Spatial patterns of water quality and plankton from high-resolution continuous *in situ* sensing along a 537-km nearshore transect of western Lake Superior, 2004

Peder M. Yurista* and John R. Kelly

Mid-Continent Ecology Division, National Health and
Environmental Effects Research Laboratory,
Office of Research and Development
U. S. Environmental Protection Agency,
6201 Congdon Boulevard
Duluth, Minnesota 55804 USA
**Corresponding Author: yurista.peder@epa.gov*

Abstract

We conducted an extensive survey of the nearshore waters in western Lake Superior along a continuous segment (537 km) from Grand Marais, Minnesota to near Eagle Harbor, Michigan on the Keweenaw peninsula. A depth contour of 20 m was targeted using a towed CTD, fluorometer, transmissometer, and laser optical plankton counter (LOPC) to gather data on temperature, conductivity, fluorescence, light transmittance, and zooplankton size and abundance. The continuous electronic data stream provided a high resolution image of spatial variability both vertically and horizontally for each parameter. We describe the character of local, regional, and complete transect with goals of revealing spatial patterns not easily detected by other technologies, and briefly compare patterns to published historical trends.

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Preliminary relationships are presented among water quality and plankton measures. Regional patterns within the lake were related to gradients in landscape character along this stretch of coastline. Strong correlations to landscape characteristics provide suggestions that nearshore water quality may reflect the quality and nature of adjacent watersheds. We have demonstrated that the adaptation of electronic instrumentation and towed survey strategies are effective in providing rapidly collected and spatially extensive data for nearshore assessment of the Great Lakes.

Introduction

Lake Superior has been studied intermittently in the past 100 years with respect to its water quality (Beeton, 1965; Weiler, 1978). It is one of the largest lakes in the world, and it has a relatively small watershed and low surrounding population densities. Studies have shown Lake Superior to be an ultra-oligotrophic lake, which has been its historical classification (Munawar and Munawar, 1978). Its oligotrophic character invites comparisons with "blue-water" open ocean conditions, and various facets of Lake Superior's plankton ecology have been of particular interest in this regard. Water quality, plankton abundance, composition, vertical distribution, and primary productivity have been assessed irregularly, while ongoing lakewide monitoring efforts have primarily studied the deeper and more offshore waters (EPA, 2000, Barbiero and Tuchman, 2001). One of the problems of sampling and assessing Lake Superior is its sheer size and volume, so that even huge numbers (100s) of sampling stations (Thomas and Dell, 1978; Weiler, 1978) do not actually survey much of the lake area or volume. The resulting conception of the lake suggests a relative homogeneity in water quality and plankton distribution, albeit with some apparent regional distinctions (Weiler, 1978; El-Shaarawi and Munawar, 1978; Munawar and Munawar, 1978; Watson and Wilson, 1978; Dermott, 1978). Regional distinctions appear to have some bathymetric basis and they also tend to distinguish the areas near the few major population centers on the perimeter of the lake (e.g., Duluth-Superior in the extreme western arm of the lake). Besides the lakewide monitoring efforts, there have also been studies at more local to regional scales of interest (Stortz et al., 1976;

Biddanda and Cotner, 2003, Johnson et al., 2004; Budd, 2004; Auer and Bub, 2004; Auer and Gatzke, 2004). A number of these have examined factors influencing water quality and plankton with respect to particular mechanisms of interaction or controlling physical phenomenon (e.g., upwelling, large tributary inflows, coastal current flow to offshore). Recent studies with spatially synoptic technologies (e.g., Megard et al., 1997; Zhou et al., 2001, Budd, 2004; Budd and Warrington, 2004; Li et al., 2004) suggest more underlying variability and patchiness in plankton distributions that might not be noticed with the relatively sparse spacing of stations and typical sampling designs employed by traditional lakewide monitoring schemes.

We have been evaluating assessment approaches that could report on the ecological status and trends for not only the offshore region, but also the nearshore waters and coastal areas (such as embayments, harbors, coastal wetlands). As part of this effort, we have been using towed *in situ* sensor technologies that are being used more regularly in ocean and large lake research (Huntley et al., 1995; Herman et al., 1993; Sprules, et al., 1998; Zhou et al., 2001; Yurista et al., 2005, 2006). These techniques allow, via continuous underway sampling, relatively comprehensive yet efficient sampling over extensive track lengths (?100 km/day). They result in water quality and plankton data resolved to the scale of meters, horizontally along the ship’s track as well as vertically throughout the water column to depths below the photic zone and well into the hypolimnion. Our interest has been in developing sampling styles and measurement strategies for nearshore waters. Nearshore waters receive some major anthropogenic inputs and associated ecological responses may arise as the character of adjacent watersheds change. Such proximal (to the landscape) responses in water quality and plankton, depending on their scale and the nature of their expression, may foreshadow future ecological change throughout the lake. A brief review of historical information, combined with appreciation for the physical dynamics inherent to the shallow nearshore zone and our own recent sampling efforts, suggest that highest levels of variability (space and time) in water quality and plankton exist in shallower coastal waters, compared with greater homogeneity of the offshore waters in the Great Lakes. Thus, the data-rich, semi-synoptic, towed sensor approach may allow us to document patterns against the background of high nearshore water variability, and simultaneously do this across a remarkable range of scales, from very fine local structure to regional trends.

In September of 2004, we towed a lengthy track to examine water column variability and patterns along a shallow bathymetric contour. We targeted a depth zone of about 15 to 30 m, and this kept us relatively close to shore (0.25 to 7 km from land). The survey was along a continuous segment of the US shoreline of western Lake Superior from Grand Marais, Minnesota to the middle of the Keweenaw Peninsula on the Upper Peninsula of Michigan (Figure 1). We present data from this study with the following objectives:

1. To present a comprehensive, high-resolution image of >500 km segment of Lake Superior coastal margin, as part of its baseline status near the start of the 21st century;
2. To use the data to reveal spatial patterns not easily detected by other technologies and briefly compare patterns to published historical trends;
3. To evaluate relationships among water quality and plankton measures; and to examine whether regional distinctions within the lake relate to gradients in landscape character over this particular stretch of coastline.
4. The purpose of the paper is, fundamentally, a descriptive contribution to a book updating what is currently known about Lake Superior. But the presentation also provides a preliminary step towards our larger goal of assessing sampling technology and sampling styles for future monitoring. Additional examination of this extensive survey will be the subject of later papers.

Methods

Survey track and rationale

Our previous studies with towed sampling technology suggest an ability to distinguish a shallow nearshore zone from waters only a few km more offshore in the Great Lakes (Yurista et al., 2006). At depths less than about 20-30 m the technology has some discriminatory power for detecting local water quality influences during summer base flow and post-stratification conditions; more local features are

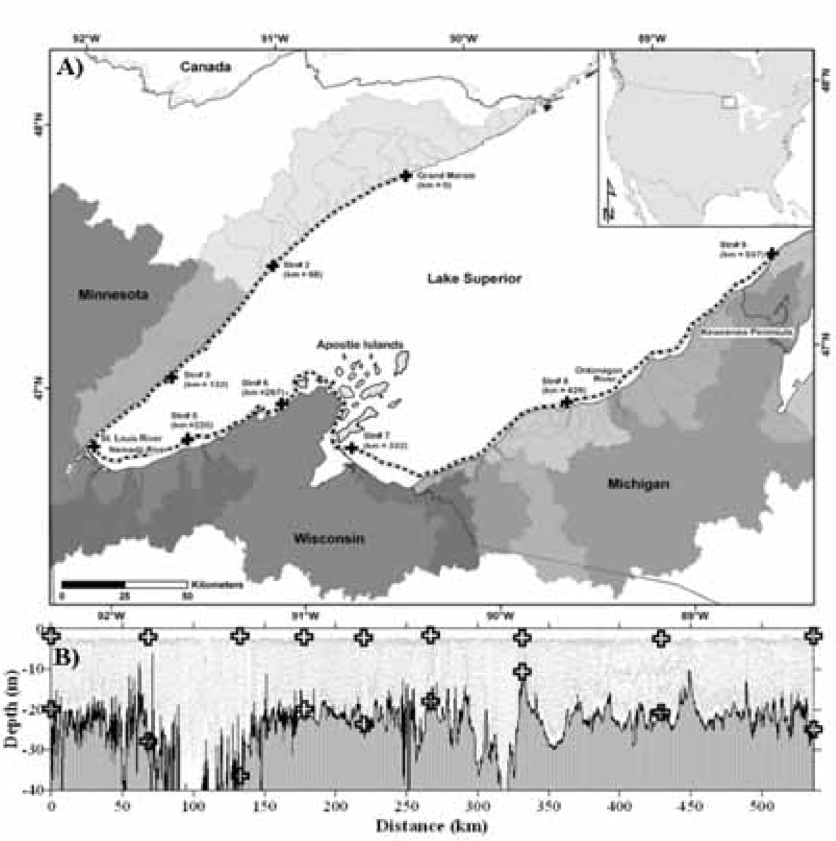

Fig 1. A) The tow track along coastline of Lake Superior starting at Grand Marais MN with fixed sample stations marked in crosses. B) The depth contour along tow-yo track (Grand Marais at 0 km) and with fixed sample locations (surface and bottom) marked in crosses.

generally detected the shallower and closer to shore one samples (personal observation).

