, for the entire time duration simulated. For example, if tidal hydrodynamics in an estuary are to be simulated for one 24-hour period, a typical model may require water depths (or water surface elevations) at the modeled segment boundaries for every 10-minute interval during the 24-hour period. Table 5-4 summarizes the input data requirements for dynamic water quality models.

Because time-varying input data are required for dynamic modeling, the input data are usually stored in separate electronic files that are accessed by the model when a simulation is performed. Most dynamic models allow optional dynamic simulation modes, where one or more of the input variables can be assumed to be temporally constant while others vary with time. For example, an estuary model may be run with assumed constant advective inflows (fresh water flows from rivers and point source flows) and time-varying water surface elevations due to tides. The simulation results from such an approach would represent the tidal mixing and dispersion of water quality constituents superimposed on a steady-state simulation of fresh water flows and point source discharges. This hybrid steady-state-dynamic modeling approach may be used more widely for TMDLs than true dynamic modeling because of the substantial data requirements associated with full dynamic modeling of a surface water body.

When a fully dynamic simulation is required, in which all principle time-varying inputs are represented, the input and computational requirements are very substantial. Given the computational power of modern desktop computers, dynamic simulation of complex receiving water systems is more practical than it ever has been. However, if a large, complex receiving water system must be simulated with a dynamic model, such work may have to be performed on a computer workstation or even a supercomputer. For example, the Chesapeake Bay hydrodynamic model developed by the Corps of Engineers is run on a workstation or supercomputer to make the required computational time acceptable.

**Table 5-4**
**Data Requirements for Dynamic Water Quality Models**

| Category | Importance of Site-specific Data | Data Sources |
|---|---|---|
| Geometry — width, depth, slope, and channel length for streams, rivers, and tidal rivers; surface area and bathymetry for estuaries, lakes and reservoirs | Essential | Most information can be obtained from topographic maps and stream gauge records. Field data for channel cross-sections may be needed. |
| Hydrology/hydraulics — time-varying design flows; depth-cross-sectional area-velocity correlations; time-varying water level elevations (tidal rivers and estuaries); vertical and horizontal density variations (for reservoirs and estuaries). | Essential | Stream gauging records supply both flow and depth-area-velocity relationships. Time of travel studies result in improved hydraulic transport estimates. Temperature and salinity data for vertical or horizontal density distributions can be obtained from water quality records or must be measured for the study. Tide data from COE or NOAA tide gauge records. |
| Point sources — location, time-varying flows, and pollutant discharges | Essential | State/EPA discharge monitoring reports (PCS system); special data collection efforts for water quality studies (e.g., TMDL); statistical estimates (e.g., Monte Carlo predictions). |
| Non-point sources — location, time-varying flows, and pollutant discharges | Essential (if non-point sources are significant) | Usually must be estimated using watershed models. Special data collection efforts for the water quality study. |
| Biodegradation/transformation rates of pollutants — includes benthic transformations | Moderate | Site-specific rates are usually obtained by model calibration and validation using water quality data collected for that purpose |
| Reaeration rates | Low | Models have one or more default reaeration rate equations; selection of appropriate equations is done during calibration and validation. |
| Sedimentation rates | Essential (if time-variable sediment transport is simulated) | Site-specific rates are usually obtained by model calibration and validation using water quality data collected for that purpose. Will need to be related to stream velocity if sediment transport is simulated. |
| Chemical/physical transformation rates for pollutants | Low | Default rates in models/literature are usually used for volatilization and chemical reactions |
| Calibration and validation water quality data sets | Essential | These are field-collected data for all target pollutants. Collected at known hydrologic and transport conditions (measured during the study), at a sufficient number of locations to provide for model calibration and validation. Time variable water quality data and hydraulic data must be collected to calibrate and validate a dynamic model. Minimum of two independent data sets is necessary. |

The data required for calibration and validation of a dynamic water quality model is extensive. Time-variable hydraulic and water quality data sets must be collected so that the model's predictive capacity can be thoroughly evaluated and estimates of the precision and accuracy of model predictions can be made. Because of the massive amounts of output data generated by dynamic modeling, statistical analysis of the results is essential to assess the simulation precision and accuracy by comparison to measured data for model calibration and validation.

### *Boundary conditions*

Important components of both steady state and dynamic receiving water models are the boundary conditions, which are the model inputs at the upstream and downstream ends of the segments being modeled. When a river or stream is being modeled, only the upstream boundary conditions on the stream segment and major tributaries affect the simulation of hydrodynamics and water quality. Downstream boundary conditions are also unimportant for models of reservoirs and lakes that discharge into a river or stream. When the simulated surface water is tidally influenced, the downstream boundary conditions are as important as the upstream conditions because they can influence hydrodynamic and water quality predictions. However, one method for dealing with the need for reliable downstream data is to establish the downstream boundary at a sufficient distance away from the area of interest to assure that the downstream boundary conditions do not influence the model predictions.

