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Simple Models and Analytical Procedures for Total Maximum Daily Load Assessment

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Introduction

The degree of analysis required for each component of TMDL development can range from simple screening-level approaches based on limited data to detailed investigations that might need several months or even years to complete (USEPA 1999).

Many simple models and analytical procedures were developed prior to the advent of fast digital computers to manage environmental impacts. Simple methods are often used when data limitations and budget and time constraints preclude using more detailed approaches. These tools are used to diagnose non-point-source pollution problems when information is relatively limited.

For watershed loading estimates, simple models and analytical procedures can be used to support an assessment of the relative significance of different pollutant sources, guide decisions for management plans, and focus continuing monitoring. Simple models estimate pollutant loads based on land use or other watershed characteristics. Typically, simple methods rely on a large-scale aggregation of these watershed characteristics and neglect detailed features of land uses and natural processes. These tools rely on generalized sources of information and therefore have low to medium requirements for site-specific data. Default values provided for these methods are derived from empirical relationships that are based on regional or site-specific data. The estimates are usually expressed as mean annual values. Simple methods provide only preliminary estimates of sediment and pollutant loadings and may only have limited predictive capability (Zhang 2005).

The major advantage of simple methods is that these tools can provide a rapid means of identifying critical pollutant loads with minimal effort and data requirements. Simple methods are typically derived from empirical relationships between physiographic characteristics of the watershed and pollutant export. In addition, simpler approaches can save time and expense and can be applied by a wider range of personnel. Simple approaches also generally are easier to understand than more detailed analyses (USEPA 1999).

Progress in science and computing, along with changing environmental problems, have allowed modelers to develop increasingly complex and comprehensive modeling frameworks. Unfortunately, this often leads to the common misconception that complex models are necessarily superior to simpler approaches. In fact, the choice of a water quality model involves trade-offs among model complexity, required reliability, cost, and time (Chapra 2003). Therefore, this paper presents a review of simple models and analytical procedures in TMDL applications and illustrates the strengths and weaknesses of utilizing simple methods in TMDL development and implementation.

Review of Simple Models and Analytical Procedures

The simple models and analytical procedures introduced in this paper may be used initially in phased TMDLs to estimate TMDLs but usually are employed to check and analyze TMDLs (Mysiak et al. 2005; Voinov 2008). Some models like the Revised Universal Soil Loss Equation 2 (RUSLE2) are auxiliary tools to identify loads like sediment yields from different catchments to prioritize implementation. Spreadsheets are typically used to list and track implementation actions as well as perform simple mass balances for checking assessments as well as for other tasks. Occasionally, in the hands of an expert, methods like a simple mass balance spreadsheet can rule out some allocations and implementation options.

Some simple models for receiving water analysis use a mass balance approach that assumes steady-state conditions. Accuracy is limited when default parameters are substituted for site-specific data. The procedure neglects seasonal variation in predicting annual loadings and considers only steady-state conditions for receiving water analysis (USEPA 1999). However, in some circumstances, getting a reasonable estimate for an average watershed water balance and contributions to constituent load may be sufficient for a TMDL to proceed.

Other models may deploy similar concepts of mass balance but employ annual or monthly time steps, avoiding the limitations of steady-state conceptual models while keeping data requirements to a minimum and avoiding the complexity of more refined numerical models. Model integration and linkage of models is often desirable for many TMDLs, where analysts can achieve greater acceptance of model-based analysis by employing existing models in widespread use. Where these modeling tools and analytical techniques do not fully characterize the system, they can be complemented with other functions or models linked to the main modeling tool to provide the needed level of analysis.

Table 1 summarizes several simple methods and analytical procedures for TMDL assessment.

Simple Mass Balance Equation

The basic principle of water quality models is that of mass balance. A water system can be divided into different segments or volume elements, also called computational cells. For each segment or cell, there must be a mass balance for each water quality constituent over time (Loucks and van Beek 2005).