On the other hand, vessel and operation safety and logistics also are a consideration. The vessel transited at about 4.5 to 5 kts during towing with some rapidly changing bottom bathymetry (especially on the north shore from Duluth to Grand Marais). We wanted to operate in waters deep enough to allow operator response time and a proper margin of safety for both the vessel and the towed instrumentation. Our track thus balanced safety and logistics of vessel operations with a desire to assess connections that relate to the landscape, but are also partially under the influence of lake processes and connected in this way to the larger lake ecology and food web. We cut across some shoreline indentations rather than follow the contour exactly parallel to shore so our track occasionally pushed us to slightly deeper water. In some of these cases, we were closer to shore in the deeper water than when at the 20-m depth contour along a more gradually sloping bathymetry (cf. north shore sections versus shoreline between Bayfield and Keweenaw peninsula).

Measurements

A CTD (SBE 19plus, SeaBird Inc.), fluorometer (Wetstar, Wet Labs), transmissometer (C-star, 10 cm path length, at 660 nm, Wet Labs), and laser optical plankton counter (LOPC, Brooke Ocean Technology, Herman et al. 2004) were towed from the *R/V Lake Explorer* to gather data on conductivity, temperature, fluorescence, light transmittance, and zooplankton size and abundance. The instrumentation array was mounted on an undercarriage fabricated for a YSI V-Fin 493 towfish. The tow package was secured to an electromechanical cable on a winch with a slip-ring for signal transmission and towed at a speed of 2.0 to 2.5 m s^{-1} (4.5-5 kts). Data was logged every 0.5 seconds and every hour a new data file was started to minimize each individual file size. A shipboard global position system (GPS) provided geo-position data that was written to computer file in synchrony with electronic data. We used geospatially referenced bathymetric data from a Questar Tangent Corporation bottom classification system that was operated concurrently, but the seabed classification results are not discussed in this paper.

Our sample track started 9-September 2004 at Grand Marais, Minnesota and extended along the US shoreline for 537 km ending 13-September 2004 near the Gratiot River just south of Eagle Harbor, Michigan on the Keweenaw peninsula (Figure 1). A sinusoid tow pattern (tow-yo) with the towfish added a vertical profile to the spatial survey pattern. We generally restricted the towfish sampling to range to within a few meters above bottom or to a maximum depth of about 40 m (Figure 1).

We stopped along the tow at nine fixed stations to collect traditional water bottle samples, with the first station at the beginning of the tow near Grand Marais, Minnesota and with the final station at the termination of the tow (Figure 1). We collected water samples at 2 m from the surface and at 2 m from the bottom for analyses of nutrients, chlorophyll, total dissolved organic carbon (TOC), total suspended sediments (TSS), anions, and cations. We collected additional vertical profiles with a SeaBird 911 rosette sampling system using separate but similar instrumentation for temperature, conductivity, pH, dissolved oxygen (DO), fluorescence, photosynthetically active radiance (PAR), and light transmittance as an independent estimate from the tow instrument samples.

Data processing and QA/QC of sensors

The towed instruments and the SeaBird 911 instruments are returned to the factory for calibration every year. In addition we conducted daily inter-calibrations in the field by suspending both instrument configurations simultaneously at a depth of approximately 2-3 m to accumulate five minutes of electronic data. We have previously established relationships between instrument packages and any drift or shifts in values are investigated and corrected when appropriate and possible. Water quality samples were compared with electronic instrumentation for additional trend observations.

Data analyses

All electronic tow data were processed and appended into one large data base file (*.dbf). Distance along the tow track from the starting location was computed from latitude and longitude. Zooplankton biomass density was computed following Yurista et al. (2005,2006) by using the cross section of the LOPC (0.0049 m^2), flow rate, and biomass of zooplankton detected in each time stamp. Flow rate was computed by time-of-flight measurements within the LOPC every 0.5 second (Brooke Ocean Technology). Size measured by an LOPC is the equivalent circular diameter (ECD) of the shadow area cast by each zooplankton. Biomass for each individual zooplankton was computed from the volume of a prolate spheroid having ECD as the major axis, ECD/1.33 as the minor axis, and density of 1.0 (Sprules et al. 1998). The LOPC settings were specified to record particles in the range of 150 microns to 3.5 cm. Re-suspension of fine clay particles do occur in Lake Superior (Stortz et al., 1976, Sydor et al., 1979) but they are not in a size range or were of significant density (total suspended solids 0.35-1.24 mg L^{-1} measured on cruise) to affect measurements. Liebig et al. (2006) compared OPC biomass with tow net biomass under varying levels of TSS. The net and OPC biomass became un-correlated at greater than 3 mg L^{-1}. The results were for an OPC but we expect the LOPC (next generation OPC) will be similar. The LOPC did not distinguish between living organisms and detritus; however, good correlation in Great Lakes environments between zooplankton biomass and previous versions of the optical plankton counter have been observed (Sprules et al., 1998; Liebig et al., 2006). Additionally, Lake Superior is not expected to have significant amounts of detritus: our assumption is that observed patterns reported in this paper primarily reflect zooplankton.

Vertical isopleth contours for each parameter along the length of the tow track were determined using a Kriging routine (Surfer 8.0, Golden Software). Kriging produces point estimates that are best linear unbiased estimators at regular grid intervals (Isaaks and Srivastava, 1989). We selected a grid with between-node distances of 0.25 km horizontally, generally the distance between a decent or ascent of the tow-yo, and 0.5 m vertically. The Kriging condensed the 451,762 records into 97,077 non-zero regularly spaced nodes.

Regressions and other statistical analyses

The regularly spaced grid estimates produced by the Kriging were used to summarize water column parameters (e.g. average, maximum, minimum, standard deviation, sum) every 0.25 km along the transect to analyze for alongshore spatial trends. The summary data (0.25 km column averages) rather than the point data were used in several analyses as described next. Plots of the summarized parameters were constructed to identify possible relationships among variables. Regional similarity along the track length was identified by nonhierarchical k-means clustering of standard-normal transformed data (Systat 9.0). Principal component analysis (PCA) was used to identify factors that influence or define the regions of similar water quality and biological makeup in the spatial structure of the nearshore environment (Systat 9.0).

Stepwise linear regressions (Systat 9.0) were conducted on the summarized parameters for algal fluorescence and zooplankton biomass concentration. Algal fluorescence was assumed to depend on the specific conductivity as a surrogate for nutrient availability, percent transmittance as a surrogate for particle attenuation of light penetration, and temperature for growth rate. Although nutrients are not measured directly by specific conductivity, specific conductivity can be used as a tracer for riverine or landscape input which serve as sources for nutrient influx and, secondly, nutrient concentrations can be expected to increase from softer waters to harder waters. Temperature was modeled as a simple quadratic function because of its known curvilinear response in biological systems and the relatively small range observed in our measurements. Zooplankton biomass was assumed to depend on the same parameters and fluorescence. The stepwise regression procedure was used to reduce potential autocorrelation between fluorescence and the other parameters.

