November 2009

Technical Memorandum

Water Quality on the Shores of Lake Huron Adjacent to the Saugeen, Maitland, and Bayfield River Mouths

By

M. Mohamed, E.T. Howell, and A. Todd

Environmental Monitoring and Reporting Branch
Ontario Ministry of the Environment

Executive Summary

A series of nearshore water quality surveys were conducted on the shores of Lake Huron adjacent to the mouths of three large rivers, the Saugeen, Maitland, and Bayfield Rivers, over the May to November period of 2003 to evaluate nutrient conditions, levels of fecal pollution and, more generally, land impacts on the nearshore. In recent years there has been public and agency concern that water quality on the southeast shores of Lake Huron is being impacted by human activity as evidenced by beach postings and complaints of fouling of shoreline by algae.

Shoreline was selected for study over areas where high relative effect from adjacent lands on the nearshore was anticipated based on the amount of drainage area to the shoreline. The study areas were adjacent to three of the five largest watersheds to the Canadian shores of the main basin of Lake Huron with a combined drainage area of approximately 7000 km^2. The watersheds of the Saugeen, Maitland and Bayfield Rivers share basic features. The majority of land is classified as agricultural, forest cover is limited, and there is a relatively low density of human population spread over several towns, communities and rural lands.

Water quality in the nearshore (up to 5 km offshore) was evaluated over a range of seasons and weather conditions. Water quality at a downstream site in each river was monitored over the study period. These sites, and additional downstream sites, were monitored concurrently with nearshore surveys. On 4 to 5 occasions per area detailed spatial data were collected by tracking water quality sensors over the nearshore and used to map conditions. Surface maps of temperature, conductivity, chlorophyll a fluorescence, beam attenuation and UV fluorescence of hydrocarbons were augmented by collection of water samples for laboratory analyses for nutrients, selected macro-ions, physical measures and the fecal pollution indicator *E. coli*. Additional field sensors (temperature, conductivity and turbidity) were periodically lowered through the water column at points over the survey track to collect information on the depth-related aspects of variability. The spatial patterns in water quality parameters were used to provide insight on the effects of river discharge on the nearshore and on features of lake circulation. Current meters and temperature sensors were deployed over the study period and provided information on lake circulation.

Discharge from the Saugeen, Maitland, and Bayfield Rivers to the nearshore of Lake Huron was responsible for much of the variability in physical-chemical conditions observed over the three study areas. Mapping of conductivity in the nearshore proved an effective way of identifying the river plumes and broader patterns of mixing of tributary discharge within the lake.
The extent to which tributary discharge affected the shoreline as inferred from the size of the mixing areas in the nearshore varied widely and roughly corresponded with fluctuations in river discharge. Large areas with elevated conductivity, contiguous with the discharge plumes from the Maitland and Saugeen Rivers, were noted during the spring and late fall surveys during periods of moderate to high relative discharge. On several occasions, the affected areas extended beyond the study areas approximately 6 km from the respective river mouths. Despite the appreciable drainage area of the Bayfield River, the direct influence of the river discharge was limited (1-2 km of shoreline) in comparison to the Maitland and Saugeen Rivers. Alongshore lake currents most frequently shaped the spatial features of water quality. The orientation of the mixing area of the discharge from the Maitland and Bayfield Rivers were often parallel to the shoreline extending away from the river mouth in the direction of the surface currents. In contrast to the approximately linear shoreline of the Maitland and Bayfield Rivers study areas, the shoreline of the Saugeen River study areas was more varied, as was the bathymetry of the nearshore, contributing to greater variability in the orientation of mixing areas as currents were deflected by various shoreline and bathymetric features.

Water discharged to the lake from the Saugeen, Maitland, and Bayfield Rivers in general contained appreciably higher levels of nutrients, particulate material, fecal pollutants (as inferred from *E.coli*), chloride, DOC and phytoplankton (as inferred from chlorophyll *a*) than the receiving lake water. There were broad fluctuations in the physical-chemical composition of the water discharged from Saugeen, Maitland, and Bayfield Rivers over the study and these changes were typically concurrent with alteration of river flow.

The connection between watersheds, major rivers, and the nearshore was highly evident in the patterns of variability in NO_2+NO_3 concentrations. The river concentrations of NO_2+NO_3 were high relative to the lake and strongly responsive to hydrological events in the watershed. In the open lake, NO_2+NO_3 concentrations were generally many times lower than river concentrations. Consequently, river discharge invariably elevated NO_2+NO_3 levels over the mixing areas in the nearshore. On occasions when river discharge was high, appreciable areas of the nearshore were affected because of the broad areas over which the discharge was transported in the nearshore before being diluted to ambient lake levels.

The spatial extent and magnitude to which TP levels were elevated in the nearshore above ambient lake levels was qualitatively lower than compared with NO_2+NO_3. Nearshore concentrations of TP were frequently low (<5-10 μg L^{-1}). Concentrations of TP in the rivers were typically elevated relative to lake ambient levels driving gradients in TP over discharge mixing areas. The highest overall TP concentrations in the nearshore were observed during late fall surveys when it was suspected that high particulate levels in the water column due to resuspension were affecting TP levels.

The patterns of nutrient levels and trophic indictors described a paradoxical condition where, at times, there was strong evidence of land-based nutrient enrichment, most notably in nitrates, yet loading of the primary limiting nutrient, phosphorus, was seemingly insufficient to appreciably alter trophic status in the nearshore as inferred from levels of chlorophyll a. Nearshore chlorophyll a concentrations based on extensive measurement, were low and rarely exceeded 2 μg L^{-1}. A boundary of 2 μg L^{-1} is sometimes used to distinguish mesotrophic from oligotrophic conditions in the Great Lakes.

Chlorophyll *a* concentrations were typically higher in the river compared with the lake, and at times higher levels of chlorophyll a over mixing areas in the nearshore appeared to be due to input of algae from the rivers. Periodically, chlorophyll *a* was elevated in the direction of movement of river discharge along the shoreline over areas beyond the locations with elevated conductivity (mixing areas) suggesting nutrient stimulation of phytoplankton. Elevation of chlorophyll *a* concentrations up to 2-4 fold in the mixing areas was observed, however, concentrations generally did not exceed 1 μg L^{-1} (excluding areas directly adjacent to the river mouths). From a correlative basis, primary production, as inferred from chlorophyll a levels, appeared unresponsive to elevated nitrogen.

Periodically, physical disturbance of the lakebed and shoreline by water movement and wave action strongly influenced water quality in the nearshore by the entrainment of particulate material into the water column. Areas of elevated turbidity were common along the shoreline. The origins of elevated levels of particulate material in the water column was inferred from correspondence with conductivity. At times broad areas of elevated turbidity independent of river mouths and unrelated to conductivity were observed. There was wide range in turbidity over the study period, from exceptional levels of water clarity to murky conditions.

The occurrence of the fecal pollution indicator *E.coli* contrasted between the river sites and the corresponding nearshore sites, presenting a seemingly contradictory picture of fecal pollution. River levels of *E. coli* varied widely, occasionally reaching levels suggestive of loading of fecal pollutants to the rivers. In contrast, levels of *E.coli* at the nearshore sampling positions were almost always near or below method detection. Nearshore levels elevated over lake background (interpreted as non-detectable *E.coli*) were periodically observed suggesting loading from river discharge or shoreline sources, however, only rarely did levels exceed 100 CFU 100 mL^{-1}. The explanation for the disparity between the lake and rivers likely lies with the details of the sampling. Nearshore sampling was limited to lake depths of >2.5 to 3 m for operational reasons and did not capture conditions in the shallow waters along the shoreline where higher levels of *E.coli* are anticipated. Also, with one exception, lake surveys were conducted at times when river levels of *E.coli* were relatively low and therefore under represent the potential influence of river discharge on the nearshore. The transient nature of *E.coli* loading to rivers makes it difficult to assess impacts on the nearshore using a lake-based survey approach such as in this study.

The focus of this study was the nearshore of Lake Huron, however, data collection extended to the lower reaches of the large rivers discharging to the study areas. Water quality in the lower Maitland, Saugeen and Bayfield Rivers was periodically impacted as evidenced by elevated levels of suspended solids, nutrient and the fecal pollution indicator *E.coli*. Efforts to protect and improve environmental quality within these rivers will serve to not only advance the ecological and resource values of these rivers but will also impact positively on the nearshore of Lake Huron.

Table of contents

1 Introduction

Anthropogenic activity on the shores of the Laurentian Great Lakes has resulted in ever-increasing disturbance of the physical, chemical, and biotic environment of these bodies of water. Impacts on water quality in Lake Erie (Lake Erie LaMP 2006) and Ontario (Lake Ontario LaMP 2006), and to a lesser extent in Lake Huron (Lake Huron Binational Action Plan 2004), are well appreciated. Direct human interaction with the Great Lakes is concentrated at the shoreline and in nearshore waters. This interface of the land and the lake is the primary area used for recreational activities such as boating, fishing and swimming. These recreational areas, as well as the residential properties on the Great Lakes shores are highly prized in Ontario.

Historically, the accessibility of Great Lakes shoreline resulted in appreciable growth of communities on the shores with ensuing resource demands and impacts on the nearshore. These coastal communities typically draw water from the nearshore to service their drinking water treatment plants. The disposal of industrial and municipal effluents is often directly or indirectly via tributaries to the nearshore. The nearshore water resource also factors prominently in electrical power generation and commercial shipping.

These resource values, coupled with the ecological importance of the nearshore environment, dictates that careful environmental management of coastal areas of the Great Lakes is a necessity for Ontario. An element of this charge is the monitoring of environmental conditions to access resource and ecological quality and to identify anthropogenic or natural stressors that may be impacting the environment. An understanding of existing conditions is therefore central to the evolution of existing environmental management regimes to maintain expected levels of resource quality.

The lands draining to the shores of the Great Lakes in southern Ontario are heavily developed. Historically, much of the natural vegetative land cover was cleared to enable a diversity of alternate land uses of which agricultural and urban/residential development figure prominently. The surface water that discharges from the tributaries of watersheds on the periphery of the Great Lakes in southern Ontario is highly variable in quality and typically reflects the land-use and geology of the watershed. A critical element in the connection between the land and the lake is the loading of tributary water to the shoreline via discharge at the mouths of rivers. The river discharge at the lake represents a summation of the character of the watershed and its influence on surface water quality within the watershed. The ability of the watershed to impact the lake is largely governed by the quality and quantity of the river water flowing into the lake acting as a point source at the river mouth.

Major rivers, with their large watersheds and correspondingly high discharge, are a considerable source of nutrients, sediment, toxicants, and potential pathogens to lakes. Additionally, large rivers often receive direct inputs of municipal and industrial effluents. The loading from large rivers may contribute to the water quality of the lake as a whole, however, it is the nearshore area directly adjacent to the river mouth where the most acute effects of river discharge will occur.

The confluence of two strong physical forces plays out in the mixing areas at the mouths of large rivers. The interplay between the ever changing physio-chemical dynamics of the lake and the variable discharge of river water result in highly unstable and diverse patterns of water quality in the nearshore.

A key source of the variability in the nearshore is attributable to the temporal dynamics of rivers varying in both the volume of water discharged, as well as the quality of that water. On a seasonal scale, Ontario rivers typically follow a pattern of the highest annual discharge during the spring melt, and another episode of high discharge (though usually smaller than the spring peak) in the fall. The discharge pattern of rivers occurs concomitantly with changes in river water quality. High river discharge during the spring melt flushes sediment and nutrients from the river bed and the surrounding watershed. During the intervening summer and early fall, discharge typically drops dramatically, especially in smaller rivers. However, at any time of the year, episodic rainfall in the river watershed, when sufficient to elevate river flow or degrade quality of the river, has the potential to affect the nearshore either by increased volume of river discharge or reduced quality of the discharge.

The complex physical behaviour of large lakes contribute to the highly changeable conditions in nearshore areas (Rao and Schwab 2007). Knowledge of lake circulation provides a framework that can be used to anticipate and interpret observed features of variability. For example, the prevailing tendency for lake water to flow parallel to the shoreline in the nearshore in periodically reversing directions along open coastline (Murthy and Dunbar 1981) has a major influence in creating the characteristic spatial patterns observed in tributary mixing areas in the nearshore. Episodic onshore and offshore lake circulation associated with upwelling and downwelling events can quickly alter temperature regimes and move materials into or away from nearshore areas (Lee and Hawley 1998). In the nearshore, wind-driven water movement erodes material from the lakebed and shoreline and can result in highly variable and quickly changing levels of particulate material (suspended sediment) in the nearshore (Vanderploeg et al. 2007). Seasonal changes in biological activity in the lake can contribute to temporal variability in features of water quality such as nutrient concentrations. This is especially true in the nearshore where there is often adequate light reaching the lake bed to support photosynthesis and more extensive and complex assemblages of plants and animals than further offshore.

The nearshore environment is in a state of constant change. Due to the extent and frequency of short-term change in environmental conditions, the nearshore remains a technically challenging setting to monitor environmental quality. There is recognition of the nearshore as a diverse and productive component of the Great Lakes facing pressing issues where attention is needed (Report to BEC 2007). The long recognized importance of the nearshore not-with-standing, a whole-lake focus has arguably dominated much of the effort to understand environmental conditions in the Great Lakes. There is a paucity of monitoring methodologies that have been tested and used to assess dynamic environmental conditions in nearshore regions. Improving upon monitoring capability for the nearshore and, in particular, the highly variable conditions in the mixing areas at the mouths of tributaries is a prerequisite to understanding these environments sufficiently to predict and respond to the effects of stressors on them.

The development and application of methods to monitor the Great Lakes nearshore and to assess the interaction with adjacent shoreline and watersheds has been an ongoing aspect of the Great Lakes Nearshore Monitoring Program. Recently, a field-based approach using arrays of water quality sensors has been developed to allow mapping of water quality features in coastal areas at high spatial resolution. The detailed point-in-time spatial representations of water quality, when supplemented with available geographic and more limited through-time water quality and physical information, provide insight on prevailing water quality and on the natural and anthropogenic factors affecting water over a study area.

In 2003, a series of shoreline water quality surveys using a spatial mapping methodology were conducted on the shores of Lake Huron adjacent to the mouths of three large rivers, the Saugeen, Maitland, and Bayfield Rivers, respectively. In this report, the findings from these surveys are presented with two objectives. First, in recent years there has been public and agency concern that water quality on the southeast shores of Lake Huron is being impacted by human activity and land-use as evidenced by beach postings and complaints of fouling of shoreline by algae (Lake Huron Centre for Coastal Conservation 2004, Lake Huron Science Committee 2005). The surveys in 2003 were executed to address a need for monitoring information which could be used to critically evaluate water quality conditions. This report attempts to provide this evaluation. The second objective is to document the complex conditions which exist in the nearshore region and demonstrate how conditions in this zone are intimately linked to the adjacent shoreline and watershed.

