FSPPC112

UNIVERSITY OF ARKANSAS
DIVISION OF AGRICULTURE
PUBLIC POLICY Center

The Role of Nonpoint Source Models in Watershed Management

Introduction

The U.S. Environmental Protection Agency (USEPA) considers nonpoint sources of sediment, nutrients and pesticides as one of the leading causes of water quality impairments (USEPA, 2010a). By definition, nonpoint source contaminants are much harder to identify and thus, more difficult to manage than point sources. This is confounded by the fact that landscape hydrology is highly variable both spatially and temporally. Consequently, efforts by the USEPA to address nonpoint sources occur at a watershed scale. A watershed is the area of land where all of the water that is under it or drains off of it goes into the same water body (Daniels et al., 2006 and 2009).

> Models integrate information over a watershed to identify Best Management Practices and critical source areas most likely to affect watershed-scale nutrient losses.

Because of the time and expense involved in monitoring water quality response to implementation of conservation measures and the growth and accessibility of computer capacity, simulation models are increasingly used to estimate the effects of watershed management. Computer simulation models represent mathematical descriptions of scientific understanding about chemical, physical and biological processes that influence both point and nonpoint source contaminant loads within a watershed. In their most comprehensive form, models can integrate information over a watershed scale to evaluate Best Management Practices (BMPs). As such, models can suggest where BMPs are most likely to decrease watershed-scale nutrient losses. In the case of TMDL (Total Maximum Daily Load) development, models can allocate load reduction targets among the model's identified contaminant sources. Thus, use of nonpoint source models provides a method of simulating long periods to estimate the relative effects of changes in climate, land use and land management practices on sediment and nutrient loadings from large, complex watersheds. As a result, models yield numerical results with which to gauge progress. This numerical ranking simplicity provides strong appeal to policymakers and managers; however, this appeal can sometimes bring false confidence and misconceptions (Boesch et al., 2001).

> "All models are wrong; some models are useful." — George Box

Model credibility can be achieved through a careful process of calibration, verification and validation. The definitions used here are derived from the work of Thomann and Mueller (1987). **Calibration** is an iterative process of fine-tuning the model to a set of field data, preferably data that were not used in the model construction. **Verification** is the statistical comparison of the model output to additional data collected under different forcing and boundary conditions. Finally, **validation** is achieved through calibration and verification so that the model is an accurate representation of the real system or watershed being assessed.

> There are many models available; selecting the right one for the job is critical.

Types of Models

Shirmohammadi et al. (2001) provided a comprehensive discussion of water quality models. They provide a list of models with their practical attributes in terms of their complexity, scale, purpose and level of validation. Shirmohammadi et al. (2001) also provide a long list of proper and improper uses of water quality models and conclude that one has to keep in mind the uncertainty associated with model simulations and use the results with caution, especially when applying a model outside the conditions used in calibration and verification.

It is of critical importance that model developers clearly define what the model is useful for and what it is not designed to do. Likewise, users must decide what they want to accomplish with a model. For example, one must consider the scale (field, watershed or basin), time (flow event, annual or multi-year) and level of accuracy (0.1 or 10 kg ha^{-1} $year^{-1}$) that needs to be simulated, as well as the amount and quality of data available. It is incumbent on the modeler to explicitly express the assumptions made in representing the system which is being modeled. These assumptions affect the model outcome. Violation of these assumptions may ultimately affect decisions based upon modeled results.

> Models play an important role in making watershed management and policy decisions to identify critical source areas and target BMPs.

Despite such cautionary realities, the role of models will be more and more important over the next decade in making watershed management and policy decisions to identify critical source areas and target BMPs. However, as Silberstein (2006) points out, the use of models to evaluate scenario outcomes often results in use outside the tested boundaries of models, with little or no data to constrain the scenarios. It is, therefore, critical that any use of nonpoint source models must be associated with data collection and monitoring to further verify model estimates.

Silberstein (2006) best summarized the role of nonpoint source models in watershed management assessment and prioritization of future actions, and rather than paraphrase his text, it is quoted below.