Relation of nearshore to landscape quality

The parameters measured in the nearshore waters were compared with watershed characterizations to identify factors that correlated with water conditions. Measures of landscape character were principal component scores determined by Danz et al. (2005) for each watershed and the associated shoreline stretches between them (referred to as segment-sheds for the rest of the paper). A segment-shed consists of a stream (>2nd order) watershed draining into the lake plus a portion or “segment” of coastline between the adjacent watershed discharge points that is not part of the watershed drainage, and recognized hydrologically as an interfluve. To do the characterization of the US Great Lakes coastal regions, Danz et al. (2005) used over 200 variables from seven general categories (agricultural, atmospheric deposition, land cover, population density, point-sources, shoreline modifications, and soils). As an example, the various agricultural parameters (~21) represent the agriculture intensity and agricultural chemical applications in the watersheds that may contribute nutrients to tributary streams or directly to the nearshore region, and provide a pressure to the nutrient base of the nearshore food web. The relative impact of all variables in each category for a segment-shed is expressed in reduced dimensions by principal component scores. Because our towed sampling crossed over 160 segment-sheds with a range in character, we investigated whether the nearshore water properties correlated with the associated watershed characterization principal components. As a preliminary exploration we did a backward step-wise multivariate regression analysis of each water quality or plankton parameter against the first principal component of each of the seven categories for the segment-sheds adjacent to each 0.25 km portion of the track.

Results

The resultant isopleth images from Kriging of the high-resolution data provide an unprecedented picture of the spatial variation along the 537 km of towed nearshore (Figure 2). The thermal environment varied from an average of 8 to 16 ?C; water clarity between 88% and 92% light transmittance relative to air; average specific conductivity ranged from 97.6 to 100.5 ?S cm^{-1} (local highs >102); fluorescence varied by a factor greater than 2 and zooplankton biomass by a factor of 6 (Figure 3). There was a general warming trend in the nearshore waters of the north shore to the south shore (Figure 3). Thermal variation from surface to bottom was observed throughout the region. Mostly weak thermoclines were noted but the depth of the thermocline varied and became deeper and more pronounced in several regions, particularly in the region between the Apostle Islands (Bayfield) and Ontonagon (Figure 2). Some areas of upwelling are suggested where the thermocline reaches the surface. Light transmittance indicated regional identity that qualitatively corresponded with shoreline character. For example, the clay bank region (Stortz et al., 1976) of the south shore (Duluth ~180 km to Apostle Islands ~280 km) was measurably less transparent than the rocky north shore (Grand Marais 0 km to Duluth ~160 km), or the Apostle Islands to Ontonagon (~330 km to ~430 km; Figure 3). Transmissivity around the Ontonagon River (~447 km) was similar to the St. Louis-Nemadji River region (~180-200 km). Specific conductivity was low (98.5 µS cm^{-1}) at the beginning of the transect with a gradual increase towards Duluth (maximum values 103 ?S cm^{-1}), with indication of tributary input from the St. Louis (~180 km) and Nemadji Rivers (~190 km). The specific conductivity gradually decreased to the end of the transect (98 µS cm^{-1}) with a spike at the

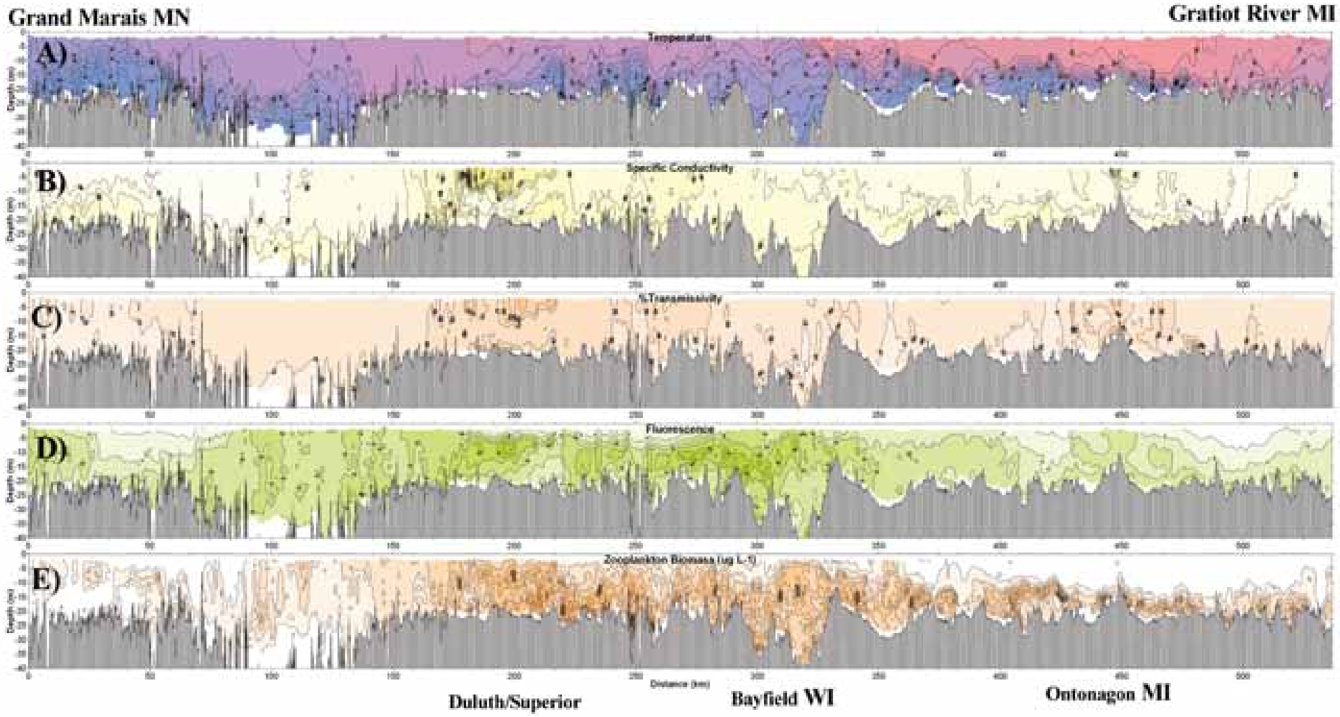

Fig 2. Contoured results for A) temperature, B) specific conductivity, C) % light transmittance for 10 cm path length, D) fluorescence, and E) zooplankton biomass.

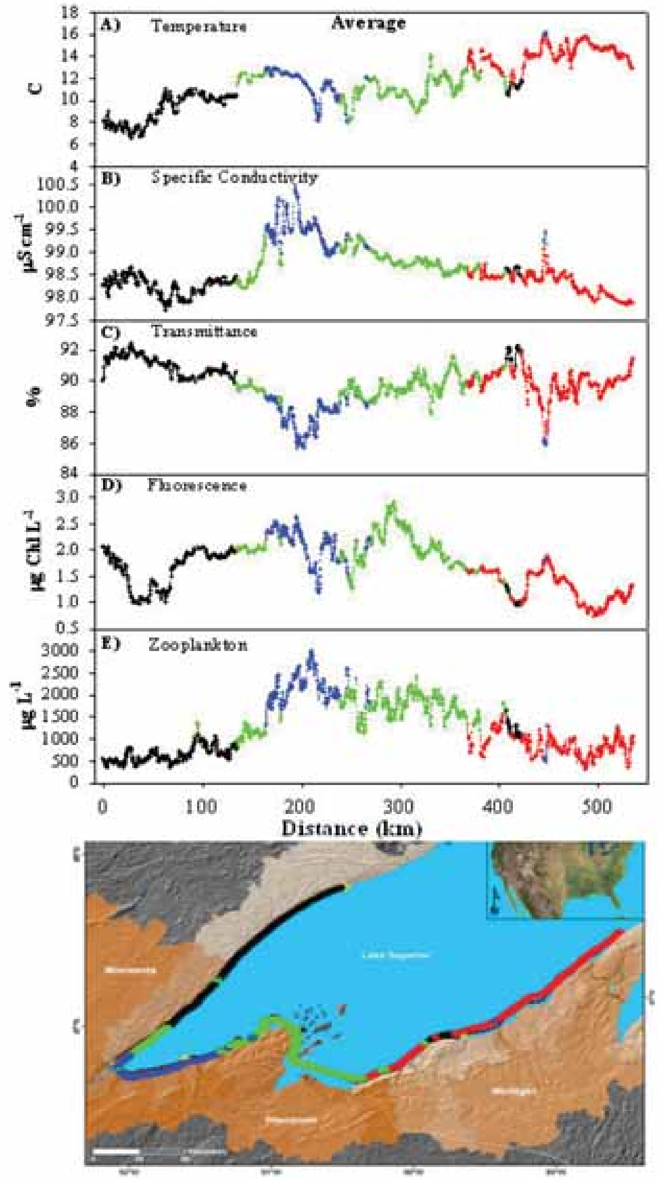

Fig 3. Spatial trends in average parameter values A) temperature, B) specific conductivity, C) % light transmittance for 10 cm path length, D) fluorescence, and E) zooplankton biomass. Color indicates four group clustering by k-means for tow data to identify regional character of nearshore waters based on temperature, specific conductivity, % transmittance, fluorescence, and zooplankton biomass.