1.1 Nearshore of South Eastern Lake Huron

The coastline of Lake Huron from Sarnia to Sauble Beach, sometimes referred to as the Southeast Shores, stands out in Ontario for the juxtaposition of land uses. Water and beach-based recreation is a significant contributor to the economies of shoreline communities. The lake is widely considered as a high quality natural environment. Lands draining to the lake are predominately rural with agricultural activities a key element of the local economies. The watersheds to the lake constitute among the heaviest concentrations of agriculture in the province. Urban development is limited to several small towns with several direct sewage-treatment plant (STP) discharges to the shores of the lake. The likelihood that watershed and shoreline-based activities impact on water quality at the shores of the lake is high, however, it is unclear as to the nature and extent of the anthropogenic effects on water quality in the lake.

There is a range in landform along the SE shores of Lake Huron, but there are several typical features. Prominent among these are the wide-spread shoreline beaches which makes the area prized for water recreation and also accents the issue of beach posting due to fecal pollution (Lake Huron Science Committee 2005). The shoreline, with limited exception, is highly exposed to the broad fetch of Lake Huron and at times subject to high energy wave action which erodes the shallow lake bed and shoreline (Lawrence and Davidson-Arnott 1997, Elfrink and Bladcock 2002). The slope of the lake bed tends to be gentle with broad areas of relatively shallow water adjacent to the shoreline. In many areas, clay cliffs and a low permeability clay-dominated plain lie immediately adjacent to the shoreline (Singer 2003). There is erosion of fine clay particles as numerous small watercourses drain the land behind the shoreline periodically delivering turbid water to the lake.

Compared to the lower Great Lakes, Lake Huron has not been as sensitive to anthropogenic eutrophication due to its larger volume and relatively less urbanization of shorelines. The offshore waters of Lake Huron remained oligotrophic during the eutrophication of the lower Great Lakes , which gained public attention in 1960s. Of all the Great Lakes, including Lake Michigan, Lake Erie, and Lake Ontario, Lake Huron had among the lowest concentrations of chlorophyll *a* (1 – 2 µg L^{-1}) and total phosphorus [TP] (approximately 5 µg L^{-1}) (Neilson et al. 1995).

Water quality is generally more variable in nearshore areas along south eastern Lake Huron compared to offshore (Stevens et al. 1985). Nicholls et al. (2001) summarized nearshore municipal water intake data for the Great Lakes from 1976 to 1999. At Goderich, median monthly (TP) concentrations ranged from 11 – 40 µg L^{-1}. Variability in water quality decreased further alongshore to the south. Median monthly TP was 9 – 20 µg L^{-1} at Grand Bend, and only 2 – 7 µg L^{-1} at Lambton. This spatial variability in water quality may have reflected the water intake depths. Resuspension of bottom sediments is expected to be greater at shallower depths due to increased wave energy. Distance from shore can also determine the proximity to river plumes, which can strongly influence nearshore water quality in the Great Lakes (Howell and Hobson, 2003). The water intakes at Goderich, Grand Bend, and Lambton were at progressively greater depths (4.9, 7.9, and 11.9 m, respectively), although the distances from shore were variable (488, 2530, 101 m, respectively). It was clear that nearshore TP was much higher and more variable compared to offshore data from other studies (Dobson 1971; Dolan et al. 1986; Beeton and Saylor 1995).

1.2 Land-use Adjacent to Study Areas

Three sections of shoreline adjacent to the mouths of three large rivers were selected for monitoring as indicative of situations where high relative levels of watershed-shoreline effects on nearshore water quality were considered likely. The areas monitored were considered to be sufficiently large to also capture areas representative of ambient nearshore conditions. Relatively few watersheds make up the majority of the drainage area to the lake despite the abundance of tributaries to the lake. The selected areas represent three of the five largest watersheds with a combined drainage area of approximately 7000 km^2. Site selection was a compromise between likely pollution contribution to the lake (based on drainage area) and field resources.

The watersheds of the Saugeen, Maitland and Bayfield Rivers share basic features. Forest cover is limited, 26, 14 and 10% in Saugeen, Maitland and Bayfield Rivers, respectively. The majority of land is classified as agricultural lands; 60, 82 and 88% in Saugeen, Maitland and Bayfield Rivers, respectively (OMNR Land Classification data; see Spectranalysis Inc. 1999). Livestock operations, predominately a mixture of cattle, hog and poultry are numerous. Cultivation of corn, wheat and soybean is widespread. A relatively low density of human pollution is spread over several towns, small communities and the rural lands. There are population centres over the study areas on the shores of the lake at Southampton-Port Elgin, Goderich and Bayfield. Goderich is the only community with a direct discharge of a waste water treatment plant to the lake. The discharge from the Southampton waste water treatment plant, however, is into the Saugeen River a short distance upstream from the lake (MOE 1990). There are additional discharges from waste water treatment plants to the rivers within the watersheds. Treatment of domestic waste by septic systems is widely used over the rural landscape of the three watersheds.

1.3 Design of Monitoring Study

The objective of the study was to describe water quality in the nearshore over a range of conditions including: time of year (season); range of weather conditions; range of discharge volumes from shoreline tributaries; and range of lake circulation conditions. Capturing nearshore conditions over the wide range of possible conditions was not possible at the time nor is it possible today. Consequently, a strategy was selected to target (time or location) collection of water quality data and ancillary environmental data that described the broadest range in conditions as practically as possible.

The variable discharge of water from tributaries along the shoreline was expected to be the largest source of variability in nearshore water quality. Consequently, knowledge of volume and quality of tributary discharge over the study period was considered essential. The major tributary discharging to the shoreline in each of the study areas was selected for through-time monitoring over the duration of the study. An active downstream station in the Provincial Water Quality Monitoring Network (PWQMN) was selected for intensified water quality sampling. In addition to regular sampling, event-based samples were targeted to provide information for more extreme conditions (e.g. heavy precipitation and snow melt). The Water Survey of Canada (Environment Canada) maintains flow gauges at the locations selected as intensive sites, which provides information on the volume of discharge through time. The intensive stations were located upriver from the lake in order to avoid “lake effect”, the periodic movement of lake water into the tributary.

There was a potential that inputs to the tributary between the intensive site and the lake might alter the quality of the water discharged to the lake from that monitored at the intensive site. Periodic water quality surveys were conducted in the tributary along a transect of sites from the river mouth to the intensive site. The surveys assessed the degree to which the results for the intensive site reflected quality of water discharged to the lake. The downstream spatial surveys were conducted at the same time as the in-lake nearshore surveys to provide a broader picture of water quality from the nearshore into the lower reaches of the major tributaries.

The nearshore zone for this study is operationally defined at the portion of the lake extending up to 5 km from the shoreline. It is anticipated that at any point in time the variation in physical, chemical and biological conditions across the wide band of water adjacent to the shores of the lake considered as the nearshore will be substantial. Quantifying the features of this variability through field sampling has long been a challenge in this environment (see GLISP 1986) and there are at present no routine or widely accepted approaches which can be used to provide robust spatial integration of water quality conditions in the nearshore.

Detailed appraisals of water quality for a limited number of points in time were accomplished by field-based surveys. The core of these multi-element surveys were detailed spatial data collected by tracking water quality sensors over the study area yielding datasets that could be used to "map" a suite of quality features over stretches of the nearshore. The information in the surface maps was augmented by collection of water samples for lab-based analysis at points over the field survey track. The more extensive field data for a limited range of parameters served as a guide to interpretation of the broader range of parameters in the lab-based data. Because of the potential for heterogeneity in physical and chemical conditions through the water column from the lake surface to the lake bed it was necessary to consider the nearshore as a 3-dimensional structure. A second suite of water quality sensors was lowered through the water column at points over the survey track to collect information on the depth-dependent changes in environmental conditions. The composite information collected over an individual survey (operationally limited to area covered in one day) provides snap-shots of conditions at a point in time. The spatial patterns are diagnostic of interactions between discharges from the shores of the lake with water quality in the nearshore. They also provide insight on features of lake circulation and how it interacts with water quality.

A shortcoming of the approach is that because results of the detailed surveys were limited to only four to five days and, while spread across as wide a seasonal range as practical (May to November), they do not capture the full range of conditions nor are they sufficient to allow a temporal integration of conditions over the study areas. At present, there appears to be no practical way to collect frequent through-time information using remote sensing which is of sufficient spatial detail to describe water quality in the nearshore.

Several types of through-time information were used to provide insight on variability in environmental conditions over the study period and to help place the results for the detailed field surveys in the context of likely normal and more extreme weather and lake circulation patterns. Instrumentation to measure water movement and temperature was deployed for the study period and provided information on frequency and timing of limnological events such as upwelling and information on norms and extremes with respect to water circulation over the nearshore. Weather data collected by Environment Canada and the local conservation authority were examined to provide context for the results of the detailed field surveys.

The field-based component of the study design was predicated on the assumption that a second phase of the study in which numerical (hydrodynamic and dispersion) modelling would be used to: 1) assess broader spatial-temporal pattern in lake circulation in the nearshore to provide a basis for integration of conditions over periods of time and locations, 2) assess dispersion and river discharge in the nearshore based on modelled behaviour of conservative substance (e.g. conductivity and nitrate) as a means to provide insight on the temporal and spatial scales at which river discharge likely affected nearshore water quality, and, 3) assess features of water quality and lake circulation at times of significant weather and limnological events. This work has focused on the Maitland River and the adjacent shoreline and is reported separately (Nettleton 2008 draft).

2 Materials and Methods

2.1 Study Areas

The nearshore areas adjacent to the mouths of three rivers, the Saugeen, Maitland, and Bayfield Rivers, respectively, discharging to the SE shores of Lake Huron, were investigated in this study (Figure 1). Water quality over a total of 29 km of shoreline was surveyed; 12, 12 and 5 km of shoreline adjacent to Saugeen, Maitland, and Bayfield River mouths, respectively. Data collection was limited to the lake area extending from the 3-m depth contour to 5 km offshore.

A tributary component of the study areas included the river reaches extending downstream from intensive river sites to the lake. The intensive stations on the Saugeen, Maitland, and Bayfield River were 12, 16, and 16 km upriver from the lake, respectively.

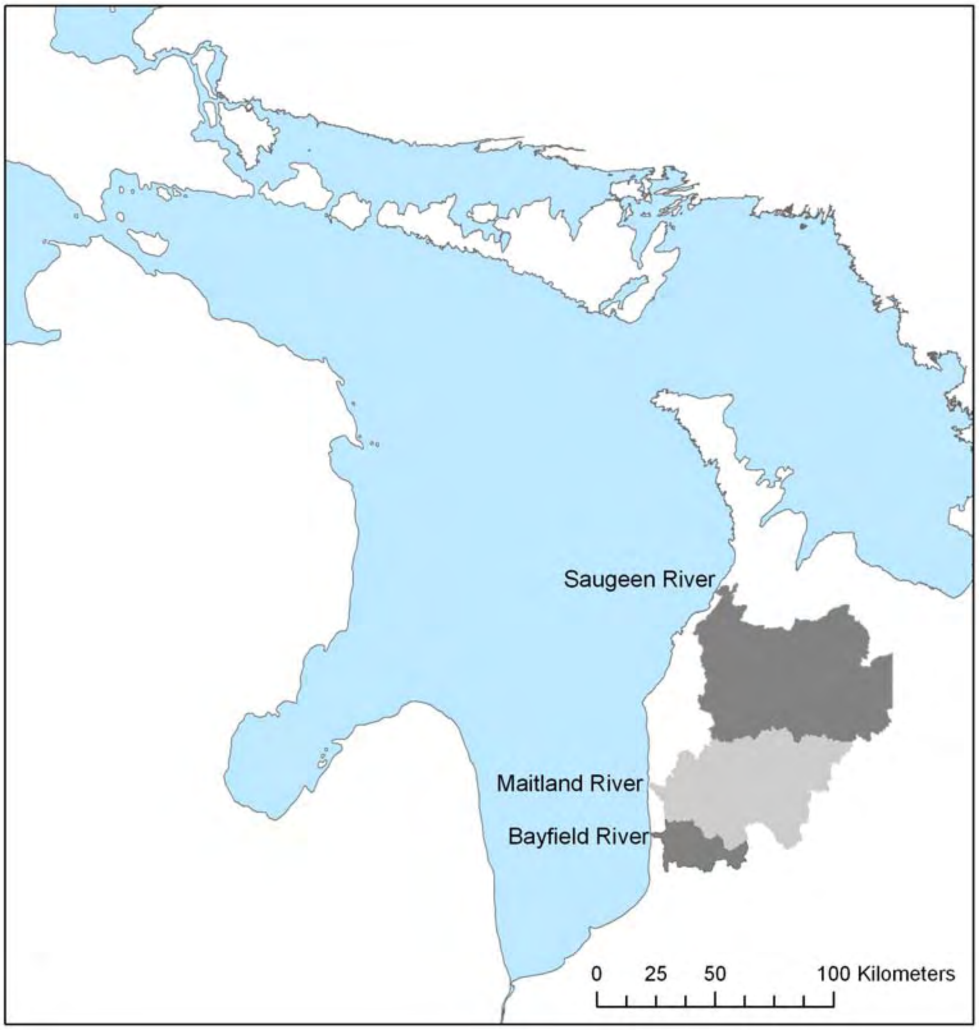

Figure 1: Location of the Saugeen, Maitland, and Bayfield Rivers. Grey regions are the watersheds of each river.

2.1.1 The Saugeen River Mouth Study Area

The northernmost study area was approximately centred on the mouth of the Saugeen River which discharges into Lake Huron at the town of Southampton in Bruce County. The extent of the nearshore study area is outlined in Figure 2 by the distribution of discrete water quality sampling stations. The most upriver sampling point in the Saugeen River is the intensive river monitoring station and is approximately 12 km upstream. At this point the river drains an area of 3960 km^2 (Environment Canada). From 1989 to 2003, the average annual discharge of the Saugeen River at the Environment Canada gauge at this location (02FC001) was 60 m^3s^{-1}, ranging from a low of 33 m^3s^{-1} (1999) to a high of 80 m^3s^{-1} (1996) for the period (HYDAT 2005). The remaining sample points in the river were used for periodic transect surveys in the river.