Simplified mass balances are typically applied in spreadsheets to discrete water volumes containing a uniform concentration of a

Table 1. Comparison of simple methods and analytical procedures for TMDL assessment

Number	Method	Advantages/benefits	Disadvantages/shortcomings	Key references/example applications
1	Simple mass balance equation	(1) Most easily understood by the users; and (2) clearly show the inputs and outputs of the calculation	The assumptions may be oversimplified and inaccurate for complex systems	McCutcheon (1989) and Chapra (1997)
2	Simple method to estimate urban stormwater loads	(1) Use of runoff coefficient and mean concentration based on EPA's NURP data; and (2) time scale is for annual and monthly events	(1) Only provides a general planning estimate of likely storm pollutant export; and (2) does not consider pollutants associated with base flow volume	USEPA (1983), Schueler (1987), and Cappiella and Brown (2001)
3	USGS regression method	(1) Based on regression equations from USGS studies; and (2) can incorporate regional variations in the estimate	Only valid for areas where regression coefficients are obtainable (i.e., regional transferability is limited)	Tasker and Driver (1988) and Driver and Troutman (1989)
4	Revised Universal Soil Loss Equation	(1) Applied and validated by broad users for decades; and (2) with consistent enhancement by USDA	Only estimates average annual erosion and sediment delivery from runoff	Wischmeier and Smith (1978), Renard et al. (1997), and USDA (2003)
5	BATHTUB	(1) Easy to use tool for eutrophication analysis for lakes and reservoirs; and (2) used routinely in the lake TMDLs when steady-state condition is sufficient for water quality analysis	(1) Only for stead-state application; and (2) the model is based on accuracy of empirical equations built in the model	Walker (1985, 1986)
6	Stream Segment Temperature Model (SSTEMP)	(1) Easy to use model that can simulate heat balance; and (2) used to analyze the effects of changing riparian shade for temperature TMDL application	Lacks many of the detailed features of dynamic models needed for complex temperature TMDLs	Theurer et al. (1984), Bartholow (2010), and Chen et al. (1993, 1998a, b)
7	Load-duration curve	(1) Has been applied in various type of TMDLs; and (2) TMDL load is expressed as a function of flow conditions	(1) Does not mechanistically relate sources and receiving water quality response; and (2) does not allow simulation of scenarios evaluating the impact of various implementation options	USEPA (2007), Risley et al. (2008), and SCDHEC (2010)
8	Simple transient mass balance models WETMANSIM; San Joaquin River Input-Output Model (SJRIO)	(1) Conceptually clear, addition/subtraction of mass; and (2) model assumptions explicit and readily changed	(1) Spreadsheet format can be cumbersome for simulations greater than one year; and (2) version control challenging because spreadsheet can be easily modified	(1) WETMANSIM is a spreadsheet based monthly water and salt balance for managed wetlands; and (2) SJRIO model performs daily flow and salt mass balance of inflow to the River and diversions from the River from surface and groundwater sources
9	GIS workflow models	(1) Object-oriented approach, easy to implement; and (2) visually appealing—takes advantage of power of GIS technology	(1) Requires acquisition and knowledge of GIS; and (2) data often lacking to fully exploit GIS application	Universal soil loss equation is a simple product of spatial coverages to obtain soil loss estimates

nonreactive material or pollutant so that concentration C and load W are easily related via flow Q as follows (McCutcheon 1989; Chapra 1997):

$$C = \frac{1}{Q}W; \qquad W = QC \tag{1}$$

The waste assimilative capacity or TMDL for any discrete volume of water containing a conservative substance or pollutant is the water quality standard in concentration of the substance multiplied by the flow rate.

Simple Method to Estimate Urban Stormwater Loads

The Simple Method (Schueler 1987) is an easy-to-use empirical equation for estimating pollutant loadings of an urban watershed by the Metropolitan Washington Council of Governments (MWCOG). The Simple Method is essentially an approach to rapidly estimate loads based on available information such as (1) catchment drainage area and impervious cover, and (2) stormwater runoff concentrations.

The Simple Method estimates pollutant loads for chemical constituents as a product of annual runoff volume and pollutant concentration

$$L = 0.226 \times R \times C \times A \qquad (2)$$

where L = annual load (lbs); R = annual runoff (in.); C = pollutant concentration (mg/L); A = area (acres); and 0.226 = unit conversion factor.

The method is best adapted for use in small watersheds of less than 1 sq mi (USEPA 1999). The Simple Method uses different impervious cover values for separate land uses within a subwatershed, including agricultural land use category. These numbers are derived from a study conducted by the Center for Watershed Protection under a grant from the USEPA to update impervious cover estimates for a variety of land uses (Cappiella and Brown 2001). The Simple Method provides estimates of storm pollutant export that are probably close to the true but unknown value for a development site, catchment, or subwatershed. It can be used for analyzing a smaller watershed or site planning. The method was developed using the database generated during a Nationwide Urban Runoff Program (NURP) study (USEPA 1983) in the Washington, DC, area and the national NURP data analysis. The equations, however, may be applied anywhere in the country. Some precision is lost as a result of the effort to make the equation general and simple.

