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Tributary phosphorus monitoring in the U.S. portion of the Laurentian Great Lake Basin: Drivers and challenges

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ABSTRACT

This paper examines the tributary monitoring network currently in place for sampling the amount of phosphorus entering the U.S. Great Lakes, focusing on the challenges faced by the agencies and organizations responsible for maintaining the network. The tributaries that are monitored vary in terms of flow, the size and terrain of the watershed being drained, and patterns of land use. Data generated by this network are used by researchers to compute lake-wide phosphorus loads. In this work, the primary drivers and challenges associated with operating an effective phosphorus tributary monitoring program were investigated through interviews with stakeholders responsible for managing a portion of the existing network. Based on these interviews, the authors identify three recommendations that policy makers interested in maintaining an effective phosphorus monitoring network in the Great Lakes should consider. The first is to provide states with incentives to support the long-term monitoring that is required to estimate phosphorus loads in tributaries to the Great Lakes; currently, most states design their programs to meet the requirements of the Clean Water Act, which results in patterns of sampling that are not necessarily useful for computing loads. The second recommendation is to facilitate the creation of a monitoring protocol that generates enough samples to identify trends and quantify loads at a level of certainty necessary for use in statistical models and load control programs. Finally, funding mechanisms capable of supporting long-term monitoring programs need to be established, with programs in Michigan and Minnesota serving as potential models.

Introduction

The Laurentian Great Lakes Basin, home to over thirty million people, has experienced a variety of ecosystem health concerns linked to human activity. One such concern is eutrophication triggered by excessive inflows of nutrients, most notably phosphorus compounds. One source of phosphorus derives from tributaries that drain the basin's watersheds, which are home to urban centers, agricultural lands, and forests. According to the International Joint Commission (IJC), these watersheds are being subjected to numerous stressors, including land use and climate change (IJC, 2003), potentially resulting in greater quantities of phosphorus entering the lakes because of increased stream flow flashiness, decreased soil infiltration rates, and greater soil erosion (Murdoch et al., 2000). This paper assesses the system currently in place for monitoring the quantity of phosphorus entering the Great Lakes from tributaries. The purpose is to assess the capacity of this monitoring system to provide current and future researchers with the data they need to quantify the amounts of phosphorus entering the Great Lakes. As changes in climate and land use occur, generating accurate knowledge about the phosphorus loading from tributaries will only become more important.

Tributary phosphorus loads are calculated as the product of locally measured instream phosphorus concentrations and tributary stream flows. Phosphorus concentration measurements typically derive from samples collected at an instant in time. Associated flows are taken from nearby stream gauges. Currently, researchers estimate time-averaged phosphorus loading from tributaries in one of two general ways. One approach is to start with the available raw data for flow rates and in-stream phosphorus concentrations and use statistical methods to estimate the time-averaged load from all tributaries, monitored and unmonitored. The other general method is to use a predictive model that relates land use and stream flows upstream of a discharge point to phosphorus concentrations, calibrating the underlying model equations with the available in-stream concentration and stream flow data. Researchers employing the first approach use statistical tools such as Beale's ratio estimator (Chapra and Dolan, 2012). Those

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employing the second approach use models such as SPARROW (Spatially Referenced Regressions on Watershed Attributes) (Alexander et al., 1998; Robertson and Saad, 2011; Smith et al., 1997) or SWAT (Soil Water and Assessment Tool) (for example, Bosch et al., 2011; DeMarchi et al., 2011).

Regardless of what approach is taken, the network of monitoring stations that sample phosphorus concentrations in tributaries to the Great Lakes represent a crucial piece of infrastructure. Both methodologies depend on quality data being generated by this water sampling network so that accurate phosphorus loads can be provided to researchers who study the impact of phosphorus on the Great Lakes ecosystem. Given the importance of these data, this paper examines the factors that have shaped the configuration of existing in-stream phosphorus monitoring programs and the challenges that agencies face in operating and maintaining these programs.

This analysis is based primarily on interviews with stakeholders associated with agencies that operate tributary monitoring stations. To identify stakeholders for interviews, this study focused on the 128 water quality monitoring stations in the basin that were used to calibrate the Upper Midwest SPARROW model (Fig. 1). These are stations that generated sufficient stream flow and phosphorus concentration data between 1970 and 2006 to meet the criteria required for calibration (Robertson and Saad, 2011). Data generated by these stations also represent a portion of the data employed by researchers utilizing Beale's ratio estimator (Dolan and Chapra, 2012). One should also note that SPARROW uses data from streams outside the Great Lakes Basin for calibration. In addition, since the current version of the SPARROW model does not cover the Canadian portion of the Great Lakes basin, we do not consider Canadian sites in the present work. Data from Canadian watersheds, however, are currently being integrated into SPARROW.

Background

Interest in the amount of phosphorus entering waterways first emerged in the early 1960s, due to concerns associated with eutrophication and anoxic conditions in rivers and lakes, especially Lake Erie (Ashworth, 1986). At that time, detergents in the U.S. contained about 10% phosphorus by weight (Turk et al., 1972), which researchers identified as a significant concern. According to Beeton (1971), one kilogram of phosphorus can facilitate the growth of 700 kg of algae. The thousands of kilograms of phosphorus entering the Great Lakes each day during this period had many detrimental, linked effects on the Great Lakes ecosystem, including excessive algal growth, anoxic water conditions, deterioration of fisheries, and drinking water taste and odor problems (Auer et al., 2010; Boyce et al., 1987; El-Shaarawi, 1987; Lee, 1973; Pothoven et al., 2009; Qualls et al., 2009; Robertson and Saad, 2011; Rosa and Burns, 1987; Watson et al., 2008).