The towns of Southampton and Port Elgin (Municipality of Saugeen Shores) with a combined population of 11,388 (2001 Canadian census data) lie along the shores of the lake within the study area. The shoreline beaches in the communities contribute to the appreciable summer influx of people to the communities. Raw water intakes drawing from Lake Huron and supplying water treatment plants in both communities are within the study area. At the time of the study the Southampton intake was approximately 2 km SW of the Saugeen River Mouth and the Port Elgin Intake was approximately 7 km SSW of the river mouth. A sewage treatment plant in Southampton discharges treated effluent to the Saugeen River approximately 1.5 km upriver within the study area.

The mouth of the Saugeen River is developed as a small port and used as a marina and docking area for commercial fishing vessels. Discharge from the river is the predominant source of land-based drainage of water to the shoreline of the lake over the study area. There are several storm sewers discharging to the lake on the Southampton waterfront (see MOE 1990) but relatively few creeks and drains to the shoreline (see Figure 2).

A notable ecological feature within the study area is a seabird colony at Chantry Island.

The topography of the lakebed over the study area is heterogeneous. The area between Chantry Island and the mainland is relatively shallow with a soft lakebed and areas of macrophyte cover. Extending around much of the remaining perimeter of the Island are shoals. Slightly north and perpendicular to the Saugeen River mouth is a comparatively deep channel flanked to the north by a shore parallel shoal and deeper channel. South of the Chantry Island shoals, nearshore depth drops progressively from the shoreline to the outer areas of the study area. With the exception of the protected area SE of Chantry Island the lakebed consists predominately of a mixture of sand and hard materials (gravel, cobble, stone, and boulders).

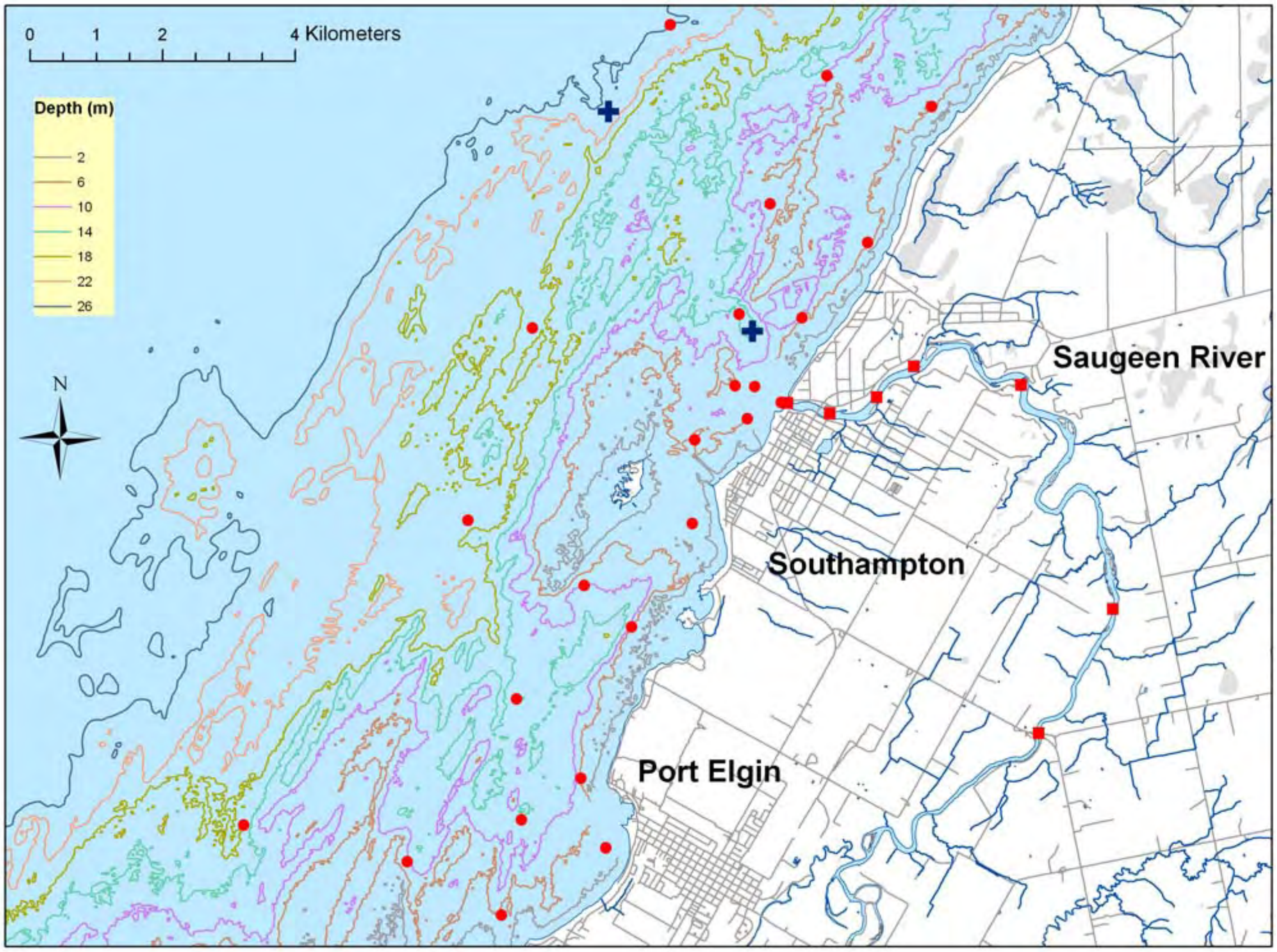

Figure 2: Map of the Saugeen River study area showing locations of discrete sampling stations (●) in the nearshore and river. Positions of instrumentation (temperature recorders and current meters) deployed over the study periods (+) are also shown. Chantry Island is located to the west of Southampton.

2.1.2 The Maitland River Mouth Study Area

The Maitland River discharges to Lake Huron at the town of Goderich in Huron County. The extent of the nearshore study area is outlined in Figure 3 by the distribution of discrete water quality sampling stations. The most upriver sampling point in the Maitland River is the intensive river monitoring station and is approximately 16 km upstream. At this point, the river drains an area of 2510 km^2 (Environment Canada). From 1989 to 2003, the average annual discharge at the Environment Canada gauge (02FE015) at this location on the Maitland River was 40 m^3s^{-1}, ranging from a low of 27 m^3s^{-1} in 1989 to a high of 58 m^3s^{-1} in 1992 for the period (HYDAT 2005). The remaining sample points in the river were used for periodic transect surveys in the river.

The town of Goderich with a population of 7600 (2001 Canadian census data) lies along the shores of the lake within the study area. The raw water intake for the Goderich water treatment plant is located approximately 1.2 km SSW of the Maitland River mouth within the study area. The Goderich sewage treatment plant discharges to the shore of the lake approximately 2.2 km south of the Maitland River mouth. Goderich is an industrial centre with a working harbour. Sub-surface salt mining and salt refining has long been a feature of Goderich. The well-protected harbour adjacent to, but not directly connected to the Maitland River serves as a port for vessel-based transport of salt products and other goods. The river is navigable for a short distance upriver with two marinas located near the river mouth.

There are three municipal beaches on the shores of Goderich and, like Southampton and Port Elgin, the area experiences an appreciable summer influx of people attributable in part to the water-related recreational opportunities. The north end of the study area extends to the edge of Points Farm Provincial Park on the shores of the lake.

The discharge from the Maitland River is the major source of land-based input of water to the shoreline of the lake over the study area. However, there are also several small watercourses that discharge to the shore of the lake (See Figure 3) as well as several storm sewers discharging to the lake on the Goderich waterfront (see MOE 1990). The discharge volumes are comparatively small relative to the Maitland River yet even small amounts of runoff may affect conditions in the immediate area of the discharge.

The topography of lakebed over the study area is comparatively simple to that of the Saugeen River study area. Nearshore depth drops slowly and progressively from the shoreline to the outer areas of the study area. The lakebed consists predominately of a mixture of sand and hard materials (gravel, cobble, stone, and boulders).

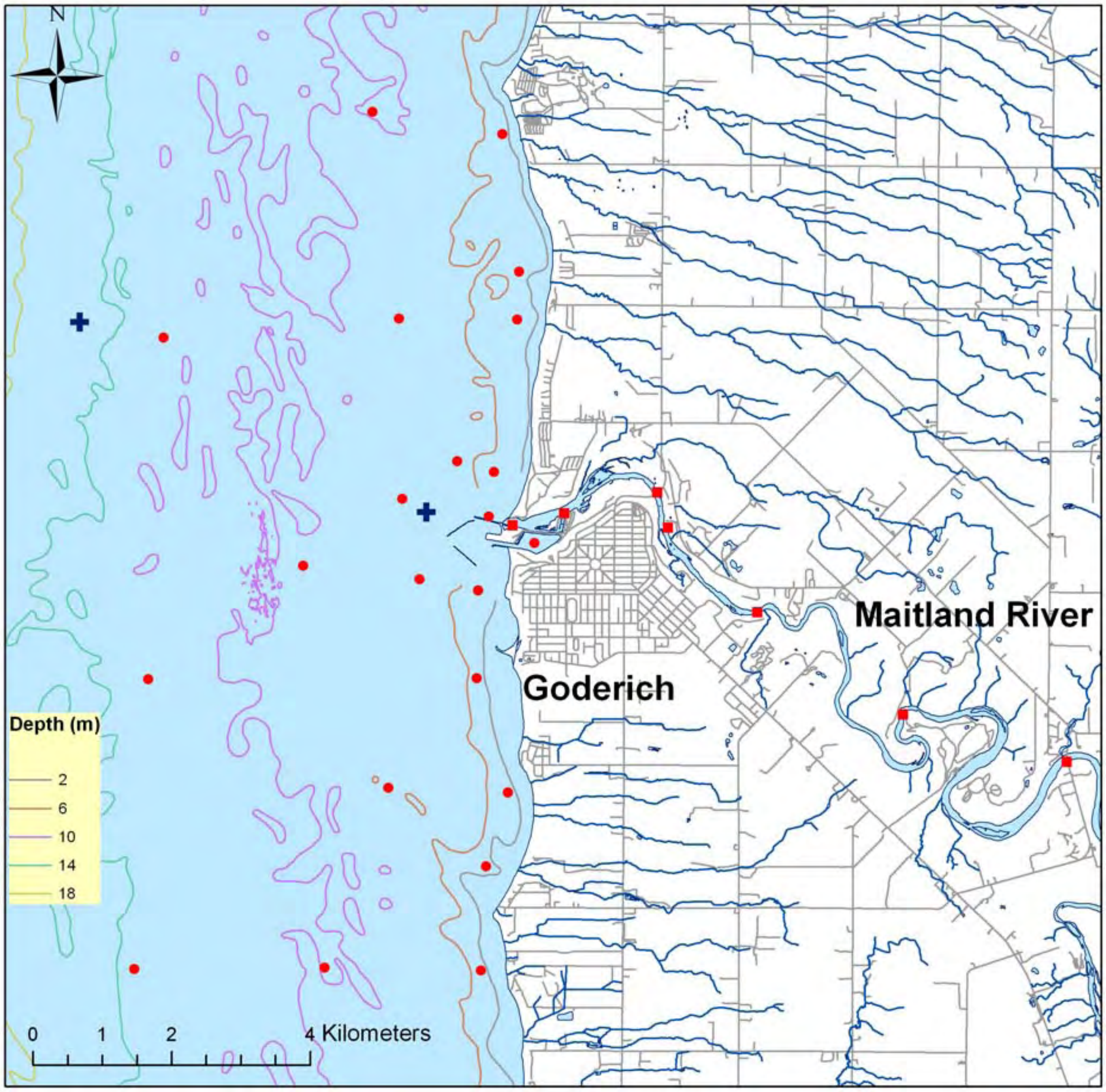

Figure 3: Map of the Maitland River study area showing locations of discrete sampling stations (●) in the nearshore and river. Positions of instrumentation (temperature recorders and current meters) deployed over the study periods (+) are also shown.

2.1.3 The Bayfield River Mouth Study Area

The Bayfield River is the southernmost of the three rivers, draining into Lake Huron at the community of Bayfield. The most upriver sampling point in the Bayfield River is the intensive river monitoring station and is approximately 16 km upstream (Figure 4). At this point the river drains an area of 466 km^2 (Environment Canada). From 1989 to 2003, the average annual discharge of the Bayfield River at the Environment Canada gauge at this location (02FF007) was 6.3 m^3s^{-1}, ranging from a low of 2.2 m^3s^{-1} in 1999 to a high of 9.7 m^3s^{-1} in 1996 for the period (HYDAT 2005). The remaining sample points in the river were used for periodic transect surveys in the river.

The community of Bayfield (within the Municipality of Bluewater) has a population of 909 (2001 Canadian census data) and lies along the shores of the lake within the study area. The two municipal beaches on the shores of Bayfield contribute to the water-related recreational opportunities in the area. The mouth of the Bayfield River is developed as a small port and used as a marina and docking area for commercial fishing vessels.

The discharge from the Bayfield River is the major source of land-based discharge of water to the shoreline of the lake over the study area. As with the Maitland River, there are a number of appreciably smaller watercourses that also discharge to the lake in this region (See Figure 4). Additionally, there are several storm sewers discharging to the lake on the Bayfield waterfront (see MOE 1990). At the time of the study Bayfield was not serviced by a communal sewage treatment plant.

The topography of lakebed over the study area is similar to that of the Maitland study area. Nearshore depth drops slowly and progressively from the shoreline to the outer areas of the study area. The lakebed consists predominately of a mixture of hard materials (gravel, stone, and boulders).

