Journal of Great Lakes Research 41 (2015) 1060–1074

Contents lists available at ScienceDirect

Journal of Great Lakes Research

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

Exploration of spatial variability in nearshore water quality using the first Great Lakes National Coastal Condition Assessment survey

John R. Kelly [a,*], Peder Yurista [a], Matthew Starry [b,1], Jill Scharold [a], Will Bartsch [c], Anne Cotter [a]

[a] US EPA, Mid-Continent Ecology Division, 6201 Congdon Blvd, Duluth, MN 55804, USA
[b] SRA International, 4300 Fair Lakes Court, Fairfax, VA 22033, USA
[c] Oak Ridge Institute for Science and Education, 6201 Congdon Blvd, Duluth, MN 55804, USA

ARTICLE INFO

Article history:
Received 23 January 2015
Accepted 28 August 2015
Available online 24 October 2015

Communicated by Stephen Charles Riley

Index words:
Nearshore
Embayments
Assessment
Phosphorus
Watersheds
Great Lakes

ABSTRACT

A comprehensive approach to assess conditions in the Great Lakes nearshore has been lacking for decades. We conducted a pilot survey in Lake Erie (45 sites) in summer 2009. The US National Coastal Condition Assessment (NCCA) was then conducted across the Great Lakes in summer 2010. The NCCA survey design provided statistically based estimates with defined uncertainty bounds for a variety of ecological indicators. For example, water quality (WQ) was measured (233 sampled sites) in the US nearshore, a resource defined with criteria to include waters to 30 m depth and less than 5 km from shore. A sub-resource of the US nearshore (151 separate sample sites) was defined using geometric criteria along the shoreline to identify small to medium embayment areas. Statistical analyses showed that embayments had higher Total Phosphorus and were more turbid than the open nearshore. We explored spatial variability in WQ results (2009, 2010) through regression analyses at multiple scales (within and across lakes) for nearshore and embayment resources. Empirical modeling identified principal drivers of spatial variability as risk factors for enrichment: water column depth and a landscape disturbance metric representing agricultural intensity as an indicator of watershed nutrient loading. Eutrophic nearshore conditions occurred at the upper end of an associated landscape disturbance gradient across watersheds of the US basin, peaking in Lake Erie. Overall results were consistent with the principles of classical limnology theory and demonstrated that a statistical survey approach can contribute to Great Lakes nearshore assessment and research.

Published by Elsevier B.V. on behalf of International Association for Great Lakes Research.

Introduction

Human population distributions are globally skewed towards coastlines, in part because the environment offered by coastal settings is attractive and highly valued (e.g. Costanza et al., 1997; Small and Nichols, 2003; Martinez et al., 2007; Barbier et al., 2011). Maintaining healthy coastal ecosystems has been a worldwide societal priority; accordingly, there has been increasing recognition of the need to monitor coastal environments, including the Great Lakes freshwater coast (Edsall and Charlton, 1997; SOLEC, 1996, 2009). Here, "coastal" refers to the coupled terrestrial and aquatic zones at the edge of large water bodies (not necessarily continents), where land and water have some significant ecological influence upon each other.

The shallow aquatic coastal zone contributes to the overall health of large lakes and can affect offshore waters through an influence upon metabolism and biogeochemical processes, food web dynamics, fisheries support, and lakewide biodiversity (e.g., Wetzel, 1992; Brazner et al., 2000; Hecky et al., 2004; Smith et al., 2007; Vadeboncoeur et al., 2011). Besides societal value and inherent ecological worth, Great Lakes (hereafter, "GL") coastal ecosystems have potential as sentinels for future lake-wide change. In the past half century, only a limited set of GL-wide, coastal assessments have been conceptualized, and even fewer attempted in a broad scale, systematic fashion (cf. Gregor and Rast, 1979, 1982; Nichols et al., 1999; Edsall and Charlton, 1997). However, recent studies have reported on GL tributaries and rivermouths, coastal wetlands, embayments, and nearshore waters as frontline receiving waters connected to, and affected by, watershed/landscape changes (e.g., Niemi and Kelly, 2007; Morrice et al., 2008, 2011; Yurista and Kelly, 2009; Makarewicz and Howell, 2012; Larson et al., 2013). The Great Lakes Water Quality Agreement (GLWQA) between the US and Canada has focused historically on offshore monitoring, but the need for a framework for nearshore assessment was re-invigorated during 2013 revisions to the GLWQA.

