Environmental Management (2012) 50:664–678
DOI 10.1007/s00267-012-9902-x

Water Quality and Plankton in the United States Nearshore Waters of Lake Huron

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Received: 13 June 2011 / Accepted: 15 June 2012 / Published online: 24 July 2012

Abstract Our goal in the development of a nearshore monitoring method has been to evaluate and refine an in situ mapping approach to assess the nearshore waters across the Great Lakes. The report here for Lake Huron is part of a broader effort being conducted across all five Great Lakes. We conducted an intensive survey for the United States nearshore of Lake Huron along a continuous shoreline transect (523 km) from Port Huron, Michigan, to Detour Passage. A depth contour of 20 m was towed with a conductivity-temperature depth profiler, fluorometer, transmissometer, and laser optical plankton counter. Multiple cross-contour tows (10–30 m) on the cruise dates were used to characterize the variability across a broader range of the nearshore. The cross-contour tows were comparable with the alongshore contour indicating that the 20-m contour does a good job of representing the nearshore region (10–30 m). Strong correlations were observed between water quality and spatially associated watershed land use. A repeat tow separated by several weeks investigated temporal variability in spatial patterns within a summer season. Strong correlations were observed across each variable for the temporal repeat across broad- and fine-scale spatial dimensions. The survey results for Lake Huron nearshore are briefly compared with a similar nearshore survey in Lake Superior. The biomass concentrations of lower food web components of Lake Huron were notably approximately 54–59 % of those in Lake Superior. The towed instrumentation survey supported the recent view of a change in Lake Huron to an ultra-oligotrophic state, which has been uncharacteristic in recent history.

Keywords Lake Huron · Nearshore · Assessment · Towing · Conductivity-temperature depth profiler · Laser-optical plankton counter

The current generation of Great Lakes monitoring and assessment is based primarily on designated and fixed offshore stations for each lake that are visited on a regular basis. Many human disturbances in coastal areas are transmitted first to nearshore waters before they mix throughout the lake. The next generation of Great Lakes monitoring and assessment will also need to evaluate an array of coastal ecosystems due to the increasing development of coastal watersheds and to recent recognition of the role of coastal food webs in whole-lake dynamics (Mackey and Goforth 2005; Niemi and others 2007). The assessments will need to include open shorelines, tributary receiving areas, coastal wetlands, and embayments. Nearshore assessment may provide a sentinel function for any impending lake-wide change through identification of locations exposed to landscape stressors. The need for nearshore monitoring is clear, but doing so efficiently

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remains a challenge while meeting assessment confidence levels for such an open, dynamic system.

The nearshore is a primary path for anthropogenic stress to the Great Lakes, although atmospheric contributions are also a well-documented source of stress (Kelly and others 1991; Pearson and others 1998). Water is actively discharged (point sources) or flows across the landscape into downstream flow networks and ultimately enters nearshore receiving waters (tributary mouths or direct coastal runoff) where it begins to mix with lake water. Identifying the linkages between anthropogenic activities in the watersheds and Great Lakes water quality must recognize that hydrodynamic processes mediate the transfer of landscape signals of stress to the Great Lakes and mixing within them.

The hydrodynamic organization of the nearshore region directs how landscape input is incorporated into the entire lake. Hydrodynamic processes were an early concern for designing wastewater discharge systems to carry effluent away from large cities (Csanady 1970). As water flows into the lake, it is initially retained or entrapped in nearshore water and does not flow directly out to offshore waters (Csanady 1970). In the spring, thermal barriers confine tributary and runoff input to warmer nearshore areas (Auer and Gatzke 2004; Rao and Schwab 2007). During the summer, alongshore currents, offshore circulation patterns, bottom and coastal friction, and velocity barriers between water masses also tend to retain and mix the landscape input in the nearshore region. Wind action generates flow predominantly parallel to the shore line with mixing alongshore five times more rapid then mixing to offshore (Rao and Schwab 2007). The rate of mixing to offshore waters, however, does increase during upwelling events from Ekman transport. Because there is a general retention of runoff in the coastal area, or at least delayed mixing with the entire lake, the nearshore presents an opportunity for a sentinel-like monitoring of stress to the Great Lakes.

Although known hydrologic constraints can help define a nearshore zone of coastal mixing, there is no singular definition of “nearshore” in standard use for the Great Lakes (Kelly 2009). Instead, a variety of operational definitions [e.g., United States Environmental Protection Agency (USEPA) 1992] have been used but not always with strict geospatial boundaries specified. For example, habitat delineations for benthic organisms may depend on light levels, thermal regimes, or turbulence zones (Minns and Wichert 2005). The point at which the bottom of the thermocline intersects the lake bottom is often used to distinguish a profundal or offshore region of relative constant temperature (e.g., 4 °C) from that of a nearshore region (Edsall and Charlton 1997) where the epilimnion extends to the bottom or nearly so (<20–30 m). In contrast, fisheries managers may consider 60- to 120-m depths as still being within the nearshore based on the collective food web ecology and interactions between inshore and offshore fish communities (e.g., Yule and others 2008). Our own experience with high-resolution cross-contour sampling in the Great Lakes (Yurista and others 2005, 2006) has indicated that the nature of the nearshore pelagic environment begins to change to a more homogeneous region beyond the 30-m depth contour. This transition is consistent with the hydrodynamic properties that structure the coastal environment as discussed previously. Accordingly we continue to evaluate strategies that recognize a hydrodynamic separation of the coastal shelf waters with the offshore waters using depth-based stratification in sample design and including comprehensive monitoring of the more variable nearshore region of the Great Lakes.

In principle, more samples are needed in heterogeneous regions (e.g., nearshore) than in homogeneous regions (e.g., offshore) to quantify variance and meet specified reporting confidence levels (e.g., Stevens and Olsen 2004; Stoddard 2005; Peterson and others 1999). Consequently, large numbers of samples and greater sample density are desired when developing a sample strategy for the nearshore to address both large spatial scales and heterogeneity. Towed sensors can provide high-density data covering large spatial areas (e.g., Kelly and others 1994; Hains and Kennedy 2002). Although towed sensors have been used in marine and freshwater research for more than a decade, this approach has yet to be generally incorporated into regular monitoring and assessment that informs management decisions. In the Great Lakes, we have been developing a towing strategy that is effective at detecting conditions and depicting pelagic conditions at localized to large scales. We initially conducted a long continuous tow in Lake Superior at a 20-m target-depth contour (Yurista and Kelly 2009) and have since shown that spatial patterns along this shoreline have been relatively persistent during several years of sampling (Yurista and others 2011). These Lake Superior studies have shown that land-use metrics in the adjacent, associated watersheds can explain as much as 73 % of the variance in water-quality and plankton variables measured along the tow track in the shallow nearshore zone. The results motivated further development and application of this approach (Kelly and Yurista [in review]) using a sequence of studies across each of the Great Lakes, including the studies reported here for Lake Huron.

It is important to evaluate what a given sampling strategy actually captures and represents in space and time regardless of the nearshore definition (whether operationally practiced or strictly defined). We conducted towing surveys in Lake Huron during 2007 that were designed specifically to investigate aspects of the space-time representativeness of a depth contour-based strategy to assess large lengths of shoreline. Our major questions to further evaluate the approach included the following:

(1) How suitably can we represent the nearshore environment using in situ sensors across a range of spatial resolutions?

(2) How reliable is a single tow as an estimate of conditions in the nearshore during different times within the summer of a given year?

The surveys provided information across the United States nearshore of Lake Huron where the landscape characteristics draining to Lake Huron represent a generally increasing disturbance gradient from north to south. Therefore, the survey design enabled a case study to further explore spatial associations between watersheds and the nearshore and allowed us to ask the following additional question:

(3) Does water-quality condition in the nearshore region of Lake Huron correlate with the character of adjacent watersheds?

