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Pre-development conditions to assess the impact of growth in an urbanizing watershed in Northern Virginia

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ABSTRACT

Pre-development conditions are an easily understood state to which watershed nonpoint nutrient reduction targets may be referenced. Using the pre-development baseline, a "developed-excess" measure may be computed for changes due to anthropogenic development. Developed-excess is independent of many geographical, physical, and hydrological characteristics of the region and after normalization by area may be used for comparison among various sub-sets of the watershed, such as jurisdictions or land use types. We have demonstrated this method by computing pre-development nitrogen and phosphorus loads entering the Occoquan Reservoir from its tributary watershed in Northern Virginia. The pre-development loads in this study were computed using the calibrated water quality models for the period 2002–2007. Current forest land was used as a surrogate for pre-development land use conditions for the watershed and developed-excess was estimated for fluvial loads of Total Inorganic Nitrogen (TIN) and Orthophosphate-Phosphorus (OP) by subtracting simulated predevelopment loads from observed loads. It was observed that within the study period (2002–2007), the average annual developed-excess represented about 30% of the TIN and OP average annual loads exported to the reservoir. Comparison of the two disturbed land use types, urban and agricultural, showed that urban land uses exported significantly more excess nonpoint nutrient load per unit area than agricultural land uses.

1. Introduction

In recent decades, watershed development and other anthropogenic activities have increased both chronic and episodic nutrient loads for many waterbodies with negative water quality consequences (Downing et al., 1999; USEPA, 2009). Dodds et al. (2008) have estimated that a conservative cost of human-induced eutrophication in the U.S. is \$2.2 billion. Nationally, the eutrophication problem is widespread, as evidenced by USEPA (2009) estimate based on chlorophyll-*a* (Chl *a*) concentrations. The report suggests that more than 50% of U.S. lakes may be classified as eutrophic (7–30 μg/L Chl *a*) or hyper-eutrophic (>30 μg/L Chl *a*). For the "coastal plain ecoregion", which constitutes areas of the eastern seaboard from Florida to New Jersey, 60% of lakes were classified as eutrophic, 34% were considered hyper-eutrophic, 6% mesotrophic (2–7 μg/L Chl *a*), and the percentage of oligotrophic (⩽2 μg/L Chl *a*) lakes was negligible. Eutrophication is known to be caused by both autochthonous and allochthonous nutrient inputs to waterbodies. It has been observed that once the flux of the limiting nutrient, such as labile phosphorus, is exceeded, for most freshwaters (even if episodic), a rapid increase in algal productivity occurs until the excess nutrient is exhausted. If the limiting nutrient flux is not sustained, the algal productivity in the waterbody may fall back to prior levels. As a consequence, a sustainable method of eutrophication control may be stemming the flow of nutrients to the receiving waterbody. It may be noted that periodically, under appropriate conditions such as waterbody stratification, autochthonous cycling of the limiting nutrient in the waterbody may increase the availability and thus the algal productivity. Even in waterbodies where the allochthonous cycling (internal loading) is prevalent, it may be expected that stemming nutrient influx will aid in controlling the severity of algal bloom. There is global evidence, along with experimental studies, that show increases in the intensity, size, and duration of algal blooms with increased nutrient loading (Heisler et al., 2008). Therefore, controlling nutrient loadings in most watersheds may offer significant mitigation to Harmful Algal Blooms (HAB) (Heisler et al.,

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2008; Paerl, 2001). It may be noted that, as suggested by Anderson et al. (2002), nutrient enrichment is not the only cause of algal blooms; other environmental conditions may also have an important role in the proliferation of algal blooms in recent times.

It is very well recognized that numerous anthropogenic activities and developments, such as farming, urban development, mining, and industrial development have raised nutrient inputs to waterbodies by both increasing the amount of available nutrients and reducing the natural buffers/sinks. In the U.S. and most of the developed world, significant strides have been made towards controlling point sources, thereby making agricultural and urban nonpoint sources of nutrients the major contributor of fluvial nutrient loads to freshwater systems (Carpenter et al., 1998; Dodds et al., 2008; Muthukrishnan et al., 2004; Novotny, 1988). Several studies have focused on controlling nonpoint pollution in the last few decades, and it is clear that solutions to the problem of nonpoint source pollution involve the application of watershed-based solutions and stormwater Best Management Practices (BMPs) (Barrett, 2008; Liu, 2011; Scholz, 2005; Simpson and Weammert, 2009; Strecker, 2001, 2004). A hallmark of watershed-based methods is stakeholder participation and support. The scale of public participation, more specifically stakeholder participation for environmental management, has increased in recent decades. This increase is evident from an analysis of reported literature (Reed, 2008). Stakeholders may be described using the Murdock et al. (2005) definition as "*people with something at stake, such as property, environmental quality, economic interest, or a desire for better environmental regulation and management*". As is clear from the definition, many of the stakeholders whose participation is required are not water resources experts and may not understand the purpose and intent of water quality criteria and goals, especially when the impacted waterbody may not be local. Further, for effective implementation of watershed based strategies multijurisdictional partnerships including states and/or counties (depending on the size of watershed) is often required. Such cooperation have been proven to be hard to achieve, because the priorities of different jurisdictions are not always aligned. Further, the frequent lack of objective and uniform methods to assign water quality improvement goals makes it difficult to establish reduction targets among jurisdictions.

