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High resolution spatially explicit nutrient source models for the Lower Peninsula of Michigan

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ABSTRACT

Nutrient loading to aquatic systems has been linked to many issues including eutrophication, harmful algal blooms, and decreases in species diversity. In the Great Lakes, algal blooms continue to plague Lake Erie and Saginaw Bay despite reductions in point source loading. Here, methods for predicting nutrient sources using GIS are described to examine the link between watershed nutrient sources, landscape processes, and in-stream loads in the Lower Peninsula of Michigan. These models predict all significant nutrient sources to the landscape at 30 m resolution over a 144,000 km^2 region, avoiding the tradeoff between scale and source detail common to many existing watershed nutrient models. The model results presented here indicate that there is a high degree of variability in nutrient landscape loading rates, even within the same land use class. Within all land use types, except unmanaged lands, loading rates for most major sources varied by at least an order of magnitude. This work provides valuable information that can be used by environmental managers regarding how and where to target efforts to reduce nutrient loads in surface water particularly in the Great Lakes region where management efforts have been ongoing since the 1960s.

Introduction

Elevated concentrations of nitrogen and phosphorus in lakes, rivers, and groundwater are a major concern for environmental managers. Excessive nutrients have been identified as one of the leading causes of river and lake impairment across the United States, including Lake Erie (USEPA, 2002a, 2009). Issues associated with nutrient loading to the Great Lakes include eutrophication, harmful algal blooms, hypoxia, and decreases in biologic diversity making water unsuitable for recreational, industrial, and municipal uses. Blooms of the cyanobacteria *Microcystis* can produce the toxin microcytin, which is hazardous to human and aquatic animal health (Davidson et al., 2012; Correll, 1998; Brittain et al., 2000; Paerl, 2008). Growth of *Cladophora*, an alga that grows on solid substrates, is not only odorous and unsightly but can clog water intake pipes. Excessive growth of algae and cyanobacteria leads to oxygen depletion that impacts benthic organisms and can cause fish kills (Auer et al., 2010; Anderson et al., 2002). Seasonal algal blooms are common in the western basin of Lake Erie and Saginaw Bay (Hinderer and Murray, 2011; Dolan and Chapra, 2012). Since the late 1960s, cooperative efforts by the United States and Canada have resulted in extensive monitoring, reporting, and legislation across the Great Lakes Basin to improve the water quality of the lakes. Legislation was passed to limit phosphorus point source effluents and establish limits on phosphorus loads to the lakes (Nicholls et al., 2001; Dolan et al., 1981; Dolan, 1993). Initial improvements were realized through point source load reduction, but since 1991 total phosphorus loading to Lake Erie has been more variable. There are signs that loading of phosphorus to Lake Erie may be increasing, a trend that has been attributed to increases in non-point sources of phosphorus (Dolan and McGunagle, 2005; Moon and Carrick, 2007). Increases in nitrate delivery to the Great Lakes, particularly from agricultural watersheds, have also been observed (Smith et al., 1987).

Addressing the impact of non-point sources on in-stream nutrient loads requires an understanding of the location and rates of nutrient application and production within watersheds. However, non-point sources of nitrogen and phosphorus are difficult to quantify, because they cannot be directly measured, and their application rates and timing affect the delivery of nutrients to surface water (Carpenter et al., 1998; Nikolaidis et al., 1998). Requirements for reporting related to sources of nutrients vary from state to state; often data is only available on a county or state level.

One approach to predict nutrient sources across large spatial scales is to use variables such as land use and population to estimate non-point loading. Another approach uses large scale estimates of nutrient inputs (such as county or state) and disaggregates these estimates to smaller areas based on relative land use. These types of approaches (which are generally used to estimate nutrient inputs in the USGS SPARROW model (Robertson and Saad, 2011)) assume that changes in land use

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or land management will lead to proportional responses in nutrient sources (Beaulac and Reckhow, 1982). This may lead to problems when there is a large degree of variability in sources within a particular land use. For instance, scaling county level fertilizer estimates based on a watershed's agricultural land use area assumes that chemical fertilizer is applied at the same rate across the county.

Another approach to estimate non-point nutrient sources to watersheds is based on the development of net anthropogenic nitrogen/phosphorus inputs (NANI or NAPI) (Han and Allan, 2008; Han et al., 2010). Results using the NANI/NAPI approach are more comparable to riverine export of nutrients since they attempt to quantify the net nutrient inputs, accounting for the loss of nutrients due to volatilization and crop fixation (Howarth et al., 1996; Han and Allan, 2008; Hong et al., 2013). These estimates are highly detailed with respect to atmospheric deposition, fertilizer application, and animal manure and have a partial accounting of nutrient losses, but they are generally aggregated at the watershed scale. Estimates that rely on watershed scale aggregation of nutrients assume that the delivery of nutrients within the watershed is uniform across space and among sources. Depending on landscape and stream factors, the proportion of nutrients delivered to a stream from a particular source will vary (Boyer et al., 2002; Robertson and Saad, 2011). Accurate estimates of riverine nutrient export can be produced using these methods, but they cannot be used to understand the role of pathway and processes in the delivery of nutrients to surface water within individual watersheds.