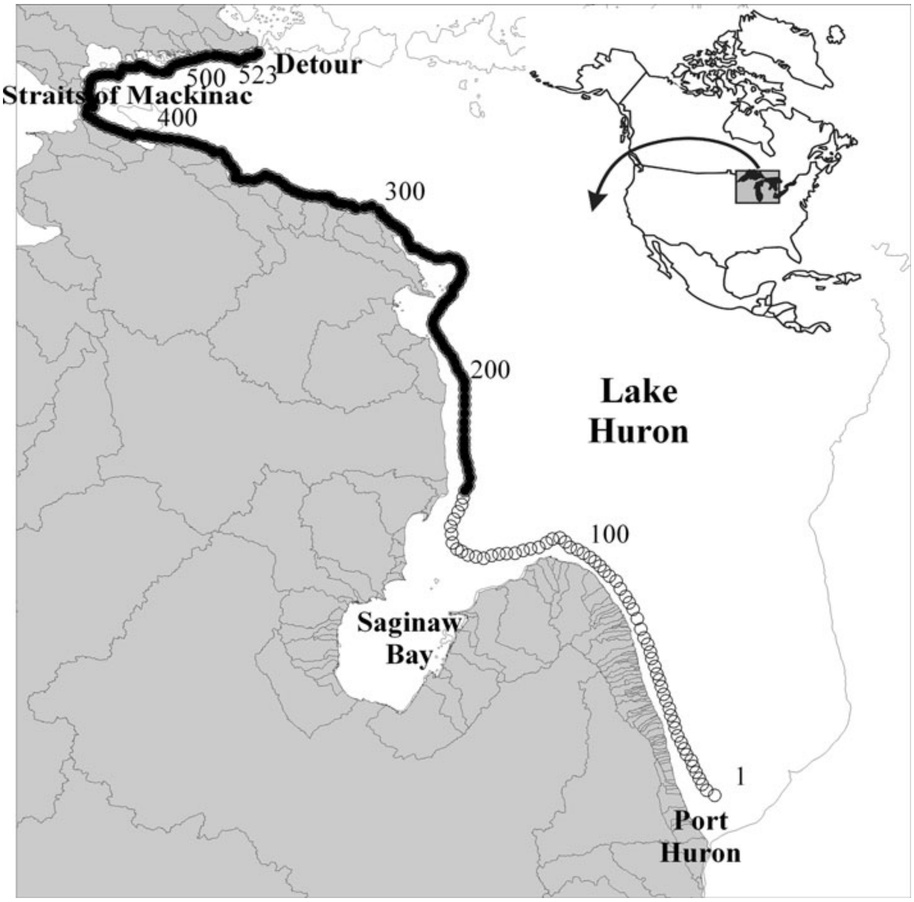
Finally, Lake Huron has recently experienced a significant decrease in food web condition (Riley and others 2008; Nalepa and others 2009; Barbiero and others 2009, 2011). To date, however, the assessments have not included a comprehensive assessment of the water quality of the nearshore. We discuss how results of this style of sampling can be used to make assessments and briefly compare nearshore conditions of the two Upper Great Lakes (Superior, Huron) reported to date.

Methods

Field Surveys

We towed electronic instrumentation along the United States nearshore portion of Lake Huron at a targeted bottom contour depth of 20 m. The tow extended from the southern end near the Huron River discharge at Port Huron to Detour Passage where the St. Mary's River enters the north end of Lake Huron (Fig. 1). The targeted tow track (523-km length) was surveyed during September 18–21, 2007, from the *R/V Lake Guardian*. We previously had surveyed much of the same contour (325 km) during July 22–24, 2007, until shipboard equipment-handling problems prematurely ended the survey. Our instrument array consisted of an SBE 19plus conductivity-temperature depth profiler [CTD; resolution conductivity 0.00001 S m^{-1}, temperature 0.0001 °C, depth 0.012 m (Sea-Bird Electronics, Bellevue, WA, USA)] with an additional

Fig. 1 Lake Huron 20-m contour tow track (2007). The September 18–21 tow is represented by all symbols, whereas the portion of the track towed during July 22–24 is shown in *solid symbols* only. The *numbers* along the track are kilometer waypoint distances for spatial reference with subsequent figures



fluorometer [Wetstar, sensitivity 0.03 μg L^{-1} (Wet Labs, Philomath, OR, USA)] and transmissometer [C-Star, wave length 660 nm, path length 25 cm, linearity 99 % r^2 (Wet Labs)] multiplexed with a laser-optical plankton counter [LOPC; minimum detection size 100 μm, coincidence limit 10^6 particles m^{-3} (Brooke-Ocean Technology, Rolls-Royce, Dartmouth, CAN) (Herman and others 2004)]. Instruments are returned to the factory yearly or biennially (LOPC) for calibration.

The in situ sensors were towed on a YSI (St.Petersburg, FL, USA) VFin493 (Yurista and Kelly 2009). Shipboard global positioning system (GPS; DGPS submeter accuracy; Trimble, Sunnyvale, CA, USA; NT-200D) provided geospatial data that was written to computer files every 0.5 s in synchrony with sensor data and bathymetric data from vessel-depth instrumentation. A sinusoid tow pattern (tow-yo) with the towfish added a vertical dimension to sensor readings with a complete tow-yo cycle (e.g., surface to bottom and returning to surface) ranging between every 0.25 and 0.5 km horizontally along the entire 523-km tow track. We towed at a target speed of 2.5 m s^{-1} (approximately 9.5 km h^{-1}) and generally restricted the towfish travel to within the range of 2 m above the bottom to approximately 3 m below the surface to avoid wake and prop wash from the vessel.

We stopped at 12 sites along the tow track in September and at 7 sites in July to collect fixed-point water samples, zooplankton net tows, and CTD profiles using an independent shipboard SBE 9 CTD [resolution conductivity 0.00004 S m^{-1}, temperature 0.0002 °C, depth 0.012 m (Sea-Bird Electronics)] system from the tow instrumentation for quality assurance. The simultaneously collected water samples for chlorophyll *a* [μg chl *a* L^{-1} ($n = 19$)] were used to convert lake-specific fluorescence (μg L^{-1}) of the towed SBE 19plus to chlorophyll *a* concentration. In addition, we conducted intercalibrations between electronic sensors on the towfish and the shipboard CTD system at each station by suspending them simultaneously at a depth in the mid-epilimnion of generally 10 m. The relationships between absolute values of parameters for the different instrument packages were checked for any drift or abrupt shifts in values using regression analyses (r^2s $= 0.99$). No corrections were necessary for any of these cruises.

Finally, we assessed variability across the breadth of the nearshore by conducting multiple cross-contour tows. A total of 18 cross-contour tows, including various repeat tows, were conducted at 14 different watersheds. Watersheds were selected in a probabilistic manner, and the cross-contour tow track was sited near the tributary mouth. We conducted cross-contour tows nominally from 10 to 30 m, and at many locations the tows were extended to include a larger cross-section (several tows to 60 or 100 m).