"Models are enormously useful as test beds for ideas and for exploring the implications of our understanding of natural systems. They are extremely valuable as data processing and analysis aids, often showing up data errors and inconsistencies that might otherwise have gone unnoticed. Models are also useful for exploring scenarios that cannot be tested in the real world. However, while this last use is a rapidly expanding one, it is also the most dangerous. As high level managers appreciate the nice graphics and, possibly, simplistic sets of options, it can be easy to lose sight of the limitations of the process that generated them. It is in this mode that models are often run outside their tested bounds, and by definition little or no data are available to constrain the scenario results. If we are to continue to learn about and improve our management of our environment, we must continue to observe it, and that means collecting data. Modeling is an important accompaniment to measurement but is no substitute for it. Science requires observation, and without that we will cease to progress in understanding our environment and, therefore, in managing it appropriately."

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Uncertainty

Uncertainty arises because of an imperfect representation of the physics, chemistry and biology of the real world, because of numerical approximations, because of inaccurate parameter estimates, and data input (Harmel et al., 2006; Shirmohammadi et al., 2006). Causes of model uncertainty can be broadly classified into model uncertainty (i.e., assumptions in mathematical equations describing relationships among complex chemical, physical and biological processes) and input uncertainty (i.e., spatially and temporally variable data representing land use and management). For example, there is a cumulative uncertainty associated with water quality monitoring used for model calibration. This uncertainty is derived from stream flow measurement, sample collection, sample preservation and storage, and analysis (Toor et al., 2008). Standardized methods to quantify this uncertainty involve forcing the model to "fit" historically measured data, if available, with predetermined limits of performance (Harmel et al., 2010). This will assist modelers in quantifying the "quality" of calibration and verification data, determining model accuracy goals and evaluating model performance. Whenever possible, the uncertainty should be represented in the model output (e.g., as a mean plus a standard deviation) or as confidence limits on the output of a time series of concentrations or flows. In many cases, the knowledge of the cause and effects of uncertainty, as well as the measurement of uncertainty, is as or more important than the model output in making "real-world" management decisions.

> Inherent uncertainty in model estimates should be clearly stated.

The tendency described earlier for decision makers to "believe" models because of their presumed deterministic nature and "exact" form of output must be tempered by responsible use of the models, such that model computations or "estimates" are not oversold or given more weight than they deserve (Boesch et al., 2001). Above all, model users should determine that model computations are "reasonable" in the sense of providing output that is physically realistic and based on input parameters that are within accepted ranges. Modelers should use all available measurements and multiple levels of comparison to evaluate if model estimates are physically realistic.

While there are many nonpoint source models available such as HSPF (Hydrological Simulation Program Fortran; Bicknell et al., 1997) and SPARROW (SPAtially Referenced Regressions On Watershed attributes; Preston et al., 2009), one of the more commonly used and widely supported models is the Soil and Water Assessment Tool (SWAT; Arnold et al., 1998; Gassman et al., 2007). This model is being used in several watershed programs in Arkansas to assess the efficiency of implementing various conservation practices on nutrient loss reductions, as well as prioritization of areas for targeted management.

Watershed landscapes are a complex patchwork of different topography, geology, soils and land use. To address this, SWAT breaks the landscape into small units of equal area. The model assumes that a dominant land use, soil type, slope and management operations cover each of these land units. While this is an approximation of reality, it is a modeling necessity, which introduces uncertainty.

> Models, like SWAT, are used in several watersheds to assess the efficiency of conservation practices on nutrient loss reductions.

Most widely used nonpoint source models are continuously being revised and updated as new research information becomes available. Some needed model improvements, specifically relevant to their use in Arkansas watersheds, include:

- New routines differentiating the fate in soil of land-applied manure from fertilizer are needed. For instance, in the current SWAT model, all the phosphorus in manure is assumed to interact with soil within one day of application and be transferred into various forms of soil phosphorus of differing availability. This is an approximation of reality, as manure (particularly poultry litter) releases phosphorus slowly over a growing season for plant uptake or loss in runoff, when rainfall induced surface flow occurs.
- While delineating subwatershed boundaries, modelers have to use best judgment as to how to route flow, nutrients and sediments from a headwater subwatershed to downstream subwatersheds. This introduces some unknown level of uncertainty in the model estimates.
- Most watershed-scale models have limited in-stream components, which are extremely important in buffering nitrogen and phosphorus inputs from both edge-of-field nonpoint sources and point sources. In-stream processes can act as sinks or sources of nutrients to receiving lakes and reservoirs that can mask water quality responses to implementation of BMPs and land conservation. Thus, accurate simulation of the forms of nitrogen and phosphorus transported in streams is vital to selection of appropriate BMPs or remedial measures that would most effectively bring about an improvement in water quality.

