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Green Bay: Spatial variation in water quality, and landscape correlations

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ABSTRACT

We conducted a high-resolution survey along the nearshore (369 km) in Green Bay using towed electronic instrumentation at approximately 15-m depth contour, with additional transects of the bay that were oriented cross-contour (49 km). Electronic sensor data provided an efficient characterization of a spatial pattern in water quality parameters. Nearshore water quality was correlated with adjacent landscape characterization. The regressions were able to explain over 80% of the alongshore variability for some parameters. The parameters with the strongest correlation were specific conductivity, beam attenuation, and chlorophyll. A clear feature of Green Bay is the loading introduced by the Fox River at the head of the bay. River loading sets up the conditions for a longitudinal gradient along the bay. Nutrient and chlorophyll gradients have persisted since first observed in monitoring surveys decades ago in spite of rapid flushing of the bay and efforts for remedial actions to restore areas of concern (AOCs). The water quality gradients were steepest in the 25-km closest to the mouth of the Fox River decreasing inversely with distance to where the bay opens to Lake Michigan. Summarized data from our 2010 tow and a concurrent National Coastal Condition Assessment (NCCA) survey compared to historical data (1971–1989) show a bay-wide rise in specific conductivity and chlorides, but only suggest highly variable total phosphorous and chlorophyll a in the inner bay. The tools employed (towed sensors, landuse characterization, and NCCA) can provide an efficient approach to a more regular and comprehensive bay-wide assessment.

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Introduction

The large spatial scale of Green Bay (4212 km^2, Bertrand et al., 1976), basin hydrodynamic processes (Miller and Saylor, 1985, 1993; Gottlieb et al., 1990), and multiple political jurisdictions have made it challenging in the past for agencies to make assessments and adequately address overall condition and spatial variability at the whole embayment scale. Yet monitoring at large spatial scales is required to sufficiently assess the entire bay, develop management plans, and evaluate responses to management plans. Spatially extensive studies have been used to address sediment quality, sinks, and loads across the entire bay with hundreds of collected samples (Manchester-Neesvig et al., 1996; Klump et al., 1997). Although similar extensive surveys for water quality have been conducted, little synthesized analysis has been published for the entire bay (Rockwell et al., 1980, and 1989–91 Green Bay Mass Balance project — GBMB). The waters of Green Bay are a shared resource for the states of Michigan and Wisconsin, and although state and local agencies conduct sampling at a number of local sampling sites (e.g., areas of concern AOCs) a coordinated routine monitoring of the whole of Green Bay is not presently being performed.

Sampling in Green Bay has been directed primarily towards the AOC areas in efforts to understand the extent of degradation, to direct remedial efforts, and to observe changes in conditions across time. The lower Green Bay and the lower Fox River for decades have been noted for eutrophication and pollution problems (Veith, 1972; Rousar and Beeton, 1973; Epstein et al., 1974; Sager and Wiersma, 1975; Bertrand et al., 1976). Similarly, the lower Menominee River, another major tributary to Green Bay, has a long history of pollution and contamination from the pulp and paper industry and chemical manufacturing facilities (Surber, 1953; Fitchko and Hutchinson, 1975; Marti and Armstrong, 1990). In contrast the upper Menominee River is in good ecological health (Riseng et al., 2010). The Fox and Menominee Rivers flow into and contribute to the condition of Green Bay and Lake Michigan (the 1st and 4th largest watershed tributaries to Lake Michigan). Remedial action plans (RAPs) within the AOCs have shown local progress (e.g., Uvaas and Baker, 2011). While these AOCs exist primarily as local problems on the scale of the Great Lakes, they also contribute to the condition to all of entire Green Bay. Contaminants from the two AOCs are transported throughout the bay by currents and circulation patterns (Gottlieb et al., 1990; Lathrop et al., 1990; Miller and Saylor, 1993; Martin et al., 1995). Additional nutrients and contaminants to the bay also are delivered by external loading from landscape activities in all the watersheds and at all spatial scales. The effect from these combined sources is not well known across the entire bay.

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The objective of the US EPA — Midcontinent Ecology Division for the current study was to take advantage of co-occurring studies to survey Green Bay comprehensively. Our interest included the nearshore region which parallels other recent efforts to improve our understanding of this component of the Great Lakes ecosystem (Mackey and Goforth, 2005; Niemi et al., 2007; Kelly and Yurista, 2013). The interest includes efforts to assess embayments (small to large), and in this case a particularly large embayment that is physically distinct from the main lake. We were interested in applying new tools of in situ towed instrument arrays (Yurista and Kelly, 2009; Kelly and Yurista, 2013) to characterize a very large bay environment, including identifying large-scale patterns and improving the basic understanding of spatial variability in the Great Lakes nearshore and embayment regions. A related objective was to examine potential linkages of alongshore conditions with adjacent landscape variability in the bay, to parallel our recent efforts along most of the open shoreline of Lake Michigan (Yurista et al. 2015) as well as the other five Great Lakes (Kelly and Yurista, 2013).

The study was framed under a Coordinated Science and Monitoring Initiative for the Great Lakes (CSMI, Richardson et al., 2012) that is directed by both the US EPA Great Lakes National Program Office and Environment Canada. CSMI is a program to involve and coordinate academia, state, and federal agencies in conducting research to address critical and high priority science, research, and monitoring needs of the Lakewide Action and Management Plans for each Great Lake on a five-year rotating schedule. A second co-occurring survey effort was under the National Coastal Condition Assessment program (NCCA, EPA Office of Water) and is conducted every five years across the continental US. The NCCA formally included the Great Lakes for the first time in 2010. The NCCA survey complemented the CSMI year-of-Lake-Michigan studies.

