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Using SWAT to determine reference nutrient conditions for small and large streams

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ABSTRACT

Developing reference criteria for nutrient conditions on streams can be difficult especially in heavily farmed or urbanized regions where most of the landscape has been impacted by human development. SWAT (soil water assessment tool) simulations permit the removal of the anthropogenic impacted land use, allowing the simulation of natural conditions and a prediction of reference conditions. A Genesee River watershed simulation was developed to determine the nutrient and sediment contributions of subbasins of the Genesee River under the current human-impacted conditions and contrasted against natural conditions. Nutrient boundary values estimated for Genesee basin small wadeable streams (34.3 μg P/L) were nearly identical to those calculated by others for small, wadeable streams (30.7 μg P/L). For large streams, the simulation-based boundary total phosphorus (TP) value (75.8 μg P/L) of the Genesee River was high compared to other observations in New York State (30 μg P/L). Causes in the variability in large stream reference values include inappropriate use of regional reference conditions, stream bank erosion, basin geology, soil type, and catchment area. When river bank stabilization was added to the simulation, a 34.3% reduction in phosphorus loading was observed, resulting in a boundary value of ~54 μg P/L. This reduction in the simulated sediment load suggested that the Genesee River has a higher natural sediment and TP load than most streams in NYS. SWAT is an effective tool for simulations of small streams and may be an effective method in determining reference conditions for large rivers.

Introduction

The establishment of nutrient criteria is an important tool in managing streams and lakes. In 1996 the USEPA and USDA were directed to set criteria for nutrients in rivers, lakes, and estuaries, and by 2001 maximum acceptable levels of nutrients in streams and rivers were to be established (USEPA, 1998a,b). Stream-nutrient criteria allow state and federal agencies to evaluate aesthetic impairments, potential interferences on human use of the resource, and negative impacts on aquatic life and to determine if excessive nutrient inputs to downstream systems are occurring (Dodds and Welch, 2000). The establishment of meaningful nutrient criteria, however, is difficult and has developed into a science of itself.

Several approaches in developing nutrient criteria are evident. The total nitrogen/total phosphorus-classification scheme developed from data on 286 temperate streams by Dodds et al. (1998) is based on the cumulative frequency distributions of chlorophyll and nutrient concentrations whereby the lower 1/3 of the range was oligotrophic, the middle mesotrophic, and the top 1/3 eutrophic. These boundaries are convenient, but seem arbitrary, and may differ from region to region depending on soil P and N levels, land use, and the interaction between N and P. As Dodds and Welch (2000) noted, more data are necessary to determine how well such a classification applies to streams in different ecoregions and how well such schemes represent pristine conditions. For example, the problem of identifying reference streams in areas where watersheds are dominated by land use, such as animal operations and cropland, may be a concern in the development of a cumulative frequency distribution. That is, how representative are the available data of all land-use conditions ranging from pristine to areas heavy in agriculture to suburban and urban settings.

In developing nutrient criteria, consideration must be given to the spatial variations in geographic phenomena that cause or reflect differences in nutrient concentration in streams. In different regions where geographic phenomena such as soils, vegetation, climate, and geology are different, baseline/pristine nutrient conditions are likely to be specific to that region and therefore reference conditions may not be applicable across regions (Rohm et al., 2002). Nutrient criteria should be based on a regional framework where soils, vegetation, climate, and geology are similar. For example, in upstate New York three Level 3 Ecoregions are evident (Ecoregion VII, VIII, XIV) (Rohm et al., 2002). Ecoregion VIII is dominated by sedimentary rock containing both nutrient-rich and nutrient-poor soils while land use includes concentrated animal feeding operations (CAFOs), cropland agriculture, and urban areas. In contrast, Region VII (mostly the Adirondack Mountains) is dominated by igneous rock while land use is characterized by extensive forests, nutrient-poor soil, short growing seasons, and limited cropland. As a result, lakes in Region VIII on sedimentary rock are expected to have more than twice the median total phosphorus (TP) of Region VII (Rohm et al., 2002), which is dominated by igneous-derived soils.

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Another key component of developing nutrient criteria is the ability to characterize the range of nutrient conditions in minimally impacted streams that drain regionally representative watersheds (Rohm et al., 2002). To achieve the goal of identifying reference watersheds, the Environmental Monitoring and Assessment Program (EMAP) employs a sampling strategy that addresses both the issues of sample representativeness and impact by collecting data from streams over large regions and filtering out sites known to be disturbed by various human uses of the landscape to produce a set of representative regional reference sites. From the reference distribution, a critical threshold-nutrient criterion is established (e.g., 75th percentile of reference sites; USEPA, 2000b; Rohm et al., 2002). This approach requires on-site recognition of impact from nonpoint sources — which can be challenging (Sheeder and Evans, 2004). For example, in areas where CAFOs may be present or in areas high in cropland agriculture, it may be difficult to locate areas where minimally impacted sites are evident (Rohm et al., 2002). Another approach to solving the problem of unavailability of pristine watersheds is to establish reference conditions to stream "reaches" where chlorophyll levels are deemed acceptable (discussed by Dodds, 2007). Little information is available on this approach (Dodds and Welch, 2000).

Another approach in developing nutrient criteria involves stream biological assemblages as indicators of nutrient enrichment. The primary response variables to nutrient pollution are nutrients, chlorophyll, total suspended solids, transparency, and turbidity (USEPA, 2000b). In addition, macroinvertebrates are recognized by the USEPA as secondary response variables that have potentially high value in nutrient criteria development (USEPA, 2000a). Aquatic macroinvertebrates are among the principal communities utilized for monitoring and assessment (e.g., Bode et al., 2002). Development of indices that incorporate taxon-specific tolerance values for specific sources of impairments, such as nutrients, has been advocated. For example, the nutrient biotic index (NBI) was developed utilizing benthic macroinvertebrate communities from wadeable streams in the state of New York (Smith et al., 2007). Corresponding nutrient concentrations (nitrate and total phosphorus) to NBI scores were established relating macroinvertebrate community data to trophic status of a stream (e.g., oligotrophic) as commonly used in lake environments.

