burn severity on runoff and erosion parameters (Goodrich et al. 2012), which supports the use of burn severity maps (Figure 2) to assess fire impacts at a watershed scale. BAER teams are interested in identifying areas of concern both within the burn area (Figure 3) and

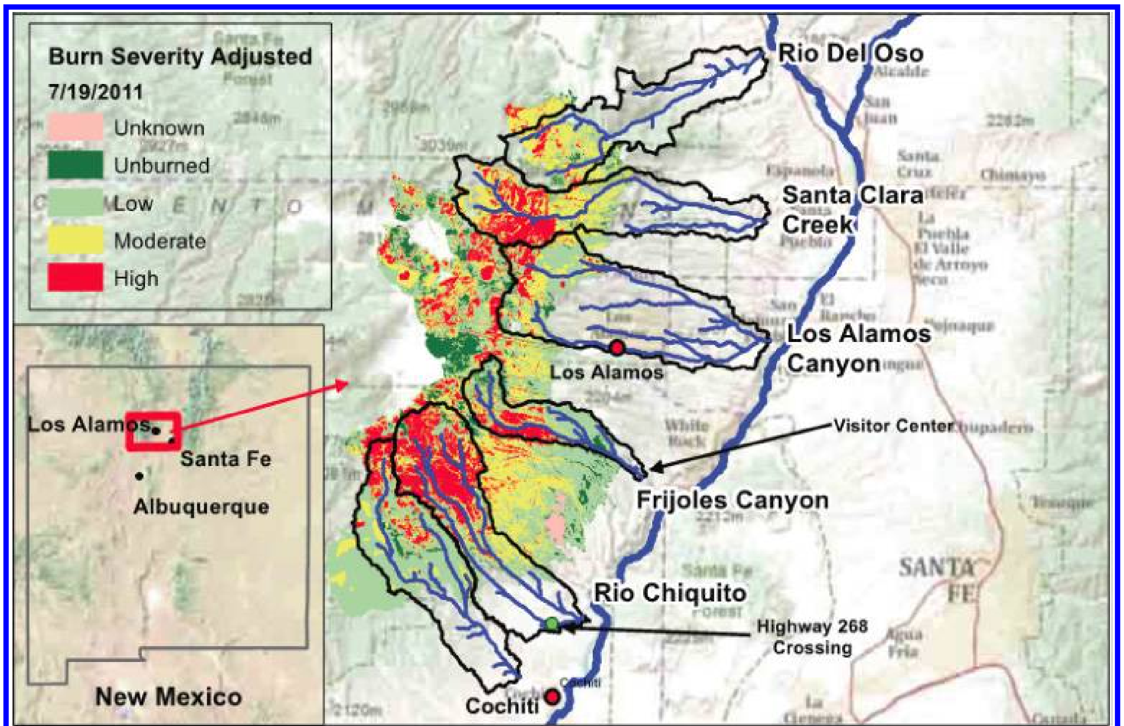

Figure 2: Burn severity map for the Las Conchas fire New Mexico, July 2011 (from Goodrich et al. 2012).

downstream, such as increased risk of flooding (Figure 4). Since wildfire severity impacts post-fire hydrological response, fuel treatments can be a useful tool for land managers to moderate this response. Sidman et al. (2015) conducted a spatial modeling approach that couples three models used sequentially to allow managers to model the effects of fuel treatments on post-fire hydrological impacts. Case studies involving a planned prescribed fire at Zion National Park and a planned mechanical thinning at Bryce Canyon National Park were used to demonstrate the approach. Fuel treatments were modeled using FuelCalc and FlamMap within the Wildland Fire Assessment Tool (WFAT). The First Order Fire Effects Model (FOFEM) was then used to evaluate the effectiveness of the fuel treatments by modeling wildfires on both treated and untreated landscapes. Post wildfire hydrological response was then modeled using KINEROS2 within AGWA. This approach provides a viable option for landscape scientists, watershed hydrologists, and land managers hoping to predict the impact of fuel treatments on post-wildfire runoff and erosion and who want to compare various fuel treatment scenarios to optimize resources and maximize mitigation results.