LOPC Field Calibration

A specific field calibration factor for the LOPC in Lake Huron was determined according to the method of Yurista and others (2009) based on Sprules and others (1998). Metered zooplankton net tows were collected in conjunction with LOPC tows on Lake Huron at 29 sites, primarily in the nearshore, with a few offshore sites included. The mesh size of 153 μm for the tow net approximated the minimum size we analyzed using the LOPC (150 μm). Net tows were analyzed for zooplankton species, abundances, and species-specific lengths. Counting and measurement statistics were based on ≥400 animals/sample. Zooplankton biomass concentrations from the net tows were calculated using the species abundance data multiplied by average dry weight determined from the length measurements and standard length–weight regression formulas (Great Lakes National Program Office 2003). A total of 4,800 animals from 10 tows were measured to determine average length by species to convert to dry weight. The biomass density from LOPC tow data were computed at 1-m-depth intervals and averaged for the water column to simulate a net tow. The spatial extent of the LOPC data from each net tow was limited to one tow-yo (between 0.25 and 0.5 km) on either side of a station or <1 km distance at the deepest station. Horizontal patchiness at the fine scales measured by the LOPC varied approximately 5 % across adjacent 0.5-km stretches measured in Lake Huron (Yurista, unpublished data from the current study 2007). The LOPC has a minimum detectable equivalent spherical diameter (ESD) of 100 μm, and only biomass concentrations estimated from ESD measurements >150 μm were used for comparison with the total net zooplankton biomass concentrations (>153 μm). The LOPC field calibration fit to the net-tow data were determined to have a geometric mean slope of 0.916, which takes into account the variability in the measurement error in both nets and LOPC data (Ricker 1982). The LOPC zooplankton biomass calculations were based on an oblate spheroid model and assumed to have a biomass specific density of 1.0 (Sprules and others 1998). The oblate spheroid model shape factor *f* (major-to-minor axis ratio) was determined to be 3.267 for Lake Huron in this study. LOPC biomass as wet weight was converted to dry weight assuming 10 % dry-wet ratio (Bottrell and others 1976).

Suspended particles are a potential source of error in computing zooplankton biomass concentrations but were not of significant density in Lake Huron to affect LOPC measurements. Total suspended solids (TSS) averaged 0.70 with a range 0.28–1.94 mg L^{-1} as measured on the cruise (A.M. Cotter, USEPA Midcontinent Ecology Division (MED), personal communication). Liebig and others (2006) compared an OPC [optical plankton counter (first-generation technology)] biomass with tow net biomass under varying levels of TSS. Their net and OPC biomass became uncorrelated at TSS >3 mg L^{-1}. We expect the LOPC (improved individual particle resolution strategy, shorter light beam path length, and second-generation OPC electronics) to have a similar or better response in environments with suspended solids that potentially attenuate or degrade the laser light beam used to detect particles. A second potential source of error could be that chain-forming algae (e.g., diatoms and blue-green algae) are large enough and abundant enough to affect LOPC estimates. Fluorescence concentrations were very low (see “Results”) and indicated that algae, including chain-forming species, were not present in any abundance to bias the zooplankton concentrations. As a final point, the LOPC did not distinguish between living organisms and detritus; however, good correlation in Great Lakes environments between zooplankton biomass concentrations and OPCs has been observed (Sprules and others 1998; Liebig and others 2006; Yurista and others 2009). Our LOPC estimates were correlated with zooplankton biomass concentrations from net tows during this study (previous text) and support that the patterns reported in this article primarily reflect zooplankton.

Spatial Data Processing

All sensor data were converted to engineering units (temperature °C, specific conductance µS cm^{-1}, depth m, fluorescence µg L^{-1}, beam attenuation m^{-1}) using manufacturer software and annual factory calibration coefficients. Sensor data were compared with water-quality point samples to corroborate and correlate sensors with similar measurements (e.g., fluorescence and chlorophyll *a*). Data were further processed with a Kriging routine to develop isopleths (SURFER 2002). Kriging produces point estimates that are best linear unbiased estimators at regular grid intervals (Isaaks and Srivastava 1989). We used a grid with between-node distances of 1 m vertically and 0.25 km horizontally, generally the distance traveled during a descent or an ascent of the tow-yo. In addition to visual inspections of isopleths images, the regularly spaced grid estimates from Kriging were used to summarize water column variables (e.g., average, maximum, minimum, SD) along the transect to analyze for spatial trends and measures of heterogeneity (Yurista and Kelly 2009). Each variable was averaged vertically across the grid point estimates through the water column every 0.25 km along the tow track. The vertically integrated averages were used in several analyses, as described later, to analyze for correlation with land-use characterization and the observation of spatial trends alongshore. Plots of the variables were constructed to visually portray and identify relationships among variables. The vertically averaged values as a function of distance along the tow track were also smoothed as a further refinement to visual interpretation of spatial trends in the data (LOWESS, SYSTAT 2004).

Statistical Analyses

Stepwise linear regressions (SYSTAT 2004) were conducted with the vertical averages of the variables of chlorophyll *a* concentration and zooplankton biomass concentration as a function of water-quality variables simultaneously measured by sensors. Specific conductance was used as a surrogate for nutrient availability, beam attenuation as a surrogate for light resources, and temperature as a controlling variable in growth rate. Although nutrients are not measured directly by specific conductance, specific conductance can be used as a tracer for riverine or landscape input, which serve as sources for nutrient influx, and nutrient concentrations can be expected to increase from waters with low to high mineral content. Temperature was modeled as a simple quadratic function because of its known curvilinear response in biological systems (e.g., Prosser 1991) and the relatively small range observed in our measurements (7.9–18.9 °C). Zooplankton biomass concentration was modeled to depend on the same variables and to include chlorophyll *a* concentration as an independent variable. The stepwise regression procedure was used to eliminate variables that did not contribute significantly to a regression and for the zooplankton regression to decrease potential autocorrelation between chlorophyll *a* concentration and variables that control chlorophyll *a* concentration.

Variables measured in nearshore waters were analyzed to determine if they were correlated with land-use characterization. We used GIS processing (ArcGIS, ESRI, Redlands, CA USA) to assign variables at every 0.25-km track segment along the tow track to an associated watershed (greater than second order). The land-use characterization for each of the watersheds of second order and larger, including their intervening shoreline (interfluves) and subsequently referred to as a “segmentsheds,” was taken from Danz and others (2005). Segmentsheds ($n = 762$) along the entire United States shoreline of the Great Lakes were characterized based on principal component scores for seven broad categories: agricultural–chemical, atmospheric deposition, land cover, population density, point sources, shoreline modifications, and soils (Danz and others 2005). The principle component scores were determined for each segmentshed using >200 variables from databases that span all United States Great Lakes coastal regions (Danz and others 2005). Detailed interpretations of the principle component scores are provided by Danz and others (2005, 2007), whereas we present just a brief outline here. The first principle component score in each category represented a relative intensity of stress due to multiple and similarly related factors within a category for each segmentshed. For example, the agricultural–chemical first principle component score represented the relative stress, compared with the other segmentsheds across the United States Great Lakes shoreline, due to various types of agricultural practices and chemical use that included but were not limited to fertilizer application (tons/ha/year), herbicide use, and soil loss (21 total databases used). Similarly, the land cover first principle component score represented the relative amount of stress to a segmentshed due to the various proportions of forest types, pasture, high-intensity residential areas, commercial urban areas, and other parameters related to land cover (23 total databases used). Principle component characterization for the other categories was calculated in the same manner using databases relevant to each category (Danz and others 2005). The average value for each water-quality variable adjacent to each segmentshed as assigned by the GIS mentioned previously was regressed using multivariate stepwise methods against the seven landscape characterizations (agricultural–chemical, atmospheric deposition, land cover, population density, point sources, shoreline modifications, and soils) for the associated segmentsheds (SYSTAT 2004).

The extent to which the 20-m contour represented the nearshore as a broader region (10–30 m) was investigated with the cross-contour tow measurements on the same date. The average for each cross-contour tow track variable was compared with the average from the equivalent length of the 20-m alongshore tow track centered on the cross-contour tow track. Regressions were determined using the paired averages.