The current paradigm of nutrient load management involves computing and assigning a Total Maximum Daily Load (TMDL) based on the maximum amount of a pollutant load that a waterbody can receive (loading capacity) and still safely meet its designated use, based on water quality criteria, antidegradation requirements, and consideration of implementation issues (USEPA, 1991). TMDLs allocate loading capacity to point load sources and nonpoint load sources through Waste Load Allocations (WLA) and Load Allocations (LA) methodologies, respectively. It may be noted that the allocation contains both natural background sources and anthropogenic pollution sources. A Margin Of Safety (MOS) to account for uncertainty in TMDL calculations is further incorporated explicitly as unallocated loading capacity, or incorporated implicitly in a TMDL through use of conservative assumptions while estimating allowable loads (USEPA, 1991). The whole process of developing a TMDL is often too complicated for lay stakeholders to understand. As a result, most stakeholder participation is limited to developing reduction strategies after the targets have been defined. It has been observed that even the basic assignment of designated use may be controversial. This situation is further exacerbated by lack of uniformity in computation of loading capacity and MOS (Reckhow, 2003). Since most nonpoint pollution control (not governed by a permit) are not mandated and are voluntary it is essential to achieve a "buy-in" from the local community. To achieve that buy-in, TMDL development policy may be augmented by an easily understood baseline such as pre-development background conditions to assess the impact of anthropogenic development and subsequently to assign water quality improvement goals. This may be particularly beneficial when a "phased approach" or adaptive management strategy for a TMDL program is being used. An adaptive management program for a TMDL, when compared to conventional approaches, recognizes uncertainty in the modeling system and uses expert and stakeholder judgment to design a cost-effective mitigation strategy. Such programs typically utilize monitoring after initial priority controls have been built to determine next steps. For example, a framework proposed for adaptive management requires continual updates to the TMDL through refined monitoring, additional controls, and/or changes in the TMDL endpoint or water quality standards (Freedman et al., 2004).

As suggested by Gibson et al. (2000), pre-development background nutrient loads (also referred to as pristine conditions) may be used as a benchmark to establish the amount of degradation a system has experienced, and may also support the development of water quality standards and criteria. However, predevelopment loads may not be easily computed, as they vary between regions based on geographical, physical and hydrologic conditions of the waterbody and tributary watershed. In addition, for watersheds that lack data for readily available reference sites, assessing such loads may require further investigation (Smith et al., 2003). The USEPA technical guidance manual (Gibson et al., 2000) suggests various methods to estimate background loads, ranging from the utilization of statistical information on the lakes in the region to applying lake models and extrapolating background conditions. If predevelopment loading conditions are estimated by a credible method, computing the increase due to current (or future) loadings provides the "developed-excess" loads that are easy to understand and may be used in conjunction with loading capacity to describe water quality degradation and to set reduction targets.

In this paper, we have described the computation and utility of developed-excess loads resulting from nonpoint sources using a test study site located in a Northern Virginia suburb of Washington DC. An initial requirement of the study approach was to estimate the pre-development conditions in the watershed before any anthropogenic activities had affected the region. No direct measurements of pre-development water quality exist. In addition, major water supply reservoirs in the study area did not exist prior to the period of increased development. However, because our interest is in quantifying and controlling loadings from anthropogenic nonpoint sources, we may still use the hindcasting method without eliminating other permanent modifications to the watershed. We have simulated the pre-development conditions, which may be taken as the nutrient load state with no anthropogenic activity present, by changing all land uses in the watershed model to forest while keeping other waterbodies and point-sources as observed in current conditions. It may also be noted that most other waterbodies and watersheds in the region, which might have otherwise served as surrogates, have also experienced changes due to varying degree of development, thereby rendering them ineffective as references for pre-development conditions. Using simulations, we have also identified locations and land use types where most of excess nutrients loads, compared to the pre-development state, originated in the region. Many of the local jurisdictions in the study area were among the early adopters of urban stormwater BMPs, and most urban and agricultural land in the watershed already has such implementations of conventional stormwater management practices. For that reason, these results may serve as a good estimate for other developing cities and towns with conventional BMPs.