Upstream hydraulic boundary conditions consist of all of the inflows, including point source and non-point source discharges, for streams, rivers, lakes, reservoirs, estuaries, and bays. Downstream hydraulic boundary conditions for estuaries and bays are usually tidal elevations, but for some models can be input as time-varying flows across the downstream boundary of the model.

Upstream water quality boundary conditions consist of the concentrations (or loadings) of all water quality constituents that will be modeled (and those constituents that will affect water quality) associated with each inflow source. When a water body is tidally influenced, the downstream water quality boundary conditions affect the modeling results near the boundary. Therefore, water quality constituent data for the downstream boundary must also be specified for model simulations.

The boundary conditions selected for TMDL modeling should be based on the nature of the water quality impairment that will be corrected. If impairment is seasonal, then the boundary conditions should represent the specific season when the impairment occurs.

Boundary conditions for steady state simulations can be specified as summarized in Table 5-5.

**Table 5-5**
**Steady-state Model Boundary Conditions**

| Boundary Condition | Considerations |
|---|---|
| Stream flows | Set at statistically-based critical flow, e.g., 7Q10; median annual flow |
| | Set at specified discharge rate from reservoir (regulated flows) |
| Water quality constituents | Set at fraction of numeric water quality criterion (e.g., 50% of criterion) |
| | Use actual data from a “reference” or “background” station (must have similar hydrology and minimal anthropogenic influences) |
| | For downstream water quality in tidally-affected waters — background data collected in unaffected areas or set boundary far from area of interest |
| Tides | Select critical conditions for mixing and dispersion |

Boundary conditions for dynamic modeling are subject to all of the requirements discussed above for steady-state models, but are further complicated because the input data must be time-variable for one or more model parameters. Stream flows, tidal elevations or flows, point source flows, non-point source flows, and the concentrations of target and related water quality constituents may all have to be provided as time-varying records for model input. Selection of the ambient conditions that these time-varying inputs are supposed to represent is a policy decision that is based on the TMDL objectives. Some examples of possible boundary condition assumptions for dynamic water quality models are shown in Table 5-6.

**Table 5-6**
**Dynamic Model Boundary Conditions**

| Boundary Condition | Considerations |
|---|---|
| Stream flows | Hydrographs (time-variable flow) for selected storm event durations and intensities |
| | May have to be spatially variable for large watersheds |
| Water quality constituents | Pollutant loadings as a function of time (“pollutographs”) at boundaries |
| | May have to be generated with dynamic model using an “undisturbed” subwatershed |
| | For downstream water quality in tidally-affected waters — background data collected in unaffected areas or set boundary far from area of interest |
| Tides | Select time-variable critical tidal conditions for mixing and dispersion |

## *Other models*

Two categories of models that may find some application in TMDLs are: (1) mixing zone models, and (2) “ecological” models. Because they are not potential candidates for use in most TMDLs, this report will only summarize their applicability and major attributes.

### Mixing zone models

As their name implies, these models are designed to predict the dilution of a point source discharge in receiving waters. They are based on theoretical and empirical equations of the hydrodynamics of a jet mixing in a larger body of ambient water. These models account for mixing caused by density and momentum differences between the discharge and ambient water. Because they are designed to calculate discharge dilution in the zone of initial dilution (relatively small portion of the receiving water), they do not typically account for important physical, chemical, or biological processes that may affect pollutant concentrations in the bulk of the receiving water. Examples of several mixing zone models are shown in Table 5-7. API has published a mixing zone guidance manual (API Publication 4664) that can be referred to for more detail.

Mixing zone models are likely to be useful only in TMDLs where water quality conditions in mixing zones are important factors in causing use impairments. This will not typically be the case. However, when sedimentation of bioaccumulative pollutants in mixing zones, and subsequent suspension and transport of the pollutants out of the mixing zone and downstream into the ambient receiving water is a significant contributing factor to a use impairment, then application of these models may be necessary.

#### Ecological models

The distinction between ecological models and some of the more complex receiving water models identified in Tables 5-1 and 5-3 is subtle. The term *ecological model* is typically used to refer to models that simulate more than one trophic level in an aquatic ecosystem (e.g., phytoplankton, zooplankton, and fish). In recent years, ecological models have been developed to simulate bioaccumulation through aquatic food chains to assess exposures to humans and wildlife.[23] These models hold some promise for TMDLs that target impairment due to bioaccumulative substances, but they require considerable amounts of data on ecosystem relationships that are often not available on a site-specific basis. Using them with default values for biological relationships is unlikely to result in a scientifically supported TMDL. Table 5-8 provides summary information on several ecological models, including models in Tables 5-1 and 5-3 that have certain ecosystem simulation capabilities.