Temporal stability in spatial patterns of the measurement variables was compared between the two tow dates (July and September) using Pearson correlation analysis. Although parameter values themselves may change over time, we asked whether the *spatial patterns* in parameter variables are persistent. For example, do areas of higher temperature or stress (e.g., nutrient input) remain higher and areas of lower temperature or stress remain lower? Are spatially referenced measurements correlated to their previous condition, and, similarly, will sources of stress that are fixed in spatial position (e.g., tributary inputs) produce consistent spatial patterns in nearshore parameter values? Each variable was tested for correlation between the two tows. The correlation was first tested on the broad scale of segmentshed reaches with their averages along the tow track. The average for each watershed reach was compared with the comparable reach in the temporal repeat tow. A finer-scale comparison of temporal stability was also computed at every corresponding 0.25-km point along the tow track. Results were considered significant if $P < 0.05$.

Results

Detailed contouring of the water column using the high-density data provided a visual image of variability in water-quality variables along the entire length of tow (Fig. 2). Temperature had no strong vertical structure across much of the tow track except for the reach south of Saginaw Bay, which appeared to be stratified and also included a probable upwelling area [Fig. 2 (km 50–100)]. The water column was unstratified in general, except for these few short stretches, with a minimal hypolimnion near the bottom. The surface waters (upper 5 m) averaged 15.45 °C (1.88 SD) with a maximum of 18.92 °C. The warmest surface waters were generally south of Saginaw Bay. Some notable features were observed in lower specific conductance values where St. Mary’s River (Lake Superior outflow) enters Lake Huron at Detour Passage and greater values around the Straits of Mackinaw where Lakes Michigan and Huron are connected. In addition, greater values were observed along the northern shore of Lower Michigan, which has substantial mining activities in some of the watersheds (United States Geological Survey USGS 2010). Zooplankton biomass concentration exhibited lower values and patchiness in the north and greater biomass concentrations in the south. The peak zooplankton biomass concentrations were associated primarily with cooler water near the bottom in the more thermally structured region of the lake, whereas zooplankton biomass concentration was lower and more dispersed across the water column when there was no strong thermal structure (Fig. 2a, e).

We averaged the water column for each variable every 0.25 km along the track to look more generally at the spatial patterns and to simplify further analyses. The summarized data exhibited the same general spatial patterns condensed to a linear dimension. Temperature exhibited a general north–south gradient, being warmer in the south but with areas along the transect indicating probable upwelling (Fig. 3). A definite pattern in specific conductance in the northern part of the tow track was observed with lower concentrations where St. Mary’s River enters Lake Huron at Detour Passage and a prominent peak at the Straits of Mackinaw where Lake Huron is connected to Lake Michigan. Beam attenuation had its most prominent peak near the St. Mary’s River plume around Detour Passage. Chlorophyll *a* concentration was relatively constant, although because of the high-resolution capabilities there was some observable pattern in the variation between 0.6 and 0.9 $\mu g\ L^{-1}$ that was apparent on both tow dates (July and September). The consistency of the pattern and the high-resolution data suggest that this is a real response to spatial position, although it may have limited biological relevance. Zooplankton biomass concentration was greater

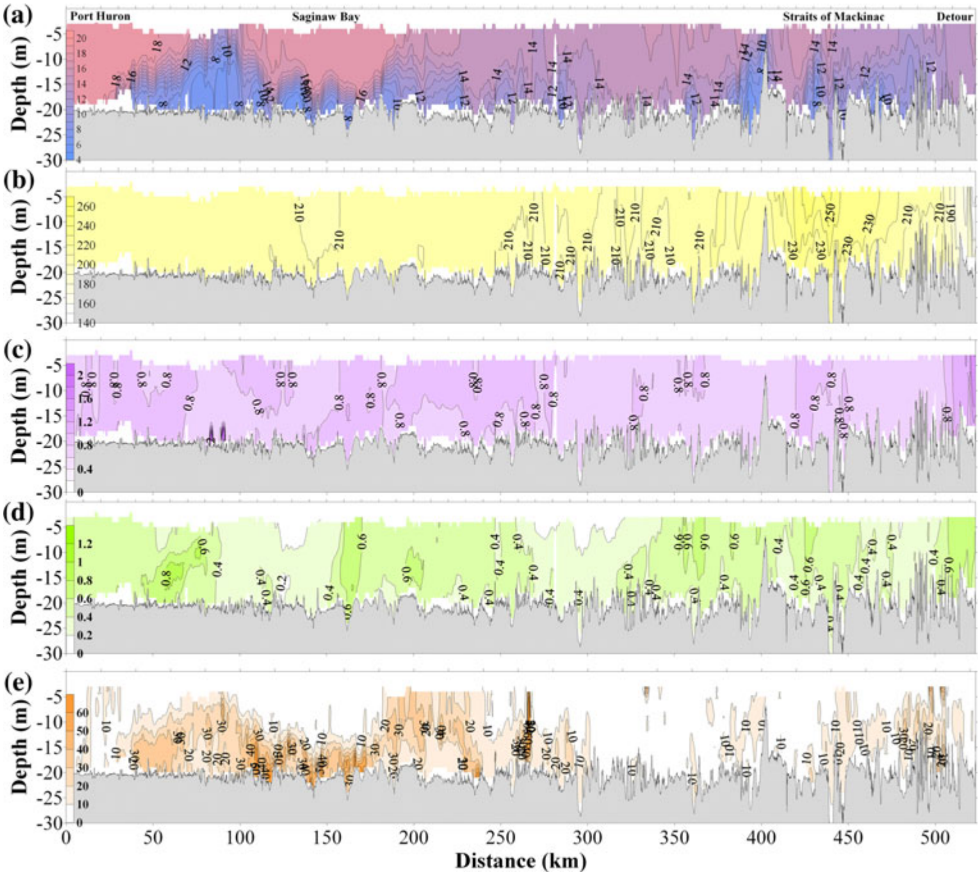


Fig. 2 Isopleth contours along the 2007 September 18–21 tow track for **a** temperature (°C), **b** specific conductance (μS cm^{-1}), **c** beam attenuation (m^{-1}), **d** chlorophyll (μg chl *a* L^{-1}), and **e** zooplankton biomass concentration (mg dry weight m^{-3}). The plot extends from the Port Huron area (0 km) to the Detour Passage area (523 km)

in the southern part of the lake (km 40–240), and there was greater variability or patchiness at localized scales (track lengths of 10–20 km). The average concentration in the southern region (20.8 mg dry weight m^{-3}) was generally more than twice that of the portion along the northern coast of lower Michigan to the Straits of Mackinaw (approximately km 300–420) (6.5 mg dry weight m^{-3}).

Chlorophyll *a* concentration was weakly correlated with controlling variables for water quality. Regression of chlorophyll *a* concentration on water-quality variables at the 0.25-km intervals had an $r^2 = 0.27$ (chlorophyll *a* concentration = $0.503 + 0.309 \times$ Beam-Attenuation $- 0.00562 \times$ Temp $+ 0.000287 \times \text{Temp}^2$, $n = 3464$, F = 430) with both tows combined. The regression term associated with the variable of specific conductance was not significant and was dropped by the stepwise regression as potentially not a good representation for nutrients across the observed range in specific conductance of our study. When the chlorophyll regressions were separated by a tow event, they were similar in the fit of the regression [$r^2 = 0.26$ and 0.31 (July and September, respectively)]. The zooplankton biomass concentration was not correlated with the water-quality variables ($r^2 = 0.05$). Similar to chlorophyll *a* concentration, regressions for zooplankton biomass concentration separated by tow did not vary much from the combined regression.