Relatively little, and no spatially comprehensive, coastal monitoring of the Great Lakes coast has occurred due to the complexity of coastal morphology, difficulties in defining nearshore and offshore areas, the large geographical extent of the coast, and lack of funding (e.g., Edsall and Charlton, 1997; Mackey and Goforth, 2005; Rao and Schwab, 2007; US EPA, 1992; Yurista et al., 2006). In contrast, large scale

* Corresponding author at: 904 Valley Drive, Duluth, MN 55804, USA.
E-mail address: jackrussellkelly@gmail.com (J.R. Kelly).
[1] Present address: Superior Water, Light and Power Company, 2915 Hill Avenue, Superior, WI 54880, USA.

http://dx.doi.org/10.1016/j.jglr.2015.09.007
0380-1330/Published by Elsevier B.V. on behalf of International Association for Great Lakes Research.

monitoring of the U. S. marine coast, including the National Coastal Condition Assessment (NCCA) has been conducted since the 1990s (US EPA, 2001). As part of the fifth National Coastal Condition Assessment (NCCA) in 2010 we were able to include monitoring of the Great Lakes coast for the first time. The survey's objective was to provide robust estimates (with quantified uncertainty levels) of the proportion of a defined aquatic area in good, fair, and poor condition. The US National Coastal Condition Report 2010 – the overall assessment of all US coastal regions – will be published in 2015 and report on the GL nearshore condition. This paper uses results of the survey to explore water quality throughout the US nearshore and demonstrate some of the utility of the monitoring data.

Here we identify sampling areas and data sources, describe rationale and survey design, and report water quality results of a 2009 pilot water quality survey in Lake Erie and a full 2010 survey (>400 sites) of the US coastline based on modified NCCA methods. Our primary objectives were to 1) characterize nearshore conditions and spatial variability, 2) compare WQ in defined sub-resource areas of the nearshore, 3) develop empirical models of watershed/landscape influences on GL nearshore water quality, and 4) use overall findings to confirm nearshore risk factors for nutrient enrichment.

Methods

Spatially defined resource survey approach

There is a generalized process for spatially balanced random probability survey for National Aquatic Resource Assessments (US EPA, 2010b; Stevens and Olsen, 1999, 2004), which the NCCA is part of. The GL NCCA began with a broad definition of the target area for the survey: "the area of the coupled water–sediment system extending from the shoreline into the open water of the lakes, but limited to a fringing, shallow nearshore band that is heavily used by humans and most vulnerable to human activities within adjacent coastal watersheds" (US EPA, 2010c). Two aspects of design were established a priori: the desired spatial scale of reporting and the aquatic resources to be included. The reporting scales were nested, two of which are explored in this paper: 1) a regional level, i.e., the entire US nearshore of the GL, and 2) each of the five major Great Lakes individually. The design required quantitative definition of the GL nearshore and dictated the level of sampling effort needed to report with adequate statistical confidence at the finest level, in this case each lake. After delineating the target nearshore area (i.e., the "resource") to be represented by a sample population, a second phase then defined a sub-resource: small to medium embayments (~1 to 100 km^2). The population of embayment polygons was partitioned from the initial broad nearshore delineation, leaving the remaining "open nearshore" sub-resource as complement. General criteria used to establish the nearshore and the embayment sub-resource are given here; further details are provided in Electronic Supplementary Material (ESM), Appendix S1.

GIS frame criteria

The notion of the shallow nearshore band (above) needed firm quantitative characterization via a Geographic Information System (GIS) to enable the draw of sites to be surveyed as a sample population representing the resource (Olsen and Peck, 2008). Many have struggled to define a GL nearshore (e.g., Nichols et al., 1999; US EPA, 1992; Edsall and Charlton, 1997; Mackey and Goforth, 2005; Mackey, 2009a, 2009b). At the time of our development, there was no available GIS layer we could use directly or modify as basis for the planned nearshore survey.