Ontonagon River (~447 km). Algal fluorescence was generally low but showed variation with higher values located between Duluth and the Apostle Islands. Zooplankton biomass was low along the rocky north shore and the Keweenaw peninsula with peak values corresponding more generally with algal intensity in the intermediate region. The structuring of data and choice of Kriging bin sizes provides for the ability to “zoom” in on specific regions to focus at finer scales (Figure 4). This intermediate region shows the influence of Duluth-Superior, and also hints at regional distinctions north and south of that area.

Across the entire tow track, regional distinctions were observed with k-means clustering (Figure 3). Five measured parameters (temperature, specific conductivity, transmittance, algal fluorescence, and zooplankton biomass concentration) were used to specify four groups that had qualitatively distinct, yet identifiable physical/chemical and biological character. The clustering produced distinct contiguous regions, rather than interspersed segments and random mixes of each cluster. The qualitative characteristics among these regions were identified with principal component analysis (Figure 5). The component loading for each parameter on the first two principal components suggests the relative direction and magnitude contributed by each parameter. The region along the north shore (~0 - 130 km) was characterized by low temperature, low conductivity, low algal fluorescence, low zooplankton biomass, and high transmittance (principal component 1). This region was distinct from the Keweenaw Peninsula region (~380 - 537 km) primarily due to the Keweenaw having a warmer temperature regime (principal component 2). The two other regions were characterized by higher biomass (both algal and zooplankton), lower transmittance, and higher specific conductivity. In these regions temperature was intermediate between the north shore and Keweenaw Peninsula regions. The distinguishing factors between the two intermediate regions were specific conductivity, transmittance, and zooplankton biomass (principal component 1). The region around Duluth/Superior (~160-240 km) had higher specific conductivity, lower transmittance, and higher zooplankton biomass but similar fluorescence signals to the region along the south shore past the Apostle Islands (~240 - 380 km) (Figure 3, 5).

Relationships between measured parameters were investigated with scatter plots and linear regressions (Figure 6, 7). We found

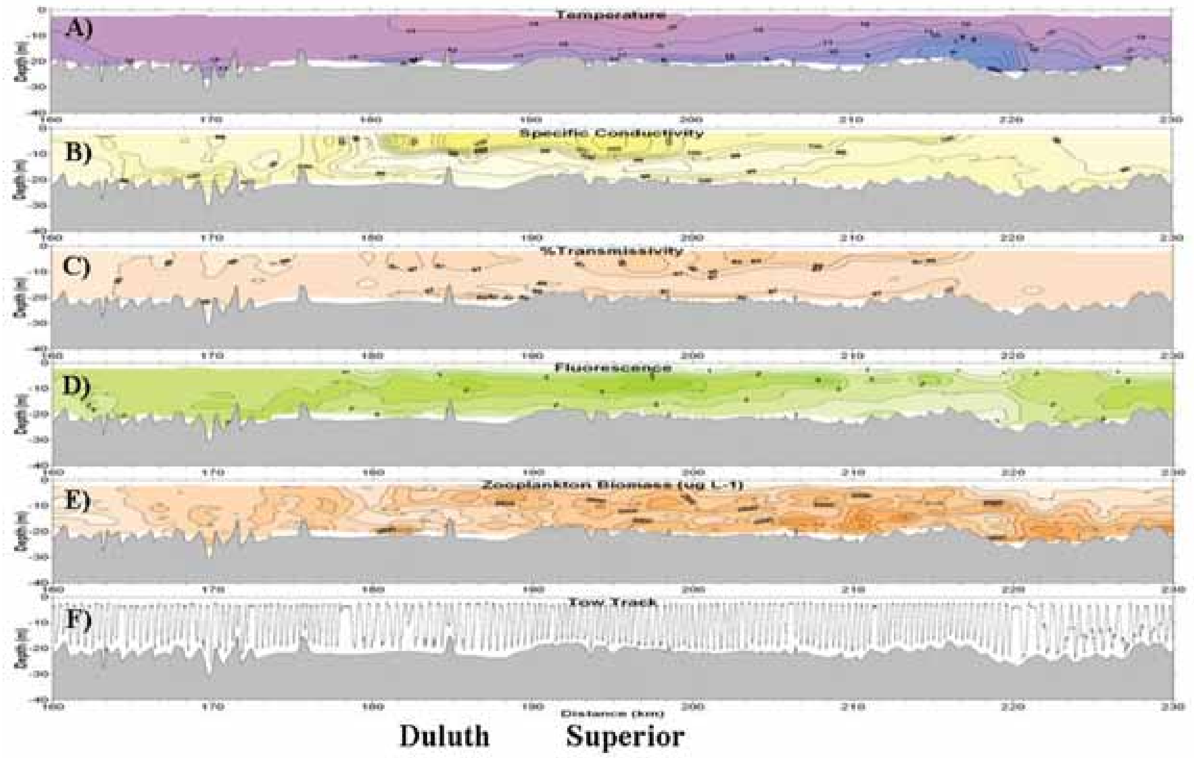

Fig 4. Reduced track to highlight region around Duluth/Superior from 160 to 230 km. Panels A) - E) same as in figure 2. The bottom panel F) includes the tow track for scale of data intensity.

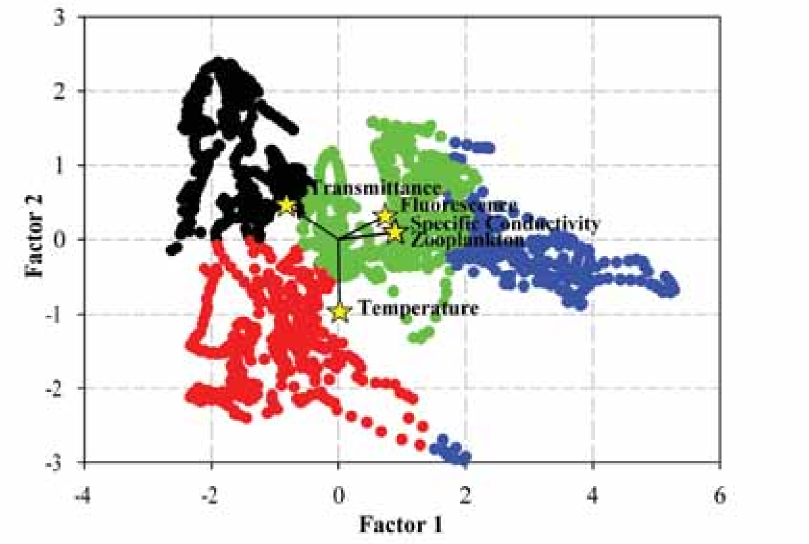

Fig 5. Principal component analysis with temperature, specific conductivity, % light transmittance, fluorescence, and zooplankton biomass. Color assignment is from k-means clustering same as in Figure 3. The characteristic loading values are depicted for each parameter on the first two principal components.