The required site-specific information for an ecological model depends upon the cause-effect relationships used in the model. The fundamental basis for such model is to define the species at each aquatic trophic level that will be represented in the model (e.g., benthic organisms, phytoplankton, zooplankton, bottom-feeding fish, highest-level predator fish). Growth and death rates for the species must be determined and incorporated in the models. When bioaccumulative constituents are the TMDL objective (e.g., mercury, dioxins), site-specific bioaccumulation factors (BAF) and/or Biota-sediment accumulation factors (BSAF) are necessary.

[23] Gobas, F.A.P.C., Pasternak, J.P., Lien, K. and Duncan, R.K., 1998, “Development and Field Validation of a Multimedia Exposure Model for Waste Load Allocation in Aquatic Ecosystems: Application to 2,3,7,8-Tetrachlorodibenzo-p-dioxin and 2,3,7,8-Tetrachlorodibenzofuran in the Fraser River Watershed,” *Env. Sci. Technol*., Vol. 32, No. 16.

**Table 5-7**
**Examples of Mixing Zone Models**

| Model | Reference | Model Capabilities |
|---|---|---|
| Cornell Mixing Zone Expert Systems Model (CORMIX) | Oregon Graduate Institute, Oregon State University, Corvallis, OR; U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | Single or multiple port submerged diffusers, buoyant surface discharge from pipe or channel. |
| | | Expert system model; Oregon version is Windows-based |
| | | Simulates near and far-field dilution in stratified or unstratified receiving water systems with potential boundary interactions (sides, bottom, surface) |
| | | Includes a graphics package |
| Visual Plumes Model System (PLUMES) | U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | Single or multiple port submerged diffusers, buoyant surface discharge from pipe or channel |
| | | Windows-based model |
| | | Simulates near and far-field dilution in stratified or unstratified receiving water systems without potential boundary interactions (sides, bottom, surface) |
| | | Includes a graphics package |
| Environmental Fluid Dynamics Code (EFDC) | U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | See Table 5-3 for more details |

Acceptable scientific methods for collecting the required site-specific data for ecological models are available. For many surface water bodies, the aquatic food web will be well defined from historic biological studies performed by state and federal wildlife agencies and regulatory agencies and universities. Scientific literature is often available to obtain growth rates and related data for such species. When such data are not available for a surface water body, then field data collection will be required to obtain the required data on the principal components of the aquatic food web that are targeted for modeling. The methods for collecting these data are well documented in the scientific literature and are often specified in state regulatory agency biological monitoring programs.

Data on site-specific BAFs and/or BSAFs are generally not available. The data required to develop these factors include water column, sediment, and aquatic animal tissue concentrations of the bioaccumulative pollutant. The field data required to develop reliable estimates of site-specific BAFs and BSAFs are described in the technical literature and state and federal guidance documents.[17, 24] Collection of these data is typically expensive and time-consuming, because it is necessary to account for both spatial and temporal variations in bioaccumulation rates. In addition, the cost of chemical analyses for bioaccumulative substances can be high because very low concentrations in the water column and sediment are important and therefore sophisticated sampling and analytical methods are required to obtain precise and accurate data.

EPA's *Compendium* describes some ecological models and assessment techniques that may be may also be useful for TMDLs. Most of these models and assessment techniques require substantial amounts of site-specific ecosystem data to enable them to be used as predictive methods.

**Table 5-8**
**Examples of Ecological Models**

| Model | Reference | Model Capabilities |
|---|---|---|
| AQUATOX | EPA Office of Science and Technology, Washington, D.C.<br>www.epa.gov/waterscience/models/aquatox/ | One-dimensional simulation of rivers and streams; stratified or unstratified lakes and reservoirs. |
| | | Simulates phytoplankton, periphyton, macrophytes, planktonic and benthic invertebrates, forage game and bottom fish |
| | | Simulates dissolved oxygen, nutrient dynamics, organic sediments, toxic organic chemicals, and bioaccumulation. |
| | | Simulates the temporal variability of selected constituents and biology in a single compartment of a water body (allows two layers for stratified system). |
| | | Must be used as sequential models when there is spatial variability in the surface water body being simulated. |
| WASP5 | U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | See Table 5-3 for more details |
| CE-QUAL-ICM, CE-QUAL-RIV1 | U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. | See Table 5-3 for more details |
| Environmental Fluid Dynamics Code (EFDC) | U.S. EPA Center for Exposure Assessment Modeling, Athens, GA. | See Table 5-3 for more details |

[24] EPA, 1995, *Great Lakes Water Quality Initiative Technical Support Document for the Procedure to Determine Bioaccumulation Factors*, EPA-820-B-95-005, Office of Water, Washington, D.C.