In 1968, the U.S. Federal Water Pollution Control Administration, a predecessor to the U.S. Environmental Protection Agency (US EPA), presented a long-term plan for controlling pollution in Lake Erie. In that plan, the in-stream monitoring of phosphorus was a relatively low priority. At the time, the main challenge involved reducing the quantity of phosphorus being released by municipal wastewater treatment plants into Lake Erie. Those facilities were responsible for 63% (16,500 metric tons) of the phosphorus entering Lake Erie each year, with much of that amount (11,700 metric tons) coming from household detergents. Only 14% (4000 metric tons) was associated with agricultural runoff and diffuse tributary loading. Industrial facilities (1000 metric tons), urban runoff (1600 metric tons), and inputs from Lake Huron (3300 metric tons) contributed the remainder (FWPCA, 1968).

These and other concerns, such as the contamination of water resources by oil and toxic chemicals, led the U.S. and Canada to sign the 1972 Great Lakes Water Quality Agreement (GLWQA) (IJC, 2005). Limitations placed on the use of phosphorus in detergents and improvements in wastewater treatment facilities resulted in a 60% reduction in phosphorus loading to Lake Erie by the early 1980s and conditions in the lake steadily improved (Hartig, 2003). In addition, a 1978 amendment to the GLWQA established target phosphorus loadings for the Great Lakes (McCone et al., 2006; USGAO, 2003), shown in Table 1

Fig. 1. Great Lakes states and location of long-term water quality sites (triangles) used in SPARROW with the U.S. portion of the Great Lakes Basin outlined in gray (Source: Meredith B. LaBeau with Great Lakes Information Network shapefiles & D.A. Saad USGS).

Table 1
Phosphorus loads in 1976 and current target phosphorus (P) loads for the Great Lakes.

Lake basin	1976 P load (metric tons/yr)	Target P load (metric tons/yr)
Lake Superior	3600	3400
Lake Michigan	6700	5600
Main Lake Huron	3000	2800
Georgian Bay	630	600
North Channel	550	520
Saginaw Bay	870	440
Lake Erie	20,000	11,000
Lake Ontario	11,000	7000

(GLWQA, 1978). The target loading rates for each Great Lake were based on their trophic state designations and derived using a mass balance model that analyzed inputs and outputs of phosphorus to and from the lakes (Chapra, 1977; Chapra and Dolan, 2012; Vollenweider et al., 1980). Inputs corresponded to phosphorus loads entering the lakes from the basin's tributaries, the atmosphere, and point sources (Dolan and McGunagle, 2005).

As phosphorus from point sources declined in Lake Erie, the relative importance of non-point sources (such as runoff from agricultural fields) and atmospheric inputs increased. In 1979, researchers estimated that 45% (9000 metric tons/year) of Lake Erie's total phosphorus loading came from non-point sources in the tributary watersheds. In the Great Lakes as a whole, non-point tributary loading contributed 46% of the total (Chapra and Sonzogni, 1979).

However, the monitoring of phosphorus in streams remained a relatively low priority. After all, conditions in Lake Erie were improving and the existing methods for estimating inputs of phosphorus had proven adequate. Furthermore, the main driver of stream monitoring at the state level, the 1972 Clean Water Act, was not geared toward the use of fixed stations for long-term monitoring. In 1976, a national task force was created to examine state-level monitoring programs, and it concluded that "too much money is being spent for too little total information" and that there is "confusion on the part of the states" in regards to what was required by the law. Members of the task force recommended that states "define a minimum number of fixed ambient stations" and redirect their efforts toward an "intensive survey approach." In particular, they recommended that every "river, lake, estuary, bay, or aquifer, where waste loads are allocated or significant water quality changes have been identified or are considered possible" be assessed every five years (US EPA, 1976). The task force indicated that states should maintain fixed ambient monitoring stations only in a limited number of key locations. For fixed sampling stations placed on streams and rivers, the recommendation was to measure total phosphorus concentrations at least once each month. However, the purpose of these fixed stations was to track national trends over the long term rather than to generate data specifically for estimating phosphorus inputs to downstream bodies of water.

In the early 1990s, after improvements in water quality led to the meeting of loading targets, a decline in government support occurred and most phosphorus monitoring concluded. The lack of funding also resulted in the cessation of most phosphorus loading estimates for the Great Lakes. Only a few phosphorus monitoring programs on Lake Erie and Lake Michigan continued. There, stream flow data were still being measured, but at some sites the rate at which phosphorus concentrations were sampled was reduced, making it difficult for researchers to accurately estimate phosphorus loads from Great Lakes tributaries (Robertson and Saad, 2011; Rossman, 2006).