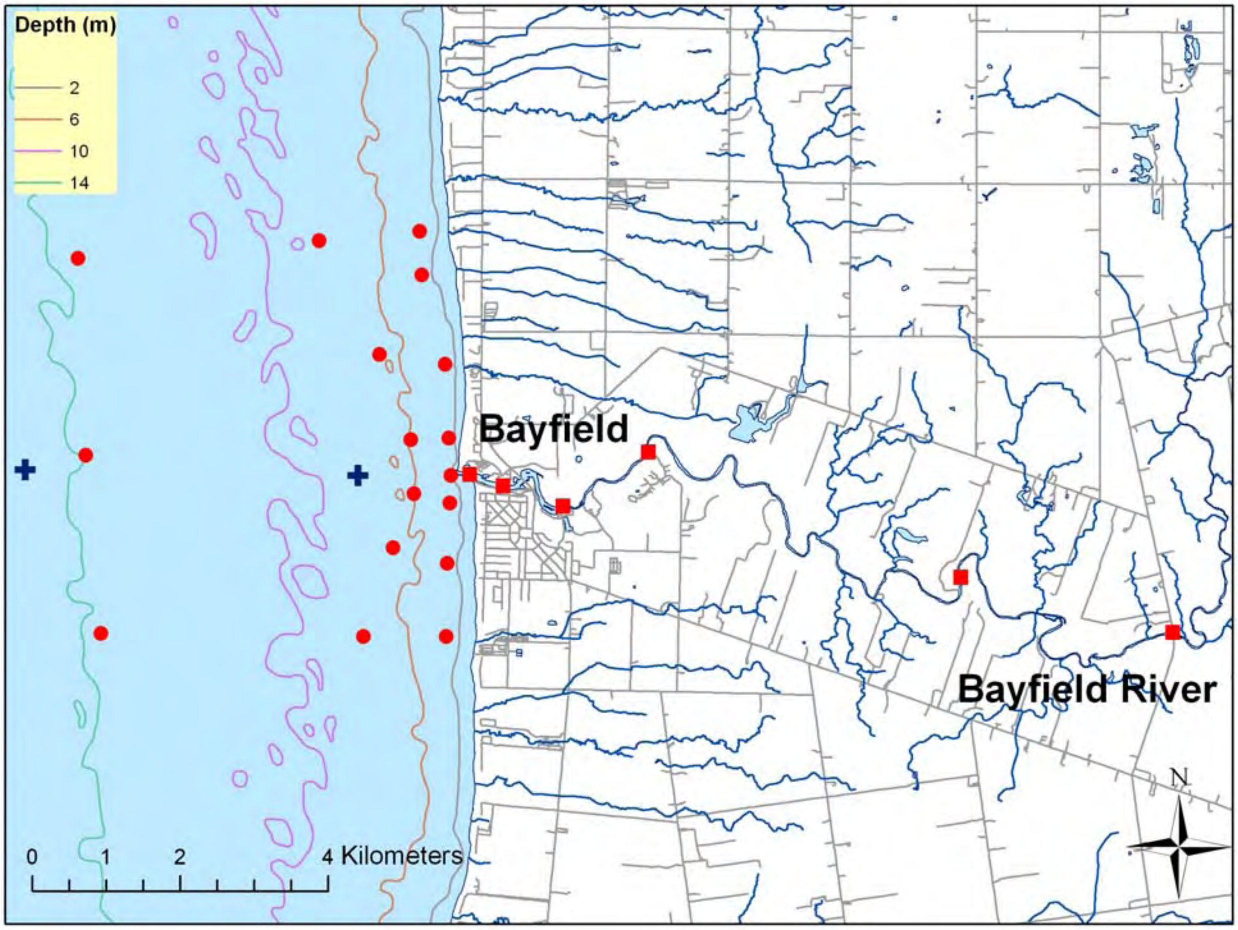

Figure 4: Map of the Bayfield River study area showing locations of discrete sampling stations (●) in the nearshore and river. Positions of instrumentation (temperature recorders and current meters) deployed over the study periods instrumentation (+) are also shown.

2.2 Nearshore Water Quality Surveys

Synoptic surveys of water quality were conducted along 5 to 12 km sections of shoreline in Lake Huron adjacent to mouths of the Saugeen, Maitland and Bayfield Rivers. Monitoring was conducted over a band of water approximately 5 km wide running parallel to the shore starting at a lake depth of approximately 3 m and moving offshore. Southampton Harbour and Goderich Harbour were included in the surveys.

Near-continuous field measurements of selected water quality parameters were made over survey tracks of the areas. Discrete water samples were collected for lab-based analysis of water quality parameters. Depth profiles of temperature and other features were taken at points over the survey tracks.

Water quality surveys were completed on four to five days spanning a seasonal range in 2003; once in spring, twice in summer (Summer 1 and 2 surveys), and twice in Fall (Fall 1 and 2 surveys). The first fall survey for the Maitland study area could not be completed because of poor weather. Study dates and areas of nearshore monitored are given in Table 1.

Table 1: Survey dates and surface area of lake examined for each of the nearshore water quality surveys.

	Saugeen River Area		Maitland River Area		Bayfield River Area	
Survey period	date	survey area (km^2)	date	survey area (km^2)	date	survey area (km^2)
Spring	May 28	77	May 27	77	May 22	42
Summer 1	July 9	62	July 8	84	July 7	36
Summer 2	July 29	48	July 31	82	Aug. 5	38
Fall 1	Sep. 17	72	cancelled		Sep. 18	38
Fall 2	Nov. 18	56	Nov. 23	64	Nov. 19	38

2.2.1 Water Sampling for Lab-based Analysis

Whole water samples for analysis of turbidity, suspended solids, conductivity, chloride, alkalinity, pH, TP, reactive phosphorus, nitrate+nitrite, ammonium+ammonia, kjeldahl nitrogen, nitrite, silicates, dissolved organic and inorganic carbon (DOC and DIC, respectively), and *E. coli* were collected at sites spanning the survey areas (see Figures 2-4). Water samples for analysis of the indicator *E. coli* were limited to shoreward sample points. Bacteriological samples were collected directly into sterile sample bottles from a depth of 1.0-1.5 m using a sampling pole. Other water samples were collected using a peristaltic pump and silicone tube, drawing water from a depth of approximately 1.5 m (near the position of the sensors used to collect in situ measurements). Samples were kept on ice after collection and transported to the Ontario Ministry of the Environment, Lab Services Branch (LSB) in Toronto within 24 hours.

2.2.2 Collection of Spatially Extensive Field Data

Near-continuous measurements of conductivity, temperature, beam attenuation coefficient, fluorescence of chlorophyll *a* and UV (hydrocarbon) fluorescence were made by tracking sensors over the survey areas. The probes were deployed at a depth of approximately 1.5 m below surface attached to bracket on the side of a survey vessel (MOE Monitor VI). Readings were logged at intervals of 5-10 m. Surveys were normally completed over a single day. On three occasions, surveys in the Southampton area were completed over two days due to logistical difficulty in completing work at the southern end of the study area. Only the results for the first day of survey are presented here due to the incompatibility of data among days because of changing lake circulation patterns.

Navigation of survey tracks (shore-parallel zig-zag) was accomplished using Hydro V6.0 in combination with a Trimble DSM GPS operating in real-time differential mode. Differential correction was achieved using a Trimble Navigation Beacon receiving corrections transmitted by United States and Canadian Coast Guard reference stations.

A suite of four generic measures of environmental conditions were used to describe patterns of variability over the area acting as surrogates for likely variability in other more specific parameters not readily measurable under field conditions. A transmissometer (Chelsea Instruments Alphatracka II) with a 0.25 m pathlength was used to measure beam attenuation at the 660 nm wavelength. A submersible fluorometer (Chelsea Instruments Aquatracka III) was used to measure fluorescence of chlorophyll *a* (peak excitation at 430 nm and emission at 685 nm). Temperature and conductivity were measured using an Ocean Sensors 300 probe. A hydrocarbon fluorometer (Chelsea Instruments UV-Aquatracka) was used to measure UV fluorescence of water (excitation at 239 nm and emission at 360 nm). Integration and logging of data were automated using a program written using Labview V4.0 running on a laptop computer. An Odum survey depth sounder reported depth at measurement points.

The majority of the water quality data were collected near the lake surface, however, limited amounts of depth profile data were collected to assess thermal stratification of the water column during the surveys. Temperature, turbidity, conductivity, and chlorophyll *a* fluorescence profiles were collected using a Chelsea Instruments Aquapack profiler.

Surface maps of water quality features based on field data, or information derived from the field data were produced by kriging analysis using Environmental Visualization System software (EVS). The geographic presentations of the data use 1:10 000 Ontario Basemaps (Ontario Ministry of Natural Resources) as the base map. ArcMap was used in the analysis and presentation of geographic information. Bathymetric information used in parts of the analysis was derived from NOAA digital mapping of 1m depth contours for Lake Huron.

2.2.3 Calibration of *in situ* measures

For each day of survey, chlorophyll *a* fluorescence was regressed against lab-based measurements of chlorophyll *a* from discrete samples collected concurrently with the track survey to provide predictive equations used to estimate chlorophyll *a* concentrations over the full survey track. The lab-based analysis of chlorophyll *a* was according to Ministry of the Environment (MOE) method RCHLO-E3169A. Water samples were filtered upon collection through nylon filters (1.2 µm pore) under diffuse light and immediately frozen on dry ice. The method includes a correction for phaeophytin, however, the minimum reporting level of 1 µg L^{-1} was too high to be of practical use given the low levels of chlorophyll *a* in many samples. Therefore, all data presented are for total chlorophyll *a*. The minimum reporting level for the method is 0.2 µg L^{-1}.

Beam attenuation coefficients (C_{660}) were calculated from the transmissometer data. Lab-determined estimates of suspended solids and turbidity for samples taken concurrently with transmissometer readings were used to empirically estimate solids and turbidity over the survey tracks from the beam attenuation data.

The strength of the calibration relationships, measured by the R^2 and visual inspection, were used to determine the suitability of the relationships to generate the derived variables of interest. On most dates, chlorophyll *a* vs. fluorescence, and turbidity vs. attenuation coefficient showed strong, linear relationships (Table 2). For the chlorophyll *a* relationships, two dates (September 18 at the Bayfield area, and July 31 at the Maitland area) resulted in relationships that were judged too weak to determine chlorophyll *a* from fluorescence. For turbidity vs. attenuation coefficient, only one survey date (November 19 at the Bayfield study area) produced a relationship that was too weak to estimate turbidity from attenuation coefficient in the spatial survey.

Table 2: Correlations between field measurements of chlorophyll *a* fluorescence and beam attenuation coefficient (660 nm) with results of laboratory analysis for extracted chlorophyll *a* (ug L^{-1}) and turbidity (FTU), respectively, for the nearshore surveys. The regressions were used to empirically estimate extracted chlorophyll *a* (ug L^{-1}) and turbidity (FTU) from field measurements, on a survey by survey basis. In some cases the relationships were considered too weak for extrapolation from the field data.

Study area	Survey period	chl *a* vs. fluorescence			turbidity vs. attenuation coefficient		
		equation	r^2	n	equation	r^2	n
Bayfield	Spring	5.0x + 0.16	0.99	13	1.5x - 0.45	0.97	17
	Summer 1	4.9x - 0.04	0.84	11	1.2x - 0.15	0.98	16
	Summer 2	4.8x + 0.01	0.93	12	1.6x - 0.32	0.99	17
	Fall 1	3.9x + 0.9	0.11	11	1.1x + 0.05	0.84	17
	Fall 2	11x - 0.16	0.98	7	2.5x - 2.47	0.70	16
Maitland	Spring	3.6x + 0.03	0.96	16	1.5x - 0.28	0.90	22
	Summer 1	3.3x + 0.08	0.98	15	1.5x - 0.33	0.89	21
	Summer 2	7.5x - 0.10	0.70	14	1.3x - 0.21	0.79	23
	Fall 2	2.6x + 0.56	0.93	12	2.5x - 3.39	0.94	21
Saugeen	Spring	3.7x + 0.05	0.89	16	1.5x - 0.45	0.99	24
	Summer 1	2.9x + 0.43	0.84	16	1.7x - 0.53	0.99	21
	Summer 2	3.6x + 0.25	0.81	10	1.7x - 0.54	0.99	17
	Fall 1	2.7x + 0.36	0.87	15	1.8x - 0.48	≥0.99	24
	Fall 2	3.0x + 0.43	0.89	14	2.5x - 3.02	0.96	21

To account for variability in the calibration of the field conductivity sensor, the absolute values of field-measured conductivity over survey tracks were adjusted to correspond with lab-based measurements on discrete water samples using linear regression between paired field and lab measurements for each day of survey.

The field track data were evaluated against the more diverse lab-based data for discrete water samples to assess the use of the continuous shipboard measures as surrogates for parameters not measured in the field.

2.3 River Monitoring

A downstream station on each of the Saugeen, Maitland and Bayfield was selected for intensive water quality monitoring for the duration of the study. Near-surface water samples for physio-chemical analysis were collected at intervals of approximately 1-3 weeks and including the days in which surveys were conducted over the adjacent nearshore. Whole water samples for analysis of turbidity, suspended solids, conductivity, chloride, alkalinity, pH, TP, reactive phosphorus, nitrate+nitrite, ammonium+ammonia, kjeldahl nitrogen, nitrite, silicates, dissolved organic and inorganic carbon (DOC and DIC, respectively), and *E. coli* were collected. The sites correspond with existing PWQMN stations and sites of flow gauges maintained by Environment Canada (gauge numbers 02FC001, 02FE015, and 02FF007 for the Saugeen, Maitland, and Bayfield rivers, respectively) and precipitation gauges maintained by local conservation authorities (Saugeen Valley, Maitland Valley and Ausable-Bayfield CAs). Hourly river discharge and daily precipitation data were obtained from Environment Canada and respective CA's. Additional water quality sampling was completed at the intensive sites (existing PWQMN sites) by CA's in partnership with the MOE Provincial Water Quality Monitoring Network. These data have been added to the water quality dataset for the intensive sites.

Additionally, water quality sampling was conducted in the downstream river concurrently with each of the nearshore surveys at the adjacent river mouth (see Figures 2-4). Whole water samples were collected for chemical/physical analysis as described for the intensive station with the exception that additional samples were collected for chlorophyll *a* analysis (analysis as described above).

2.4 Operational Designation of Sub-regions and Watershed-affected Areas Within the Nearshore

The nearshore was operationally divided into two sub-regions based on distance from the shoreline to assist in spatial comparisons of data over the larger area. The area from the shoreline to 4 km offshore was designated as the 'proximate' region. The most offshore portion of the study area (>4 km offshore) was defined as the "distant" region. The "distant" region is considered a transition zone between the nearshore and offshore of the open lake. Results for the distant region were used as a surrogate for offshore conditions and a basis of comparison with the more watershed–affected conditions in the areas closer to shore (proximate region).

For each day of survey the nearshore study area was further divided into segments reflecting the spatial extent of effects of tributary discharge or shoreline interaction on environmental conditions as inferred from two water quality-based indices.