## Web Sites

The following web sites provide information on TMDL models and modeling techniques. Most of the publicly available models described in this report can be obtained from these web sites.

- http://www.epa.gov/ost/wqm/
- http://www.epa.gov/ceampubl/
- http://www.epa.gov/waterscience/models/allocation/
- http://www.wes.army.mil/el/elmodels/index.html#wqmodels
- http://smig.usgs.gov/SMIC/

# References


EPA, 1983, *Technical Guidance Manual for Performing Waste Load Allocations, Book IV: Lake and Impoundments, Chapter 2: Nutrient/Eutrophication Impacts*, Office of Water, Washington, D.C.

EPA, 1984, *Technical Guidance Manual for Performing Waste Load Allocations, Book II: Streams and Rivers, Chapter 3: Toxic Substances*, EPA 440/4-84-022, Office of Water, Washington, D.C.

EPA, 1985, *Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling (Second Edition)*, EPA/600/3-85/040, Environmental Research Laboratory, Athens, Georgia.

EPA, 1987, *Processes, Coefficients, and Models for Simulating Toxic Organics and Heavy Metals in Surface Waters*, EPA 600/3-87-015, Office of Water, Washington, D.C.

EPA, 1986, *Handbook: Stream Sampling for Waste Load Allocation Applications*, EPA/625/6-86/013, Office of Research and Development, Washington, D.C.

EPA, 1990, *Technical Guidance Manual for Performing Waste Load Allocations, Book III: Estuaries, Part 1: Estuaries and Waste Load Allocation Models*, Office of Water, Washington, D.C.

EPA, 1990, *Technical Guidance Manual for Performing Waste Load Allocations, Book III: Estuaries, Part 2: Application of Estuarine Waste Load Allocation Models*, Office of Water, Washington, D.C.

EPA, 1991, *Guidance for Water Quality-based Decisions: The TMDL Process*, EPA 440/4-91-0, Office of Water, Washington, D.C.

EPA, 1992, *Technical Guidance Manual for Performing Waste Load Allocations, Book III: Estuaries, Part 3: Use of Mixing Zone Models in Estuarine Waste Load Allocations*, EPA-823-R-92-004, Office of Water, Washington, D.C.

EPA, 1992, *Technical Guidance Manual for Performing Waste Load Allocations, Book III: Estuaries, Part 4: Critical Review of Coastal Embayment and Estuarine Waste Load Allocation Modeling*, EPA-823-R-92-005, Office of Water, Washington, D.C.

EPA, 1995, *Great Lakes Water Quality Initiative Technical Support Document for the Procedure to Determine Bioaccumulation Factors*, EPA-820-B-95-005, Office of Water, Washington, D.C.

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

EPA, 1997, *Technical Guidance Manual for Developing Total Maximum Daily Loads, Book 2: Streams and Rivers, Part 1: Biochemical Oxygen Demand/Dissolved Oxygen and Nutrients/Eutrophication*, EPA 823-B-97-002, Office of Water, Washington, D.C.

EPA, 1999, *Protocol for Developing Nutrient TMDLs, First Edition,* EPA 841-B-99-07, Office of Water, Washington, D.C.

EPA, 1999, *Protocol for Developing Sediment TMDLs, First Edition,* EPA 841-B-99-004, Office of Water, Washington, D.C.

EPA, 2000, *Protocol for Developing Pathogen TMDLs, First Edition*, EPA 841-R-00-002, Office of Water, Washington, D.C.

EPA, 2001, *Watershed Characterization System — Users Manual*, Region 4, Atlanta, Georgia.

Fischer, H.B., List, E.J., Koh, R.C.Y., Imberger, J., and Brooks, N.H., 1979, *Mixing in Inland and Coastal Waters*, Academic Press, Inc., San Diego, California.

Gobas, F.A.P.C., Pasternak, J.P., Lien, K. and Duncan, R.K., 1998, "Development and Field Validation of a Multimedia Exposure Model for Waste Load Allocation in Aquatic Ecosystems: Application to 2,3,7,8-Tetrachlorodibenzo-p-dioxin and 2,3,7,8-Tetrachlorodibenzofuran in the Fraser River Watershed," *Env. Sci. Technol*., Vol. 32, No. 16.

Martin, J.L. and McCutcheon, S.C., 1999, *Hydrodynamics and Transport for Water Quality Modeling*, CRC Press, Inc. Boca Raton, FLA

Thomann, R.V. and Mueller, J.A., 1987, *Principles of Surface Water Quality Modeling and Control*, HarperCollins Publishers, Inc., New York, N.Y.

Texas Natural Resource Conservation Commission, June 1999, *Developing Total Maximum Daily Load Projects in Texas: A Guide for Lead Organizations*, GI-250, Austin, Texas.

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

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