The Simple Method is adequate for decision making at the site planning level. For example, it may be used to estimate runoff pollutant concentration from urban drainage areas. Runoff volume is estimated using runoff coefficients for the fraction of rainfall converted to runoff. A correction factor is used to account for those storms that do not produce runoff. Potential applications of the Simple Method are to estimate pollutant loading from an uncontrolled development site or to estimate expected extreme concentrations that will occur over a specified time period (USEPA 1999).

USGS Regression Method

The USGS Regression Method (Tasker and Driver 1988) is an example of a statistical-based method. This method estimates source loading as a function of several variables such as land use, percentage of imperviousness, drainage area, and mean annual rainfall. The USGS has developed equations for determining pollutant loading rates based on regression analyses of data from sites throughout the country (76 gauging stations across 20 states).

The regression approach is based on a statistical description of historic records of storm runoff responses on a watershed level (Tasker and Driver 1988). This method may be used for rough preliminary calculations of annual pollutant loads when data and time are limited (Tasker and Driver 1988; Driver and Troutman 1989). Inputs required for this level of modeling include drainage data, percent imperviousness, mean annual rainfall, general land use pattern, and mean minimum monthly temperature. Application of this method provides mean planning loads and corresponding confidence intervals for storms. The most significant explanatory variables in all of the linear regression models were total storm rainfall and total contributing drainage area. Impervious area, land use, and mean annual climatic characteristics were also significant explanatory variables in some linear regression models (Driver and Troutman 1989).

The USGS Regression Method gives mean storm-event pollutant loads and corresponding confidence intervals. The method is used to estimate the pollutant concentration from urbanized watersheds and relies upon a statistical approach to estimate annual, seasonal, or storm-event mean pollutant loads. The method is valid only for areas where regression coefficients are obtainable (i.e., regional transferability is limited). The method typically applies to smaller watersheds, although a specific size range of the watersheds was not provided by USGS.

Revised Universal Soil Loss Equation

The Revised Universal Soil Loss Equation 2 (RUSLE2) (USDA 2003) is an updated advanced erosion prediction technology that uses the familiar empirical structure of the Universal Soil Loss Equation (USLE) and RUSLE1. This conservation planning tool has an extensive history of development beginning with the Universal Soil Loss Equation (Wischmeier and Smith 1978), then RUSLE (Renard et al. 1997) and been used on farms and ranches as well as for planning roadside protection and soil erosion in strip mining. A computer interface makes RUSLE2 easily used and adaptable to special conditions.

Robust and computationally efficient, RUSLE2 estimates the effects of soil, climate, and land management on sheet and rill erosion and sediment delivery from hillslopes; it also estimates the size distribution and clay enrichment of sediment delivered to the channel network in a watershed. This software is linked to extensive databases maintained by the USDA's Natural Resources Conservation Service (NRCS) and to other computer programs. For TMDL assessment, RUSLE2 allows a water quality analyst to specify a representative runoff event sequence at a site using soil characteristics, land management techniques, and a user-specified return period that can be coupled with a channel erosion and routing model. This software is flexible, easy to use, and has extensive, reliable databases for almost any climate, soil, and land management alternative in the United States.

RUSLE2 estimates average annual erosion and sediment delivery from runoff. Like the USLE, erosion is calculated as the product of several factors: rainfall and runoff factor R; soil erodibility factor K; slope length factor L; steepness topographic factor S; cover and land management factor C; and support practice factor P. However, in RUSLE2, these factors are no longer independent, and computations are done on a daily or event basis so that the product of the annual averages of these factors may not be equal to the sum of the daily values. Another difference from USLE is that RUSLE2 represents sediment transport and deposition on concave areas so that the RUSLE2 concept defines hillslopes from the top of a hill and through depositional areas, ending in a concentrated flow channel.

A strength of RUSLE2 as a tool for TMDL development is the extensive database that includes climate and soils descriptions for every county in the United States. Land management scenarios are organized into 78 crop management zones. Each scenario represented using RUSLE2 is created by combining field operations (e.g., grading, tillage, planting, applying materials, or harvest), vegetation growth over time, and residue decomposition, biomass, and cover. As of January 2011, the NRCS database contained over 29,000 management scenarios composed of combinations of approximately 600 tillage and field operation records, 1,400 vegetation records, and 140 residue records. At that time, the database also contained about 600 choices of support practices consisting of contour systems, hydraulic element systems (diversions, terraces, and impoundments), and strip-barrier systems.