Built Environment Assessment: The K2 model can be used to predict runoff and peak flows in a built environment (Kennedy et al. 2013). Additionally, new tools have been designed for AGWA to parameterize K2 for built environments. The GI/LID (Green Infrastructure/Low Impact Development) tool will allow users to assess the impacts of LID practices on flooding and stormwater capture (Korgaonkar et al. 2014). The K2 model can represent the effect of water harvesting, detention/retention basins, pervious surfaces, and channel modification. Tools have also been developed that allow the user to describe the characteristics of a home lot, with and without LID practices and to manually define the flow network within an urban watershed. The impact of different combination of LID practices can be assessed and compared to obtain the "optimal" design.

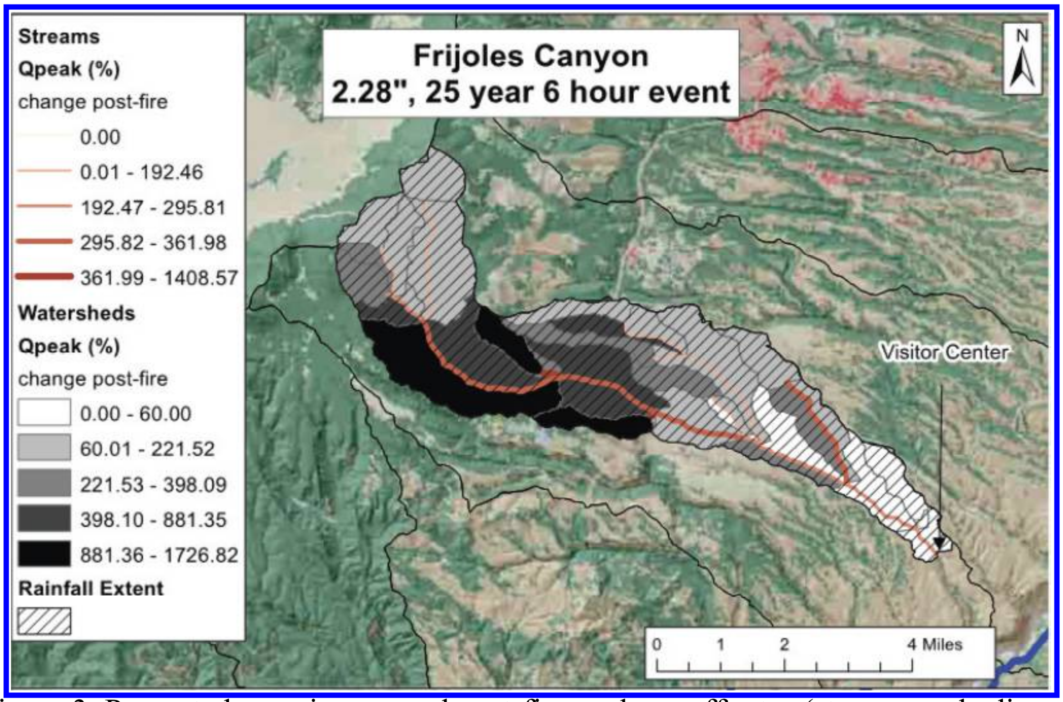

Figure 3. Percent change in pre- and post-fire peak runoff rates (streams and adjacent contributing areas) for the 6-hour, 25-year design storm as simulated by AGWA/KINEROS2. The diagonal shading indicates spatially uniform application of rainfall over the entire watershed (from Goodrich et al. 2012).

CONCLUSIONS

AGWA is a GIS-based hydrologic modeling tool that supports many aspects of watershed assessment and analysis including identifying areas at risk based on current or future conditions, evaluating effectiveness of LID (built environments) and BMP (range environments) practices, and supporting post-fire assessments. Future research will include incorporating the ability to model nitrogen and phosphorus loads in built environments. More LID practices (e.g. swales, bioretention facilities, infiltration basins, and filter strips) will be included in the GI/LID tool. Improvements are being made in the post-fire parameterization to better represent temporal changes associated with post-fire recovery.