Ultimately, the NBI is viewed as a management tool establishing and enforcing regional nutrient criteria to assess nutrient enrichment, determine a stream's general trophic state, determine the point at which water quality can be classified as impaired, and establish corresponding nutrient concentrations above which invertebrate communities show impairment (Smith et al., 2007). However, macroinvertebrate assemblages respond to toxic substances, such as pesticides, aromatic hydrocarbons, ammonia, and metals, not simply to nutrients (Miltner and Rankin, 1998). Also, the NBI represents an integrated biological response to both allochthonous- and autochthonous-derived carbon, unlike measurements of typical stream nutrients (N and P) (Makarewicz et al., 2014). If a stream is heterotrophic, the NBI will reflect a macro-invertebrate assemblage derived from allochthonous sources (e.g., leaves) independent of nutrients observed in a stream and autochthonous sources. If heterotrophic, the NBI should provide a good estimate of trophic state but not necessarily a good indicator of nutrient impact on downstream systems such as a lake (Makarewicz et al., 2014). Annual measurements of nutrients allow a better assessment of nutrient impact on downstream systems and also allow a comparison to regulatory standards, but these annual measurements may not reflect the trophic state of a stream as they do not account for allochthonous-produced carbon.

The weight-of-evidence approach has been recommended by the USEPA to address the complex nature of deriving nutrient criteria (Smith and Tran, 2010). The weight-of-evidence approach for defining nutrient criteria incorporates various aspects of the chemical and biological approach to define trophic state, along with more refined statistical approaches (percentile analysis, non-parametric deviance, change point determination, cluster analysis) (Smith and Tran, 2010; Smith et al., 2013) to determine change points or boundaries. This approach incorporates into it some of the same limitations of other methods as described above.

The several approaches/methodologies mentioned are quite useful and have evolved over time. However, in many areas where agriculture predominates, the availability of "pristine watersheds" is problematic and has stymied the development of regulatory standards (e.g., Dodds et al., 1998; Smith et al., 2007, 2013; Smith and Tran, 2010) despite significant efforts to develop various approaches of identifying reference watersheds. Others suggest that the EMAP approach underestimates boundary criteria (Sheeder and Evans, 2004; Pickett, 1997). Sheeder and Evans (2004) and Dodds and Oakes (2004) indicate that the selection of the reference watershed is frequently labor intensive, very difficult, and if found will not have physical characteristics similar to an impaired watershed. There is need for a method of determining river baseline nutrient concentrations in watersheds with different degrees of human impact (Dodds and Oakes, 2004). Here we provide an alternative to approaches dependent on naturally occurring "pristine streams" in determining reference values for the development of nutrient criteria by applying a simulation approach that allows the removal of point and nonpoint sources by returning the landscape virtually to a pre-European condition.

Over the past four decades, advances in computer technology have led to the increasing use of computer models in watershed management. Numerous operational models or conceptual models were developed: e.g., SSARR (Rockwood et al., 1972), the tank model (Sugarawa et al., 1976), HEC-1 (Hydrologic Engineering Center, 1981), the ARNO model (Todini, 1996), TOPMODEL (Beven and Kirby, 1979), and CREAMS (Knisel, 1980, and for a general review Arnold and Fohrer, 2005). Early models, however, had gaps that rendered them incomplete, insofar that they did not include important processes such as evapotranspiration and subsurface flow (Arnold et al., 1998). Furthermore, models that might include more watershed processes failed to incorporate them at high enough spatial resolution to be truly spatially effective and effective at simulating watershed processes (Arnold et al., 1998). With the constant increase in computational power over the past decade has come the ability to include all these necessary parameters into a watershed model. Also, the simultaneous development of geographic information systems (GIS) has led to a great increase in model power. Geographic information systems permit the management of scale issues and large data sets that plagued past modelers.

Several watershed models are available, but the soil and water assessment tool (SWAT) was chosen for this study. The advantage of using SWAT is that it allows for daily spatially explicit predictions of nutrient levels across an entire watershed with user-defined hydrologic response units. SWAT is a basin-scale, continuous-time model that can be used to predict the impact of watershed management on water quality (Arnold et al., 1998; Gassman et al., 2007). It has proven effective for assessing water resources and nonpoint pollution issues for a large range of environmental conditions and scales around the world (Gassman et al., 2007). Scenario modeling using SWAT, as we do here, has become common (e.g., Bosch et al., 2013; Randir, 2003; Schilling et al., 2008; also see Gassman et al., 2007 for a review). We employed SWAT to contrast current nutrient levels in the Genesee River watershed against simulated natural conditions. Potentially, SWAT is another approach to determine reference nutrient conditions in a stream draining a watershed. This approach should work in any watershed, small (<1-m depth and watershed area <1296 km^2) or large (>1-m depth and watershed area >1296 km^2), even if it is heavily influenced by anthropogenic activities because it does not require pristine watershed conditions (i.e., reference conditions) to develop nutrient criteria for a watershed, allows consideration of loading of nutrients rather than concentration data which can be misleading and provides an annual simulation rather than an estimate of stream nutrient levels based on short-term (e.g., summer) sampling. Lastly it allows a customized approach to any given watershed with its variable slopes, soils, land use, and climate. Another plus of this approach is that it allows managers to consider and test remediation strategies.

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