Although an individual one-dimensional hillslope profile is the fundamental unit over which RUSLE2 computes erosion and sediment delivery, RUSLE2 can also be accessed through the application programing interface to estimate distributed hillslope runoff and sediment yields. Distributed hillslope runoff and sediment yield calculations can be used with ephemeral gully and channel models to estimate sources and sinks of sediment from gullies and streams and to route sediment to a watershed outlet.

Accurate development of sediment TMDLs must deal with the complexity of sediment generation and transport through watersheds, which include erosion and deposition on the hillslopes, delivery to channels, and sediment scour or deposition within the channels. Implementation of a sediment TMDL assessment requires evaluation of management alternatives that reduce sediment delivery to the channels in a watershed. The RUSLE2 framework covers most of the field management alternatives that farmers use on hillslopes to prevent soil loss.

As an example based on the USLE, the EPA's screening procedures can be used to assess point and nonpoint source loadings and atmospheric deposition loads. Agricultural nonpoint loads are based on the USLE, Soil Conservation Service [SCS, now the Natural Resource Conservation Service (NRCS)] runoff curve number procedure, and loading functions using enrichment ratios. Urban nonpoint loads are estimated using the buildup-washoff concept (i.e., the buildup-washoff concept accounts for incremental buildup of nutrients between storms).

BATHTUB

BATHTUB is an empirical lake eutrophication model developed for the USACE in the 1980s based on data from USACE reservoirs (Walker 1985, 1986). It is a steady-state eutrophication model applicable to lakes and reservoirs based on empirical assessments of reservoir data.

BATHTUB is designed to facilitate application of empirical eutrophication models to reservoirs or lakes. The program formulates steady-state water and nutrient mass balances in a spatially segmented hydraulic network that accounts for advective transport, diffusive transport, and nutrient sedimentation. Eutrophication-related water quality conditions (expressed in terms of total phosphorus, total nitrogen, chlorophyll a, transparency, organic nitrogen, nonorthophosphorus, and hypolimnetic oxygen depletion rate) are predicted using empirical relationships previously developed and tested for reservoir applications. To provide regional perspectives on reservoir water quality, controlling factors, and model performance, BATHTUB can also be configured for simultaneous application to collections or networks of reservoirs.

The basic elements defining each application include (1) segments, which are reservoir zones specified in a one-dimensional, branched network (e.g., upper pool, midpool, near dam, and different tributary arms); and (2) tributaries, which are inflow or outflow streams, each associated with a particular segment. The BATHTUB model can assess the impacts of changes in water and/or nutrient loadings and impacts of changes in mean pool elevation during the growing season and estimate nutrient loadings consistent with given water quality management objectives.

BATHTUB is a tool for modeling reservoirs, chains of lakes, lakes with multiple inlets, or situations where more detailed nutrient and water budgets are required. BATHTUB is used routinely in developing nutrient-based TMDL studies.

Stream Segment Temperature Model

Stream Segment Temperature Model (SSTEMP) is a scaled-down version of the Stream Network Temperature Model (SNTEMP) developed by Theurer et al. (1984). This USGS-supported model is based on a simplified heat balance. The model simulates steady-state stream temperatures for a specified time period and location in a stream or river (Bartholow 2010).

The SSTEMP program requires inputs describing the average stream geometry, as well as (steady-state) hydrology and meteorology plus stream shading. SSTEMP optionally estimates the combined topographic and vegetative shade as well as solar radiation penetrating the water. It then predicts the mean daily water temperatures at specified distances downstream. It also estimates the daily maximum and minimum temperatures. Unlike the large network model SNTEMP (Bartholow 2010), this program simulates single-stream segments for a single time period (e.g., a month, week, or day) for any given set of model specifications. Initially designed as a training tool, the SSTEMP program may be used satisfactorily for a variety of simple cases. The SSTEP model is especially useful to perform sensitivity and uncertainty analysis. With good-quality specifications, SSTEMP should adequately reproduce mean daily water temperatures throughout a stream reach. Users should not expect too much from SSTEMP if the input values are of poor quality or if the model's assumptions were not met.