Reliable estimates of non-point sources are necessary to develop strategies to manage these sources and predict how they will change with future climate and land use. Here we present GIS methods that have been developed to generate a high-resolution and spatially explicit accounting of nutrient sources across the entire Lower Peninsula of Michigan. The resulting descriptions provide a basis to quantify non-point sources and establish a comprehensive method to estimate sources of nutrients at large spatial scales, which can be used as inputs to watershed nutrient loading models.

Methods

Nutrient accounting methods using GIS were developed to estimate nitrogen and phosphorus inputs from five non-point sources: atmospheric deposition, chemical agricultural and non-agricultural fertilizer application, manure production/application, and septic tanks. It is important to note that the methods described here are intended to account for the gross total nitrogen and phosphorus that enter the watershed. These estimates do not account for the loss of nutrients to sinks within the landscape, the potential source of nutrients from landscape legacy, or the storage and potential export of nutrients in biomass (Van Breemen et al., 2002). They also do not account for factors that impact the delivery of nutrients to surface water. These estimates are intended to be used in conjunction with a nutrient delivery model such as SPARROW to predict nutrient loads observed in surface water.

Nutrient loading rates for each non-point source were estimated for 30 meter cells across the Lower Peninsula (LP) of Michigan. Point source nutrient loads were derived from the EPA's Discharge Monitoring Report (DMR) Pollutant Loading Tool.

Study domain

Source models were constructed for Michigan's LP, which has watersheds that drain to 3 of the 5 Laurentian Great Lakes: Lakes Michigan, Huron, and Erie. The most common land use in the Lower Peninsula is row crop agriculture, which comprises 26% of the land area. Urban and range land make up 13 and 14% of the land area, respectively. The remaining 47% of the land area is unmanaged land cover including forest, shrublands, barren, water, and wetlands (Fry et al., 2011). Fig. 1 shows the model domain, indicating the general land use classes.

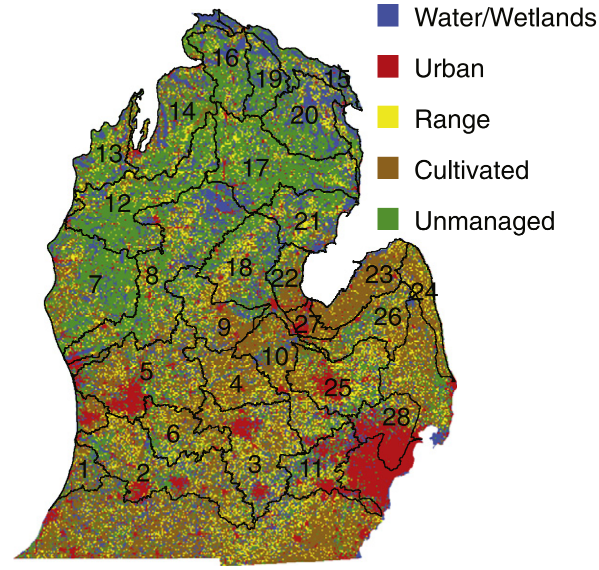

Fig. 1. Land use in the model domain based on the 2006 National Land Cover Database (NLCD; Fry et al., 2011). "Unmanaged" includes NLCD barren, forest, and shrubland. The HUC-8 watersheds located fully within the model domain are shown with black outlines. The numbers correspond to the "ID" field in Table 2.

Since nutrient loading is generally studied at the watershed scale, the HUC-8 watersheds located entirely in the study domain were selected for further analysis. These watersheds are shown in Fig. 1 overlying the map of land cover. Watersheds in the southern portion of the study area are dominated by row crop agriculture and urban areas including Grand Rapids, Lansing, and Detroit. The primary land cover in the northern portion of the study area is forest and other unmanaged land covers with small pockets of agriculture.

Non-point source models

Atmospheric loading

Atmospheric loading of N and P occurs via both wet deposition (delivered by precipitation) and dry deposition (attached to dust particles that settle to the surface). Wet deposition is typically estimated by collecting precipitation in a sampler and analyzing for nitrogen and phosphorus compounds. The concentrations of nitrogen and phosphorus compounds along with the amount of precipitation collected are used to estimate rates of deposition. Dry deposition rates are estimated by multiplying modeled particle deposition velocities by measured atmospheric concentrations of compounds (USEPA, 2010).

Atmospheric data were available from three networks that monitor atmospheric deposition: 1) the National Atmospheric Deposition Program (NADP) (NADP, 2007), a wet deposition monitoring program in the United States, 2) the Great Lakes Precipitation Network (GLPN) (Lisa Bradley, personal communication, 2011), which is a joint project between the United States and Canada established to monitor wet deposition to each of the Great Lakes, and 3) the U.S. Environmental Protection Agency's dry deposition monitoring network called the Clean Air Status and Trends Network (CASTNET) (USEPA, 2010). Weekly data was downloaded from CASTNET, which reports fluxes of nitrate (NO_3^-), ammonium (NH_4^+), and nitric acid (HNO_3) via dry deposition. Wet deposition from the Great Lakes Precipitation Network was obtained from the Canada Centre for Inland Waters, which collects samples monthly and measures Total Kjeldahl Nitrogen (TKN) along with the sum of nitrate and nitrite (NO_2) denoted as NO_x. TKN includes both organic and ammonia (NH_3) nitrogen, so TKN and NO_x were summed to obtain an estimate of total nitrogen. The GLPN also measures concentrations of phosphate in precipitation, and this was used to estimate atmospheric deposition of phosphorus. National Atmospheric Deposition