The patterns in nearshore water quality and lower food web components were correlated with the land-use characterization of Danz and others (2005). Land-use stress to Lake Huron is transmitted to the segmentshed reach in the nearshore as the primary expected receiving area for each tributary. The average water-quality measures across the nearshore reach were significantly correlated to characteristics of the adjacent segmentsheds as indicated by the stepwise multivariate linear regressions (Table 1) and the related model predictions (Fig. 4). Generally four or five of the seven stressor categories were retained in the regression models. Segmentshed land cover and atmospheric deposition were retained in all models; population density, soil type, and agriculture–chemical applications were the other stressors frequently included in regressions. Overall results suggest a strong linkage of adjacent segmentshed character with nearshore water quality and plankton concentrations. The regressions explained approximately 40 % of the variability in nearshore water-quality parameters. There are some noticeable departures from the close coupling of the regression model and some observed values, e.g., specific conductance where the connection with Lake Michigan (Straits of Mackinaw approximately km 440) and Lake Superior (St. Mary's River at Detour Passage km 523) appears to overwhelm the landscape influence (Fig. 4a).

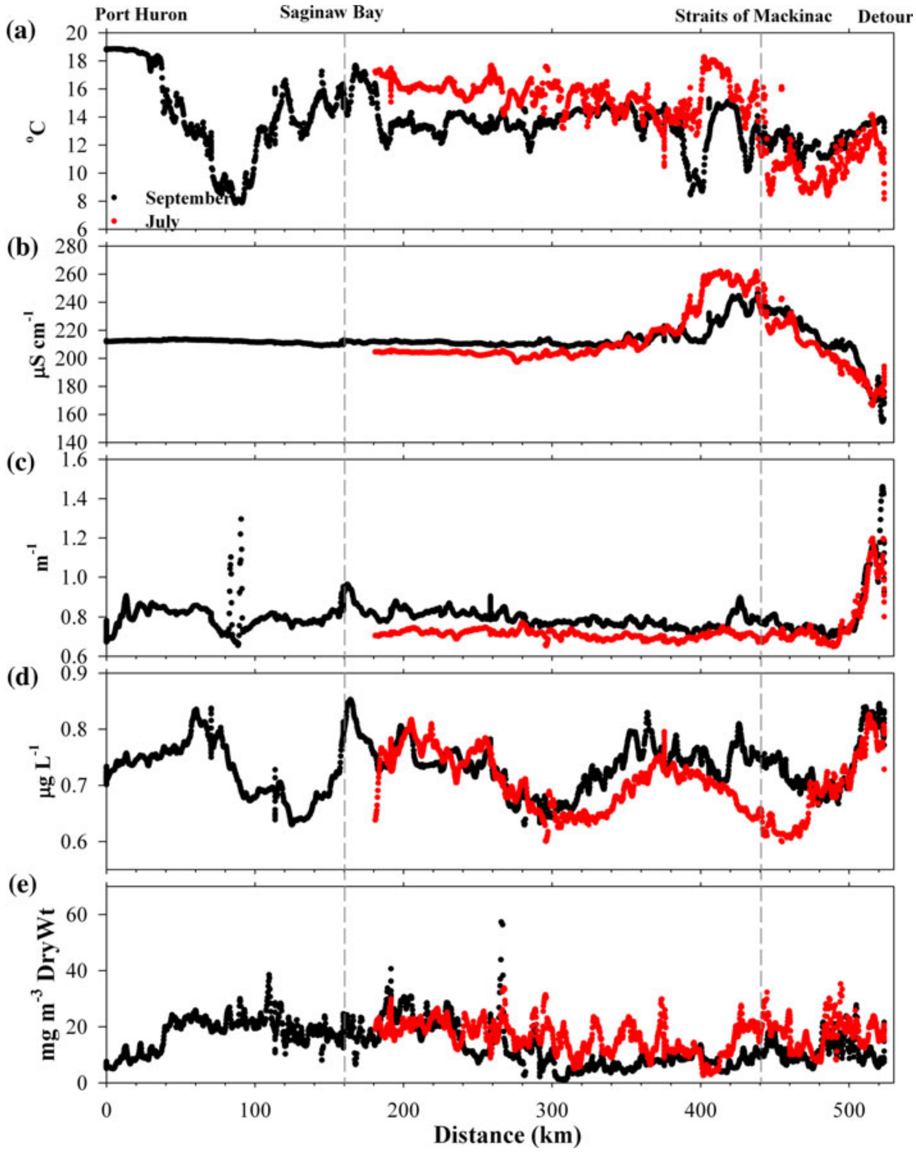


Fig. 3 Averaged water column values every 0.25 km along tow track length for **a** temperature (°C), **b** specific conductance (µS cm^{-1}), **c** beam attenuation (m^{-1}), **d** chlorophyll *a* (µg chl *a* L^{-1}), and **e** zooplankton biomass concentration (mg dry weight m^{-3}). Values for the July 22–24 tow are in *red* and for the September 18–21 tow are in *black*

Regressions of the cross-contour averages against the 20-m tow track indicated a near one-to-one correspondence (Fig. 5). The only notable departure was at the Detour Passage sample location where St. Mary's River from Lake Superior entered Lake Huron. In both July and September, specific conductance and beam attenuation relationships indicated outliers at the Detour Passage site.

Temporal stability in the spatial patterns for each variable was apparent across large spatial scales. When the tows from separate dates were superimposed, the spatial patterns were visually consistent although several weeks had elapsed between surveys (Fig. 3). Broad-scale patterns or features persisted over time. Tests for similarity of the pattern along the tow track with Pearson correlation analysis indicated a strong level of correlation within variables in space across time (Table 2). At the segmentshed level of organization, the correlation coefficients were high [0.53–0.88 ($n = 23$)] and significant [$P < 0.001$ to 0.01 (Table 2)]. At the more detailed level of every 0.25 km, the correlation was still strong [0.40–0.85 ($P < 0.001$; $n = 1370$)] where local parameter values were subject to more variability. The average chlorophyll *a* concentration and zooplankton biomass concentration across time along the entire tow indicated similar values. For the region of overlap in tows (180–523 km), the July survey chlorophyll *a* concentration and zooplankton biomass concentration were 0.70 (0.08 SD) µg chl *a* L^{-1}and 16.5 (5.7 SD) mg dry weight m^{-3}, whereas the same region in September was 0.73 (0.04 SD) µg chl *a* L^{-1} and 11.8 (7.7 SD) mg dry weight m^{-3}, respectively. The entire tow length average in September (0 to 523 km) was 0.73 (0.05 SD) µg chl *a* L^{-1} and 13.8 (7.6 SD) mg dry weight m^{-3}.

Table 1 Step-wise linear regression parameters determined for water-quality correlation to land-use characterization for the combined cruises (July and September 2007)[a]

Combined surveys	Beam attenuation (m^{-1})	Chlorophyll *a* ($\mu g\ l^{-1}$)	Specific conductance ($\mu S\ cm^{-1}$)	Zooplankton biomass (mg dry weight m^{-3})
Constant	0.7547	0.6993	208.66	18.24
b(Agriculturechem AC1)	NA	NA	2.6487	–2.0576
c(Land cover LC1)	–0.0135	–0.0154	–2.0778	–1.1987
d(Atmospheric deposition AD1)	0.0236	0.0174	–7.0732	3.9858
e(Population PD1)	–0.0277	–0.01273	4.50394	NA
f(Point-source discharges PS1)	0.0051	NA	NA	NA
g(Shore-line alteration SL1)	NA	NA	NA	–2.5431
h(Soil types SO1)	0.0131	0.0185	2.8994	NA
n	97	97	97	97
F	12.76	13.48	9.82	16.58
P	<0.00001	<0.00001	<0.00001	<0.00001
r^2	0.412	0.369	0.351	0.419