The SSTEMP model is not specifically designed for TMDL analysis and lacks many of the detailed features of complex model adapted for the first temperature TMDL in Oregon (Chen et al. 1993, 1998a, b). However, SSTEMP can be used to analyze the effects of changing riparian shade or the physical features of a stream and examine the effects of different stream withdrawals and returns on instream temperature for TMDL-related applications.

Load-Duration Curve

The load-duration curve (LDC) approach allows for characterizing water quality concentrations at different flow regimes. The pollutant load is expressed as a function of all flow conditions, including critical flow condition (USEPA 2007). This statistical-based approach quickly estimates existing and allowable loads with limited information. Some practitioners value the insight that load-duration curves provide into the relationship between water quality impairment and hydrologic regime (ASCE 2017).

The first step in a TMDL analysis using a load-duration curve is to generate a flow-duration curve, which is a cumulative frequency curve of daily mean flows without regard to chronology of occurrence (Leopold 1994). The flow-duration curve includes all flows observed at a stream gauge for the applicable period of record. Flow rates are typically sorted from the largest value to the smallest. For each flow, the flow-duration curve provides the corresponding percent of time that a magnitude of flow is equaled or exceeded. The percentage of time is the flow-duration interval or flow-duration percentile (Risley et al. 2008). Once a flow-duration curve has been created, a load-duration curve is created by multiplying flow by the applicable water quality criterion or target. The independent x-axis remains as the flow-duration interval, and the dependent y-axis depicts the load at specific point in the watershed where flow monitoring data are available. A specific curve derived from flow and the water quality criterion therefore represents the allowable load at each flow condition. Points above that curve represent exceedances of the water quality criterion and are therefore excess loads. Those points below that curve represent compliance with the water quality criterion and allowable pollutant loads.

A fecal coliform TMDL development in South Carolina prepared by the South Carolina Department of Health and Environmental Control (SCDHEC 2010) is one example that illustrates the use of the load-duration curve approach. An appendix in the EPA guide *An Approach for Using Load Duration Curves in the Development of TMDLs* (USEPA 2007) describes a case study in which load-duration curves were used to support TMDL development. Important information can be derived from a load-duration curve to support TMDL assessment. The extent of the impairment can be visually assessed based on the number of loads that are greater or less than the allowable loading curve. The nature of the impairment can also be inferred based on when the loads occur (USEPA 2007). Loads that are greater than the curve for allowable pollutant loads during low-flow conditions are likely indicative of constant discharge, such as wastewater-treatment plants. Those loads are greater than the curve for allowable pollutant loads during wet weather conditions likely reflect contributions associated with sheet and rill erosion, washoff processes, and, potentially, streambank erosion. Those loads plotting above the curve at the high and small ends of the curve reflect extreme hydrologic conditions of flood or drought. If sufficient data are available, the load-duration curve method accurately identifies the allowable and existing loads at the point in the stream where the data were collected and can be used to meet the basic regulatory requirement for TMDL development. Load-duration curves are relatively easy to develop and offer insight into critical conditions.

On the other hand, although the relative importance of low-flow point sources versus wet weather nonpoint sources can often be identified from the load-duration curve, no specific information is provided regarding what types of point or nonpoint sources exist in the watershed. Load-duration curves also do not allow simulation of scenarios evaluating the impact of various implementation options. The load-duration curves do not mechanistically relate sources and water quality response. Therefore, forecasting load reduction effects on impairments on a what-if basis are impossible because it cannot define the relationship of cause and effect.

Simple Transient Mass Balance Models

For some TMDL modeling requirements, standard models are not sufficient, and custom applications need to be developed. In the majority of cases, these models utilize the concept of mass balance by first developing a hydrology budget for the three-dimensional volume representing the system being analyzed. In some cases, the system volume is subdivided into a number of vertical layers to improve representation of the interactions between above surface, root zone, shallow, and deep groundwater aquifers. The configuration of the model depends on available data and the chemistry of the contaminant being regulated. Spreadsheets have been used to good effect to develop both simple steady-state and transient mass balance models.