relationships that commonly exist between various parameters; as algal fluorescence increased so did zooplankton biomass; as specific conductivity (surrogate for nutrients and minerals) increased so did algal biomass; as specific conductivity increased light transmittance decreased. Regressions that correlated algal fluorescence and zooplankton biomass with the other tow parameters were significant. For algal fluorescence as a function of the measured parameters temperature, specific conductivity, and transmittance the relationship retained all the parameters at $p < 0.05$ level in a step-wise regression. The relationship was expressed as Fluor = -4.27 + 0.744*Temp - 0.0367*Temp^2 + 0.140*SpCond - 0.128*%Transmittance ($p < 0.0001$, $r^2 = 0.54$). A model which included zooplankton biomass as a potential top-down effect on algal fluorescence did not improve the relationship ($r^2 = 0.54$). A similar model for zooplankton biomass (Z(µg) = -69252 + 899*Temp - 40.7*Temp^2 + 745*SpCond - 84.8*%Transmittance - 92.3*Fluor; $p < 0.0001$, $r^2 = 0.74$) also retained all parameters. The regional spatial structure in fluorescence and zooplankton biomass

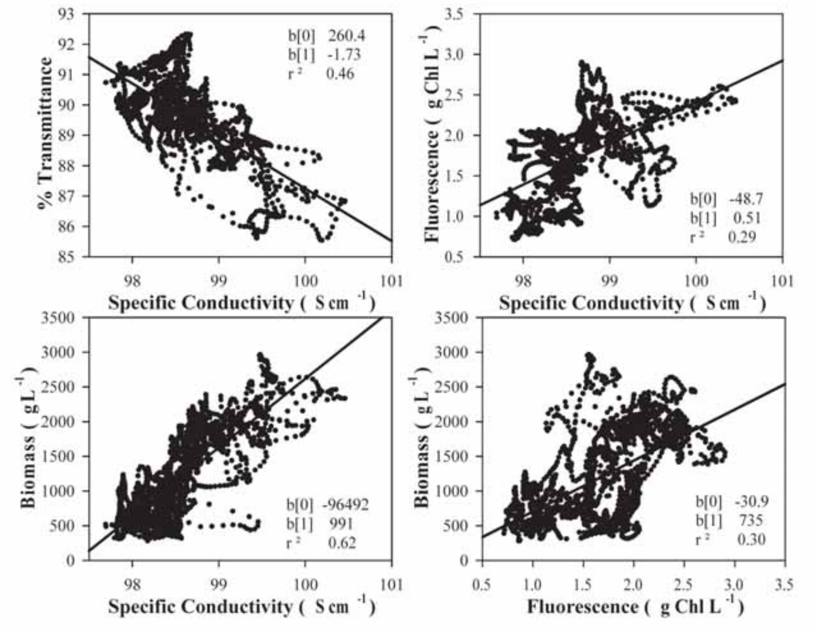

Fig 6. Plots of selected tow parameters that exhibited significant correlation. Linear regression statistics are for Y=b[0] + b[1]*X.

was captured in the general shape of the predictions (Figure 7). Nonlinear models might slightly improve some of the fits, but these are very strong relationships nonetheless; biology is quite well predicted by water quality variations.

Preliminary exploration of relationships between landuse in the segment-sheds indicated correlations that predict the character of the nearshore water environment as measured by towed instrumentation (Figure 8, Table 1). Parameters or stressor categories that were generally retained across most models included agriculture-chemicals, atmospheric deposition, and soils. Major variation across the track and the identified regional distinctions were both captured by the predictive models using landscape character.

Fixed station chemistry was observed to have some spatial variation. In general, Lake Superior has low nutrients and dissolved ion concentrations for a limited range of variation (Table 2), and

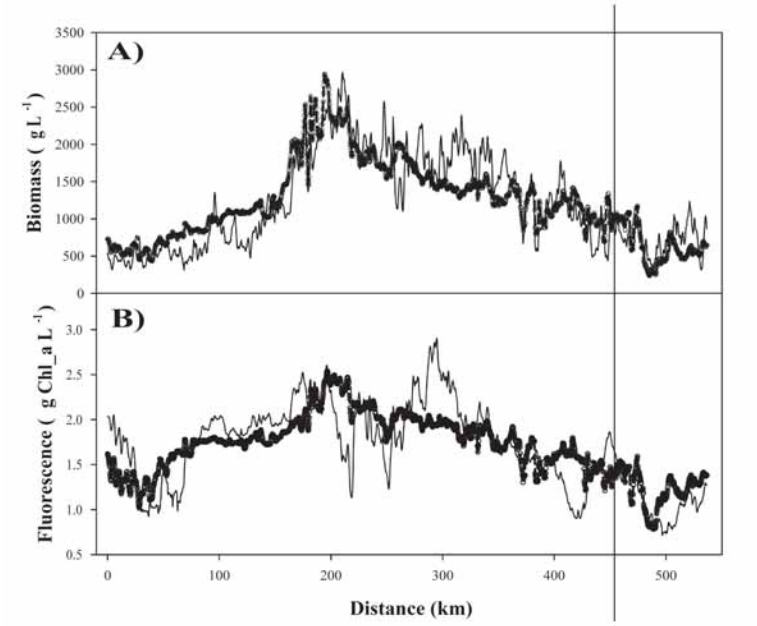

Fig 7. Multivariate regression for A) zooplankton biomass and B) algal fluorescence as a function of water parameters measured by tow instrumentation. The continuous lines represent measurements while the solid dots are from the regression relationships. The relationships were: A) Z(mg) = -69252 + 899*Temp - 40.7*Temp^2 + 745*SpCond - 84.8*%Transmittance - 92.3*Fluor, $p < 0.0001$, $r^2 = 0.74$.; B) Fluor = -4.27 + 0.744*Temp - 0.0367*Temp^2 + 0.140*SpCond - 0.128*%Transmittance, $p < 0.0001$, $r^2 = 0.54$.

these values and variation are similar to historical measurements. The tow data was compared with fixed station data by taking the average of nine Kriged grid points (3x3 block) that encompassed each bottle sample location. There was good correlation between tow data and the fixed point samples (Figure 9). Sensors and wet chemistry do not measure the exact same things but there were some significant relationships. Linear regressions for transmittance as a function of total suspended solids (TSS) resulted in the best fit ($r^2 = 0.59$). Fluorescence as a function of chlorophyll a had the largest variance ($r^2 = 0.23$) but the range over which the measurements were made was small (0.67 - 1.89 µg Chl a L^{-1}). Specific conductivity as a measure of dissolved ions was correlated to the sum of cation and anion concentrations ($r^2 = 0.40$).

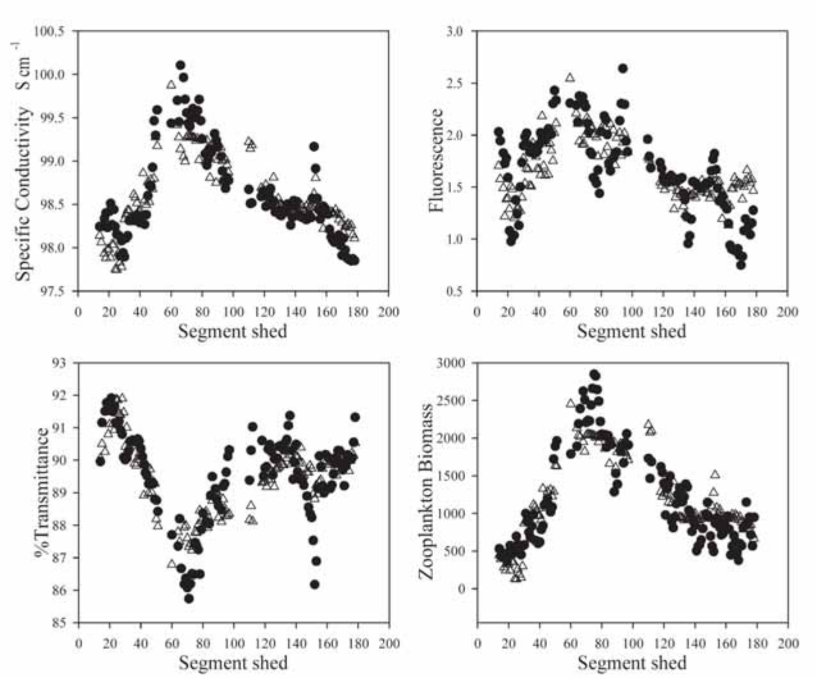

Fig 8. Multivariate regression on measured nearshore water properties as functions of segment-shed characterization parameters. The x-axis is ordinal in distance along the tow track by segment-shed ID from the Canadian border and increasing with progression around the lake. The y-axis is the measured or predicted average tow property values for each segment-shed. The solid circles are measured property values, and the open triangles are the predicted property value based on segment-shed parameter characterizations. Regression results are in Table 1.