ACKNOWLEDGEMENTS

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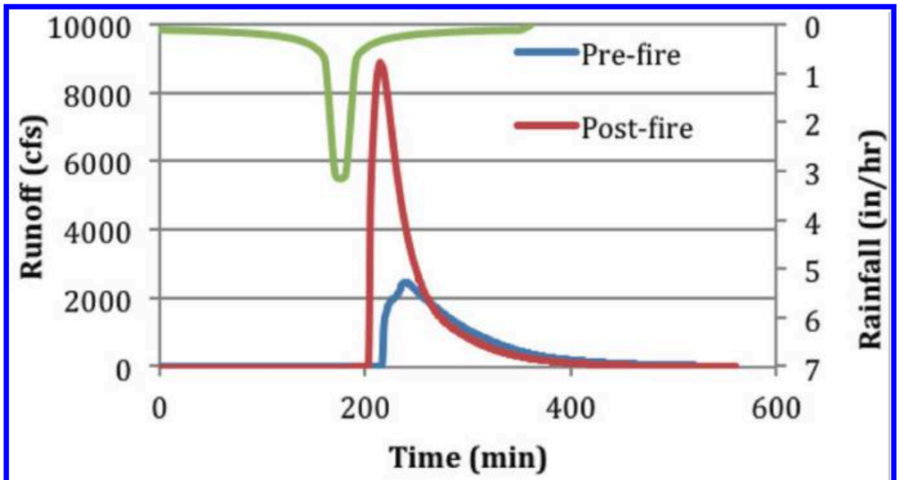

Figure 4. Simulated pre- and post-fire hydrographs at the Frijoles watershed outlet adjacent to the Bandelier National Monument Visitor Center for the 6-hour, 25-year design storm of 58 mm (2.28 in.) (from Goodrich et al. 2012).

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TMDL Modeling Approaches, Model Surveys, and Advances

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Abstract

Under section 303(d) of the Clean Water Act, states, territories, and authorized tribes are required to develop lists of impaired waters, those not meeting water quality standards, and establish priority rankings and Total Maximum Daily Loads (TMDLs) for those waters. The TMDL is the maximum load that a waterbody can receive and still meet water quality standards and includes loads from point sources and well as non-point and background sources, along with a margin of safety. Mathematical models are commonly used to establish the linkage between material loading from the watershed and point sources and the water quality response of the receiving water body in order to establish the TMDL and evaluate implementation alternatives. The selection and application of credible models are crucial steps in the TMDL process. The ASCE/EWRI TMDL Analysis and Modeling Task Committee was established, in part, to conduct comprehensive review and evaluation of available approaches and models for TMDL development. A series of available models were reviewed, including watershed, hydraulic, and water quality models applicable to TMDL development. The source, capabilities and applicability of each model or modeling approach was summarized. As part of that review, a survey was conducted for each state of selected approved TMDLs in order to identify what approaches and models were in common usage by waterbody type and cause of impairment. This paper provides a summary of the task committee's review of modeling approaches and advances in those approaches as well as a summary of the state TMDL survey.

Keywords:

Models; Total maximum daily loads; TMDL; Water quality.

INTRODUCTION

A Total Maximum Daily Load (TMDL) is part of a process whereby impaired or threatened waterbodies and the pollutant(s) causing the impairment are systematically identified and a scientifically-based strategy—a TMDL—is established for correcting the impairment and restoring the waterbody or eliminating the threat of impairment (USEPA 1999a). While in the past, regulatory control has focused on individual waterbodies and point sources, under the TMDL process all sources (point and non-point) must be considered (USEPA 1991; USEPA 1999a, b; USEPA 2001; USEPA 2002a, b), which poses unique scientific and regulatory challenges.

The TMDL is inherently a quantitative analysis (Figure 1a), whereby first the problem is identified and numeric targets, or endpoints, must be established that equate to attainment of the water quality standard in order to compute a TMDL. Point, non-point, and background sources of pollutants entering the receiving water of concern must be identified and quantified. For non-point source assessment, mathematical models are often used to estimate nutrient runoff, erosion, and other loading rates (USEPA 1991). A quantitative link between sources and targets, or cause-and effect relationship, must then be established to determine the capacity of the waterbody to assimilate loads in order to establish the maximum allowable pollutant load to address the site-specific nature of the problem. The loading, or assimilative capacity reflects the maximum amount of a pollutant that may be delivered to the waterbody and still achieve water quality standards (USEPA 1999a). Here also predictive water quality models are typically used to develop linkages between sources and targets (Martin and Kennedy 2000).