One common agreement is that depth helps distinguish nearshore and offshore systems, because many ecological characteristics and processes scale with depth. For an offshore boundary, some have suggested that the approximate depth at which the summer thermocline impinges on the bottom separates a well-mixed nearshore zone from a stratified offshore zone; 30 m is often recommended. This strategy would include much of Lake Erie (e.g., Edsall and Charlton, 1997) in the nearshore, so it is problematic. To accommodate this issue, Wang et al. (2015), in recently developing a GIS description/classification of the GL nearshore, switched to a maximum water depth boundary of 15 m in Lake Erie. In contrast, we used a combination of maximum depth and distance-from-shore criteria across the entire GL shoreline. Physical limnologists (Murthy and Dunbar, 1981; Csanady, 1970; Rao and Schwab, 2007), have pointed out that coastal currents are in part a function of boundary friction forces (the shoaling bottom leading to the shore itself), creating shore parallel currents that limit cross-shore exchanges and partially isolate a nearshore zone during summer stratification to be a zone that initially receives and accumulates (to a degree) discharges from land. Commonly, the distinction between nearshore and offshore current zones appears at distances about 3 to 10 km from shore. We chose a limit of 5 km from shore (analogous to a 3 nm limit historically used in the coastal ocean), wide enough to include the hydrodynamic system accumulating, and thereby vulnerable to, materials delivered from land (e.g., Rao and Schwab, 2007; Kelly and Yurista, 2013; Yurista et al., in press). The distance criteria put Lake Erie's outer edge near the 15 m water depth. The NCCA frame and nearshore classification of Wang et al. (2015) differ principally at the margins: 1) at bathymetrically unusual offshore locations, 2) in large bays (like Green Bay or Saginaw Bay) where more area was excluded by NCCA (due to the distance limit), and 3) at the land interface, as Wang et al. (2015) classified 0–3 m waters as a separate "coastal margin zone." We do not argue for one scheme over the other, and the NCCA frame was not designed as a classification tool but as a survey design necessity; it served the purpose to define a resource and allow rigorous exploration of WQ variability.

The nearshore and its identified sub-resources

The dual criteria (e.g., within 5 km from shore *but* limited to the shoreline area waters ≤30 m in depth) were used to automate a GIS process to delineate the nearshore.

Depth and distance criteria set general bounds, but we also needed to establish how to include/exclude features along the shoreline: river mouths and embayments created at the landward boundary by shore geomorphology, as well as features internal to the zone like islands, shoals, and isolated deep bathymetric depressions. There were two main processing steps, one that first defined a waterline (the land–water interface as a linear feature), and one that used depths within grid cells to define where within-zone features like islands and/or deep pockets occurred (Fig. 1).

For the waterline feature, contiguous water-only cells at the shore (distinct from those cells with a land elevation attribute) were located and then dissolved together as single, continuous outline of the GL shore. The feature was buffered by 500 m landward (to include upstream at rivermouths) and 5 km lakeward to produce provisional land and offshore boundaries. The landward buffer was an attempt to include features like small tributaries, marginal ponds and small embayments connected by rather narrow openings in the shoreline, and other minor indentations of the shoreline that might not otherwise be included. Only the resulting shallow water polygons of the five main Great Lakes were selected, i.e., connecting channels and Lake St. Clair were excluded. Following application of the depth and distance criteria, only shallow water polygons within the 5 km lakeward buffer not separated from the waterline by waters deeper than 30 m were selected. The process produced the base nearshore area, termed Nr.

Nr was the parent area from which we partitioned an embayment (Em) sub-resource using geometric criteria. For this, we borrowed from the marine realm, following a definition attributed to the Geneva Convention on the Territorial Sea and the Contiguous Zone Article 7 (Hodgson and Alexander, undated, in US EPA, 1992):

"A bay is a well-marked indentation whose penetration is in such proportion to the width of its mouth as to contain landlocked waters