Area of Nearshore Affected by River Discharge Plume

The area over which the discharge plume of the major rivers (Saugeen, Maitland and Bayfield Rivers) was less than 90% diluted relative to distant area lake water was used as an indicator of the area affected by the discharge plume of the major river in each area. Using conductivity as a conservative tracer of river discharge, the concentration boundary of the plume-affected area was calculated as:

$$\text{Boundary} = 0.1(\mathrm{R}c-\mathrm{O}c) + \mathrm{O}c$$

Where R*c* is the conductivity of river water and O*c* is the conductivity of the distant area of the nearshore. For example, if the conductivities of the distant area and the river mouth were 200 and 500 $\mu S\ cm^{-1}$, respectively, the boundary for the plume-affected area would be 230 $\mu S\ cm^{-1}$. The area over the interpolated surface with conductivity greater than 230 $\mu S\ cm^{-1}$ would comprise the estimate of the plume-affected area. An assumption in the approach is that the major rivers are the primary contributors to elevated conductivity. While the calculated areas in many cases primarily reflect the influence of the major river, in other instances, there are additional shore-based sources contributing to elevated conductivity and the affected areas contribute to the calculated areas. Plume-affected areas calculated in this manner are not concentration-dependent, so allow comparisons of plume size across different parameters, dates, and areas.

Area of Tributary and Shoreline Influence

The area of the nearshore affected by tributary and shoreline inputs to the lake was operationally estimated for each survey by determining the surface area in the proximate region where levels of chlorophyll *a*, NO_2+NO_3, and turbidity were 2X or more than in the distant region.

The approach assumes that the conditions in the distant region reflect those of the offshore. For the dates where offshore data are available (see below), this appears to be reasonable assumption, with some exceptions. In cases where the levels in the distant region are elevated compared to the offshore, the calculation will be an underestimate of area directly affected the shoreline.

Both discharges to the shoreline (e.g. tributary discharge and surface runoff) and shoreline processes (e.g. shoreline erosion) effect environmental conditions in nearshore and will contribute to the disparity between proximate and distant regions.

2.5 Deployed Field Instrumentation

Temperature

Continuous temperature recorders were deployed at multiple depths from mid-May to late November at sites in the Saugeen and Maitland River study areas (See Figures 2 and 3). The lake temperature data collected in the Maitland River study areas is used as representative of conditions in the Bayfield River study area. At both study areas, strings of temperature recorders (Onset Stowaway Tidbit Temperature Loggers) were deployed at an onshore (approximately 1 km from shore) and an offshore site; 4.7 and 6.7 km offshore at the Saugeen and Maitland River areas, respectively. Temperature recorders were also deployed at multiple locations in each river. Data for sensors deployed approximately 0.5 km upstream of the river mouth are reported here.

Lake currents

Profiling current meters were deployed at onshore and offshore sites in each of the study areas for the duration of the study (see Figures 2, 3 & 4). Bottom-moored acoustic Doppler current profilers (ADCP- RDI Workhorse 600 kHz) recording at 30-minute intervals were used to assess lake circulation. At the Saugeen and Maitland study areas, the ADCPs were deployed in the vicinity of the thermistor strings. In the Bayfield River area ADCPs were moored approximately 1.3 km from the shore and another 6 km from shore. Current data are reported here for near-surface currents in the band of water approximately 3 to 5 m from the lake surface (and reflective of conditions in the water layer used primarily for water quality sampling). Additional ADCPs were deployed in the Saugeen River area but are not reported here.

Damage to the onshore Bayfield ADCP resulted in most of the data being lost with the exception of portions of spring and fall data.

Lake currents were resolved into shore-parallel (alongshore) and shore-perpendicular (cross-shore) vectors using:

$u_i = S_i \cos(\varphi - \theta)$
and:
$v_i = S_i \sin(\varphi - \theta)$

where u and v are the alongshore and cross-shore current vectors (cm s^{-1}), respectively. S_i is the total current speed, while θ and φ are the current direction and the shoreline azimuth angles, respectively. The shoreline azimuth angles at the river mouths of the Maitland, Bayfield and Saugeen Rivers are 3°, 177° and 33°, respectively.

2.6 Offshore water quality

Selected offshore water quality data, collected by Environment Canada during 2002 and 2004 and by the United States Environmental Protection Agency (USEPA) in 2003, were compiled to compare with nearshore water quality data collected in this study. Data for four Environment Canada, and nine (USEPA) offshore stations in southern Lake Huron, ranging from 20 to 60 km offshore were used in the comparisons.

3 Results

3.1 Quality and Quantity of Discharge from Saugeen, Maitland and Bayfield Rivers to Lake Huron

3.1.1 Discharge Volumes in 2003

Discharge of all three rivers to Lake Huron followed a similar pattern, with a spring increase from February to June and a large peak in discharge occurring from mid-March to early April. From approximately June to October, discharge was greatly reduced. A second phase of increased discharge, though smaller than the spring peak, occurred from October until the end of the year.

Data collected by Environment Canada at stream flow monitoring gauges on each of the rivers at the intensive water quality monitoring sites were used to infer discharge to Lake Huron. For the study year, mean daily discharge of the Saugeen River at the gauge site was 59 m^3s^{-1} (Figure 5). Minimum mean daily discharge was 10 m^3s^{-1}, occurring on September 12th and 13th, while maximum daily discharge, recorded on March 22, was 437 m^3s^{-1}. The Maitland River mean daily discharge for the study year was 42 m^3s^{-1} (Figure 6). There was a 134-fold difference between minimum mean daily discharge, which was 2.2 m^3s^{-1} (Sept.12-Sept. 14), and the maximum mean daily discharge of 312 m^3s^{-1} (March 22). By far the smallest of the three rivers, the Bayfield River's mean daily discharge for 2003 was 6.7 m^3s^{-1} (Figure 7). The Bayfield River had the most variability in discharge; minimum mean daily discharge was 0.17 m^3s^{-1} on September 11, while the maximum mean daily discharge was 81 m^3s^{-1} (on March 21), a 476-fold difference between the two.

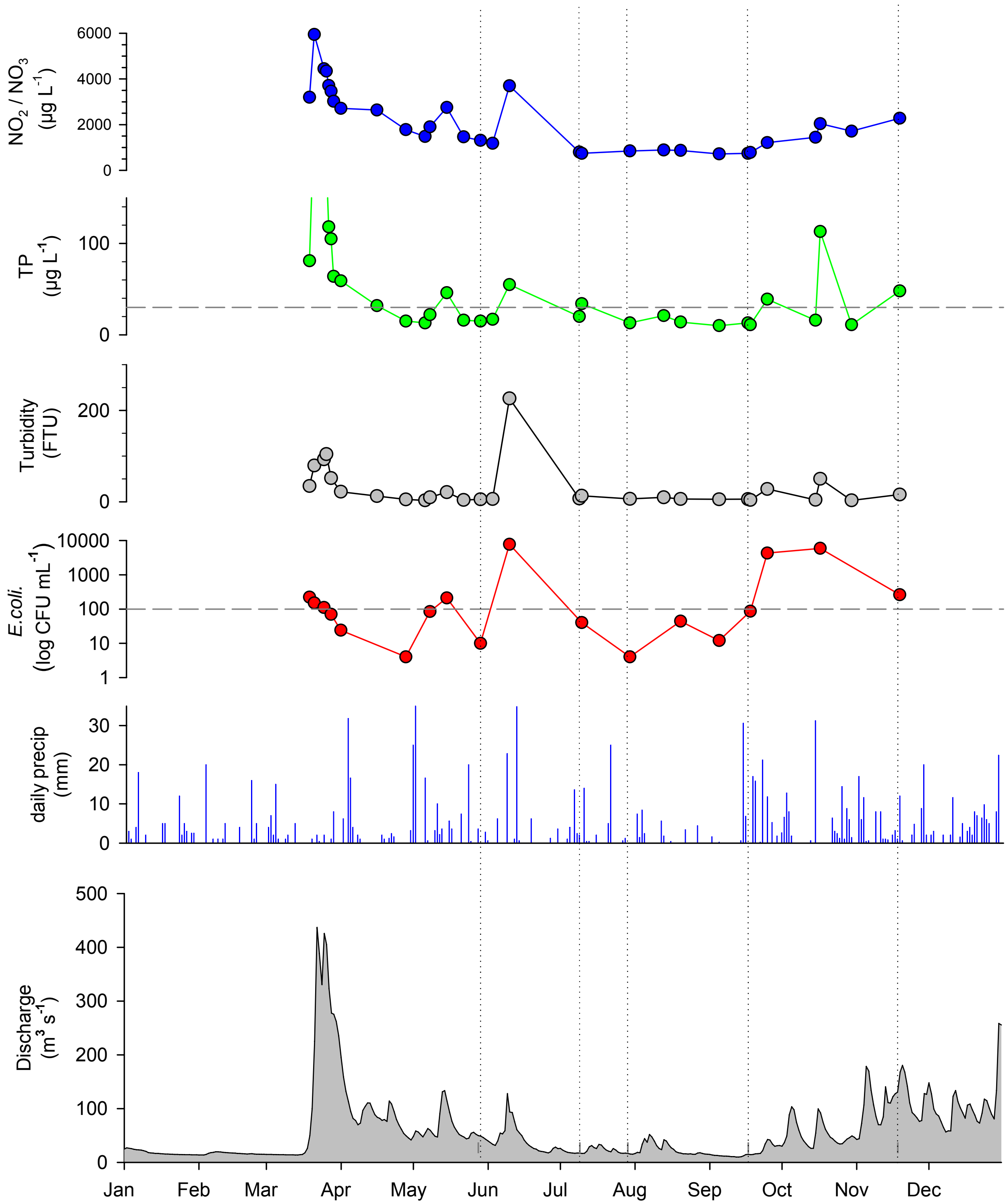

Figure 5: Nitrate plus nitrite (NO2+NO3) concentration as nitrogen, total phosphorus (TP) concentration, turbidity, *E. coli* concentration, daily precipitation, and daily river discharge (EC 02FC001) at the intensive monitoring station at the Saugeen River for 2003. TP concentration values of 249, 178, and 183 µg L^{-1} occurring on March 20, 24, and 25th were omitted to limit axis scale. Dotted vertical lines indicate dates that nearshore surveys were conducted. Dashed horizontal lines indicate the Provincial Water Quality Objective for TP and *E. coli*.

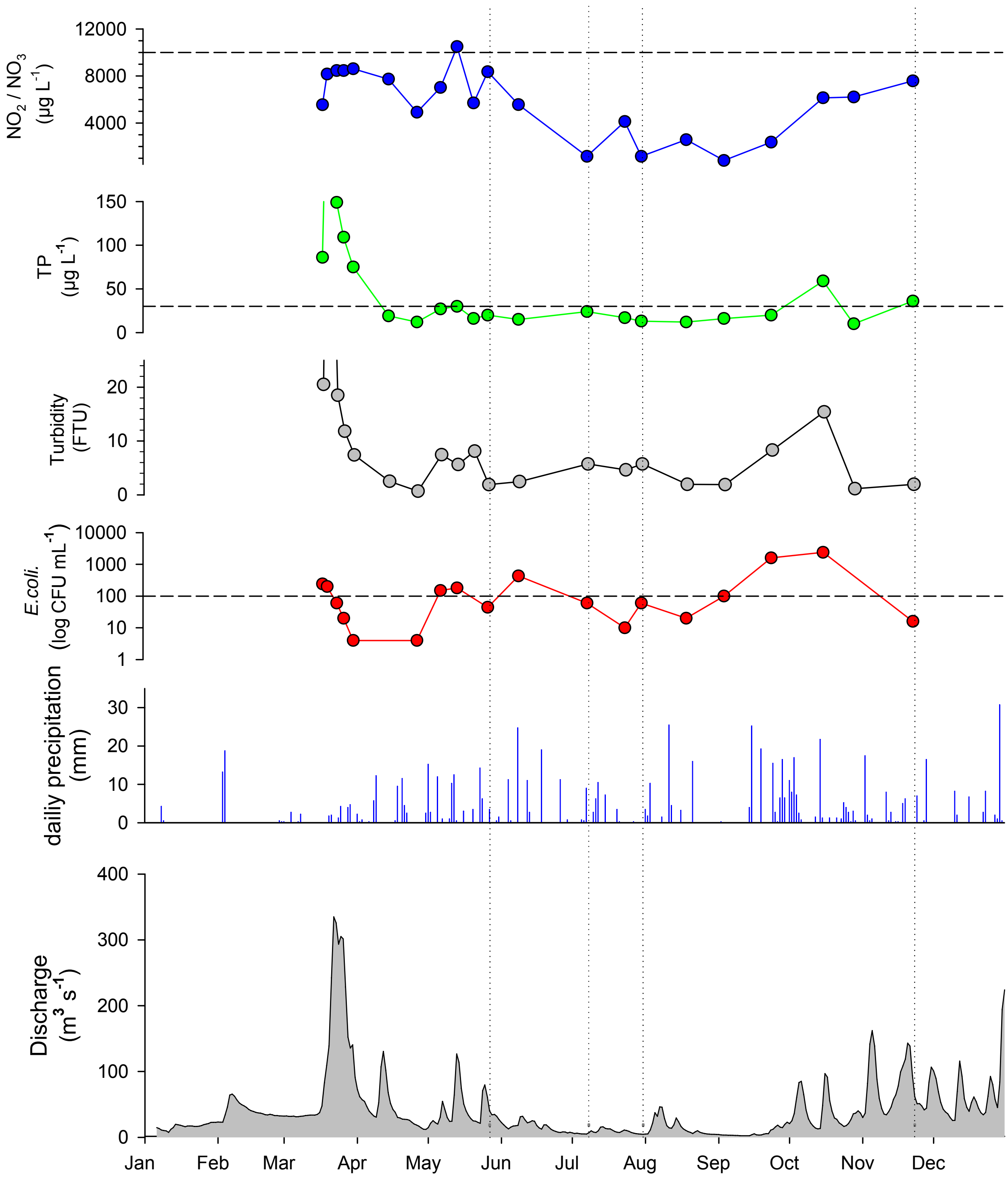

Figure 6: Nitrate plus nitrite (NO_2+NO_3) concentration as nitrogen, total phosphorus (TP) concentration, turbidity, *E. coli* concentration, daily precipitation, and daily river discharge (EC 02FE015) at the intensive monitoring station at the Maitland River for 2003. A TP concentration value of 315 µg L^{-1}, and a turbidity value of 100 FTU, both occurring on March 20 were omitted to limit axis scale. Dotted vertical lines indicate dates spatial surveys were conducted. Dashed horizontal lines indicate the Provincial Water Quality Objective for TP and *E. coli.*