> Every watershed is different in ways we can't always identify or estimate, such that it's dangerous to use a model calibrated for one watershed to estimate changes in another watershed.

Challenges to Prioritizing Watersheds

There are unique challenges to the reliable estimation of flow, nutrient and sediment discharge using nonpoint source models relevant to Arkansas, which include:

- It is essential that all nutrient inputs and sources in the watershed be accurately represented and quantified. For example, in watersheds with significant urban development, there has been limited data available on nutrient (particularly nitrogen) discharge from wastewater treatment facilities. To address this, assumptions of discharge related to population size and growth as well as wastewater treatment technology have to be made, bringing uncertainty to model estimates. If during the calibration process, point source inputs are underestimated or overestimated, this will be reflected in estimates of nonpoint source contribution.
- Nutrient transformation, fate and discharge from wetland areas are poorly simulated by many landscape models. Thus, in watersheds with a significant portion as wetlands, estimation of flow, nutrient and sediment discharge will have a high degree of uncertainty, particularly at smaller watershed scales.
- Limited data on septic system number, age, location and efficiency of operation will affect estimation of nutrient discharge from watersheds with a large number of such systems.
- Adequate long-term (~ 10+ years) monitoring is essential to reliable model calibration. In many watersheds outside Northwest Arkansas, this is limited. Despite the presence of several U.S. Geological Survey flow-monitoring gauges in some watersheds, there is often a limited amount of long-term water quality data that would be sufficient to estimate nutrient and sediment loads in streams (representative of storm and base flow). A well-distributed network of monitoring stations across all land uses, topographic conditions and subwatersheds of the larger watershed would assist in model evaluation and verification when estimating at smaller scales.
- Estimated nutrient and sediment loads have some inherent uncertainty based on discharge measurements and water sample collection, handling and analysis. The technique to estimate nutrient and sediment loads also introduces some degree of uncertainty, which is not often quantified or reported.
- Assumptions are made as to the application of poultry litter to land within a certain distance of the producing farm. Effective litter transport programs can influence these assumptions and the estimation of nutrient loss from pastures.

Conclusions

Calibrated process models of watershed runoff and water quality tend to be more useful as forecasting (extrapolation) tools than quantitative predictors of contaminant transport. Because most water quality models employ similar conceptual formulations for modeled processes, databases of typical model parameters would greatly help in application of such models, as well as for hydrologic parameters. Parameters used to model BMPs (e.g., removal efficiencies) are even sparser. In reviewing these challenges a decade ago, the National Research Council concluded and recommended that "agencies that sponsor watershed and water quality models should also sponsor development of databases of typical modeling parameters and case studies; such databases and meta-databases would inordinately ease the effort in modeling new locations" (National Research Council, 2000).

In spite of the effort and resources expended on the Chesapeake Bay model (Linker et al., 2002; USEPA, 2010b), it was suggested a decade ago that "...three caveats need to be appreciated in interpretations of the watershed-water quality models: (1) the model estimations are very sensitive to several uncertain assumptions, (2) the models estimate 'average' conditions in a variable world and (3) the models assume immediate benefits of source reductions in the Bay's tidal waters" (Boesch et al., 2001). Unfortunately, these caveats are still true and relevant to any watershed to which models are applied.

Models can be useful tools for the synthesis and evaluation of our understanding of systems. As management tools, they can only begin to describe the variables specified per se in the model. Management concepts such as "sustainable, healthy ecosystems" are not quantifiable and cannot be a variable estimated from a numerical model. Great care must be given to identifying the appropriate parameters to estimate and the measures to be applied to these parameters. The assumptions that enter into this definitional process are often as important as the science developed in an attempt to achieve the stated goals.

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FSPPC112-7-11N