In the late 1990s, one of the remaining continuous data collection programs in the tributaries of the western basin of Lake Erie, the National Center for Water Quality at Heidelberg University, suggested that phosphorus loadings, particularly dissolved phosphorus, were increasing (Cha et al., 2010; Millie et al., 2009; Richards et al., 2010); indeed, significant summer blooms of algae returned to western Lake Erie in the 2000s (Ouellette et al., 2006). In addition, trends associated with climate change and shifting patterns of land use amplified concerns associated with the increased incidence of algal blooms in Lake Erie and the other Great Lakes. Hence, in 2004, the Twelfth Biennial Report on the Great Lakes Water Quality called for improved phosphorus monitoring from point and non-point sources to determine the contributions of tributary loads (IJC, 2004; McCone et al., 2006). Several researchers also commented on the need for increased spatial and temporal resolution in phosphorus monitoring and for collecting samples over a range of streamflows, especially during high-flow events, to increase the accuracy of trend and load analyses (Cha et al., 2010; Johnes, 2007; Moatar and Maybeck, 2007; Saad et al., 2011). However, according to Saad et al. (2011), if current trends in monitoring funding continued, data for the development of regional loading models would further decline.

Here, we examine the challenges associated with maintaining a network of tributary phosphorus monitoring sites in the Laurentian Great Lakes. To better understand the status and trends associated with tributary water quality monitoring within the Great Lakes Basin, we interviewed knowledgeable stakeholders at agencies responsible for managing portions of this water quality monitoring network. Our primary objective was to gain insight into the plans of agencies and to identify potential steps for improving the capacity of the existing tributary network in terms of its ability to generate data useful to researchers interested in determining the impact of phosphorus entering the Great Lakes from tributaries.

Interviews

To examine the factors and challenges associated with maintaining a tributary monitoring network, we conducted interviews with the representatives of nine state, federal, university, or private organizations that maintain phosphorus monitoring sites in tributaries of the Great Lakes. The interviews were conducted in February through April of 2012. Some sampling sites are used by multiple organizations; in those cases, we associated the site with the agency that collected the most water quality samples. In addition, there are some monitoring agencies in the U.S. portion of the Great Lakes Basin that were not included in this research because limited data collection with high phosphorus detection limits prevented them from meeting the criteria associated with the SPARROW calibration process. For example, the metropolitan sewage districts of Green Bay, Milwaukee, and Chicago fall into this category.

The interviews, which were recorded and transcribed, consisted of ten multi-part, open-ended questions applicable to continuous, intermittent, and ceased monitoring sites (questions are listed in Appendix A). Ceased monitoring sites are those where phosphorus concentrations were measured for some period in the past, such as in the 1980s and 1990s, but where sampling was eventually discontinued. Intermittent sites are sites where sampling was discontinued but has since been restarted. Continuous sites are those that have been sampled continuously, without a gap in the data. The interviews were conducted with program managers, coordinators, and directors of the tributary monitoring programs associated with SPARROW calibration sites, each of whom had intimate knowledge of the monitored sites, program goals, and program needs.

With the exception of Heidelberg University's Center for National Water Quality, all of the interviewed organizations were government agencies. The Heidelberg University program is a private non-governmental program that relies on a combination of private and public funds to maintain their monitoring network and associated research. Most of the other programs were state-operated and designed to meet state-level goals that are generally associated with meeting the requirements of the Clean Water Act and not necessarily for monitoring chemical inputs into the Great Lakes. Also interviewed was a representative from the recently-initiated USGS Forecast/Nowcast Great Lakes Nutrient and Sediment Loadings program, which is funded by the Great Lakes Restoration Initiative (GLRI). The GLRI is a federal program that supports projects associated with protecting near-shore health and wetlands from pollution, cleaning up toxic areas, and combating invasive species (GLRI, 2012). The USGS Forecast/Nowcast program involves the collection of water quality data, including phosphorus concentrations and stream flows at 30 Great Lakes tributary sites.

Results and discussion

The results of the interviews are presented in four sections. First, we describe the reasons given for the original establishment of each organization's tributary water quality monitoring programs. We then examine and summarize challenges and concerns associated with water quality monitoring programs in the Great Lakes basin. Next, we explore perceptions of the future of monitoring programs in the basin. Finally, we address the main organizational challenges of phosphorus monitoring in the Great Lakes region, focusing on the requirements for developing and maintaining a long-term program without data gaps.

Rationales for establishing water quality monitoring programs

Six out of the nine interviewees—all representatives of state agencies—pointed to the Clean Water Act of 1972 as the impetus for developing a phosphorus monitoring program. Section 305b of the Act requires that states characterize the condition of their water bodies in a report that is updated every two years, and Section 303d requires states to identify those water bodies that are impaired. State agencies performed some phosphorus monitoring in the 1960s, mainly in large rivers affected by the disposal of wastewater, and some representatives mentioned programs such as the Area of Concern program associated with GLWQA as factors influencing their monitoring programs, but for states, the Clean Water Act has been the most important factor shaping their programs.

The USGS tributary monitoring program started sampling in the Great Lakes basin in the early 1970s as a part of the National Stream Quality Assessment Network. This program was not driven the by Clean Water Act but was a nationally-funded project to sample a number of key tributaries for the assessment of trends and loads (Survey — WIUSGS). Monitoring at these sites decreased in the mid-90s, and many sites were completely discontinued due to changes in the funding priority of the USGS.

