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# Landscape-scale modeling of water quality in Lake Superior and Lake Michigan watersheds: How useful are forest-based indicators?

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ABSTRACT

The Great Lakes watersheds have an important influence on the water quality of the nearshore environment, therefore, watershed characteristics can be used to predict what will be observed in the streams. We used novel landscape information describing the forest cover change, along with forest census data and established land cover data to predict total phosphorus and turbidity in Great Lakes streams. In Lake Superior, we modeled increased phosphorus as a function of the increase in the proportion of persisting forest, forest disturbed during 2000–2009, and agricultural land, and we modeled increased turbidity as a function of the increase in the proportion of persisting forest, forest disturbed during 2000–2009, agricultural land, and urban land. In Lake Michigan, we modeled increased phosphorus as a function of ecoregion, decrease in the proportion of forest disturbed during 1984–1999 and watershed storage, and increase in the proportion of urban land, and we modeled increased turbidity as a function of ecoregion, increase in the proportion of forest disturbed during 2000–2009, and decrease in the proportion softwood forest. We used these relationships to identify priority areas for restoration in the Lake Superior basin in the southwestern watersheds, and in west central and southwest watersheds of the Lake Michigan basin. We then used the models to estimate water quality in watersheds without observed instream data to prioritize those areas for management. Prioritizing watersheds will aid effective management of the Great Lakes watershed and result in efficient use of restoration funds, which will lead to improved nearshore water quality.

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## Introduction

Water quality in lakes is profoundly influenced by the characteristics of the watersheds that support them (Allan et al., 1997; Arnold and Gibbons, 1996; Gergel et al., 2002). As the world's largest source of surface fresh water, the Laurentian Great Lakes are an important resource for the eight U.S. states and one Canadian province that border them. A recent analysis of data collected by the Bureau of Labor Statistics suggests that 1.5 million jobs are directly connected to the Great Lakes, and these jobs generate $62 billion in wages (Vaccaro and Read, 2011). In this study, we evaluate the relationship between landscape conditions, including novel forest predictors, in the watersheds of Lake Superior and Lake Michigan and water quality in streams draining those watersheds. These tributaries influence the water quality of the nearshore area of the Great Lakes, so our research will have an important application in the management of nearshore water quality for beneficial uses by fisheries and people. The nearshore region – defined as that portion of the lake directly influenced by contributing watersheds and extending from the shoreline to 20–30 m of depth (Edsall and Charlton, 1997; Mackey and Goforth, 2005) – is particularly important because it is used as a drinking water source, for recreation, and is an important aquatic ecosystem (Fuller and Shear, 1995).

The Great Lakes Restoration Initiative (GLRI) is a multi-million dollar investment to improve the health of Great Lakes watersheds by addressing toxic substances, invasive species, nearshore health and non-point source pollution, habitat and wildlife protection and restoration, and education, monitoring, evaluation, communication, and strategic partnership (WHCEQ, White House Council on Environmental Quality et al., 2010). In Fiscal Year 2010, 255 million dollars were awarded to 16 different federal agencies and 163 million dollars were awarded to other partners as grants (http://greatlakesrestoration.us/projects.html). In an era of shrinking resources, the Action Plan (WHCEQ, White House Council on Environmental Quality et al., 2010) identified the need for methods to target watersheds where management and restoration activities could be rapidly and effectively applied. Nonpoint source pollutants contribute to the degraded conditions in the Great Lake nearshore areas, but these sources can be challenging to pinpoint for restoration and management (Riseng et al., 2010). The Action Plan

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identifies soluble reactive phosphorus, soil erosion, and pollutants as contaminants, so we developed models to predict and rank watersheds for two related variables, instream total phosphorus (TP) and turbidity (NTU [nephelometric turbidity units]).

There is a large literature describing the methods used to predict stream delivery of chemical and physical pollutants using watershed variables (e.g., land use, surficial geology). The methodologies used to model water condition in the Great Lakes have ranged from single watersheds (Bosch, 2008) to the entire U.S. basin (Robertson and Saad, 2011). There is a trade-off between the amount of time and data that are needed for a model and the spatial scale the model can describe. Mechanistic (or deterministic) models (e.g., Soil Water Assessment Tool (SWAT); Bosch, 2008) use complete, computational characterizations of watersheds (e.g., topography, hydrology, climate) to predict detailed nutrient and sediment exports. Mechanistic models are data intensive and would be difficult to parameterize for an entire Great Lake basin. A hybrid mechanistic–statistical method called SPAtially-Referenced Regression On Watershed attributes (SPARROW; Smith et al., 1997) uses a mass-balance approach that combines observed water quality and watershed features to model watershed export. This method can be used for larger spatial scales, and was recently completed for the Great Lakes (Robertson and Saad, 2011); it will provide a reference point for comparison with our models. We selected a statistical approach using landscape characteristics and observed water quality in multiple watersheds to create models that predict instream water quality (Lopez et al., 2008). Our method has the advantage of being effective for a large spatial area, while not having the intense data requirements of mechanistic models; it is also readily applicable to watersheds not already modeled using landscape characteristics alone, which is more difficult for other models, such as SPARROW. Our models also utilize higher resolution spatial data (30-meter pixels) compared to SPARROW, which uses county-level estimates of agricultural land use (Smith et al., 1997). Our models also utilize a newly available forest database that tracks the persistence and disturbance of forest through time. Forest has been closely linked to high quality water (de la Crétaz and Barten, 2007), especially in relation to intense human development, and forest also represents a wide range of potential restoration activities (e.g. tree planting, riparian buffer restoration). We developed models that can be used to address water clarity issues (NTU), in addition to nutrients (TP), so they can be used in association with the SPARROW models to link water quality with watershed and forest conditions.