Discussion

Views at multiple scales

The high-resolution data and contoured isopleths obtained from our extended nearshore transect depict a number of features in water quality and plankton. Theoretical ecologists have argued that one should look at both the scale above and the scale below a phenomenon in ecology to fully understand its basis (e.g. Odum, 1983, O’Neill et al., 1986, Levin, 1992). Our survey observations ranging from local,

Table 1: The retained parameters with estimated coefficients from backward stepwise linear regressions linking watershed characterization parameters to nearshore water properties for the models observed in Figure 8, where Property = Constant + a*AC + b*LC + c*AD + d*PD + e*PS + f*SL + g*SO. The parameters (AC=Agriculture, LC=Land cover, AD=Atmospheric deposition, PD=Population density, PS=Point source, SL=Shoreline modification, SO=Soils) are the first principal component scores determined by Danz et al. (2005). The estimated parameter coefficient for nearshore water properties is shown, while "-" indicates that parameter was not retained (with p=0.05) for the associated model.

	Specific Conductivity	**%Light Transmittance**	**Fluorescence**	**Zooplankton Biomass**
CONSTANT	100.5	85.3	2.278	3691
AC	0.251	-0.356	0.101	401.4
LC	-	0.494	-	-
AD	0.134	-0.446	-	127.4
PD	-	-	0.103	-
PS	-	-	-	-
SL	0.202	-	-	139.1
SO	-0.053	-	-0.0373	-42.27
r^2	**0.666**	**0.611**	**0.432**	**0.732**

to meso-scale, to full transect length perspectives provides an excellent case in point. A short introductory paper can only touch on the many interesting features revealed by this study, but three general observations serve as examples, each at a different spatial scale.

(1) *At localized scales, an input from many tributaries is suggested as patches of surface or mid-water with higher specific conductivity values.* This was apparent at our transect position, generally 0.5-2.0 km but up to 7 km from shore and in water 20 m deep or greater. Virtually every small conductivity and transmittance patch is directly adjacent to a tributary mouth along the shore. Perhaps the best and largest examples are associated with the St. Louis, Nemadji, and Ontonagon Rivers, and the Keweenaw Waterway (~180, ~190, ~447, and ~515 km respectively; Figures 2, 4). Patches appear along the tow at the location of the Temperance, Beaver, and Lester Rivers (~45, ~93, ~175 km) of the north shore which, due to the steepness of the bathymetric slope, were often less than 0.5 km from

Table 2: Chemistry data from fixed sample stations for surface (2 m) and bottom (2 m above bottom). Minimum detection limits in first row. Values that were below the detection limit are reported as one half the detection limit.

	NH_4	**SRP**	**NO_x**	**TP**	**TN**	**Cl^-**	**$SO4^=$**	**Si**	**K^+**	**Na^+**	**Ca^{++}**	**Mg^{++}**	**DOC**	**TSS**	**VSS**	**Chl-a**
Units	**µg N L^{-1}**	**µg P L^{-1}**	**µg N L^{-1}**	**µg P L^{-1}**	**µg N L^{-1}**	**mg L^{-1}**	**mg L^{-1}**	**mg SiO_2 L^{-1}**	**mg L^{-1}**	**mg L^{-1}**	**µg L^{-1}**	**mg L^{-1}**	**mg L^{-1}**	**mg L^{-1}**	**mg L^{-1}**	**µg L^{-1}**
Detection Limit	**2.0**	**2.50**	**1.0**	**4.0**	**5.0**	**0.02**	**0.02**	**0.0005**	**0.23**	**0.03**	**0.35**	**0.01**	**0.58**			
Station #																
1s	6.9	1.25	396	4.30	376	1.74	3.05	2.28	0.47	1.21	11.31	3.02	1.50	0.54	0.45	1.31
1b	8.1	1.25	434	4.56	429	1.82	3.04	2.41	0.47	1.20	10.82	2.93	1.34	0.37	0.37	0.97
2s	14.1	1.25	388	5.27	393	1.77	3.05	2.22	0.46	1.21	10.47	3.05	1.53	0.55	0.48	1.13
2b	6.9	1.25	403	4.96	389	1.69	3.03	2.32	0.45	1.18	10.06	3.15	1.54	0.50	0.43	1.23
3s	11.4	1.25	379	8.46	461	1.77	3.09	2.13	0.44	1.22	9.94	3.18	1.54	0.57	0.49	1.34
3b	8.2	1.25	420	5.97	416	1.71	2.88	2.35	0.43	1.19	9.75	3.22	1.48	0.35	0.28	1.10
4s	15.5	1.25	392	5.78	372	1.95	3.18	2.15	0.45	1.40	9.88	3.28	1.70	0.79	0.48	1.73
4b	10.1	1.25	397	7.97	391	1.90	3.23	2.27	0.44	1.35	9.78	3.20	1.59	1.01	0.55	1.63
5s	12.8	1.25	383	5.52	413	1.84	3.13	2.28	0.43	1.28	9.72	3.14	1.58	0.86	0.48	1.49
5b	11.7	1.25	449	6.50	410	1.81	3.18	2.56	0.42	1.15	9.62	3.31	1.44	1.12	0.38	0.67
6s	16.4	3.35	397	4.75	455	1.83	3.14	2.32	0.42	1.27	9.62	3.23	1.56	0.70	0.35	1.39
6b	8.4	1.25	400	6.18	385	1.78	3.03	2.18	0.42	1.23	9.57	3.14	1.51	1.24	0.57	1.89
7s	7.3	1.25	365	4.71	355	1.72	3.04	1.97	0.42	1.19	9.63	3.05	1.59	0.65	0.40	0.88
7b	15.3	1.25	400	8.67	375	1.78	2.98	2.05	0.43	1.19	9.77	3.14	1.58	0.81	0.45	1.29
8s	10.7	1.25	368	4.67	373	1.75	3.11	1.93	0.41	1.16	9.72	3.08	1.51	0.64	0.31	1.02
8b	11.8	1.25	397	4.90	383	1.78	3.14	2.13	0.41	1.15	9.64	2.99	1.37	0.92	0.48	1.24
9s	16.6	1.25	384	6.01	371	1.35	2.14	2.04	0.40	1.12	9.54	3.15	1.46	0.47	0.32	0.73
9b	27.9	3.62	410	6.25	412	1.68	3.16	2.21	0.40	1.12	9.62	3.25	1.31	0.52	0.38	1.05

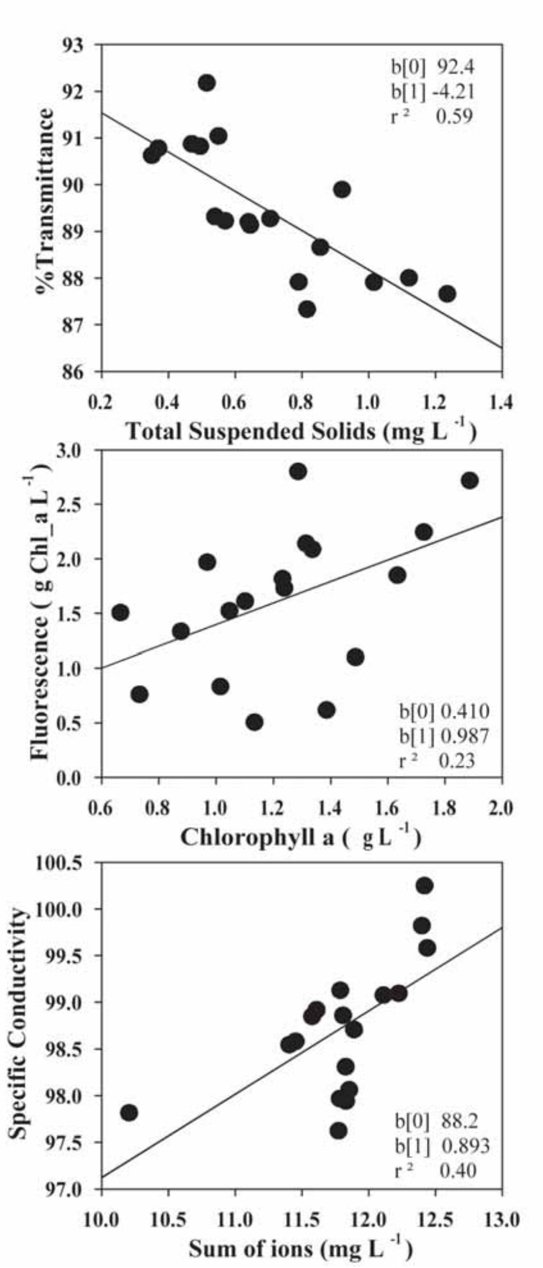

Fig 9. Correlation of towed instrument data with fixed station data. The electronically measured data from the tow fish is on the y-axis and the bottle chemistry data is on the x-axis. Linear regression statistics are for Y=b[0] + b[1]*X.

shore. The 20 m contour along the south shore was generally further from land because of a shallower bathymetric slope, but some patches are observable at Iron, Bad, and Black Rivers (~215, ~340, and 388 km).