Wetland Management Simulator

The Wetland Management Simulator (WETMANSIM) (Quinn 2004) spreadsheet model is an example of a customized monthly mass balance model of seasonal wetland hydrology and salinity. The model was developed specifically for managed wetlands that receive water as canal deliveries in the fall, hold water in shallow impoundments during the winter, and release the bulk of the ponded water during spring wetland drawdown. Depending on water availability, the wetlands are flood irrigated one or more times during the late spring and early summer months to encourage the growth of moist soil plants that provide wetland habitat and food resources for migratory waterfowl. The high clay content of wetland soils that desiccate and crack during the summer months and swell when wetted required the use of a water displacement infiltration algorithm rather than the typical Richards equation formulation used by most models. Monthly time steps were sufficient to provide analysts and regulators with the necessary relationship between applied water salinity and the salinity of wetland drainage return flows to the receiving water body. The simple monthly steady-state spreadsheet formulation made it easy to adapt the model to create individual submodels for private wetlands and for State and Federal wildlife refuges that allowed more local control of salt loading by these entities. WETMANSIM is fairly typical of customized TMDL models used in TMDL development that are well matched to TMDL objectives and available data.

San Joaquin River Input-Output Model

The San Joaquin River Input-Output Model (SJRIO) (CVWB 2004) is an example of a customized mass balance model where neither a monthly nor annual steady-state conceptual model was sufficient for analysis of the options being considered by the TMDL. In this case, the concept of real-time salinity management was being explored, which involved improved coordination of saline drainage return flows produced on the west side of the San Joaquin River Basin to coincide with reservoir releases of high-quality snowmelt runoff from the east side of the Basin. This operational concept became the basis of regulatory policy and an amendment to the Basin's water quality control plan. For this TMDL modeling approach, the scenario needed to be tested for a range of river basin hydrologic conditions and water year types ranging from wet to critically dry. River hydrology and water quality are largely determined by releases from state and federally-managed reservoirs on the east side of the Basin. Hence, another model was needed to simulate the linkage between climate and water storage that included the logic behind water release policies under various water storage scenarios. This auxiliary model was linked to the SJRIO model to develop an implementation strategy for the salinity TMDL, and the 30-year hydrologic time series it provided allowed the strategy to be tested for a historic sequence of water year types. This is an example of model integration and linkage. In this case, linkage of a simple mass balance accounting model with another model capable of creating a historic time series of flow and water quality conditions to support the technical TMDL methodology.

GIS Workflow Models

Increased use of GIS and high-resolution remote-sensing analysis in support of TMDL modeling has given rise to simple object-oriented modeling toolboxes where coverages of land use and other measurable data are combined to yield estimates of key decision variables. A common application of this methodology is erosion modeling. The RUSLE2 example presented previously is a model easily adapted to this technique.

Another example is the ArcView Generalized Watershed Loading Functions (AVGWLF) tool (Evans and Corradini 2016), which facilitates the use of the Generalized Watershed Loading Functions (GWLF) Model via a GIS software (ArcView) interface. The AVGWLF tool is suitable for application to generalized watershed loading, source assessment, and seasonal and interannual variability. The AVGWLF tool has been extensively used in the Northeast and mid-Atlantic regions. This tool has been adopted by Pennsylvania as a statewide model for TMDL development and agricultural land management (USEPA 2005; Evans and Corradini 2016).

The main advantages of GIS workflow modeling are model transparency, the ability to perform operations over a discretized model mesh that provides great spatial details, and the appeal of the visualization associated with this approach. This technique works well with simple models where data such as land use can be readily represented in a GIS. The technique is less effective for more complex models where the factors are less easily visualized or discretized.

Summary

Simple methods require expert judgment to interpret empirical relationships between watershed characteristics and pollutant loads to receiving waters. A few of these methods may use existing databases and typically can vary in sophistication from a simple spreadsheet program or handheld calculator. In some cases, they could be in the form of an easy-to-use computer-based numerical modeling tool. Simple models and methods are often used when limited data availability and budget or time constraints preclude the use of more sophisticated methods.

Based on the review of several examples of simple models and analytical procedures, simpler approaches can save time and expense to support TMDL estimates. Simple approaches also generally are easier to understand than more detailed analyses by a broad range of users. The trade-offs associated with using simple approaches include a potential decrease in forecast accuracy and often an inability to make predictions at fine geographic and time scales (e.g., watershed-scale source predictions versus model detailed estimates, and annual versus seasonal estimates) (USEPA 1999).

The major advantage of simple methods is that these tools can provide a rapid means of identifying critical loading areas with minimal effort and data requirements. The major disadvantage of using simple methods is that only gross estimates of nutrient loads can be provided, which are of limited value for determining loads on a seasonal or finer time scale. Another disadvantage is that simple methods are of limited use for evaluating the effect of nonpoint-source control (USEPA 1999).