The recently established GLRI-funded USGS Forecast/Nowcast monitoring program is being directed by the USGS in cooperation with several state agencies. According to the coordinator of the USGS-GLRI monitoring project, the GLRI funding "gave us the opportunity to implement a tributary monitoring program as a part of the National Monitoring Network for U.S. Coastal Waters and Tributaries … and give a real world example of how to operate these multi-state sites around the Great Lakes." The National Monitoring Network for U.S. Coastal Waters and Tributaries (National Water Quality Monitoring Council, 2006) is an initiative developed by stakeholders concerned about the nation's coastal waters, which includes the Great Lakes. In addition to a framework for selecting potential monitoring sites, the National Monitoring Network Design initiative includes a list of recommended water quality constituents to measure and recommendations on the frequency of sample collection. The coordinator of the USGS-GLRI project notes that this "monitoring is essential to figure out the processes and changes that are happening at these sites in the Great Lakes Basin" (Survey — USGS-GLRI).

Heidelberg University's program began in 1969 as an educational project, with the early program goal being to "conduct and develop accurate mass balance calculations for P [phosphorus] sources going into Lake Erie … and see what benefits came from point source removal." In 1981, the mission of the monitoring program shifted to include a broader assessment of the contributions of both point and non-point sources in the watersheds of western Lake Erie. The current purpose of the monitoring program "is to minimize the adverse impacts of agriculture on water resources in our area, streams and rivers into Lake Erie … recognizing the importance of food production and agriculture as a major industry in this area, but also monitoring the large economic consequences from the nutrients entering the lake Erie ecosystem" (Survey — Heidelberg). The Heidelberg program was able to continue its monitoring throughout the 1990s when many other monitoring programs began to reduce sampling frequency and sites. This monitoring program, which has continued to the present, has been made possible by Heidelberg's ability to assemble funding from multiple funding sources, including federal and state agencies and private sources associated with the fertilizer and agricultural industry. The resulting data set has enormous value for all Great Lakes research and management actions.

States have significant flexibility in determining how best to characterize the waters of the state and in facilitating the protection and restoration of their designated uses (CWA). Most of the programs (five of the nine) selected their sites, in the words of one interviewee, to "provide a broad spatial coverage over a range of land coverage and ecotypes for the purpose of assessing conditions and trends … and also sites were selected in conjunction with a USGS flow gauging station" (Survey — WIUSGS) so loads could be determined. Additionally, the programs chose sites that were major contributors of flow "to document the water quality for a certain percent of surface water … thereby picking them for size" (Survey — WDNR). Over the years, each state has developed its own approach to monitoring. Many programs (four out of nine) have seen the number of sites diminish over time. Most of these changes were due to funding issues (Survey — MIDEQ, OHEPA, WIUSGS, NYDEC). With the decrease in funding, many of the state programs devolved into meeting only state policy objectives driven by the needs of the CWA, which was to assess the conditions of inland state waters, not the Great Lakes. As a result, the collection frequency at fixed locations dropped and new rotation-based monitoring programs were developed to characterize the condition of rivers. This change, which occurred in the late 1980s and 1990s, significantly altered the amount of tributary data collected.

Concerns and challenges

All interviewees noted that a significant challenge is securing funding and managing the staff and infrastructure required to maintain a sampling program and complete all phases of monitoring and assessment associated with tributary monitoring. In the case of total phosphorus measurements, the sample must first be collected and delivered to a certified laboratory for analysis. The results are then recorded in an internal database and/or submitted to a central federal or state database for dispersal to potential users of the data. Hence, the overall effort requires the services of many different actors, including technicians capable of maintaining sampling equipment, sample collectors, site managers, laboratory specialists, quality control specialists, computer database supporters, and ultimately, scientists who can analyze the data in ways that fulfill the explicit mission of the program.

The Heidelberg program, which collects daily samples from ten sites, illustrates the challenges faced by organizations. At each monitoring site, three samples are collected per day. These samples must be retrieved by a technician and brought to the organization's laboratory for processing. The equipment also has to be maintained on a regular basis. The two technicians and one lab manager who perform these tasks also are responsible for moving "the data from the analytical equipment into the computers." Each monitoring station costs "in the neighborhood of $40,000" per year to operate. Scientists who make use of the data are also an integral part of Heidelberg's program.

Most of the state agencies lack a sufficient number of personnel to maximize the value of the collected information. Five state agencies stated that difficulties in calculating loads and trends was one of the largest challenges associated with monitoring programs. According to MIDEQ, the major challenge is "really maximizing the value of information collected … it has been a challenge to really integrate across the media to get a comprehensive picture of what monitoring is telling us." The Indiana interviewee indicated that we "currently lack the staff resources to fully utilize these data and to explore different methods for determining trends." Such responses suggest that adequate funding for analysts is required if states are to make optimal use of the data they collect and that ways to share expertise among states should be explored.

The Heidelberg program is an example of a monitoring program where researchers are not only collecting data, but also are utilizing the data to assess issues such as the factors responsible for algae blooms in western Lake Erie. The active use of the data for research can ensure that the data are being collected, assessed for quality, and stored appropriately.

There are also challenges associated with making the data available and accessible to external researchers. Phosphorus water quality data can be stored in and made accessible through the USGS centralized water database National Water Inventory System (NWIS) and EPA's water quality database for housing state data (STORET) and through specialized state-level and organization-specific websites for making data available. The federal databases enable site, state, and watershed specific analysis, and most, but not all, programs "load [their] chemistry data to the EPA national data warehouse" (Survey — NYDEC) or to the USGS NWIS database (Survey — WIUSGS and USGS-GLRI). Although most states load their chemistry data into STORET, those data are not available for several years after they are collected, making STORET only useful for retrospective analyses. According to MIDEQ, making data accessible is "always a challenge … but we have a state system in place where people can actually access the data … that are more user friendly than STORET."