The sequence of events in the water quality modeling process (Figure 1b, Chapra 2003), begins with the selection of the appropriate modeling tool, then the application of the tools to available data, determining the reliability of the tool and then the use of the modeling tools in supporting decisions. As with the TMDL process, the modeling process is often iterative and the process is adaptive (Chapra 2003), with each step providing feedback to other steps, as indicated by the two-way arrows.

While the typical sequence of events in the TMDL and modeling process may be similar or the same, the specific steps in and tools used in the process may vary widely depending on the complexity of the issues, pollutant of concern and waterbody (e.g. rivers and streams, lakes and reservoirs, estuaries and coastal waters). Model structure is often specific to types of pollutants of concern, while there are a wide variety of pollutants causing impairments, as illustrated by Figure 2 for the top 25 causes of impairment (making up 85% of the total listed impairments), ranging from conventional pollutants (e.g. pathogens, nutrients, algae, oxygen), to toxic materials and invasive species. However, in TMDL applications another issue is that the nature of TMDLs is driving the watershed-based paradigm to water quality modeling. As a result, often multiple models must be linked over multiple media (Figure 3) to relate the loadings (point and non-point) and management alternatives (e.g. best management practices) to the end point (attainment of water quality).

The selection of appropriate models and the implementation of those models is often a difficult task, and that selection may often be based on issues other than purely technical, such as due to constraints posed by time, funding and data. Since the selection of appropriate and credible models and consideration of their implementation issues are crucial steps for TMDL development and analysis an ASCE/EWRI TMDL Analysis and Modeling Task Committee (Padmanabhan et al. 2014) was established to review the appropriate models and associated issues for TMDL development. The Task committee is under the ASCE/EWRI Watershed Management Technical Committee, Watershed Council and was formed in September 2011. The overall goal of the task committee is to produce a guidance document relevant to the TMDL modeling process and implementation issues. This paper will first provide an overview of the models under review. The source, capabilities and applicability of each model or modeling approach are summarized. In addition, an informal survey was conducted for each state of selected approved TMDLs in order to identify what approaches and models were in common usage by waterbody type and cause of impairment.

MODEL OVERVIEW

Over the past 75 years, engineers have developed water quality models to simulate a wide variety of pollutants in a broad range of receiving waters (Chapra 2003). The development and evolution of many of these water models was described by Chapra (2011) in which he divided the evolution of water-quality modeling into four stages related to dissolved oxygen (1925–1960), computerization (1960–1970), eutrophication (1970–1977) and toxic substances (1977–1990). These models were typically developed and confined in their application to receiving waters, and often specific to a particular type of receiving waters (e.g. one-dimensional models of rivers and streams).

Over these same periods, models of hydraulics and sediment transport were developed, usually for purposes other than water quality such as hydraulic design, prediction of sedimentation and scour, etc. Similarly, a variety of hydrologic models were developed, primarily for predicting runoff and flooding, with the development of the first comprehensive model the Stanford Watershed Model (Crawford and Linsley 1966). During this period the widely used HEC-1 model was developed by the USACE Hydrologic Engineering Center which later became HEC-HMS along with HEC-2 which became HEC-RAS (*http://www.hec.usace.army.mil/software/hec-ras/downloads.aspx*).

Also, the SWMM, Storm Water Management Model (Huber and Dickson 1988) was developed for the USEPA for runoff in storm sewer systems. Similarly, the USDA Agricultural Research Service USDA (ARS) developed a series of models for predicting water and sediment runoff.

During the stages of evolution described by Chapra (2011) and the first 30 years following the Clean Water Act (CWA) the focus was on point sources, and water quality models were often based on steady-state conditions, where critical conditions were low flows (e.g. 7Q10) and high temperatures for waste load allocations related to oxygen. However, for those waterbodies which following implementation of point source controls that still do not meet basic water quality standards (are impaired) TMDLs are required which includes allocation of both point source loads (the Wasteload Allocation or WLA) and non-point source loads (the load allocation or LA). The TMDL Program was brought to the regulatory forefront in part due to the large number of lawsuits filed by environmental groups against the states and the EPA, beginning in the 1980's but primarily through the 1990's. The shift in focus from waste load allocations to implementing TMDLs required a water quality modeling paradigm shift from steady-flow point sources and in-stream environment to the watershed and TMDLs are essentially driving the watershed approach to water quality management (Martin and Kennedy 2000).