[a] Variable = Const + b*AC1 + c*LC1 + d*AD1 + e*PD1 + f*PS1 + g*SL1 + h*SO1, where landscape characterization values for each watershed [AC1, LC1, AD1, PD1, PS1, SL1, and SO1 (see text for definitions)] are from Danz and others (2005) (stepwise inclusion exclusion probability of 0.05)

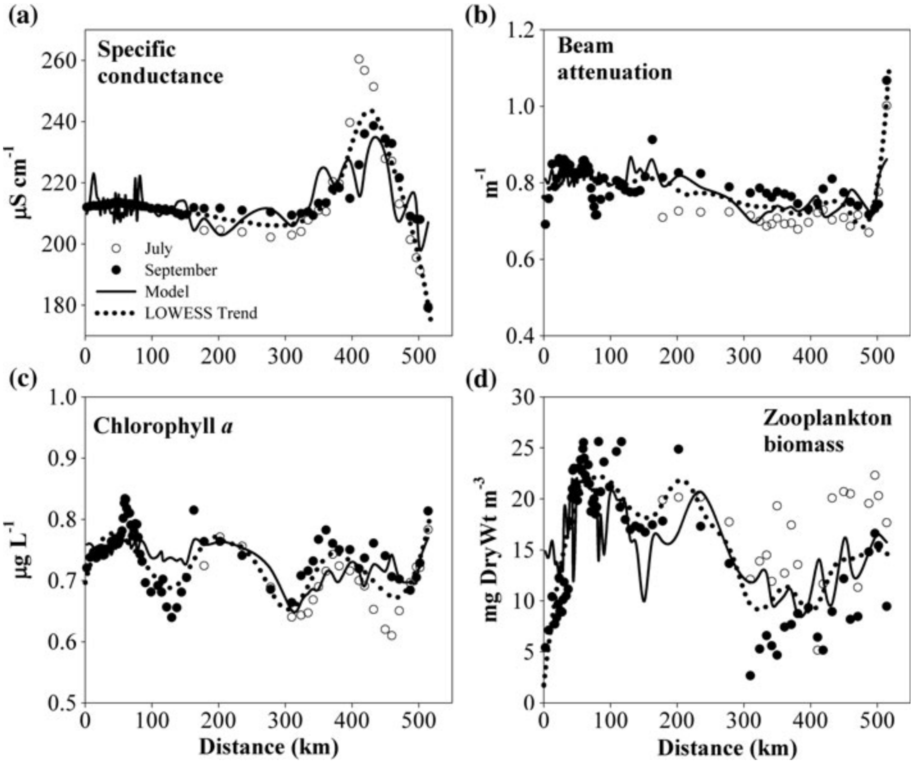


Fig. 4 Average parameter values for the tows along each segmentshed contributing area for **a** specific conductance ($\mu S\ cm^{-1}$), **b** beam attenuation (m^{-1}), **c** chlorophyll *a* (μg chl *a* L^{-1}), and **d** zooplankton biomass concentration (mg dry weight m^{-3}). Stepwise regression to landscape character is plotted as the *continuous line*. The *dotted line* is a LOWESS *smoothed trend line* determined from plots in Fig. 3

Discussion

The findings of this study in Lake Huron are part of a broader development and application effort we have been conducting across all of the Great Lakes (Yurista and others 2005, 2006, 2009; Kelly and Yurista (in review)).The 2007 Lake Huron studies were specifically designed to address three topics as follows:

(1) Can we represent the water quality of a nearshore of a large lake with a comprehensive survey along the shore using in situ sensors?
(2) Can the survey help to identify the probable influence of landscape-level disturbances on the nearshore?
(3) How do the survey results help contribute to an assessment of the present condition of this lake?

Representation of Nearshore in Space and Time

Sampling at a specific depth contour (20 m) did represent the average condition for a broader nearshore region (10–30 m). We addressed the variability of the breadth of the nearshore region, which may be several kilometers in

Fig. 5 Cross-plot of 20-m contour average values compared with cross-contour (10–30 m) average values. The *dotted line* is the one-to-one relationship. The *solid black line* is the regression through the origin in all panels and with regression slope *b[1]* indicated. The *filled circles* are from the September tow, and the *open circles* are from the July tow. Outliers with high leverage are identified on **b** and **c**. **a** temperature (°C), **b** specific conductance (μS cm^{-1}), **c** beam attenuation (m^{-1}), **d** chlorophyll *a* (μg chl *a* L^{-1}), and **e** zooplankton biomass concentration (mg dry weight m^{-3})

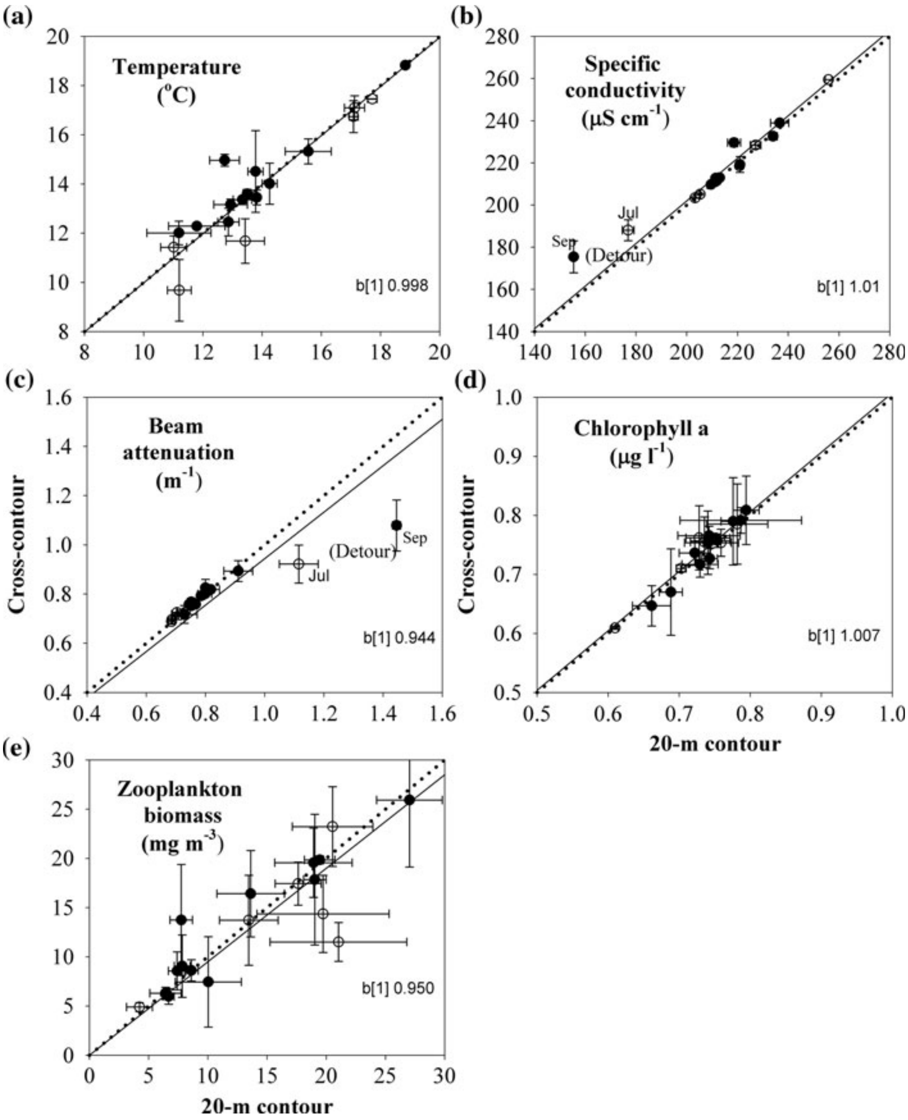


Table 2 Correlation between temporal measurements (July 22–24 and September 18–21, 2007) along the tow track by position at a distance every 0.25 km ($n = 1370$) or by a coarser regional average at the segmentshed shoreline reach ($n = 23$) scale

