Ecological Modelling 277 (2014) 27–37

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Effects of future urban and biofuel crop expansions on the riverine export of phosphorus to the Laurentian Great Lakes

Meredith B. LaBeau[a], Dale M. Robertson[b], Alex S. Mayer[a,*], Bryan C. Pijanowski[c], David A. Saad[b]

[a] Michigan Technological University, Department of Civil and Environmental Engineering, 870 Dow Environmental Sciences, 1400 Townsend Drive, Houghton, MI 49931, United States
[b] U.S. Geological Survey, Wisconsin Water Science Center, 8505 Research Way, Middleton, WI 53562, United States
[c] Purdue University, Department of Forestry and Natural Resources, 305 FORS Building, 195 Marsteller Street, West Lafayette, IN 47906, United States

ARTICLE INFO

Article history:
Received 11 October 2013
Received in revised form 16 January 2014
Accepted 20 January 2014
Available online 13 February 2014

Keywords:
Nutrient loads
Nutrient fate and transport modeling
Land use change
Land use scenario modeling
Urban land use
Agricultural land use

ABSTRACT

Increased phosphorus (P) loadings threaten the health of the world's largest freshwater resource, the Laurentian Great Lakes (GL). To understand the linkages between land use and P delivery, we coupled two spatially explicit models, the landscape-scale SPARROW P fate and transport watershed model and the Land Transformation Model (LTM) land use change model, to predict future P export from nonpoint and point sources caused by changes in land use. According to LTM predictions over the period 2010–2040, the GL region of the U.S. may experience a doubling of urbanized areas and agricultural areas may increase by 10%, due to biofuel feedstock cultivation. These land use changes are predicted to increase P loadings from the U.S. side of the GL basin by 3.5–9.5%, depending on the Lake watershed and development scenario. The exception is Lake Ontario, where loading is predicted to decrease by 1.8% for one scenario, due to population losses in the drainage area. Overall, urban expansion is estimated to increase P loadings by 3.4%. Agricultural expansion associated with predicted biofuel feedstock cultivation is predicted to increase P loadings by an additional 2.4%. Watersheds that export P most efficiently and thus are the most vulnerable to increases in P sources tend to be found along southern Lake Ontario, southeastern Lake Erie, western Lake Michigan, and southwestern Lake Superior where watershed areas are concentrated along the coastline with shorter flow paths. In contrast, watersheds with high soil permeabilities, fractions of land underlain by tile drains, and long distances to the GL are less vulnerable.

1. Introduction

The Laurentian Great Lakes (GL, see Fig. 1) contain 18% of available global fresh surface water. Approximately 10% of the U.S. population lives in the GL basin contributing watersheds, supporting a non-farm economy of $3.7 trillion gross domestic product (GDP), which is 30% of the GDP for the U.S. and Canada combined (USEPA, 2009; Austin et al., 2007; Grunwald and Qi, 2006; Krantzberg and de Boer, 2006). While the importance of the freshwater resources in the Great Lakes cannot be overstated, the GL continue to experience ecosystem impacts from anthropogenic disturbances.

The Great Lakes receive water and accompanying nutrients from many tributaries draining areas ranging with forests, intensive farming, and large urban centers. Nutrient input from these tributaries is extremely variable (Robertson and Saad, 2011). The nutrient loading has caused eutrophication to various degrees, including excessive growth of planktonic and attached algae, turbidity, changes in biotic composition, undesirable taste and odor, and promotion of anoxic conditions to various degrees (Pauer et al., 2011; Evans et al., 2011; Michalak et al., 2013; Zhou et al., 2013). Policies and programs put into place to protect GL water quality date back to 1972 with the GL Water Quality Agreement (GLWQA) signed jointly by the U.S. and Canada and amended in 1978, 1987, and most recently in 2012 (GLWQA, 2012). The GLWQA has identified phosphorus (P) as the nutrient of primary concern for eutrophication in the Great Lakes and defined target P loads for each lake.

The U.S. Environmental Protection Agency (USEPA) has also developed a national strategy to reduce concentrations of P by establishing waterbody-specific nutrient criteria, including the Great Lakes (USEPA, 1998). Although reductions in loading have reduced most open-lake eutrophication problems, except for Lake Erie, eutrophication problems are still common in many nearshore areas and embayments (Michalak et al., 2013).

---

* Corresponding author. Tel.: +1 906 487 3372.
E-mail address: asmayer@mtu.edu (A.S. Mayer).

0304-3800/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ecolmodel.2014.01.016