The Heidelberg program makes "all the data available on [our] website … and [we] have an analytical template that you can download and do exploratory analysis." Given the number of different databases, data users—such as researchers interesting in modeling the amount of phosphorus flowing into the Great Lakes—spend an inordinate amount of time collecting data from various state, federal and private databases. The U.S. EPA has established a new data portal that is designed to provide a common access site for integrated water quality analysis (Water Quality Exchange). If successful, it could simplify the collection of data from federal, state, tribes and other organizations (EPA, 2012). However, this tool was not discussed by any of the monitoring organizations.

Not surprisingly, many interviewees noted that securing adequate funds to operate a monitoring program was a challenge. The funding of a tributary monitoring program in the Great Lakes varies from the $15,000 to $40,000 per site per year depending on the temporal sampling design and parameters tested for phosphorus stations at the interviewed monitoring sites. The annual costs of collecting water quality data and maintaining the sampling program range from $400,000 to $1.2 million (Table 3) for the programs that reported estimated the expense of their monitoring programs.

Most of the interviewees (six out of eight) indicated that their organization had to assemble funds to support monitoring efforts from a variety of different pools, such as federal EPA funds, point-source discharge fees, tipping fees (fees that are charged for solid waste disposal), and short-term grants. Heidelberg stated that its "funding [source] has constantly shifted and we have had to spend an inordinate amount of time chasing funding to keep the stations going." All of the programs have had funding sources end, causing them to shut down monitoring sites and reprioritize their efforts.

Interviewees also indicate that monitoring is a low priority when compared to water-related permitting and compliance efforts. This is especially a problem when different groups within an agency are competing for the same pool of funds—such as when "a block of money comes to the state to the Division of Water for many programs, not just monitoring" (Survey — NYDEC). As a result, when funds are limited, monitoring may be the first aspect of a water quality program to be cut, since most states seem inclined to hold on to their higher priority programs, such as their permitting programs. As one stakeholder summarized,

> "It is very short-sighted, because how do you know if things are effective or you are spending money in the right place if you are not out there doing the monitoring to figure out where the problems are? … Compare monitoring to going to get a physical every year. How much longer do you need to keep getting a physical? You need to keep doing it. It is not like you get to the end of a process and you are all done. That is the problem. Funding is a problem, [and] monitoring is the first to cut when budget get tight."

As the Minnesota Pollution Control Agency states, "a lot of it gets back to project-based monitoring that is funded by some short-term source … that kind of funding does not lend itself to long-term monitoring."

A few states have addressed the funding challenge by passing legislation that provides for the long-term funding of monitoring programs. In 2008, Minnesota passed an amendment to the state's constitution that increases state sales tax by 0.375% and sets aside some of those funds for "water monitoring, protection, and restoration." The Legacy Amendment, as it's called, will secure funds for water quality monitoring for the next 25 years. It has allowed the Minnesota Pollution Control Agency to jump-start its "event-based water quality monitoring

Table 2
Organizations interviewed about their water quality monitoring network and the number of sites operating during historic and modern time periods. Intensity of site monitoring is indicated by average number of observations per site.

State	Miles of Great Lakes shoreline[a]	Organization	Number of sites operating 1975–2002	Number of sites continuing after 2005	Average number of observations per site
Ohio	312	Heidelberg University Center for Water Quality Research (Heidelberg)	8	7	9000
Ohio	312	Ohio Environmental Protection Agency (OHEPA)	11	1	180
Indiana	45	Indiana Department of Environmental Management (INDEM)	24	19	220
Michigan	3052	Michigan Department of Environmental Quality (MIDEQ)	32	7	210
Minnesota	189	Minnesota Pollution Control Agency and Western Lake Superior Sanitary District (MNPCA)	8	7	270
New York	408	New York State Department of Environmental Conservation (NYDEC)	9	6	350
Wisconsin	820	USGS[c] Wisconsin Water Science Center and Wisconsin Department of Natural Resources (WIUSGS & WDNR)	34	24	330
Pennsylvania	51	Pennsylvania Department of Environmental Quality	2	0	150
			Total: 128	53	
US Great Lakes	4940	USGS Great Lakes Restoration Initiative Forecast/Nowcast Program	30[b]	30	

[a] Shorelines of the Great Lakes in each state (www.michigan.gov/deq).
[b] In the past managed by USGS via state agencies, may overlap with state-by-state counts.
[c] United States Geological Survey.

Table 3
Approximate operational monitoring costs (not including salaries) by responding agencies.

Monitoring program	Cost per site	Annual cost
Heidelberg University	$40,000	$400,000
New York Department of Conservation	NA	$400,000
Michigan Department of Environmental Quality	NA	$400,000: fixed station sampling $200,000: rotating program
USGS Great Lakes Restoration Initiative Forecast/Nowcast Program	$25,000/basic site $30,000/additional wastewater sampling $40,000/additional virus sampling	$1 to 1.2 million
Indiana Department of Environmental Management	NA	$755,000
Wisconsin DNR Lake Michigan Phosphorus Load Monitoring	$15,000–$20,000	$75,000 to $100,000

including phosphorus on all 86 major watersheds in the state of Minnesota." Michigan also has funds secured by legislation. In 1998, the state passed the Clean Michigan Act, which set aside approximately $45 million for water quality monitoring. The MIDEQ network has spread these funds out over at least 15 years. For the last "eight years MI government programs have been getting cut pretty much every year," but through this act, MIDEQ forecasts that secure funding for monitoring efforts will persist for many years.