Measurements	Pearson correlation coefficient *r*			
	0.25 km	*P*	Segmentshed	*P*
Temperature (°C)	0.430	<0.001	0.632	0.001
Specific conductance (μS cm^{-1})	0.797	<0.001	0.831	<0.001
Beam attenuation (m^{-1})	0.845	<0.001	0.877	<0.001
Chlorophyll *a* (μg L^{-1} chl *a*)	0.534	<0.001	0.527	0.010
Zooplankton (mg dry weight m^{-3})	0.406	<0.001	0.612	0.002

width (Rao and Schwab 2007), by conducting cross-contour tows centered on watersheds. Eighteen cross-contour tows taken concurrently with the two alongshore tows exhibited strong correlations between alongshore and cross-contour tows for all of the water-quality variables. The correlations indicated a regional consistency and that the alongshore 20-m contour is a reasonable representation of the larger nearshore region, which is more than a (tow) line and has breadth to its spatial qualities (Fig. 5). There were some specific anomalous locations, such as in and around a meandering plume of high outflow, in this case from St. Mary's River (Detour Passage). In addition, although our previous experiences have indicated that small tributaries (second and third order) can be identified within the nearshore region by the tow data (particularly in <5–10 m of water), their relative contribution is small in volume compared with the entire nearshore water mass and is disbursed across long reaches of the coast through alongshore mixing (Yurista and Kelly 2009; Yurista and others 2011).

Although identifying local input points and plume dynamics is an important part of research into coastal processes, this may be of less importance for assessing a general nearshore condition. Missing a small tributary plume on a contour tow will not greatly change the representation of the greater spatial nearshore region, even though it may not capture the anomalies within that specific plume. A high parameter concentration within a small tributary plume can present a biased representation of the larger nearshore region. For example, a small plume will be recognized to exert less influence on the condition of nearshore waters when it becomes mixed and dispersed into the larger spatial region than would be suggested by concentrations and conditions in the plume (proximal source of stress), which are noticeable at the local scale. It is the resultant stress on the larger region targeted by our tow-based survey that contributes to the overall condition in a nearshore assessment. Considering our results (Fig. 5), the depiction of the nearshore using a consistent depth contour appears to be a reasonable strategy to produce water-quality and plankton results representative of a broader spatial zone in the nearshore.

A repeat tow along an extensive portion of the tow track showed a generally stable spatial pattern in terms of water quality and plankton biomass along the shoreline. Our repeat tow surveys were separated by 7 weeks and provided a measure of representativeness across temporal and regional scales of the nearshore during peak biological sampling conditions (Fig. 3). The average value of some measures varied as expected (e.g., temperature between late July and early September), but the regional-scale spatial patterns (i.e., at scales greater than tens of kilometers) showed remarkable consistency over time despite all of the dynamic processes involved in the nearshore environment. Temporal stability also is a function of the spatial scale of observation. This seems to be suggested by the analysis listed in Table 2 and further reinforced by comparing particular track locations with respect to different scales of summary for the surveys (e.g., Figs. 3, 4). At the scale of entire segmentsheds (approximately tens of kilometers), the correlation across time was generally a bit stronger than at the finer scale (0.25-km bins) (Table 2). At the finer-length scales, there were clearly some areas with substantial variability from survey to survey [e.g., Fig. 3 (Straits of Mackinac)]. Differences observed at specific areas over time were more evident in plankton indicators (chlorophyll *a* and zooplankton biomass concentrations) and temperature, which each generally had a bit more spatial variability than the other water-quality patterns that were more robust at both the regional and more local scales. Thus, although differences in repeated surveys were apparent and more pronounced at finer scales, the notable result was that a single one-time continuous tow survey (<3 days elapsed time) was able to capture the essence of a persistent spatial trend and variability in nearshore character.

Our repeat surveys suggested the alongshore spatial pattern across the nearshore was more stable than previously expected. The highly dynamic and variable natures of nearshore systems had raised concern in the past for the representativeness of a one-time measurement, whether it was performed with traditional point samples or with a continuous-tow measurement. These concerns were based on processes that were expected to randomly alter conditions in space and time. One factor expected to influence the variability was mixing along the shoreline due to nearshore currents. Average nearshore currents of only a few centimeters per second can result in kilometers of water movement and mixing per day (Beletsky and others 1999; Rao and Schwab 2007). Current reversals also move water back and forth along the nearshore, thus further mixing tributary input along the shoreline reach. A continuous tow provides information regardless of current direction showing the overall effect of mixing and water-mass transport along the shoreline. The holistic effect of the alongshore currents can therefore be captured in a single tow. A second factor expected to affect temporal variability at a measurement site was weather. Variation is introduced through turbulent wind mixing and tributary input patterns as a result of rain events. The total magnitude of landscape and watershed impact to the nearshore will be realized as these local inputs or anomalies become mixed and distributed into the larger-scale region. A continuous tow is capable of monitoring the effective impact at the larger regional scale at which monitoring and assessment samples are expected to accurately represent conditions in the lake. Although mixing and transport from alongshore currents and weather events blur the immediate connection with adjacent landscapes, the central portion of a nearshore reach adjacent to a segmentshed will experience a stronger landscape signal than further away along the coast as mixing, dilution, and transport occur. Even given an array of sources of variability, the correlation of nearshore parameters to the immediate landscape was highly significant in our data (Table 1); we suggest that the linkage would be even stronger if the nearshore region were not so physically dynamic.

Our results for Lake Huron, combined with previous results (Yurista and others 2011), suggest that additional processes are also acting to constrain disruptive events of along shore currents and weather events and that these processes tend to maintain or re-establish regional patterns in nearshore conditions. For example, nearshore entrapment (Csanady 1970) will resist disruption and mixing of waters out into the offshore. In addition, the input of landscape stressors through tributaries, both at base and high flow, will continually amend local conditions as the correlations to the landscape demonstrate (this article; Yurista and others 2011). These observations suggest that the nearshore has an underlying regional character that can be monitored, and therefore nearshore assessment on the scale of the Great Lakes is more tractable than previously expected. The synoptic survey approach was efficient and effective at broad scales, whereas contributions at finer scales were not as easily differentiated due to mixing and transport. Additional analyses and research will be conducted as we continue the evaluation of this approach to distinguish contributions and effects from adjacent segmentsheds due to along shore mixing.

Land Use as an Influence on the Nearshore

Strong correlations were observed for all water-quality variables with the landscape-disturbance metrics for the associated segmentsheds. The segmentsheds represented a large gradient in landscape stress from north to south, which was a key feature of this study allowing us to examine the effect of land use on the nearshore. Stepwise linear regressions for the combined tow surveys (Table 1) indicated that landscape characterization explained approximately 40 % of the variation in the variables. The land-use characterizations may likely have some autocorrelation among the various retained variables: When there are agricultural impacts, there will be associated land-cover impacts (e.g., less forest cover), and when there are urban areas and population density impacts, there will be fewer agriculture or forested areas. The seven stressor categories are not all mutually orthogonal (i.e., independent in a mathematical sense). The stepwise regression was used to help minimize some of the effect of this autocorrelation on the regression models. For simplicity, we presented the combined results of both cruises (Table 1) to indicate the overall connection across the season to the landscape-disturbance factors that may influence adjacent nearshore water quality. Similar results were obtained for the individual surveys. Still, approximately 60 % of the variability was not explained by the regression models. Any comprehensive whole lake-management plan should also consider additional within-lake factors, such as internal nutrient recycling, upwelling, and currents. Targeting land-use variables alone will not fully address water-quality issues in the nearshore region, but it will provide one element of a multicomponent approach. The multivariate regressions suggested a strong linkage of water quality to watershed properties, and it is of note that there were low values and a generally small range in some sensor values (e.g., chlorophyll *a* concentration). It is likely that the statistical power to detect the correlations was due to the combination of a rather broad range in landscape metrics along the Lake Huron coastal region, from very low to very high across the characterization of Danz and others (2005, 2007), and to the high-density synoptic sampling across many shoreline segmentsheds ($n = 74$), which provided a large number of observations. The high-density data have the spatial scale and resolution to discriminate among the differences in water-quality variables, which would not be statistically possible when monitoring with less synoptic and lower-density sampling approaches.