On the other hand, not every tributary had an adjacent identifiable patch in the nearshore. This could be a consequence of: variations in recent and localized rainfall; local current/water motions which create variation in the effectiveness of tributary plume mixing; variations in the solute strength of tributaries; differential spacing of tributaries along the shore, some with aggregation to a more regional influence rather than individual expression; and/or an inherently minimum detectable tributary size/volume discharge. These factors can be further explored, but the regular observation of so many local features embedded within a larger scale sampling is an inherent advantage to this type of survey style.

(2) *At the mesocale, there appear distinct segments along the transect.* This is evident in Figure 2, and more pronounced in Figure 3, based on clustering of the overall set of sensor measurements (Figure 5). There is only minor overlap in character among these regions at the transitions between segments, with the delineations being relatively distinct. The regions are largely uniform and contiguous with little or no interspersed banding of the other class types. The small amount of scatter in classification might be attributed to classification error or to a large amount of localized environmental variability. The contiguous bands also indicate that the tow path remained in nearshore waters and did not cross into offshore regions of potentially differing water quality.

Attributes which contribute to distinctiveness of segments include: the range and average of values for each parameter, the unique mix of values among parameters, and the vertical distribution of parameters within each segment. Different levels of "patchiness" or small-scale variability within each segment may also be an integral part of the distinctive character that can be used to define segments.

The overall character of the north shore (0 to 135 km; Figure 3, black) was cool temperatures, clear water, low specific conductivity (mild increase around Silver Bay ~90km), and slight vertical structure but little horizontal variation in physical features. Biological biomass was found to be low with a very slight vertical structure and slight increases in fluorescence and zooplankton to the south localized to Silver Bay (~90 km) and southward.

On either side of the mid-section (135 to 165 and 248 to 369 km; Figure 3, green) was a region characterized by moderate temperature, moderately clear water, low to moderate specific conductivity, and moderate plankton levels. On the south side, fluorescence peaked at mid-depths and often at slightly shallower depths than zooplankton, but both had stronger vertical structure in distribution along this track stretch. No strong tributary features were observed in this section except perhaps around Bad River (~340 km).

Overall character of the mid-section (165 to 248 km; Figure 3, blue) showed strong outflow of St. Louis and Nemadji Rivers with elevated specific conductivity, moderate temperature, and higher turbidity as surface plumes. The plumes extended a bit northward but more generally and extensively southward along the south shore. There was an associated stimulation of plankton (fluorescence and zooplankton) with this outflow. The highest plankton concentrations were observed in this region. There appears to be a slight spatial offset and time lag between fluorescence and zooplankton stimulation, with elevated and peak fluorescence within or at edges of specific conductivity plume, and peak zooplankton at slightly lower depths and more downstream (along south shore). The region north of St. Louis River showed small patches of specific conductivity and some level of associated plankton that are probably from a string of small tributaries (Lester River ~175 km and southward). There were specific conductivity patches and some associated plankton patches of elevated concentrations, which appear somewhat distinct from the St. Louis outflow, but far less pronounced.

Eastward along the Keweenaw peninsula (369 to 537 km; Figure 3, red) was a progression of warmer surface temperatures, with a stronger stratification in vertical physical structure. This region was the warmest, had clear water, low specific conductivity except at the Ontonagon River (~447 km), and low biological biomass. Accompanying patterns in biology followed some undulations along the thermocline. Fluorescence and zooplankton both had strong vertical structure in distribution with peaks near the bottom.

The general perception has developed over time that there are regionally identifiable areas of Lake Superior in both water column properties and bottom sediments (Cook and Johnson, 1974, Stortz et al., 1976, Munawar and Munawar, 1978, Dermott, 1978, Thomas and Dell,1978, Johnson et al., 2004). The extent and delineation of this regional character for some parameters is interpolated from relatively sparse spatial sampling, but even when hundreds of samples are available, significant distances are involved between sample points. Our fixed stations provided limited power for resolving regional variability yet were comparable in sample density to many current lake wide studies. The fixed station chemistry was used primarily to relate the towed data to traditional laboratory chemistry methods (Figure 9). The towed instrumentation provided the fine scale resolution at spatial distances where regions of similarity can be more easily identified (Figure 3), whereas the variation in fixed station water chemistry was not striking or large but was consistent with earlier studies and temporal trends in nitrate (Weiler, 1978, Bennett, 1986).

Temperature gradients along the tow transect are consistent with the regional classification of thermal regimes for Lake Superior (Bennett, 1978). Maximum surface temperatures in Lake Superior are generally observed in September, the time of our survey. The temperature was lowest in the more northerly portion of the tow where coastal upwelling often maintains low temperature conditions, and was warmest along the south shore, which experiences higher maximum temperatures (Bennett, 1978). The high density temperature data with extensive spatial coverage allows for identification of thermal intrusions, tilting thermoclines, and extensive spatial patterns in temperature gradients. Satellite-based measures of surface temperature (advanced very high resolution radiometers, AVHRR) provide near real-time maps available on the internet (http://coastwatch.glerl.noaa.gov/cwdata/). Surface data can be augmented and enhanced with vertical depth data from tows to identify vertical mixing processes. The historical data provided the first estimates of thermal budgets and processes (Phillips, 1978; Bennett, 1978) but older methods are being supplanted by new technologies that provide the spatial detail needed to refine our knowledge of lake wide processes.

Specific conductivity had detectable variation (Figure 2, 3) that imparted spatial structure (Figure 2, 3). The general average of our data (~98.5 µS cm^{-1}) is consistent with data reported in Weiler (1978). Again, local intrusions (tributary input) and spatial variation are little resolved in traditional data sets. The historical view is that lake wide conductivity does not change over the year (Weiler 1978) and an overall average imparts knowledge of condition of the whole lake, yet quantification of spatial scales for sources and sinks leads to identifying local and lake wide variation that are important in identifying and understanding dynamic physical processes. Ion and nutrient budgets and spatial mixing and distribution can be improved with application of new technology to provide details that were previously not available. Identification of correlations and processes that link landscape sources will move us to greater understanding of condition and change in condition of nearshore regions.

Regional areas also may be subject to geospatial constraints not experienced across the entire lake. In shallower waters nearshore, wind direction and speed affect light transmittance on short time scales by resuspension and mixing of bottom sediments and shoreline erosion. The region from Duluth to the Apostle Islands is affected by red clay geological deposits. The intermittent suspended clay load, of which 75% is from bank erosion, 20% from resuspension and 5% from runoff (primarily the Nemadji River), in this vicinity make light transmittance a dynamic property (Stortz et al., 1976, Sydor et al., 1979, personal observation). The results from our tow data, where the region between Duluth and the Apostle Islands had the lowest light transmittance, are similar to the expectations from previous studies (Stortz et al. 1976, Schertzer et al., 1978; Sydor et al., 1979). In the bedrock regions and steep bathymetry of the north shore, light transmittance was far less affected by wind resuspension and shoreline erosion.