The standard practice in modeling is to identify the dominant processes and identify the simplest models sufficient to meet the needs of the project (USEPA 2005). Models include suites of equations that represent most processes based on the understanding of real-world setting. Thomann and Mueller (1987) established that the simplest model sufficient to answer management questions with confidence should be applied. If data availability does not reach the level that a detailed model requires, then a simpler model should be employed.

The choice of a water quality model involves trade-offs among model complexity, required reliability, cost, and time. An adaptive approach to modeling would start with simpler models at the initial phases and then progress to more complex frameworks as additional data are collected and as more focused remedial measures are assessed (Chapra 2003). Starting with simple analyses and iteratively expanding data collection and modeling as the need arises is the best approach (NRC 2001). Within the limitations of their design functionality and underlying assumptions, the simple models and analytical procedure can be useful in the TMDL assessment.

Acknowledgments

The TMDL Analysis and Modeling Task Committee of the American Society of Civil Engineers' Environmental and Water Resources Institute was formed to address concerns and challenges over the current practices of analysis and modeling in the TMDL development and implementation in terms of analysis technique, model selection, data requirement, calibration, confirmation testing, and uncertainty reporting. The committee investigated some of the current practices of analysis and modeling in TMDL development and implementation and reported the technical challenges in a report entitled *Total Maximum Daily Load Analysis and Modeling: Assessment of the Practice*, published by ASCE Press in 2017. Authors of this paper are members of the Task Committee, and the paper is partly based on the findings of the Task Committee and expansion of original publication.

References

ASCE. 2017. *Total maximum daily load analysis and modeling: Assessment of the practice*. Reston, VA: ASCE.

Bartholow, J. 2010. *Stream network and stream segment temperature models software*. Fort Collins, CO: US Geological Survey.

Cappiella, K., and K. Brown. 2001. *Derivations of impervious cover for suburban land uses in the Chesapeake Bay watershed*. Ellicott City, MD: Center for Watershed Protection.

Chapra, S. C. 1997. *Surface water-quality modeling*, 844. New York: McGraw-Hill.

Chapra, S. C. 2003. "Engineering water quality models and TMDLs." *J. Water Resour. Plann. Manage.* 129 (4): 247–256. https://doi.org/10.1061/(ASCE)0733-9496(2003)129:4(247).

Chen, Y. D., R. F. Carsel, S. C. McCutcheon, and W. L. Nutter. 1998a. "Stream temperature simulation of forested riparian areas. I: Watershed-scale model development." *J. Environ. Eng.* 124 (4): 304–315. https://doi.org/10.1061/(ASCE)0733-9372(1998)124:4(304).

Chen, Y. D., S. C. McCutcheon, D. J. Norton, and W. L. Nutter. 1998b. "Stream temperature simulation of forested riparian areas. II: Model application." *J. Environ. Eng.* 124 (4): 316–328. https://doi.org/10.1061/(ASCE)0733-9372(1998)124:4(316).

Chen, Y. D., S. C. McCutcheon, T. C. Rasmussen, W. L. Nutter, and R. F. Carsel. 1993. "Integrating water quality modeling with ecological risk assessment for nonpoint source pollution control: A conceptual framework." *Water Sci. Technol.* 28 (3–5): 431–440. https://doi.org/10.2166/wst.1993.0446.

CVWB (Central Valley Water Board). 2004. *Amendments to the water quality control plan for the Sacramento River and San Joaquin River Basins for the control of salt and boron discharges into the lower San Joaquin River.* Central Valley Water Board Final Staff Rep.

Driver, N. E., and B. M. Troutman. 1989. "Regression models for estimating urban storm-runoff quality and quantity in the United States." *J. Hydrol.* 109 (3–4): 221–236. https://doi.org/10.1016/0022-1694(89)90017-6.

Evans, B. M., and K. J. Corradini. 2016. *MapShed version 1.5: Users guide*. University Park, PA: Penn State Institutes of Energy and the Environment.

Leopold, L. B. 1994. *A view of the river.* Cambridge, MA: Harvard University Press.

Loucks, D. P., and E. van Beek. 2005. *Water resources systems planning and management: An introduction to methods, models and applications*. Paris: UNESCO.