The landscape linkage models were strong and reproduced most of the spatial patterns observed in the tow data (e.g., Fig. 4). LOWESS trend averages smoothed the general alongshore patterns and were closely paralleled by the model predictions. The landscape-predicted models often had more local variation than the measured segmentshed variables in either tow survey [Fig. 4 (e.g., specific conductance)]. This is quite likely because the landscape models did not account for the alongshore mixing and transport that occurred across shoreline reaches for any given watershed. This implies that inputs from individual watersheds are most likely distributed across larger-distance scales in the nearshore region than just the adjacent shoreline. The full reach of direct measureable impact will be addressed with additional analyses that include weighting factors for watershed size, spatial distance to alongshore position, and alongshore current speeds. However, our first-order analysis of the variation and regional character in nearshore water quality showed it can be linked to landscape character.

The strong correlations in spatial patterns of land-use characterization, in conjunction with the robustness of the spatial patterns of water-quality variables (Lake Huron repeat tows) for both Lake Huron (Table 1) and Lake Superior (Yurista and Kelly 2009; Yurista and others 2011), suggest that the water quality in the nearshore region may be organized and moderated by landscape activities. We recently reported (Yurista and others 2011) that repeated track sampling in the nearshore of Lake Superior during a time span of several years also gave evidence for a strong regular spatial pattern at regional scales of observation. In that case, as here, there were areas of consistently higher and lower parameter values and plankton biomass along the shoreline. During the past, the notion has been that the dynamic processes and nature of hydrodynamics in the nearshore region were expected to create a highly variable environment; however, landscape input and its entrapment or retention in the nearshore (Csanady 1970) appears to continuously help structure and maintain the regional character of the nearshore water-quality variables as observed with the repeated tow.

The Lake Huron tow survey also identified types of areas where identifying a direct and generalized (or time-invariant) coupling of shoreline to adjacent nearshore may be problematic. These include distinct areas of strong hydrodynamics where localized landscape influences are perhaps overwhelmed. Examples for Lake Huron are the St. Mary's River (Detour Passage km 530) large outflow (e.g., Fig. 5) and the exchange from Lake Michigan across the Straits of Mackinac [km 460 (Fig. 3)]. The regressions to the segmentshed characterization had greater residual errors in these regions (Fig. 4). The St. Mary's River discharge appears to reflect large interlake flow from Lake Superior and not necessarily local landscape input. However, the interlake region of Lake Huron with Lake Michigan shares a similar geological continuity as well as land cover and population characteristics. The 6.25-km-wide Straits of Mackinac have complex current flows and reversals, although there is net advection through the straits (Saylor and Sloss 1976). We interpret the specific conductance spatial pattern along this reach as reflecting both interlake flow and local landscape influence along the northern portion of Michigan's Lower Peninsula [Fig. 3 (km 400 to 460)]. Alongshore towing can help distinguish regions that are not strongly connected to local land-use conditions.

Assessment of the Utility of a Comprehensive Shoreline Approach

A towed sensor survey has application (1) for trends and assessments that include the nearshore of a lake (Yurista and Kelly 2009; Yurista and others 2009) and (2) for relative condition assessment compared with other Great Lakes. A recent collapse in the offshore fisheries and lower food web of Lake Huron has been reported (Riley and others 2008; Nalepa and others 2009; Barbiero and others 2011). Our observations of low values of both chlorophyll *a* concentration and zooplankton biomass concentration throughout the nearshore are consistent with the observed trend toward oligotrophic conditions noted for offshore waters of Lake Huron, although there is generally no historical information on the shallow nearshore with which to make similar comparisons. However, we can make a comparison of the Lake Huron nearshore results with those of a similar continuous tow survey conducted in Lake Superior [535 km (2004)] that provides a relative status of the lower food web components in the nearshore of each lake. The surveys were conducted at the same time of year (early September) using the same instrumentation and used the same analysis procedures previously described in Methods. The average tow result for chlorophyll *a* concentration was notably lower in Lake Huron (0.73 μg chl *a* L^{-1} ± 0.05 SD) than in Lake Superior (1.24 μg chl *a* L^{-1} ± 0.11 SD). We found that zooplankton dry-weight concentrations indicated a similar trend in the relationship between the lakes as did the comparison of chlorophyll *a* concentration. The average Lake Huron zooplankton biomass concentration was also lower (13.8 mg m^{-3} dry weight ± 7.6 SD) than for Lake Superior (25.5 mg m^{-3} dry weight ± 12.6 SD) (Yurista and Kelly 2009; Yurista and others 2009). Standing biomass concentrations (zooplankton and chlorophyll *a*) of Lake Huron had values that were approximately 54–59 % of those in Lake Superior. The comparison supports the recent observation of a change in the condition of Lake Huron to an uncharacteristic ultra-oligotrophic state. This study is a first comprehensive synoptic survey for the United States shore of Lake Huron and is significant for that reason over and above contributing to the understanding of nearshore variability in developing a monitoring strategy. We suggest that continued assessments using towed technology will allow efficient capture of information useful for trend analysis within a given lake as well as comparisons among lakes.

Conclusion

Towed instrumentation provides data at a high frequency and resolution that is necessary to detect diluted landscape impact or signals retained in the nearshore region before they are diluted even further as the nearshore eventually mixes out into the lake. Stressors accumulate in a receiving body, and the results of our study indicate that they can be detected. This principle underlies trend analysis at the whole-lake level used for detecting stressors and their effects. We have taken advantage of a high number of measurements and the retention of signal in nearshore waters in our survey strategy to capture the end result of landscape input and hydrodynamic processes along the nearshore. The strategy can identify areas of tributary input and document the extent of alongshore mixing and variation in the data. We have found in the measurements that (1) the width of the nearshore (10–30 m) can be represented well by the 20-m contour; (2) the nearshore water quality was correlated to land-use character; and (3) a spatial robustness during repeat summer surveys was evident in the regional character of the nearshore, which supports the utility of a single assessment or monitoring event during summer stratification and peak biological activity. Towed instrumentation has a great potential as a tool for measuring and documenting realized impact to nearshore water quality, which can be further used to assess best-management practices across regional landscapes, such as those associated with food production (e.g., lost fertilizer, feed lot runoff, riparian zone pastures, etc.). The correlations to current land-use character can be used to inform alternate choices in land-use activities and their predicted affect on ecosystem services (e.g., fisheries, drinking water, recreation, etc.) of the Great Lakes nearshore and eventually document the effect of management decisions. We have shown an approach that uses acquisition of high-density data with high-spatial coverage to document the condition of the nearshore region of the Great Lakes and in this case support previous observations of an ultra-oligotrophic trend for Lake Huron.

Acknowledgments We thank the USEPA Great Lakes National Program Office for ship time on the *R/V Lake Guardian*. We thank R. Barbiero for many good comments that helped improve the manuscript; M. Starus for editorial review; and three anonymous reviewers for comments that helped us improve the manuscript. This work was funded entirely by the USEPA. The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the USEPA.

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