Historical data on lower trophic levels are taxonomically oriented (Watson and Wilson, 1978, Munawar and Munawar, 1978). The LOPC data is size oriented, although it is possible to deduce some taxonomic information (Herman et al., 1993; Sprules et al., 1998; Sprules, 2001). The zooplankton densities we measured (count data, converted to biomass in Figure 2) are in the same general order of traditional measures (10^3-10^5 m^{-3}, Watson and Wilson, 1978). The added detail in the electronic data provide an alternate view of the zooplankton trophic level using biomass, size structure, and spatial distribution. New approaches are needed to effectively incorporate this type of detail into assessment criteria (Yurista et al., 2005, 2006). The newer technologies provide detail in spatial distribution of organisms with reduced processing time (Sprules, 2001) that can only be approximated using traditional methods with greater effort in sampling intensity and strategy (e.g. Kuns and Sprules, 2000). High density regions are unlikely to be sampled by traditional means due to patchiness and skewed distributions (Megard et al., 1997) and are of great importance to trophic energy transfer but are easily identified with new technology. The fluorescence estimates of chl_a are consistent with current (Table 2) and past measurements (Munawar and Munawar, 1978).

(3) *Viewed from the scale of the entire transect, there appears to be a strong correspondence between the physical structure of the water column, especially in terms of thermal patterns, and the distribution of biology, particularly the distribution of zooplankton biomass*. There was a general trend for zooplankton to distribute throughout the water column dependant on thermocline "strength" and depth, with the spatial correspondence independent of the general level of biomass. Along the north shore, zooplankton were distributed throughout the water column in moderate temperature water with little stratification. Along the Keweenaw peninsula, with higher surface temperatures, the zooplankton congregated in the moderate temperature water at or below the thermocline. In each case the total zooplankton biomass in the water column was similar. Most zooplankton across all regions were observed at temperatures in the general range of 8 to 14 C.

The north shore region (0 to 50 km) had an upwelling event during our sampling period. Although we did not follow a transect across the lake, this event was inferred from the thermal structure on both sides of the open lake toward the Keweenaw Peninsula. Prevailing north-west wind patterns appear to have pushed warmer water toward the south-east area of the Keweenaw, tilting the thermocline across the lake with a deeper, stronger thermocline along the Keweenaw, and a resulting weak temperature gradient and an upwelling pattern of cooler water along the north shore. Upwelling may have an impact on zooplankton abundance.

Others have noted or commented on the theme of tilting thermoclines and upwelling events and zooplankton distribution in Lake Superior (Megard et al., 1997; Zhou et al., 2001). Their studies have identified zooplankton distribution patterns that are strongly associated with the thermocline structure in nearshore (0-5 km, <50 m depth; Megard et al., 1997) and offshore (> 10 km, > 100 m depth; Zhou et al. 2001). Our study confirms some of their observations and adds other details and features across a much larger study area (537 km). The inclusion of temperature in prediction of zooplankton biomass argues for a physical basis in regulating zooplankton not just in the local vertical dimension, but also on an integrated water column basis in the horizontal dimension. Our observations suggest there is indeed a broad-based, perhaps common and fundamental role for physical and thermal structure in affecting the distribution of zooplankton. There seems a basis for arguing that variations of the bio-physical connection are a principal reason there exist some different distinctive characteristics that we can identify at segment-level scales of the transect in western Lake Superior.

Preliminary models of nearshore plankton in Lake Superior

The regional spatial structure was captured in the overall form of regression model predictions, but variations at the smaller localized scale of an autocorrelated stochastic component (Stockwell et al., 2002) were less well captured. We have not yet addressed the stochastic component in our multivariate regression. Significant correlations were found for both fluorescence and zooplankton biomass as functions of the simultaneously measured sensor parameters: temperature, specific conductivity, and transmittance (Figure 7). Interestingly, fluorescence was helpful in describing zooplankton, but zooplankton biomass was not helpful in describing fluorescence. Two points need to be mentioned. First, a “top-down” feature (Carpenter et al., 1985), i.e., of zooplankton control of phytoplankton patterns, thus was not generally indicated; this could be due to lags in development of phyto- and zoo- plankton in near-field response to tributary inputs or to the basic oligotrophic character in the lake. Second, it is possible that phytoplankton aggregates are being detected by the LOPC as a covariate in zooplankton biomass estimates and lead to some auto-correlation of the data. The general low abundance levels and community composition typically dominated by phytoflagellates and nonnoplankton (Munawar and Munawar, 1978) of Lake Superior phytoplankton would tend to minimize this effect. Results suggest one simple model can be applied across all the nearshore regions (cf. Figures 6, 7); we have not tried to describe each region independently. If a general model is valid, any change over time in the empirical relationship between the lower trophic levels and water quality therefore could indicate an alteration to the functioning of the nearshore.

Landscape characteristics also predicted water quality and plankton of the nearshore environment as measured by towed instrumentation (Figure 8, Table 1). The correlation of land use measures to towed parameters suggests a basic connection between the relatively open nearshore waters, and human activities at the scale of small segment-sheds (or groups of similar segment-sheds) across the surveyed stretch of Lake Superior's coastal drainage basin. A strong landscape influence has been described for small, relatively isolated lakes or streams contained within different landscape settings (Kratz et al., 1987, 1997; Kling et al., 2003). But we do not know of other studies within a Great Lake that have revealed such a strong apparent pattern as observed, suggesting co-variation of nearshore waters with adjacent coastal landscape at local to regional scales.

Limnologists have developed relationships between nutrient loading (TP) and plankton (both phyto- and zooplankton biomass) (Schindler, 1974; Dillon and Rigler, 1974; Pace, 1984; Carpenter et al., 1985; Carpenter, 1988; Nixon, 1992; Mazumder, 1994; Hall et al., 2003). The patterns of water quality/plankton distribution that we have resolved (at a variety of scales) followed the well-established paradigm of biological stimulation from mineral inputs — i.e., the "bottom-up"concept or "agricultural model" of aquatic scientists (e.g., McQueen et al., 1986; Nixon, 1995). While it is clear that a principal area of stimulation is in the Duluth-Superior outflow region of our survey (Figure 4), the simple enrichment paradigm applies across the whole transect, as shown by the generally strong relationships of water quality and biology in Figure 6 (specific conductivity - biology plots).The enrichment paradigm emerges against the backdrop of local variations in bathymetry and many other parameters (climate, circulation) along the transect. Temperature is a big contributor to *in situ* variability, and it is striking how well biological distributions, in vertical and horizontal space, follow temperature variability over the transect. Thus, several fundamental concepts of limnology appear merged in our high-resolution data set, even though, as noted patterns are pronounced in different ways depending on the scale at which the observation is being made (Levin, 1992).

Conclusions

Traditional sampling methods for aquatic systems often have collected point samples from a very small volume of water (e.g., Niskin bottles), or aggregated organisms over variable spatial distribution (e.g., nets); follow-up lab-based analyses (chemical or taxonomic) are often time and labor intensive and these costs restrict the density of stations in a field survey. Although not a replacement for all measures, for what it *can* measure well, the technology of modern electronic sensors provides the means for obtaining high spatial resolution over extensive space, with efficiency. New developments in instrumentation (e.g. nitrate by UV spectrophotometry, Johnson and Coletti 2002) will extend the array of measurements that we can make while using the spatial survey strategies we are refining. We continue to evaluate this new technology in development of new assessment methods to provide new indicators, such as size spectra for zooplankton as a complement to taxonomic measures (Yurista et al., 2005). Our results demonstrate that both the adaptation of electronic instrumentation and towed survey strategies provide greater insight through a highly detailed view of the whole picture.

Our survey has confirmed a number of previous observations of spatial patterns in Lake Superior water quality and biology, yet the detail added by high resolution allows for greater precision in observing local phenomena and delineation of regional character, while retaining an overview of extensive spatial scales. We were able to identify patch size with better precision than past sampling practices have been able to. With the increased data density we observed relationships of lower trophic levels to the immediate environment (temperature, dissolved ions, light transmittance) in a simple bottom up model that was applicable over 537 km. We further observed a correlation of nearshore water quality and lower trophic level status to landuse conditions in the adjacent contributing watersheds. The observed linkage to landscape character provides a basis for developing monitoring designs and correlations for assessment of causality of nearshore condition.

Results from the towed *in situ* technology provide a rapid and spatially extensive methodology to acquire data that will be helpful in developing monitoring and assessment designs that would use coastal ecosystems as sentinels for anthropogenic disturbances on the edges of the Great lakes.

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