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Benthic macroinvertebrate assemblages in the US nearshore zone of Lake Erie, 2009: Status and linkages to landscape-derived stressors

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A B S T R A C T

As a pilot for the 2010 US National Coastal Condition Assessment, we conducted a survey of benthic macroinvertebrates in the US nearshore zone of Lake Erie during August–September 2009. A probability-based survey design was used to select 45 sites from the nearshore (the region within the 30 m contour and $\leq$5 km from shore). The dominant taxonomic group was dreissenid mussels, with a mean density of 8415 ± 1826 (SE) m^{-2}. Other major taxa included oligochaetes (2736 ± 442 m^{-2}) and chironomids (794 ± 139 m^{-2}). The three major taxa were distributed throughout the nearshore, with the highest densities in the western basin. Lake-wide mean density of the burrowing mayfly *Hexagenia* was 114 ± 39 m^{-2}; however, it was present only in the western basin, where its mean density was 356 ± 141 m^{-2}. Stepwise multiple linear regressions across sites revealed significant correlations of several benthic macroinvertebrate assemblage metrics with landscape measures of anthropogenic stress in adjacent coastal watersheds. The Shannon diversity index, the oligochaete trophic index, taxon richness, and densities of chironomids and *Hexagenia* were significantly related to agricultural activity in basin watersheds. Other significant landscape-level explanatory variables included population density, shoreline modification, atmospheric deposition, and land cover. Study results provide evidence that benthic macroinvertebrate assemblages in the nearshore zone of Lake Erie are responsive to landscape-derived stressors emanating from adjacent watersheds. Ancillary regression analyses reinforce the concept that responses in benthic metrics appear to be mediated through site-level trophic enrichment effects in the open nearshore.

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Introduction

Nearshore waters of the Laurentian Great Lakes are of particular concern for environmental protection, management, and restoration (Mackey and Goforth, 2005; Niemi et al., 2007). These regions are productive and provide important habitat for fish, waterfowl, and organisms at lower trophic levels. Nearshore areas provide valuable ecosystem services including provision of drinking water, commercial fisheries, boating, and swimming. Nearshore waters are of interest for assessing and monitoring ecological condition of lakes because close coupling with the landscape causes the nearshore zone to exhibit effects of anthropogenic stressors from the adjoining coast and watersheds sooner than offshore waters (Yurista et al., 2011). Proximity to shore also makes nearshore areas particularly susceptible to stressor inputs from adjacent watersheds.

Benthic macroinvertebrate assemblages are useful indicators of condition for aquatic ecosystems (Wiederholm, 1980). They reflect and integrate variable localized environmental conditions of the sediments and overlying waters because they are closely associated with the sediments, relatively sedentary and long-lived (Cook and Johnson, 1974; Cairns and Pratt, 1993). Responses of benthic macroinvertebrate assemblages include changes in taxonomic richness and composition. Benthic macroinvertebrates perform key functions within aquatic ecosystems, including sediment processing, nutrient cycling and transfer of energy through food webs, and are important for ecosystem management (Covich et al., 1999). Indicators based on single species as well as assemblages of benthic macroinvertebrates have been developed for the Great Lakes. For example, density of the burrowing mayfly *Hexagenia* has been adopted as an indicator of environmental condition for Lake Erie and other mesotrophic waters of the Great Lakes (Reynoldson et al., 1989; USEPA, 1992; OLEC, 2004). Oligochaete community composition has also been used as an indicator of trophic condition in the Great Lakes, based on the tolerance of species to varying levels of organic enrichment (Howmiller and Scott, 1977; Milbrink, 1983). No comprehensive indices of benthic macroinvertebrate community composition, similar to the index of biotic integrity of Karr (1981) for stream fish, have been widely accepted as indicators of environmental condition for the Great Lakes; however, measures of taxon richness and densities of taxa have been used extensively in comparative studies of environmental condition (USEPA, 1992).

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Benthic macroinvertebrate assemblages in Lake Erie have undergone numerous changes during the last several decades. *Hexagenia* was historically abundant throughout the western basin of Lake Erie until 1953, when populations were virtually extirpated due to anoxia resulting from cultural eutrophication (Reynoldson et al., 1989; Britt, 1955). During the 1980s and 90s, following reductions of nutrient inputs, *Hexagenia* populations recovered in the western basin, spreading from remnant nearshore populations (Krieger et al., 1996; Schloesser et al., 2000). During 1997–2000, populations remained abundant in the western basin, though densities varied over time, and spread to the southwestern nearshore region of the central basin; however, they declined in the central basin during 2001–2004 (Krieger et al., 2007). During the late 1980s, two species of dreissenid mussels invaded Lake Erie, with profound impacts on the ecosystem (Vanderploeg et al., 2002). Zebra mussels (*Dreissena polymorpha*) were established in the western basin of Lake Erie in 1986 and by 1990 had spread throughout the lake (Griffiths et al., 1991). Quagga mussels (*Dreissena bugensis*) were first observed in the eastern basin of Lake Erie in 1989 (Mills et al., 1993). By 1995 *D. bugensis* had spread throughout the lake and had become the dominant species of dreissenid in the eastern basin (Mills et al., 1999), and by 2002 it was the dominant dreissenid throughout the lake (Patterson et al., 2005). In the nearshore region of the western basin of Lake Erie, total densities of oligochaetes and proportions of tubificid worms tolerant of extreme enrichment decreased from 1961 to 1982, indicating decreased pollution and eutrophication during this time frame (Schloesser et al., 1995). Soster et al. (2011) documented 72–80% declines in densities of naidid and tubificid oligochaetes in western Lake Erie between 1982 and 1993, during the period of expanding dreissenid populations. They attributed the declines to a combination of decreased anthropogenic phosphorus inputs and increased filtering activity of dreissenid mussels.