McCutcheon, S. C. 1989. *Water quality modeling: Volume I, River transport and surface exchange*, 334. Boca Raton, FL: CRC Press.

Mysiak, J., C. Giupponi, and P. Rosato. 2005. "Towards the development of a decision support system for water resource management." *Environ. Modell. Software* 20 (2): 203–214. https://doi.org/10.1016/j.envsoft.2003.12.019.

NRC (National Research Council). 2001. *Assessing the TMDL approach to water quality management*. Washington, DC: National Academy Press.

Quinn, N. W. T. 2004. *WETMANSIM v. 1.00: Wetland management simulator: Spreadsheet model of potential water quality impacts of Level IV water supply on salt loading to the San Joaquin River.* Technical Memorandum. US Bureau of Reclamation.

Renard, K. G., G. R. Foster, G. A. Weesies, D. K. McCool, and D. C. Yoder. 1997. *Predicting soil erosion by water: A guide to conservation planning with the revised soil loss equation (RUSLE): Agriculture handbook No. 703*. Washington, DC: US Dept. of Agriculture Agricultural Research Service.

Risley, J., A. Stonewall, and T. Haluska. 2008. "Estimating flow-duration and low-flow frequency statistics for unregulated streams in Oregon." US Geological Survey Scientific Investigations Rep. 2008-5126, Revision 1.1. Accessed August 15, 2017. http://pubs.usgs.gov/sir/2008/5126/section3.html.

Schueler, T. S. 1987. *The Simple Method in controlling urban runoff: A practical manual for planning and designing urban BMPs*. Washington, DC: Metropolitan Washington Council of Governments.

SCDHEC (South Carolina Department of Health and Environmental Control). 2010. "Total maximum daily load document RS-05590, Big Creek watershed: Fecal Coliform bacteria." Accessed August 15, 2017. https://www.scdhec.gov/HomeAndEnvironment/Docs/tmdl_bigCreek.pdf.

Tasker, G. D., and N. E. Driver. 1988. "Nationwide regression models for predicting urban runoff water quality at unmonitored sites." *Water*

Resour. Bull. 24 (5): 1091–1101. https://doi.org/10.1111/j.1752-1688.1988.tb03026.x.

Theurer, F. D., K. A. Voos, and W. J. Miller. 1984. *Instream water temperature model*. Rep. No. FWS/OBS-84/15. US Fish and Wildlife Service. [18]

Thomann, R. V., and J. A. Mueller. 1987. *Principles of surface water quality modeling and control*. Harper & Row. [19]

USDA. 2003. "Revised universal soil loss equation 2." Accessed August 15, 2017. https://www.ars.usda.gov/southeast-area/oxford-ms/national-sedimentation-laboratory/watershed-physical-processes-research/research/rusle2/revised-universal-soil-loss-equation-2-overview-of-rusle2/.

USEPA. 1983. *Results of the nationwide urban runoff program*. Final Rep. Washington, DC: USEPA.

USEPA. 1999. *Protocol for developing nutrient TMDLs (first edition)*. Rep. No. EPA 841-B-99-007. Washington, DC: USEPA.

USEPA. 2005. *TMDL model evaluation and research needs*. Rep. No. EPA/600/R-05/149. Washington, DC: USEPA.

USEPA. 2007. *An approach for using load duration curves in the development of TMDLs*. Rep. No. EPA 841-B-07-006. Washington, DC: USEPA.

Walker, W. W. 1985. *Empirical methods for predicting Eutrophication in impoundments: Report 3. Phase III: Model refinements*. Technical Rep. E-81-9. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Walker, W. W. 1986. *Empirical methods for predicting Eutrophication in impoundments: Report 3. Phase III: Applications manual*. Technical Rep. E-81-9. Vicksburg, MS: US Army Engineer Waterways Experiment Station.

Voinov, A. A. 2008. "Conceptual diagrams and flow diagrams." In *Encyclopedia of ecology*, edited by S. E. Jørgensen and B. D. Fath, 731–737. Elsevier. [20]

Wischmeier, W. H., and D. D. Smith. 1978. *Predicting rainfall-erosion losses: A guide to conservation planning: Agriculture handbook No. 537*. Washington, DC: US Dept. of Agriculture Agricultural Research Service.

Zhang, H. X. 2005. "Water quality models for developing soil management practices." In *Water encyclopedia: Vol. 1: Water quality and resource development*, edited by J. H. Lehr, 248–255. New York: Wiley.

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