Nonpoint Source Pollution: Why TMDLs are Controversial*

Richard Shepard, PhD
Applied Ecosystem Services, LLC

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Introduction

Nonpoint source pollution (NPS) policy and regulation under the Clean Water Act (CWA) is difficult for regulatory agencies, and is open to challenge as being too restrictive or not sufficiently restrictive. The accepted standard for regulating nonpoint source pollutants are total daily maximum loads (TMDLs) which affect all natural resource operations, among others.

The two major questions regulators need to answer are:

1. How to predict contaminant concentrations in unsampled areas?
2. How to determine sources and their relative contributions to support TMDLs?

NPS, by definition, originates from broad areas of residential, commercial, and industrial activities; that is, almost everywhere. Contaminants of concern include toxic metals (e.g., mercury, arsenic, cadmium, zinc), plant nutrients (e.g, nitrate and phosphorus), and organic compounds (e.g., herbicides, insecticides, rodenticides, fungicides). The two biggest issues involved with developing NPS regulations such as TMDLs and aquatic life criteria are the lack of sufficient data and how existing data are analyzed.

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While most NPS regulatory attention is focused on aquatic ecosystems (stream networks and river basins), the issues of data paucity and appropriate analytical methods also applies to soils (such as former industrial sites called brownfields) and sediments under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA; also known as Superfund) among other environmental laws.

Data

The most frequent challenge to any proposed environmental regulatory action is the paucity of data used to make the decision. This is true for regulations under the Clean Water Act, Endangered Species Act (ESA), National Environmental Policy Act (NEPA), Comprehensive Environmental Response, Compensation, and Liability Act, and others. Environmental data are not collected as are data for research projects; most are baseline or compliance monitoring collections supporting regulatory approvals. Sample sites tend to be clustered around metropolitan areas and widely dispersed throughout the rest of the drainage basin. Collection frequency is sporadic and not on a period that captures the variability of the data collected. Unless a permitted site is on a wadeable stream sample collection locations tend to be based on convenience of access (e.g., a bridge with safe parking on either side) and ease of obtaining water (e.g., lower a bucket on a rope and bring it up full.)

The spatial and temporal variability of environmental data, especially those used to make policy and regulatory decisions, need to be analyzed using methods that accommodate these conditions. Unfortunately, these methods are not always applied because they are not familiar to many environmental data analysts. This makes how these data are analyzed, interpreted based on established ecological theory, and explained to nontechnical decision-makers and the public the most important aspect of addressing nonpoint source pollution and establishing technically sound and legally defensible TMDLs appropriate for each portion of the river network and adjacent land uses.

Geochemical data (the chemical constituents in water, sediments, soils, and rocks) are very different from business, financial, and other, more familiar types of data. These differences mean that analytical models developed for the other types are almost always wrong for geochemical data.

Some of these differences include:

- Chemical concentrations can never be less than zero. This means that models that allow negative values produce incorrect answers when applied to environmental chemical data. For example, any descriptive or explanatory statistical model that is based on the Gaussian (normal) frequency distribution (the familiar "bell curve") can have negative values, which chemical concentrations cannot have.
- Toxic metals and organic contaminants are commonly in such low concentrations that they cannot be detected by the analytical chemist using electronic instruments; that is, the concentration "signal" cannot be distinguished from electronic circuitry "noise." These nondetects (censored) data are frequently as high as 80% of all samples analyzed. The censored data represent important information about the composition of the geochemical sample and must be properly incorporated into calculations of basic descriptive statistical summaries of the data (mean, variance, standard deviation), ecotoxicology, and forecasts of future concentrations of that constituent.
- When a sample of water, sediment, or soil is sent for chemical analysis only a limited set of constituents are examined. There may be dozens of metals and hundreds or thousands of of inorganic and organic compounds in the sample so the measured set is not representative of the complete chemical environment. Mining geochemists were the first to recognize the importance of these limited compositions of chemical constituents and developed the theoretical and statistical basis for analyzing them. Briefly, each set of analyzed chemicals is a defined composition and it is the relative proportions of each element in the composition that has meaning.

Use of any data analytical model that assumes environmental data are no different from other data will produce wrong results. Applying wrong results to environmental policies and regulations cannot achieve the intended results.

Analyses

The goal of TMDLs is to reduce pollutant concentrations in surface and ground waters. To effectively determine practical limits on the discharge

of contaminants requires knowing local sources and concentrations. By definition, nonpoint sources of pollutants are diffuse so sources and quantities must be assessed indirectly by measuring concentrations in various media throughout the area of interest. Under the best circumstances, NPS regulatory decisions are based on limited data. This means that the analyses must be appropriate for comparatively small data sets and accommodate the lack of regular sampling intervals as well as spatial and temporal variability. In other words, the analytical models must be fit to the available data rather than trying to force the available data into a rigidly-structured model.

Two fundamentally different types of geochemical analytical models are available for analyzing contaminant concentrations in waters, sediments, and soils: deterministic differential equation models and stochastic/empirical statistical models.