Prior to 1970 many water quality studies on the Great Lakes were performed by individual institutions and state or provincial agencies and were not comparable in sample design or methods (USEPA, 1992). Studies generally targeted limited areas of known or suspected pollution and could not be used for basin-wide estimates. Most studies in Lake Erie focused on the western basin. In response to the 1972 Great Lakes Water Quality Agreement, the US and Canada instituted surveillance and monitoring programs in the Great Lakes, but efforts focused on offshore waters. A comprehensive and integrated approach for monitoring ecological condition in the Great Lakes nearshore zone was still lacking.

The National Coastal Condition Assessment (NCCA) is a probability-based survey, conducted by the US Environmental Protection Agency (EPA) and partners, designed to provide statistically valid reports of the condition of the Nation's coastal waters (USEPA, 2009). Although the NCCA has focused on coastal marine waters for decades, the EPA Office of Water made plans to incorporate the Great Lakes for the first time in 2010; this was seen as particularly useful given the general lack of a consistent and regular approach to monitor nearshore areas of the Great Lakes (USEPA, 1992). In 2009, we conducted a pilot study to evaluate logistics and feasibility of applying the NCCA survey approach to the Great Lakes. A second goal of this study was to evaluate what indicators would best serve the purposes of a condition assessment, addressing overall health of the biological community as well as sources of stressors likely contributing to detected impairments. The study was conducted in conjunction with the Cooperative Science and Monitoring Initiative (CSMI) for Lake Erie in 2009 (Richardson et al., 2012), a mechanism for lake-wide complementary research efforts; thus Lake Erie was selected for the pilot study.

This paper focuses on one of the principal biological indicators used in the survey, the benthic macroinvertebrate community. We implemented a lake-wide probability survey of the US nearshore waters of Lake Erie to obtain unbiased lake-wide estimates of benthic macroinvertebrate assemblage metrics and densities of major taxa for two purposes: 1) to provide the information needed to apply benthic metrics to describe ecological condition and 2) to investigate the relationships between benthic macroinvertebrate assemblages and landscape characteristics in the nearshore region of Lake Erie.

Methods

Survey design

We used a probability-based survey design (USEPA, 2009) to select sites representing the US portion of the nearshore zone of Lake Erie. Generally, the process for developing and implementing a spatially-balanced probability survey involves five basic steps: 1) identification of an intended area, referred to as the target population, to be characterized; 2) definition, using GIS, of the spatial extent of the identified resource(s) of interest, referred to as the frame; 3) selection of a set of survey sites to form the sample "population" representing the resource; 4) sampling of the selected sites; and 5) analyses to report on the defined resource area.

For the present study, the target population was the Lake Erie "nearshore". The frame was defined using bathymetry obtained from the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) (http://www.ngdc.noaa.gov/mgg/greatlakes/greatlakes.html). The shoreline was modified to reach 500 m up river mouths and to include harbors behind break walls (some of which were not within the existing bathymetry). The criteria used basin-wide to define the outer boundary of the nearshore frame were a combination of depth and distance from shore. The outer boundary extended to the 30 m depth contour, or to 5 km from the closest shoreline point, whichever was reached first moving out from the shoreline. The rationale for using these boundaries to identify the targeted coastal zone of interest was as follows. The 30 m contour was selected to approximate the depth where the seasonal thermocline impinges on the bottom which helps identify a mixed nearshore water column distinct from the stratified offshore. Several studies have shown that the 30 m depth boundary can often discriminate inshore and offshore conditions (e.g., Yurista et al., 2006; Kelly et al., 2011). The 5 km limit was chosen to constrain the target area of interest to one that generally lies within a distinct coastal boundary layer (Csanady, 1972; Murthy and Dunbar, 1981; Rao and Schwab, 2007) where longshore currents dominate, cross-shelf exchange is restricted, basin drainages are directly received, and landscape signals may therefore accumulate (especially during late summer). Used jointly, the 30 m/5 km constraint serves to normalize across contrasting conditions such as the Minnesota north shore of Lake Superior, where a 5 km boundary would encompass waters in excess of 100 m depth, compared to Lake Erie, where the 30 m depth contour extends far into the offshore basin due to its generally shallow depth. For Lake Erie, the application of the boundary criteria resulted in a nearshore band of somewhat consistent width, extending an average distance of 4.99 km (maximum 5.08 km, minimum 4.59 km) from the US shore. The average depth at the US outer boundary was 13.8 m, with a maximum of 30.5 m and a minimum of 1.1 m (in the shallow western basin). The total area of the frame was 2864 km^2.

To establish the sample population, a generalized random-tessellation stratified (GRTS) survey design was used to select 45 sites in the US nearshore zone of Lake Erie (Fig. 1). The GRTS survey design provides a spatially balanced sample while allowing for variable inclusion probability and dynamic adjustment of sample sizes (Stevens and Olsen, 2004). The data analysis and reporting include appropriate statistical weightings for each site, as established by the survey design.

Sample collection and processing

Sampling was conducted from August 13 to September 19, 2009. At each site, benthic invertebrates were collected using a single standard ponar grab (0.046 m^2). Each sediment sample was elutriated in a basin with a 500 μ mesh sleeve on the outlet. The residue containing