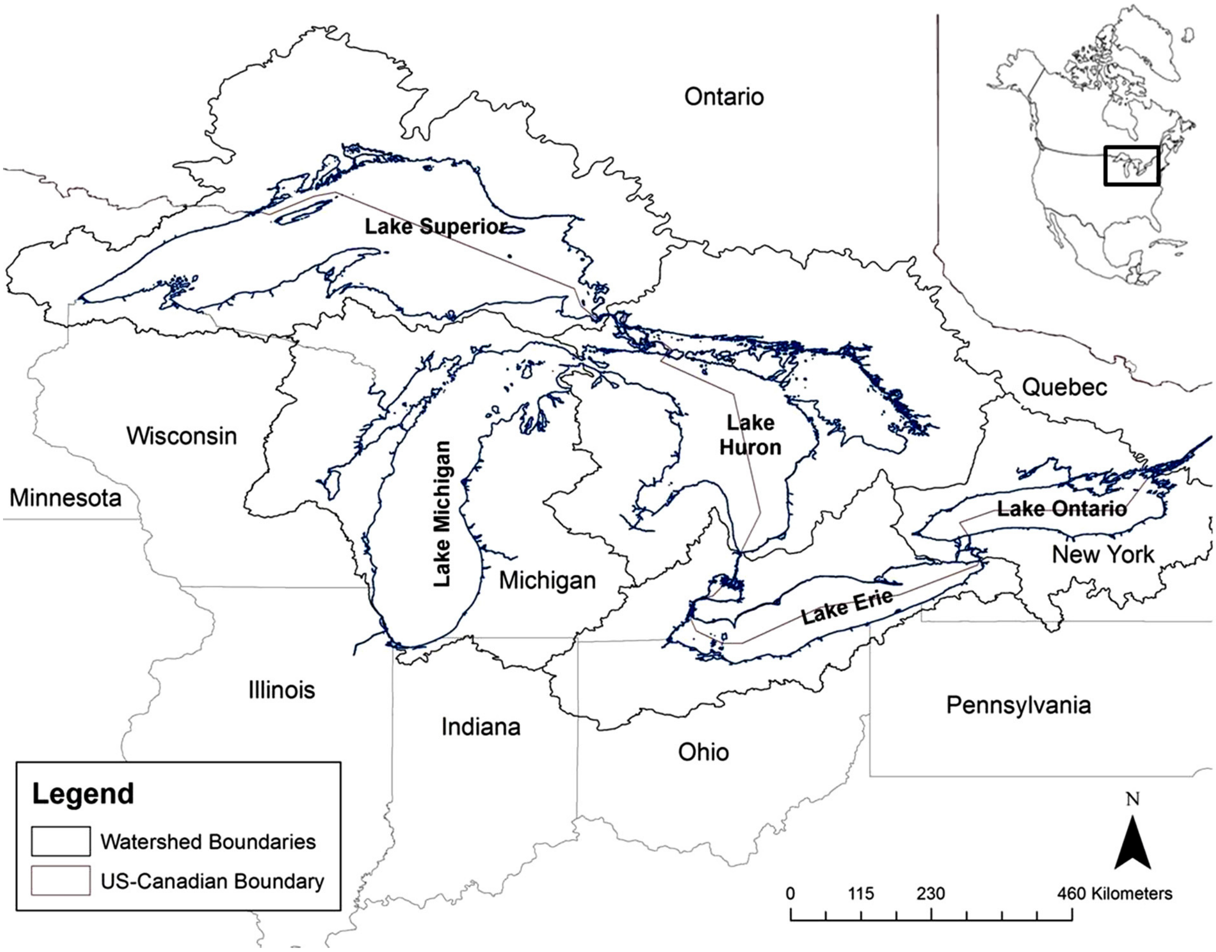

Fig. 1. Location map for the Laurentian Great Lakes.

Descriptions of nutrient sources are typically made in terms of point sources, which usually emanate from a pipe or well-defined outlet, and nonpoint sources, which tend to reach streams via runoff from the land surface. The current paradigm is that the majority of P loads emanating from the GL watersheds are derived from nonpoint agricultural sources (Robertson and Saad, 2011; Auer et al., 2010); however, at a local scale, inputs from point sources are still significant (Robertson and Saad, 2011).

Land use in the GL basin has changed rather dramatically over recent decades (Nechyba and Walsh, 2004; Greene, 1997). From the 1970s to 2000s, Pijanowski and Robinson (2011) found that in three major metropolitan areas of the Upper GL basin (Detroit, Chicago, and Milwaukee), along with the Muskegon, Michigan, area, urban land use approximately doubled while agricultural land use decreased. If the trends in growth of the urban areas and population continue in the future, P exports to the GL in the future could change (Southworth et al., 2007). Furthermore, potential agricultural intensification, due to, for example, biofuel feedstock crops, could counteract recent regional decreases in agricultural land use (Plourde et al., 2013), also leading to potential increases in P loading to the GL.

Predictive tools are needed to help understand the complex interaction between land use change, human activities, and P loads (units of mass per time). Given limited resources for restoration and mitigation, these tools that can identify high impact areas across the GL basin could be used to prioritize management efforts. Traditional analytical approaches for assessing the impacts of human activities on water quality have been based on the development of detailed, predictive models (Johnes, 1996). Modeling nutrient loads in watersheds typically relies on one of two techniques: deterministic modeling or statistical modeling. Process-based deterministic models simulate nutrient transport in watersheds based on relationships between land use characteristics and nutrient sources, migration of nutrients to adjacent waterways, and fate and transport in the waterways. In deterministic export-coefficient modeling, rates of nutrient delivery from a variety of sources are provided as model inputs and corresponding fractional export coefficients are used to estimate loading rates to adjacent waterways (Johnes, 1996; Young et al., 1996; McGuckin et al., 1999; Johnes and Heathwaite, 1997). In contrast, statistical models are based on regression-derived relations between flows, nutrient loads, and environmental characteristics (Daly et al., 2002).

Many studies have used deterministic models to simulate water quality at the catchment scale in the GL basin, including the Soil and Water Assessment Tool (Arnold et al., 1998; Bosch et al., 2013). The spatially explicit SPARROW (SPAtially Referenced Regression On Watershed attributes) model has been used to model water quality constituents at regional scales (Preston et al., 2011), including the GL basin (Robertson and Saad, 2011).

Exploration of the impacts of land use and land cover change on water quality has been accomplished previously by coupling land use cover change models, including the artificial neural network-based LTM (Tayyebi et al., 2012; Pijanowski et al., 2002a,b; Tang et al., 2005) (used in this study) combined with water quality models. The limitations of these previous studies are that they do not: (a) assess the impacts of expanding agriculture on P loadings,