Deterministic differential equation models

This type of model has been a mainstay of the EPA and other agencies since the 1970s. The most commonly used models include the Hydrological Simulation Program – FORTRAN (HSPF), Stream Water Quality Model (QUAL2E/K, and Biotic Ligand Model (BLM).

Deterministic means that the output of the next time step is determined by the value of the previous time step. The models attempt to simulate water quality conditions over time by using mathematical equations to define how concentrations change. The output of the equations at each time step is intended to represent the continuous dynamics of a river system.

There are many reasons why models such as HSPF, QUAL2E, and BLM produce flawed results, including use of fixed mathematical equations to represent natural ecosystem dynamics. This approach is explained in the HSPF version 10 User's Manual:

> "To design a comprehensive simulation system, one must have a consistent means of presenting the prototype, in our case the real world. We view it as a set of constituents which move through a fixed environment and interact with each other. Water is one constituent; others are sediments, chemicals, etc. The motions and interactions are called processes."

This is an engineering approach to the structure and function of natural

ecosystems. The model designer fixes how the system works and the user must then collect (or randomly assign) values for the many component inputs. Unfortunately for regulators and the regulated public, natural environments are not fixed; they constantly vary.

Another reason deterministic differential equation models do poorly as the basis for establishing environmental regulations is also found in the User's Manual for HSPF version 10:

> "The use of models that simulate continuously the quantity/quality processes occurring in the hydrological cycle is increasing rapidly. Recently there has been a proliferation in the variety of models and the range of processes they simulate. This has been a mixed blessing for the user. To get the benefits of simulation, he has to select a model ... then spend much effort massing and manipulating the huge quantities of data the model requires."

Rarely, if ever, are there huge quantities of environmental data available to analysts in support of environmental regulations such as TMDLs.. Of equal importance is accepting that river systems and the basins that drain into them are not deterministic; they are highly dynamic (that is, stochastic). For example, headwater streams in mountains vary in temperature by as much as 40°F from early morning to late afternoon during the summer. Physical, chemical, and biological activities at the same time of day vary by aspect (the compass direction of downstream flow), elevation, water velocity, and riparian zone cover.

Environmental regulators need to understand that deterministic models are used to simulate assumed, fixed processes of entire natural ecosystems, not to explain observed concentrations of contaminants at isolated locations at varying intervals of time. The processes could be theoretical while the measured concentrations are actual. Simulation of processes does not allow evaluation of cause-and-effect (locating sources of the concentrations measured at specific locations), permit prediction of concentrations at unmeasured locations, quantify the relationships of spatial and temporal variability, nor measure the amount of error in the models used.

Of greater importance to regulators and the regulated public is asking how such deterministic models answer the two questions in the introduction: how to predict concentrations in unsampled areas and how to determine causality in flowing water ecosystems that change spatially and tem-

porally on several different scales, from hourly, through seasonally and annually, to longer terms caused by changing climates.

Stochastic statistical models

Statistical models make no assumptions about the data to which they are applied, nor to natural ecosystems. They are based on well-established mathematical probability theorems and are fit to the existing data. Statistical models overcome the regulatory limitations of deterministic models such as those described above.

Because most environmental data used to determine and justify regulations are limited in abundance, and often not available for points (or areas) of particular interest, it is sometimes beneficial to simulate the behaviors of large data sets.

Statistical simulations are performed using different subsamples of the available data using bootstrap and Markov Chain Monte Carlo (MCMC) techniques. Such simulations usually involve tens of thousands to millions of simulations with the variability of outputs quantified and the one best fitting the existing data objectively determined.

There are multiple statistical models appropriate for environmental geochemical data. These models not only summarize descriptions of the existing data, but quantify causality (cause-and-effect), forecast (make predictions), quantify relationships among different components, and allow previous experiences to contribute to our understanding of natural ecosystem dynamics, including geochemical pollutants from diffuse, nonpoint sources.

Of particular value in assessing available water chemistry data to support TMDL allocations are spatial, and spatio-temporal, statistical models. There are three broad categories of spatial statistical models: point process, geochemical, and areal. Of the three, geochemical models are used to interpolate chemical concentrations at locations between defined sampling locations, and to extrapolate beyond the range of sampled locations. The results are predictions of how the constituent of concern is distributed throughout the river system, even though samples have not been collected and analyzed from the entire river network. Variability of concentrations are objectively quantified and can be measured over time at specific locations using spatio-temporal models. Of high value to regulators and the regulated public is that the goodness-of-fit of model results to the existing

data are quantified and can be compared among different models applied to the same data set.

Conclusion

Developers of deterministic differential equation models understand that they are applying their ideas of fixed processes in natural ecosystems to the the equations they use. The limitations of this approach in the real world of regulatory science should be of concern to everyone. How environmental data are analyzed to develop and justify environmental regulations should be a critical component of regulatory science. When the desired results are to be technically sound and legally defensible, apply appropriate statistical models. TMDLs as solutions to nonpoint source pollution need this analytical approach.