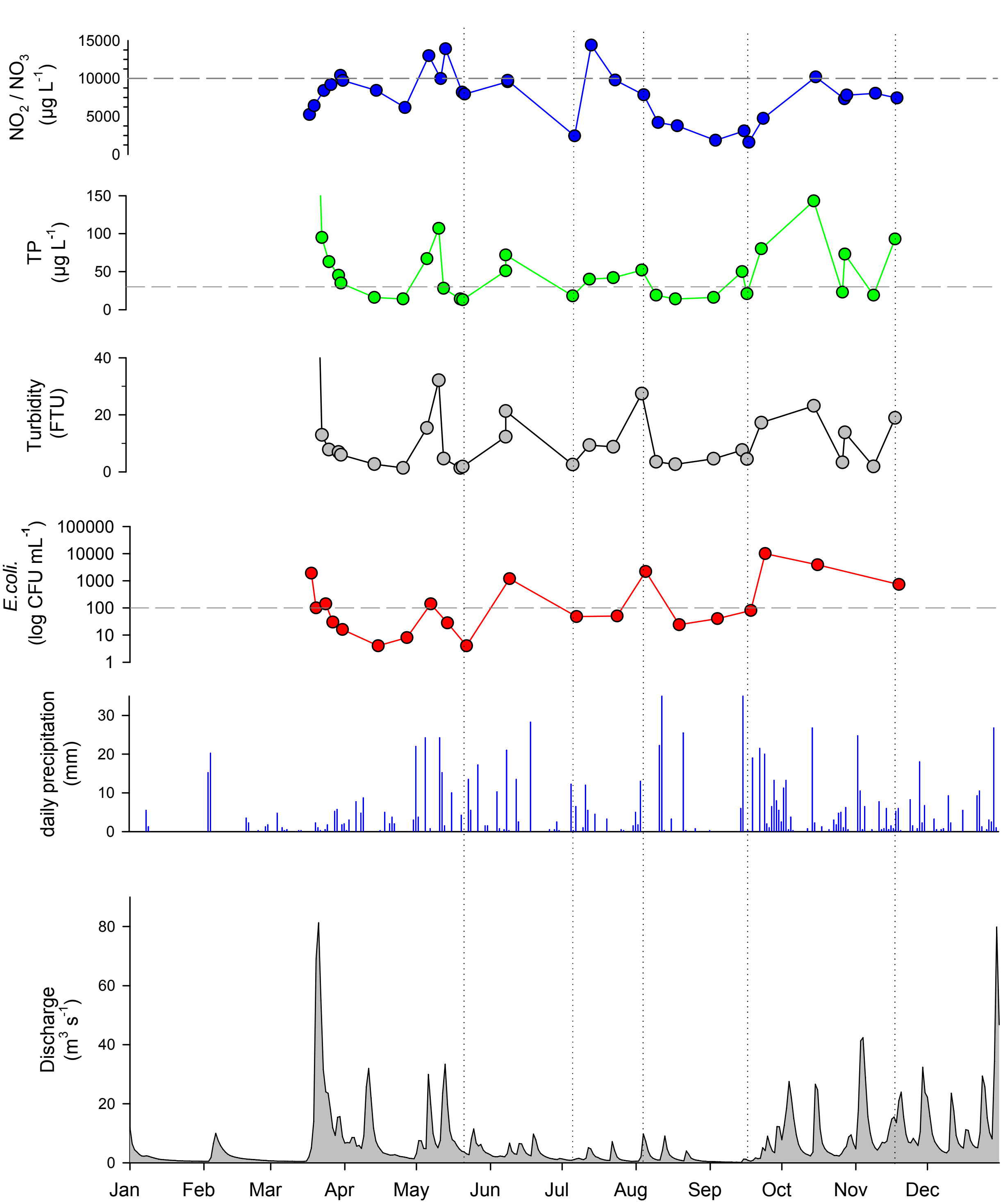

Figure 7: Nitrate plus nitrite (NO_2+NO_3) concentration, total phosphorus (TP) concentration, turbidity, *E. coli* concentration, daily precipitation, and daily river discharge (EC 02FF007) at the intensive monitoring station at the Bayfield River for 2003. TP concentration values of 393 and 486 µg L^{-1}, and turbidity values of 101 and 162 FTU, both occurring on March 18 and 20, were omitted to limit axis scale. Dotted vertical lines indicate dates that spatial surveys were conducted. Dashed horizontal lines indicate the Provincial Water Quality Objective for TP and *E. coli* concentration.

3.1.2 Water Quality in 2003 at the Intensive Monitoring Stations

Turbidity, and the concentrations of NO_2+NO_3 and TP in each river, fluctuated by an order of magnitude or more for the sampled period (Table 3). *E. coli* concentrations were even more variable, with fluctuations of almost four orders of magnitude for the period.

Table 3: Summary of water quality measures over the 2003 study period at the intensive monitoring stations on the Saugeen, Maitland and Bayfield Rivers.

Measure	River	median	mean	min	max	variance
NO_2+NO_3	Saugeen	1970	2256	718	5940	1.7×10^6
(µg L^{-1} N)	Maitland	6140	5773	824	10500	7.5×10^6
	Bayfield	7985	7694	1610	14400	1.1×10^7
TN	Saugeen	2825	2996	1086	7550	2.4×10^6
(µg L^{-1})	Maitland	6880	6636	1484	11410	8.2×10^6
	Bayfield	8550	8384	2160	15070	1.1×10^7
TP	Saugeen	37	60	10	249	4.0×10^3
(µg L^{-1})	Maitland	20	51	10	315	5.7×10^3
	Bayfield	44	73	14	486	1.2×10^4
Turbidity	Saugeen	9.5	29	2.9	226	2.1×10^3
(FTU)	Maitland	5.7	11	0.7	100	4.3×10^2
	Bayfield	7.7	18	1.4	162	1.0×10^3
*E. coli**	Saugeen	85	1068	4	7700	5.1×10^6
(CFU 100 mL^{-1})	Maitland	60	311	4	2400	3.9×10^5
	Bayfield	65	1032	4	10000	5.2×10^6

* data have not been log transformed.

Concentrations of NO_2+NO_3, TP, *E. coli,* and turbidity levels increased rapidly following peak discharge in March at each of the intensive monitoring stations (Figures 5, 6 & 7). From April to September levels of these parameters fluctuated. From September to November, an increase in TP, turbidity, and *E. coli* occurred in all the rivers, coinciding with the increased fall river discharge. In September, NO_2+NO_3 increased substantially in the Bayfield and Maitland rivers, but only slightly in the Saugeen River. In contrast to the other measures, NO_2+NO_3 did not decrease after the initial fall rise in discharge, to the end of the study period.

NO_2+NO_3

The Maitland and Bayfield Rivers showed similar patterns in fluctuations of NO_2+NO_3 concentrations over the study period (Figures 6 & 7), though the Bayfield River had the highest and most variable NO_2+NO_3 concentrations. NO_2+NO_3 concentrations in the Bayfield River ranged from 1610 to 14400 µg L^{-1}, with a median concentration of 7985 µg L^{-1}. NO_2+NO_3 concentrations in the Bayfield River exceeded the Ontario Safe Drinking Water (OSDW) Act (O. Reg. 169/03) levels of 10000 µg L^{-1} on 5 sampling dates and the Canadian Council of Ministers of the Environment (CCME) guideline of 2940 µg L^{-1} for nitrate on 27 of 30 sampling dates. For the Maitland River, the median NO_2+NO_3 concentration over the study period was 6140 µg L^{-1}, ranging from 824 to 10500 µg L^{-1}. Maitland River NO_2+NO_3 concentrations exceeded the OSDW levels on one sampling date, and the CCME guideline concentration on 16 of the 21 sampling dates. The Saugeen River had the lowest median NO_2+NO_3 concentration of 1970 µg L^{-1}, ranging from 718 to 5940 µg L^{-1}. This exceeded the CCME guideline concentration on 10 of the 34 sampling dates, but never exceeded the OSDW levels.

TN

Total nitrogen concentrations in each of the rivers were very similar in range and variability to NO_2+NO_3 concentrations. TN was calculated as the sum of NO_2, NO_3, NH_4^+ and total organic nitrogen. A large portion of the N in the study rivers could be accounted for by NO_2+NO_3. In the Saugeen River, NO_2+NO_3 was, on average, 72% of the TN concentration, ranging from 49% to 92% of TN. In the Maitland River, 83% of TN was on average NO_2+NO_3, ranging from 56% to 92% of TN. The portion of TN comprised of NO_2+NO_3 in the Bayfield River was even higher, ranging from 73% to 96%, with an average of 90% of the TN as NO_2+NO_3.

TP

TP concentrations in the rivers were more variable than were NO_2+NO_3 concentrations, though all three rivers showed generally the same patterns of change throughout the study period. Very high concentrations of TP occurred in late March to early April, coinciding with the spring peak in discharge, with a second smaller peak, occurring with the fall increase in discharge. The Bayfield River had the highest spring peak concentration of TP, and the highest median TP concentration. It also had the most variable TP concentration of the three rivers. Median TP concentration in the Bayfield River was 44 µg L^{-1}; exceeding the interim Provincial Water Quality Objective (PWQO) for streams and rivers of 30 µg L^{-1} on 18 of the 30 sample dates. The Saugeen River, with median TP concentration intermediate to the other rivers (37 µg L^{-1}), exceeded the interim PWQO on 19 of the 34 sampling dates. Median TP concentration in the Maitland River was 20 µg L^{-1}, exceeding the interim PWQO on 7 of the 21 sampling dates.

Turbidity

Turbidity fluctuations followed a similar pattern as TP concentration, with a large spring peak in turbidity, and a smaller one in fall. Median turbidity of the Saugeen River was the highest of the three rivers at 9.5 FTU, ranging from 3 to 226 FTU, while median turbidity of the Bayfield River was 7.7 FTU (1.4 to 162 FTU). The Maitland River had the lowest median turbidity of 5.7 FTU, but, like the other rivers, had a large range in turbidity, from 0.7 to 100 FTU.

E. coli

As noted, *E. coli* concentrations were highly variable. Concentrations ranged from close to the lower detection limit in each river, to a maximum over the study period of 2400 CFU 100 mL^{-1} for the Maitland River, 7700 CFU 100 mL^{-1} for the Saugeen River, and 10000 CFU 100 mL^{-1} for the Bayfield River. Median *E. coli* concentrations were similar in all of the rivers; 60 CFU 100 mL^{-1} at the Maitland River, 65 CFU 100 mL^{-1} at the Bayfield River, and 85 CFU 100 mL^{-1} at the Saugeen River. In both the Maitland and Saugeen rivers, *E. coli* concentrations exceeded the PWQO (100 CFU 100 mL^{-1}) on 7 of 18 sampling dates. At the Bayfield River, the PWQO for *E. coli* was exceeded on 8 of 20 sampling dates. While highly variable, the temporal pattern in *E. coli* concentration over the sampling period was similar in all the rivers. This suggests that large-scale phenomena, such as precipitation, were important in fluctuations of *E. coli* concentration.

3.1.3 Variability in River Water Quality Downstream from the Intensive Monitoring Station to Lake Huron

During each of the nearshore water quality surveys additional tributary sampling was conducted along the Saugeen, Maitland and Bayfield Rivers from the intensive river station to Lake Huron to investigate variability in conditions along the river course. One purpose of the sampling was to determine if conditions observed at the intensive station were reflective of the river discharge to the lake recognizing that there were additional loadings and disturbance of the river below the intensive station. The periodic movement of lake water into the “lake-affected” portion of the lower river further contributes to variability in physical and chemical conditions the lower river.

NO_2+NO_3

NO_2+NO_3 concentrations usually decreased from the intensive stations to the outflow at each of the rivers (Figures 8,9 & 10). Changes in NO_2+NO_3 along the length of the lower Saugeen River were small compared to the changes seen in the Bayfield or Maitland rivers. The greatest proportionate change in NO_2+NO_3 concentration from the most upstream station to the river outflow in the Maitland River was observed on the first summer survey (July 8), with a decrease of 237 µg L^{-1} (20%) in NO_2+NO_3 concentration. On other survey dates there were minor changes in NO_2+NO_3 concentration in the Maitland River. In the Bayfield River, NO_2+NO_3 concentrations decreased from upstream to outflow on four of the five sampling dates. On July 7 and August 5, appreciable decreases in NO_2+NO_3 in both magnitude and proportion were observed. There was a 940 µg L^{-1} (39%) drop in NO_2+NO_3 concentration from the most upstream station to the outflow on July 7, while on August 5, there was a 990 µg L^{-1} (13%) drop. The majority of NO_2+NO_3 loss on these dates occurred very close to the river mouth likely reflecting dilution by influx of lake water.

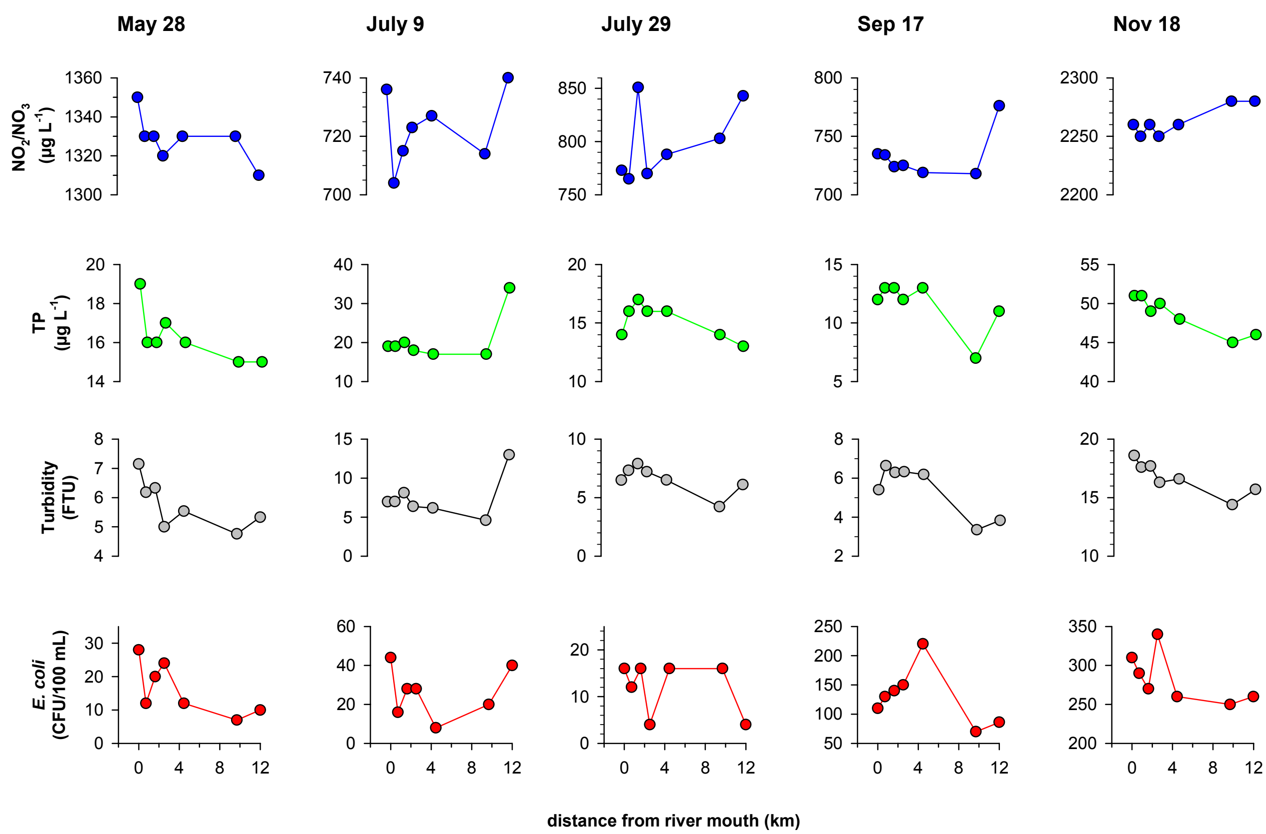

Figure 8: Water quality measures at stations extending from the intensive monitoring station to the mouth of the Saugeen River on each of the nearshore survey dates (see Table 2).