Differences in sampling regimes

The sampling regimes employed by monitoring programs in the Great Lakes Basin vary significantly. Furthermore, over the history of tributary water quality monitoring in the Great Lakes Basin, many programs have altered the design of their monitoring programs to reflect state needs, funding, and management choices. The type of protocol that a monitoring program employs can affect the usefulness of the data generated for the purpose of estimating nutrient loads and trends.

Historically, a number of the state programs had monthly ambient tributary monitoring (Survey — NYDEC, OHEPA, WDNR, INDEM, MIDEQ). Eventually, many of these monitoring programs scaled back their sampling frequency and number of sites because of funding constraints and changes in program objectives (Table 4). Currently, as indicated in Table 2, the average number of observations per site per annum varies among the different state, federal, and private tributary monitoring programs. The program at Heidelberg University, for example, collects a vastly greater amount of data than any other agency in the tributary monitoring network, with an average of 9,000 measurements each year compared to 150–350 for other programs.

Part of the reason for the variation in sampling regimes is that significant variation exists in terms of how states comply with the requirements of the Clean Water Act. For example, programs in Ohio, Indiana, Michigan and New York utilize a dual monitoring program consisting of a fixed station program and a rotating program (Table 4). The fixed station programs target "specified tributaries, basically the major tributaries … near the mouths prior to discharging to the lake" (Survey — MIDEQ). The fixed stations are sampled either monthly or quarterly depending on the state program goals and objectives. The fixed station program in Michigan includes flow-stratified samples on six of the monitoring sites (Survey — MIDEQ) to understand loads at different flows. The monitoring program rotates intensive sampling of different basins among river basins within the states to intensively sample more sites. This rotating program runs on a 5–10 year cycle depending on the sampling regime. The suite of approaches allows states "to extrapolate results to understand the nutrient levels in a large majority of state's streams in a given two-year period" (Survey — MIDEQ) as required by the Clean Water Act. Although a rotating approach allows a state to characterize a greater range of its waters for less money, the data are difficult to interpret for trends and inter-annual variability is hard to quantify.

In contrast, programs in Minnesota, Heidelberg and USGS-GLRI incorporate use flow-stratified approaches to sample during a range of flow events. In particular, some strategies focus on high-flow events because these events are often associated with a greater proportion of phosphorus loads than low-flow. The program in Minnesota operates a major watershed loading program that samples their sites 30 times per year based on both high-flow runoff events and base-flow background concentrations. Heidelberg conducts daily samples at all of its sites, which allows for capturing the range of a site's flow regime. The Heidelberg program is unique in that it collects daily samples at all of their sampling sites in the basin. The USGS-GLRI multi-state program conducts monthly sampling with the addition of up to six storm events per year at each of their 31 sites. In conclusion, the sampling regime differs spatially and temporally among all of the monitoring programs. These programs also have little coordination of their goals and objectives.

Wisconsin and Heidelberg operate Great Lakes-specific monitoring programs that are not associated with state-wide assessments. In the case of Wisconsin, the goal is to "specifically assess the waters of the Great Lakes Basin area in Wisconsin" (Survey — WDNR) through five water quality sampling sites. This program assesses rivers within the

Table 4
Interview responses to questions on sampling design and frequency from different organizations for their sampling programs.

Organization code	Program	Current sampling frequency
WDNR	Long-Term Trends Monitoring Program	Monthly to quarterly
	Lake Michigan Phosphorus Monitoring Program	Monthly (flow proportional)
WIUSGS	National Surface Water Quality Assessment Program	One active site: monthly
MNPCA	Major Watersheds Load Monitoring Program	30/year (most in response to runoff events)
Heidelberg	National Center for Water Quality Research	Daily
OHEPA	Fixed Monitoring Program	Quarterly
	Rotating Basin Program	5–6 samples/half year every ten years
INDEM	Fixed-station Monitoring Program	Monthly (potential shift to quarterly)
	Probabilistic Monitoring Program	Nine-year basin rotation with intensive sampling
MIDEQ	Targeted Monitoring Program	1. Monthly for 6 sites (flow-proportional) 2. Quarterly for 25 sites, but once every five years monthly
	Probabilistic Monitoring Program	Quarterly 50 sites rotating every year
NYDEC	Permanent Routine Monitoring Program	6/year
	Intensive Monitoring Program	5 year basin rotation: 10/year
USGS-GLRI	USGS Great Lakes Restoration Initiative Forecast/Nowcast Program	Monthly + up to 6 storm events

Lake Michigan watershed monthly with a flow-stratified protocol. The Heidelberg Lake Erie tributary monitoring program in Ohio assesses the waters of the western Lake Basin to understand the impact of agriculture on water quality. In addition, New York is in the process of establishing such an effort: “there is a separate group in New York that is just starting to concentrate on Great Lakes monitoring, they don't really have any monitoring setup, they are just using our results, but they may move on from what we are doing to sample in a more intensive way” (Survey — NYDEC), to assess a greater portion of the Great Lakes tributaries.