The high resolution and traditional grab sample data collected through both survey efforts increased observational capacity with which to address some basic questions: 1) Can new survey approaches and new technology capture the character and variability of water quality conditions along the shoreline, 2) can we identify regional water quality patterns or spatial structure in the heterogeneity of a large embayment, 3) is there evidence alongshore conditions are correlated with adjacent landscape character?

Methods

Site description

Green Bay is a discrete water body that is connected to and discharges into the northwest portion of Lake Michigan. Green Bay is a large water body of 4212 km^2, has a maximum depth of 54 m, and contributes approximately one third (40,000 km^2) of the watershed area of the entire basin of Lake Michigan (Ahrnsbrak and Ragotzkie, 1970; Bertrand et al., 1976). The major tributary to Green Bay is the Fox River based on volume and pollution load (Bertrand et al., 1976; Maccoux et al., 2013). Green Bay is subject to inputs from several other large rivers such as the Menominee, Peshtigo, Oconto, and Escanaba. Multiple point-sources, landscapes, and watersheds also contribute to the bay. Within the bay large-scale hydrodynamic processes act to shape the character of the bay through tributary flow rates, inertial currents internal to the bay, stochastic weather events, and complex mixing dynamics in the region of its connection to Lake Michigan. Water exchange occurs with Lake Michigan through four main channels (5.2 km^2 in total cross section) in the northeast portion of the bay (Fig. 1). Persistent inflow takes place below 20 m in all four channels and outflow primarily through only one channel (Miller and Saylor, 1985; Gottlieb et al., 1990). There is another long narrow man made canal between Green Bay and Lake Michigan at Sturgeon Bay with a small cross section (<~100 m wide and 7 m deep) that has a much lower water exchange with Lake Michigan (Saylor, 1964).

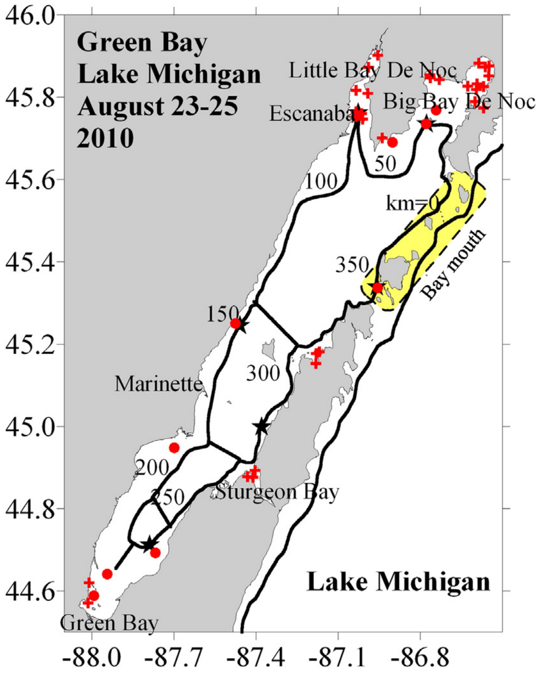

Fig. 1. Tow track along the targeted 15-m depth contour with kilometer identifiers (km = 0 near the center of bay mouth connection to Lake Michigan) for August 23–27, 2010 survey of Green Bay. Also shown are cross-contour transects and fixed sample locations MED (stars), NCCA (circles) and embayment enhancement (crosses). Also shown is a tow track from Lake Michigan September 9–15 2010. The Green Bay mouth to Lake Michigan (Baymouth) is highlighted.

Field surveys

Our first objective was to increase the spatial extent and data density of parameter observations across Green Bay by using towed sensor arrays described more fully elsewhere (Yurista and Kelly, 2009; Yurista et al., 2012a,b; Kelly and Yurista, 2013). We only briefly describe the major elements here. We towed electronic instrumentation along the nearshore of Green Bay to follow a targeted bottom contour depth of generally 15-m (Fig. 1). However, we approached the 10-m contour in the shallower southwestern portion of the bay near the city of Green Bay to capture more of the regional signal within ~5 km of the shoreline, and crossed deeper waters around the channels separating Green Bay from the main body of Lake Michigan. The average distance to shore along the transect was 3398 m (2730 m SD) with a minimum of only 85 m and a maximum of 11,533 m off a shallow flat south of Escanaba (Fig. 1). The survey was conducted during 23–27 August 2010 from the RV *Lake Explorer II*. The tow encircled all of Green Bay (369 km) with four additional cross-contour tows conducted during the time available on the cruise. The four cross-contours in Green Bay resulted in an additional 49 km of tow data that varied in length from 8.5 to 17.5 km among the individual cross-contours. The survey was conducted during the summer low-flow period with river discharge during our cruise below the 2010 summer average from the major tributary (Fox River), and with the previous peak flow more than 10 days prior (USGS, http://waterdata.usgs.gov/wi/nwis/uv/?site_no=040851385&PARAmeter_cd=00065,00060 last visited 08/05/2014). The flows suggested that we did not sample after or during an unusual, extreme, or unique event.

Our instrument array consisted of a SeaBird 19plus CTD, augmented with a fluorometer (Seapoint), transmissometer (Wet Labs, C-star @ 660 nm), SUNA NO3 analyzer (Satlantic Inc.), and all multiplexed with a laser-optical plankton counter (LOPC, Brooke-Ocean Technology, 2004; Herman et al., 2004), ship GPS data, and bottom depth sonar. Sensor data with ship position and bathymetric data were multiplexed and written to a computer file every 0.5 s. A sinusoid tow pattern

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