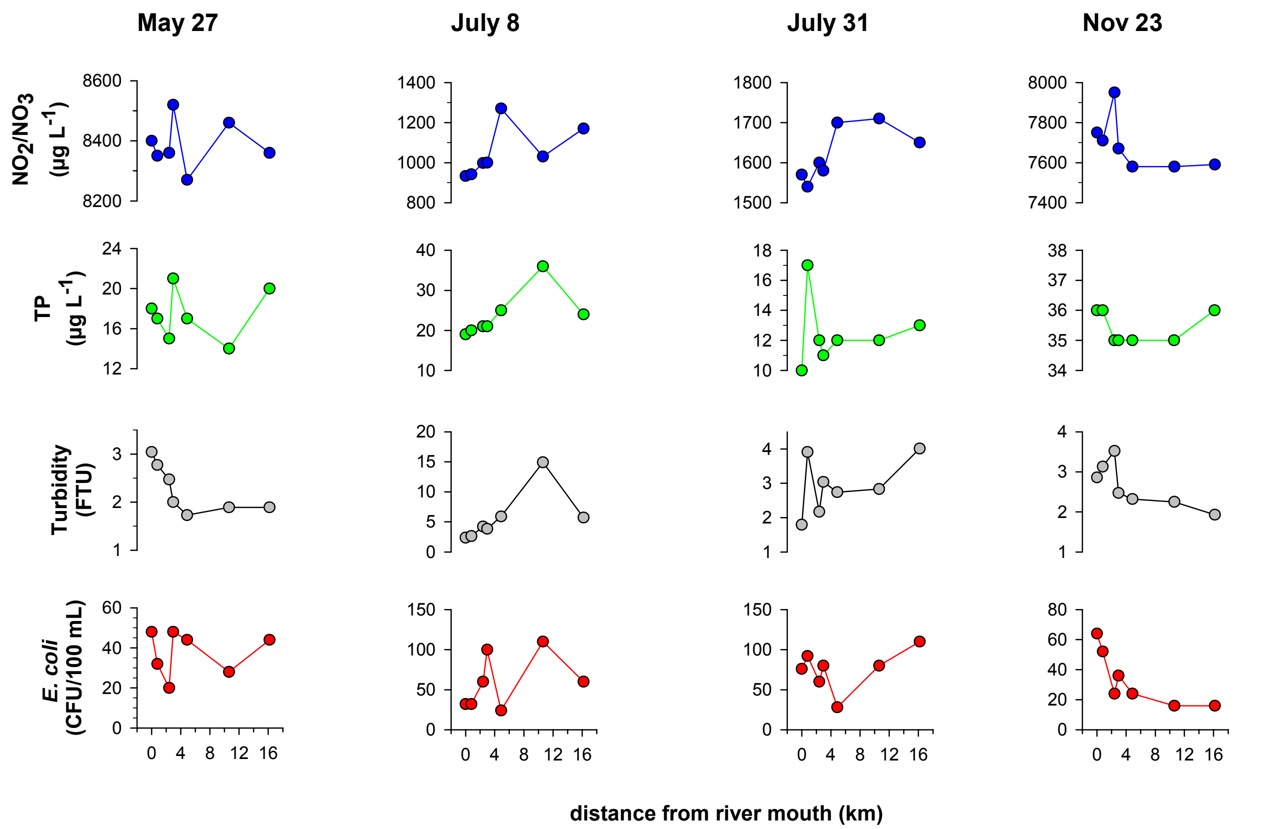

Figure 9: Water quality measures at stations extending from the intensive monitoring station to the mouth of the Maitland River on each of the nearshore survey dates.

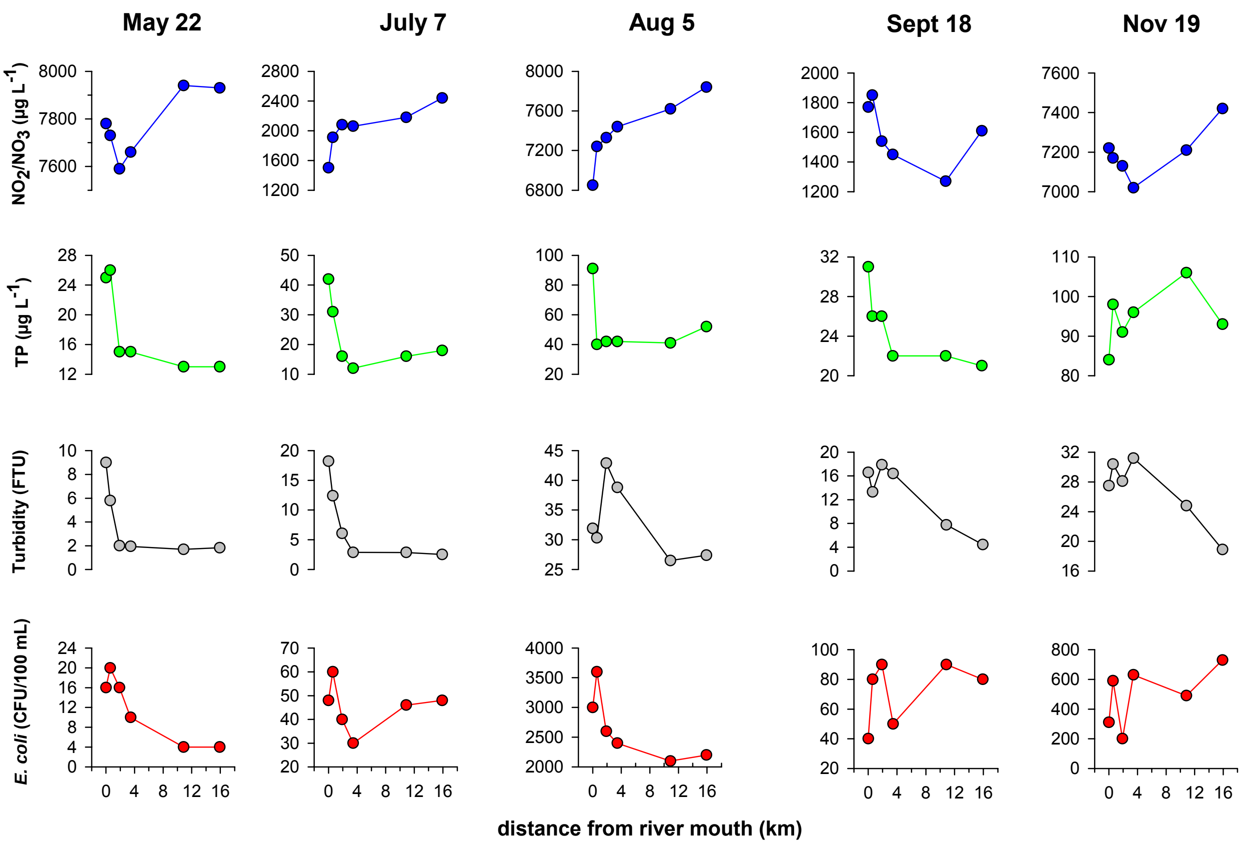

Figure10: Water quality measures at stations ranging from the intensive monitoring station to the mouth of the Bayfield River on each of the nearshore survey dates.

Turbidity

Unlike NO_2+NO_3, turbidity often increased downstream along the rivers. This was especially apparent at the Bayfield River, where turbidity increased from the upstream to downstream on all sampling dates. On May 22 and July 7, turbidity showed a pattern of a very rapid increase just at the river mouth, increasing by approximately 4 and 6- fold at the last few stations, respectively. On September 18 and November 9, turbidity increased more gradually from the upstream to the downstream stations.

TP

Like turbidity, TP rarely decreased between the intensive station and the river mouth, and sometimes showed dramatic increases in concentration close to the river mouth. In the Saugeen River, TP showed small increases (1 to 5 µg L^{-1}) between the most upstream compared with the most downstream station. The exception to this was the first summer survey (July 9), where TP concentration showed a relatively large drop of 15 µg L^{-1} (44%) between the PWQMN station and the river mouth. In the Maitland River, TP concentration changed little between the PWQMN station and the river mouth, though appreciable fluctuations in TP concentration along the river course were often observed. Conversely, TP concentration in the Bayfield River increased toward the river mouth on all dates except November 19, with pronounced increases occurring near the river mouth on May 22, July 7, and August 5. While the relative values varied, the pattern in TP concentration along the length of the rivers was usually very similar to that of turbidity, suggesting that an appreciable proportion of the TP in the rivers was particulate and possibly related to physical disturbance of the river bed near the river mouth.

E. coli

E. coli concentrations often showed erratic changes in concentration between the intensive stations and the river mouth. In some cases, concentrations of *E. coli* increased toward the river mouth, mimicking the pattern of increase in TP and turbidity. At the Saugeen River, *E. coli* concentrations were higher at the river outflow than at the most upstream station, though there was only a clear pattern of increasing *E. coli* concentrations on May 28 and November 18, however, the absolute concentration ranges were small.

Except on November 23, *E. coli* concentrations in the Maitland River did not follow a clear trend from upstream to outflow fluctuating over a small range of values. On November 23, the concentrations of *E. coli* in the Maitland River increased steadily; the outflow containing a three-fold higher *E. coli* concentration than the station furthest upstream. The magnitude of this increase was, however rather modest; increasing from 16 CFU 100 mL^{-1} at the PWQMN station, to 64 CFU 100 mL^{-1} at the river mouth.

On three of the five sampling dates at the Bayfield River (May 22, July 7, and August 5), *E. coli* concentration showed a pattern of increase toward the river mouth. *E. coli* concentrations were especially high on August 5, with peak concentrations of 3600 CFU 100 mL^{-1} which was found at the second-last station before the river outflow (station 60). As a comparison, the second highest *E. coli* concentration measured in this study was 730 CFU 100 mL^{-1} on November 9, also in the Bayfield River. The highest value measured from the other rivers was 340 CFU 100 mL^{-1} on November 18 from the Saugeen River. While not as apparent as the similarity in TP and turbidity levels, the pattern in *E. coli* concentration along the rivers was often similar to that of turbidity. As with TP, this suggests that a portion of *E. coli* may have been associated with particulate material.

3.1.4 River Water Temperatures

The temperature of water discharged from a tributary relative to that of the receiving water of the lake is a key factor determining how the tributary water will mix with the lake water and consequently how it will influence water quality in the area of the discharge. Tributary water tends to warm more quickly in the spring and cool more rapidly in the fall than the open lake resulting in seasonal changes in relative water density and a tendency for floating and sinking tributary discharge plumes in the spring and fall, respectively. Water temperatures near the mouths of the three major tributaries were monitored over the study period to provide insight on temporal variability in relative tributary/nearshore water temperatures and how this might affect water quality in the nearshore.

The temperature patterns over the course of the study period were similar for all three rivers. River temperatures were dynamic, often fluctuating by several degrees Celsius over the course of a few days (Figures 11, 12 &13). The Bayfield River temperature was slightly more variable than that of the Maitland and Saugeen rivers, appearing to mimic the nearshore temperature more closely than the Saugeen and Maitland rivers. This pattern was observed in both the river mouth station, and the station 0.5 km upstream (data not shown). From early June to early July, river temperatures increased, then declined slightly, and plateaued (though continuing to fluctuate) until mid-September, after which river temperatures progressively declined. The temperature of each of the three rivers (at the river mouth) was higher than the surface water of both the proximate and distant regions of the lake from the beginning of the study period to early July. The difference between river and lake temperature diminished from July to mid-September, with river temperatures slightly higher, or equal, to that of the lake. From mid-September to late November, river temperatures were generally lower than that of the lake.