According to Heidelberg, “in a typical time-based (date sampling program) you are not going to characterize the high flow end, which is where all the action is in terms of loading,” unless high-flow samples are collected in addition to a time-based program. The importance of continuous monitoring networks and sampling regimes in water quality concerns across the Great Lakes is apparent in recent efforts to study the problem of increased algal blooms in the Western basin of Lake Erie from increases in phosphorus loads (GLC, 2012; Michalak et al., 2013). Indeed, the International Joint Commission (IJC) issued a letter stating the lack of understanding of the deterioration of the nearshore waters of Lake Erie is “a consequence of decisions to curtail nutrient monitoring and control (state and federal) programs” (IJC: Letter to Governments, 2010).

The increased incidence of algal blooms may be associated with recent increases in dissolved reactive phosphorus (DRP) concentrations (Daloğlu et al., 2012), which may be linked to current agricultural practices. The trend of increasing DRP was discovered through Heidelberg University's daily monitoring program, underscoring the importance of having long-term data. Without the continuous data set from Heidelberg University, which extends back to 1975, researchers and managers would have been ill informed as to the status of Lake Erie phosphorus loads since 1995. The Heidelberg program was able to generate this data only because managers of that program succeeded in securing funding from a variety of sources and collaborations. The IJC reinforces this point, stating that “dedicated funding for long-term monitoring of phosphorus export from major tributaries should be secure and permanently funded so that progress or lack of progress under the Great Lakes Water Quality Agreement can easily be discerned”(IJC: Letter to Governments, 2010).

The use of different sampling regimes also complicates another issue raised by interviewees, which is that there are minimal organizational connections between state monitoring programs. Most programs collect data required to fulfill their particular mission, which can differ significantly from state to state. There have been efforts within agencies to collect data throughout the basin for estimating background loads and concentrations (Robertson, 1997; Robertson and Saad, 2011), but not to develop a regional monitoring network. Recently, however, the USGS-GLRI program is coordinating a multi-state effort to link the tributary monitoring stations within various states together for a holistic look at the Great Lakes Basin. The USGS-GLRI program is attempting to “convince cooperators (partners, other agencies) of the value of the multi-state monitoring program” (Survey — USGS-GLRI) and link the various tributary monitoring sites into a long-term network for the Great Lakes Basin. With an intertwined network of data providers, the data collection and costs can be shared through partnerships to “have a shared use of data for greater coverage on the same site” (Survey — NYDEC). Although this infrastructure is currently not in place in most sampling programs, it may be a necessary component for future longevity of these complex organizational structures.

The success of tributary phosphorus monitoring in the future requires an adequate organizational structure, sufficient funding, and effective sampling protocols for understanding in changes in phosphorus concentrations and loads. At the same time, many program managers have doubts about being able to meet these requirements in years to come, at least without strong inter-agency collaboration. The MIDEQ hopes they will be able to secure funding for staff and monitoring by obtaining support for another bond initiative but this effort, “can be very political and it can polarize who supports it and who does not … If we are not successful, then there is no way to avoid that fact that the amount of monitoring we do is going to drop.” Funding challenges could also lead to combining monitoring programs with increased inter-agency collaboration, greater organizational structure to support and continue monitoring efforts.

Conclusions

The importance of being able to accurately estimate the distributed tributary loading of phosphorus to the Great Lakes has increased over the last several decades. As the amount of phosphorus associated with point sources declines, efforts to reduce the incidence of destructive algal blooms will increasingly depend on understanding and managing non-point, distributed tributary loadings. Future changes in land use and climate will further complicate this task, and adapting to these changes will depend on having accurate estimates of how phosphorus inputs are changing over time.

Currently, researchers who assess phosphorus loadings and estimate future loads make use of one of two general methodological approaches. The accuracy of both approaches, however, depends on researchers having continued access to tributary phosphorus concentration data generated by water quality monitoring programs. In this paper, we investigated the concerns and challenges associated with maintaining effective tributary water quality monitoring programs through interviews with managers responsible for some aspect of the existing programs.

Results from these open-ended interviews suggest three issues that policy makers interested in maintaining an effective phosphorus tributary monitoring network in the Great Lakes basin should consider. First, the objectives driving the development and operation of tributary monitoring programs vary across the basin. The requirements of the Clean Water Act provide the main motivation for many of the state-based agency programs, with most of the state programs selecting a monitoring design to provide broad spatial coverage of their state waters and for quantifying point source impacts in their rivers, which does not necessarily generate the type of long-term data useful to researchers who estimate phosphorus inputs to the Great Lakes. The Heidelberg University monitoring program, on the other hand, has produced quality long-term data sets and represents an intensive study of loads to the western Lake Erie basin. This program represents a significant effort to understand the relationship between agricultural practices and phosphorus sources flowing into Lake Erie. Although the ultimate goal is to inform management actions, the program is driven more by scientific questions than by a policy initiative. The USGS-GLRI program, a nationally-administered and funded effort, is designed to document the short-term status of water quality across the entire Great Lakes Basin and to potentially support future Great Lakes management plans and the development of watershed models.

The variety of monitoring program goals and objectives results in spatial and temporal differences in sampling frequency and design. Minnesota's program, for example, involves the collection of 30 phosphorus samples per year, incorporating both ambient and storm nutrient sampling. This sampling design is meant to meet Minnesota's goals and objectives of characterizing seasonal and annual phosphorus loads. The Heidelberg program involves collection of daily phosphorus data. The daily sampling design is meant to generate sufficient data to provide reliable estimates of phosphorus loads, which will inform strategies for minimizing the impacts of agriculture on water resources in western Lake Erie. The collection of flow-stratified data through storm event sampling by the USGS-GLRI, WDNR and MIDEQ enables the data to be used in models and trend analysis by reducing the amount of error in estimations. However, other state programs, including OHEPA, INDEM, and NYDEC, collect only ambient phosphorus data on a monthly to quarterly basis to characterize their state waters as specified by the

CWA. These protocols do not include flow-stratified or storm event sampling.