The goal of this research is to provide the U.S. Environmental Protection Agency (USEPA) and watershed managers with models to predict water quality in gauged basins to predict future changes in water quality associated with landscape changes in the watersheds, and to prioritize the ungauged watersheds of Lake Superior and Lake Michigan for restoration. We will link the landscape characteristics in each basin to observed water quality in streams that contribute to nearshore water quality. The models will then be applied to ungauged sites to identify areas with watershed conditions that may lead to degraded water quality. Ranked watershed groups can then be used to target the areas in the basin where management is most needed and where restoration dollars can be most efficiently spent.

## Material and methods

Lake Superior is located in the headwaters of the Great Lakes watershed and is bordered by Ontario to the north and Minnesota, Wisconsin and Michigan to the west and south. It has the highest surface elevation, largest total water volume, and greatest depth of the five Great Lakes (Fuller and Shear, 1995). Due to the relatively undeveloped nature of the watershed, Lake Superior has the lowest concentration of open water phosphorus, and, although the status of nearshore phosphorus likely is also low, it has not yet been assessed (EC, Environment Canada and USEPA, United States Environmental Protection Agency, 2009). Lake Michigan is the only lake located entirely within the United States, bordered by Wisconsin, Michigan, Illinois, and Indiana, and it has higher nutrient and pollutant loadings than Lake Superior. Lake Michigan is the second largest Great Lake by volume with the second greatest maximum depth. The current status of open water phosphorus concentration is rated as good with an improving trend in Lake Michigan, while nearshore phosphorus concentration remains poor (EC, Environment Canada and USEPA, United States Environmental Protection Agency, 2009). We used multiple landscape data types to describe the conditions present in watersheds of Lakes Superior (U.S. only) and Lake Michigan. Only the U.S. side was included in our modeling because comparable datasets for predictor and response variables (with the exception of forest disturbance data) were not readily available for the Canadian watershed of Lake Superior.

### *Water quality data*

Water quality data were retrieved from EPA's STOrage and RETrieval (STORET) database and USGS's National Water Information System (NWIS). We augmented the water quality data for Lake Superior with collections from the Wisconsin Department of Natural Resources. The study interval was limited to the years 2005 to 2009 to overlap with the landscape data, especially the recent forest disturbance class and the forest inventory data, and to limit the amount of climatic variation occurring during the interval. To model the most active period of stream flow when the transport of large quantities of nutrients and turbidity (i.e., sediment) occurs, the models described the spring runoff period (March to June; Detenbeck et al., 2003). Multiple water quality variables were available for the basins, but after considering the spatial and temporal availability, along with the number of observations for each variable that was below the minimum detection limit, we selected two: total phosphorus (mg/L) and turbidity (NTU). Total phosphorus (TP) is a commonly collected primary nutrient variable in monitoring programs and is associated with enrichment from human sources. Turbidity is a measure of water clarity and was selected, as opposed to total suspended solids, because there was acceptable temporal and spatial coverage of the data and no samples were below the minimum detection limit. In the Lake Michigan watershed, NTU data were available at fewer sites than TP, so there were fewer watersheds (23) with NTU observations to use in the modeling. We modeled concentrations rather than loads (quantity delivered per unit time) because stream flow data were not available for all watersheds. By focusing on the hydrologically-active spring season, we should indirectly account for the periods when the greatest amounts of nutrients and sediments are entering the nearshore areas of the lakes.

### *Landscape data*

Principal components analysis was used to identify collinearity between continuous landscape variables (Table 1), and some were excluded because of redundancy. The loadings of each variable on the first two principal components were examined graphically, and we provide details on which variables were excluded below. The selected variables were then used to build models to predict water quality. Data were obtained from multiple sources and summarized in ArcMap (version 9.3.1, Redlands, CA) using the Spatial Analyst extension. General boundaries for the Lake Superior and Michigan watersheds were defined by the 10 digit Hydrologic Unit Code (HUC10) from the Watershed Boundary Dataset (http://datagateway.nrcs.usda.gov, Accessed July 19, 2010). We used the National Hydrological Dataset Plus (NHDPlus; http://www.horizon-systems.com/nhdplus/index.php, accessed 25 June 2010; USGS, U.S. Geological Survey, 2009) to characterize the stream network. Artificial paths (i.e., artificial connections through lakes and impoundments) were removed, because we were only interested in actual streams in relation to water quality stations.