The TMDL modeling approach then often required the linkage of watershed, hydrodynamic and water quality models. In some cases atmospheric loads or models were also required (e.g. for mercury where atmospheric deposition is often a significant source). Groundwater models were also required in some applications to estimate loads from the groundwater or surface/groundwater flow interactions (Figure 3). The issue was that in many cases these models were not designed to work together and/or not designed for the continuous simulations required for TMDLs. The result was often a "Patchwork Quilt" of models, a term commonly used to refer to "a collection of miscellaneous or incongruous parts; a jumble" as opposed to a seamless integrated modeling system designed for the purpose of establishing TMDLs.

Many of the problems and issues associated with models and modeling systems for TMDLs have been resolved over the last decade, but many issues remain. In many cases the issues impacting the selection and application of models are site and chemical specific, such that the selection of an appropriate modeling system is critical.

There have been a variety of documents and papers providing guidance on models and model selection. USEPA (1991) provided guidance on model applications. Shoemaker et al. (1997) in the "The Compendium of Tools for Watershed Assessment and TMDL Development" summarized available techniques and models, including watershed-scale loading models, field-scale loading models, receiving water models, and integrated modeling systems that, for example, link watershed-scale loading with receiving water processes. Shoemaker et al. (2005) provided a more updated review of available models and examined modeling research needs to support environmental decision-making for the 303(d) requirements for development of total maximum daily loads (TMDLs) and related programs such as 319 Nonpoint Source Program activities, watershed management, stormwater permits, and National Pollutant Discharge Elimination System (NPDES) discharge evaluations. Borah and Bera (2003, 2004) reviewed the mathematical bases and applications of watershed-scale hydrologic and nonpoint-source pollution models. Muñoz−Carpena et al. (2006) lead a group of researchers (committee) who reviewed the status of TMDL modeling tools and published a set of articles on models for different impairments.

The models under review by the ASCE/EWRI TMDL Analysis and Modeling Task Committee include what are considered to be: A) simple or Analytical Models, B) Watershed Models, and C) Receiving Water Models. In addition, the committee is reviewing integrated modeling systems (e.g. BASINS) that provide data and or linkages for multiple models. This paper is limited to a listing and brief discussion of the model groups above (A-C).

Analytical Models

Analytical models and procedures range from simple mass balance expressions to analytical models, most of which can be applied with a minimum of data and time. These models, as described in the following section, are commonly used in TMDL development. The methods and models under review by the ASCE/EWRI TMDL Analysis and Modeling Task Committee include:

1. Simple Mass Balance Models: These models are based on simplified mass balance relationships, typically assuming a completely mixed reactor, a non-reactive material, and steady-state conditions such as in the form of (Chapra 1997)

$$C = \frac{1}{Q}W; \quad W = QC \qquad \text{Equation 1}$$

   where (W) is the rate of loading, the assimilative capacity is only due to flow (Q), and C is the concentration (e.g. the standard).

2. Load Duration Curves (USEPA 2007): Cumulative frequency curve of daily mean flows without regard to chronology of occurrence (Leopold, 1994) converted to load duration by multiplying the flow values by the applicable water quality criterion or target and a conversion factor. The independent x-axis is the Flow Duration Interval (FDI) or "percent of time", as in a cumulative frequency distribution, while the y-axis represents the load value associated with that percentage (rather than the flow).
3. SIMPLE METHOD: The Simple Method (Schueler, 1987) is an approach to rapidly estimate loads based on available information such as sub-watershed drainage area and impervious cover, and stormwater runoff concentrations. Load estimates are the product of annual estimated runoff volume and pollutant concentration.
4. RUSLE2: USDA-Natural Resources Conservation Service, public domain, modification and update of universal soil loss equation; predicts rill and interrill erosion by rainfall and runoff. Database available that includes climate and soils descriptions for every county in the United States.
5. BATHUB: This model was developed for the USA Corps of Engineers and has limited distribution. This is an empirical, steady-state eutrophication model applicable to lakes and reservoirs, and based on empirical assessments of reservoir data (Walker, 1985; 1986).
6. SSTEMP: This USGS supported model simulates steady-state stream temperatures for a specified time period and location in a stream or river (Bartholow, 2010).