Second, these differences in frequency and design limit the ability of the various programs across the Great Lakes to coordinate efforts for collaboration and data sharing. Under current policies, those in charge of state programs have relatively few incentives to engage in tributary monitoring that supports an integrated water quality assessment at the Great Lakes Basin scale. As might be expected, most state programs focus on assessing their bodies of water in ways that satisfy the requirements of the Clean Water Act as opposed to how their tributaries affect loadings to the Great Lakes. The new USGS-GLRI program is implementing a cross-basin monitoring effort to assess the waters of the Great Lakes, but the effectiveness of this effort could be increased if there were incentives for state-level programs to participate in basin-wide efforts. In the end, the success of the basin-wide program depends on collaboration across the region from federal, state, and local agencies to fund and develop monitoring sites that fit into the goals of the USGS-GLRI program. This suggests that an adjustment to most state-level policies would be desirable so as to provide program managers with an incentive to alter their sampling regimes in ways that support basin-focused efforts.

Finally, the consistency of funding for tributary water monitoring programs varies by program, complicating any long-term effort to generate sufficient water-quality data for use in understanding phosphorus trends and loads. Most state monitoring programs, with the exceptions being those in Minnesota and Michigan, continuously face the possibility of funding cuts. Minnesota's long-term data collection program is funded through a 25-year commitment to use state taxes for that purpose. Michigan's program has roughly 15 years of funding through the Clean Michigan Initiative Act, which allocates bonds for environmental and natural resources protection. For most other programs, securing consistent funding is a difficult task, especially since monitoring is commonly a lesser priority than activities such as permitting in some states' environmental programs. Hence, many of these programs face challenges securing funds sufficient for sustaining a long-term monitoring network, which include costs associated with personnel, supplies and equipment, and the sampling of multiple sites at a frequency high enough to be useful. Similarly, funding for the USGS-GLRI program is temporary, and the Heidelberg program depends on the entrepreneurial efforts of researchers to secure funds.

Given these issues, we recommend the following actions for improving monitoring networks for assessing phosphorus loads into the Great Lakes:

1. Provide states with incentives to support the monitoring of phosphorus for the purpose of estimating loads to the Great Lakes. Among other things, doing so will encourage state-level program managers to participate in discussions involving basin-wide goals and how to adjust their sampling region in ways supportive of those goals.
2. Identify phosphorus monitoring protocols that include enough samples to identify trends and quantify loads at a level of certainty necessary for use in statistical models and load control programs. Establishing such protocols will help program managers across the basin to develop an integrated plan for characterizing phosphorus loads in the Great Lakes Basin by establishing similar sampling frequencies and site selections criteria. The National Monitoring Network for U.S. Coastal Waters and Tributaries (National Water Quality Monitoring Council, 2006) sampling design recommendations could provide a basis for consistent protocols.
3. Develop funding mechanisms consistent with long-term policy goals. If the goal is to generate data for the long-term monitoring of phosphorus loads, the funding mechanism must be sufficient to meet those goals without agencies having to constantly fight for resources. For states, the funding programs in Michigan and Minnesota can serve as potential models. In addition, greater inter-agency collaboration could also result in greater federal funding for long-term monitoring.

The implementation of these recommendations would represent an important step toward developing a coordinated system of monitoring for the purpose of providing data to researchers who model the distributed tributary loading of phosphorus into the Great Lakes, both for the purpose of better understanding lake dynamics and to prioritize ecosystem restoration efforts in the face of changes in land use and climate.

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Appendix A. Open-ended multipart interview questions for all programs and individual programs assessed

For all programs:

1. What was the original motivation for establishing the monitoring programs associated with the rivers that feed the Great Lakes?
   a. What factors led to the selection of these specific sites?
   b. What type of monitoring is currently performed?
   c. Do you know if the type of monitoring and/or methodology has changed over time?
2. How are the monitoring sites funded?
   a. Has the source of that funding changed over time?
   b. Is the funded tied to generating data for a specific purpose?
   c. What is the approximate expense of maintaining these stations?
   d. Has it been a challenge to secure sufficient funding?
3. What have been the largest challenges associated with managing the site, processing the data and making it accessible?
   a. How much data is required for usability?
4. What are the goals or original goals of the monitoring program?
   a. What is the frequency structure of the network and how is it determined?
5. Would you describe the monitoring program as being tied to the research program of specific individuals or linked to larger institutional goals?

For monitoring programs that ceased operating:

6. What were the reasons for ending the monitoring program?

For monitoring programs that ceased operating and have been resumed:

7. What led to the monitoring program being resumed?
   a. Was a new source of funding involved?
   b. Did the type of monitoring change?
   c. Has the gap in data posed unexpected challenges?

For monitoring programs that have been intermittent:

8. What are the reasons for the monitoring program being intermittent?
   a. Did the source of funding change?
   b. Are there any special challenges associated with intermittent monitoring?

Questions for All Sites:

1. What is required to maintain effective monitoring?
2. What do you see as the future of this monitoring program?

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