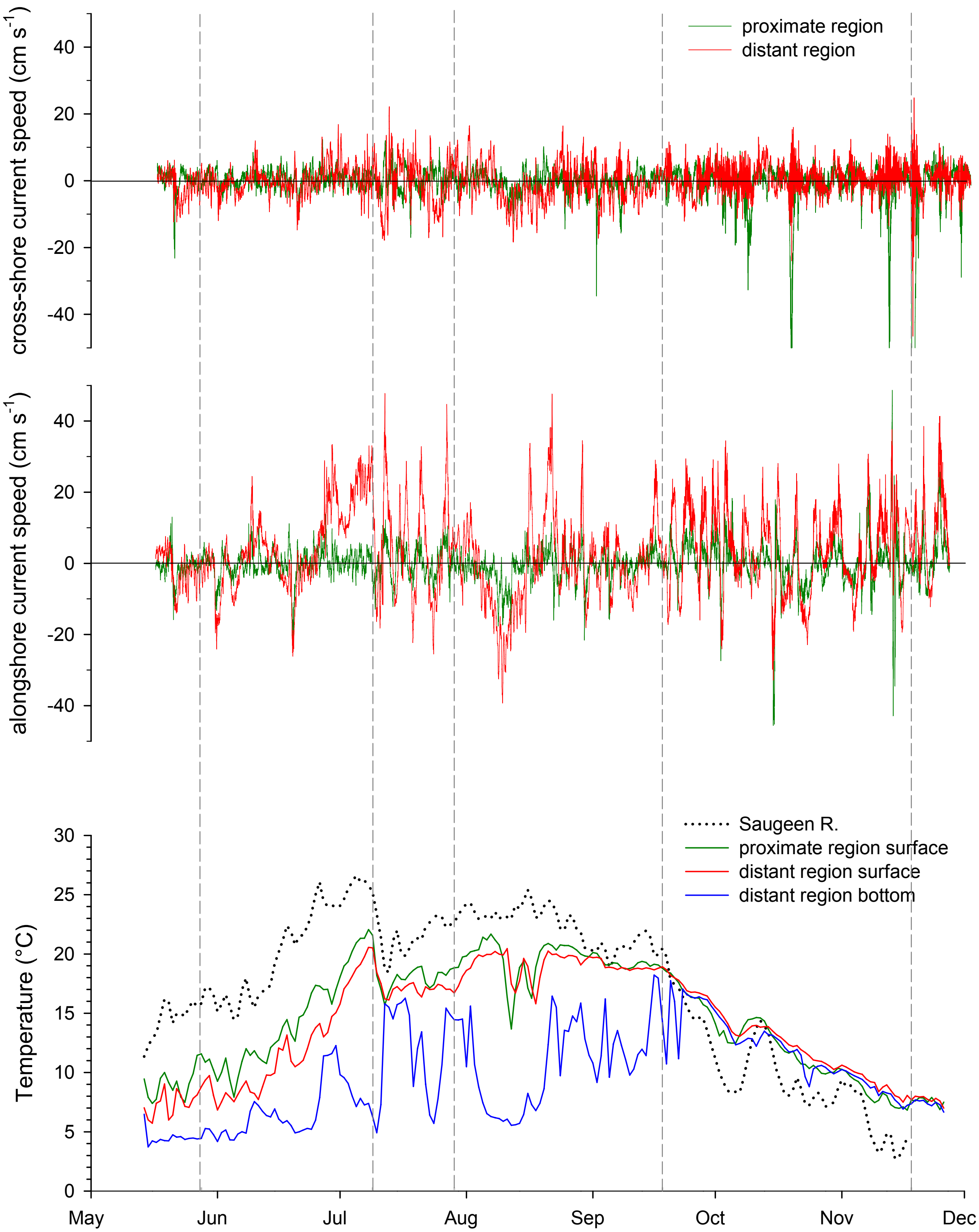

Figure 11: Cross-shore and alongshore current speeds and daily mean water temperature in the proximate and distant regions of the Saugeen River study area and at the mouth of the river in 2003. Positive cross-shore and alongshore current speeds are East and North-directed currents, respectively. See Figure 2 for locations of instrumentation. Current speeds are for the water layer approximately 3 to 5 m from surface. Dashed vertical lines indicate the time of nearshore water quality surveys.

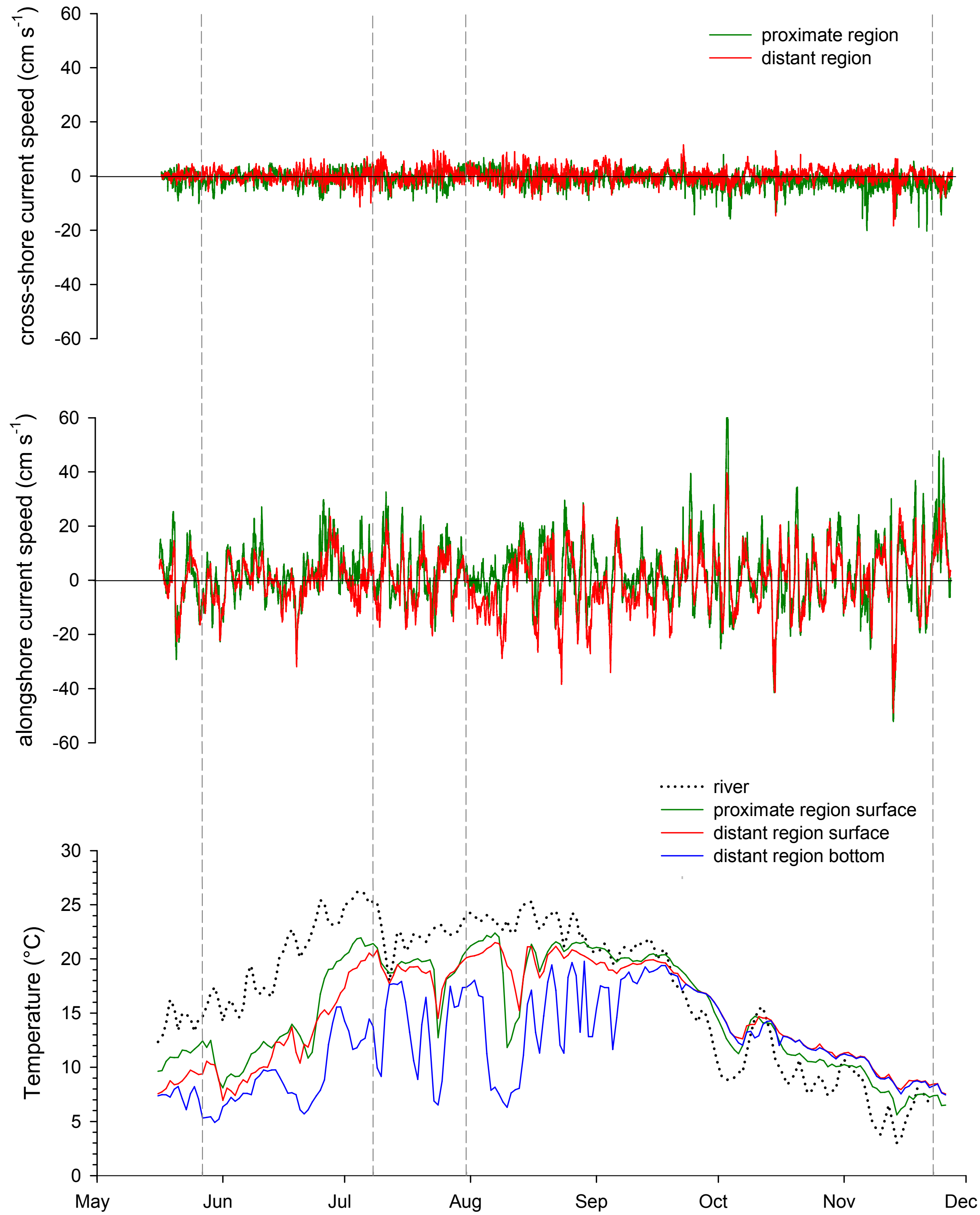

Figure 12: Cross-shore and alongshore current speeds and daily mean water temperature in the proximate and distant regions of the Maitland River study area and at the mouth of the river in 2003. Positive cross-shore and alongshore current speeds are East and North-directed currents, respectively. See Figure 3 for locations of instrumentation. Current speeds are for the water layer approximately 3 to 5 m from surface. Dashed vertical lines indicate the time of nearshore water quality surveys.

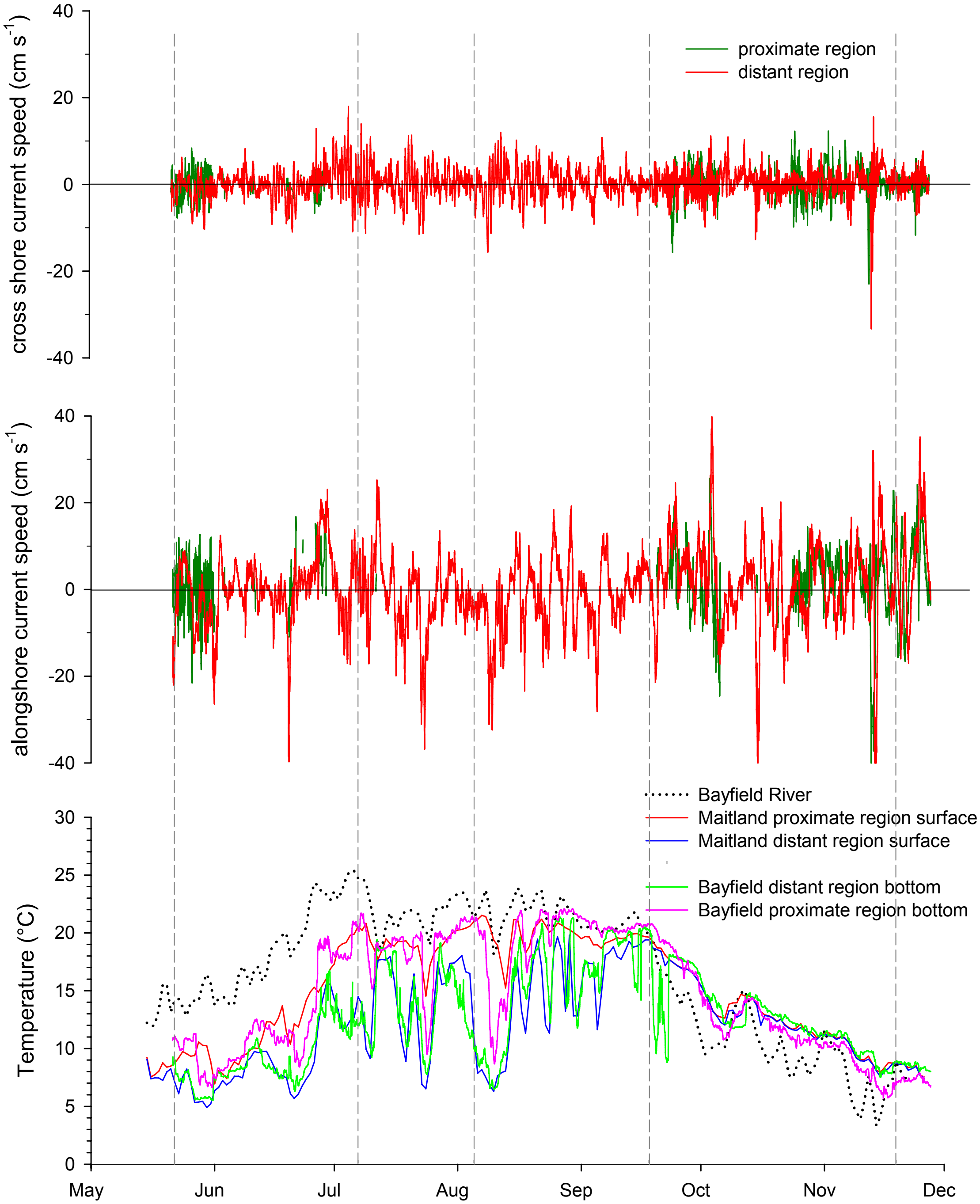

Figure 13: Cross-shore and alongshore current speeds in the proximate and distant regions of the Bayfield River study area and at the mouth of the river in 2003. Positive cross-shore and alongshore current speeds are East and North-directed currents, respectively. See Figure 4 for locations of instrumentation. Current speeds are for the water layer approximately 3 to 5 m from surface. Lake temperature data for the Maitland study area is included for reference because lake surface temperature data are not available for the Bayfield study area. Dashed vertical lines indicate the time of nearshore water quality surveys.

3.2 Physical Conditions in the Lake Nearshore

3.2.1 Lake Temperature

Prolonged periods of stable thermal stratification did not occur in any of the nearshore study areas. From the beginning of the study period until late September, surface temperatures of both the distant and proximate regions were generally higher than near the lake bottom (Figures 11,12, & 13). Frequent periods of downwelling were observed resulting in near isothermal conditions. Periodic upwellings resulting in short-term depression of surface and sub-surface temperatures was a feature of all study areas. Both upwelling and downwelling episodes were more frequent and more pronounced at the Maitland distant region than at the Saugeen distant region. From September onward, isothermal conditions prevailed at the distant region indicating complete mixing of the water column.

In general, the surface temperatures of the proximate region mimicked that of the distant region. The proximate region surface temperatures were, however, more variable than that of the distant region. Additionally, proximate region surface temperatures were generally higher than that of the distant region in spring and generally lower than the distant region in autumn. Upwelling episodes, while observable at the distant surface waters, were typically more pronounced at the proximate region sensor sites.

3.2.2 Water Circulation in the Nearshore

The depiction of flows in the surface layer at the position of the current meters in the proximate and distant regions of the nearshore demonstrates several well-known features of water movement on the open shoreline of Lake Huron. Alongshore flow of water in the surface layer of the nearshore dominated at all study areas (Figures 11,12, & 13). Flow reversals on the order of days were typical. Consequently, materials discharged to the shoreline tends to move along the shoreline for short periods (days) and then flow backwards in the opposing direction. The magnitude of cross-shore flow (i.e. flow towards or away from shore) was low relative to alongshore flow with the exception of isolated periods.

The magnitude of alongshore flow exceeded 20 cm s^{-1} on multiple occasions at the current meters placed in the distant region indicating energetic conditions, strong flows and an appreciable capacity to move materials along the shoreline.

The lower magnitude of flow observed at the proximate region compared with the distant region at the Saugeen study area reflects the more physically complex shoreline. Chantry Island, along with the combination of reefs and heterogeneous bathymetry along the shoreline, results in deflection of water flow along the shoreline. Flow patterns are more varied among locations than at the relatively open and linear shorelines of the Maitland and Bayfield study areas.

Physical data are shown for the surface layer only. More complex flow patterns occur through the water column, however, a fuller discussion of lake hydrodynamics in the nearshore is beyond the scope of this report.

3.3 Features of Nearshore Water Quality in 2003

3.3.1 Nearshore Distant Region

Results for the distant region stations were used to describe ambient conditions in the nearshore. The gradients in water quality between the distant region stations and stations in the Saugeen, Maitland and Bayfield Rivers were used to indicate the potential for discharge from the rivers to affect water quality in the proximate region.

Levels of water quality parameters at the distant region stations were generally much lower, and less variable, than at river stations (Table 4). Across all of the study regions, concentrations of TP in the river outflows (river mouth stations) ranged from 3 to 18 times higher than at average of the distant region stations. Similarly, river concentrations of NO_2+NO_3 were from 2 to 18 times higher, and river chlorophyll *a* concentrations were 2 to 23 times higher than those of the distant stations. Turbidity at the distant stations was typically well below 1 FTU and appreciably lower than at the river mouths. However, during the second fall survey, turbidity was elevated at the distant stations and over all the study regions due to physical disturbance of the shoreline and lake bed during a preceding period of high winds.

NO_2+NO_3 and TN

On most dates, NO_2+NO_3 concentrations at the distant regions of each of the study areas were similar, ranging from 286 to 461 µg L^{-1}. The exception was the Maitland spring survey, where the average NO_2+NO_3 concentration over distant region stations (1001 µg L^{-1}) was more than twice the average concentration for the distant region stations during any other survey. As with the rivers, the majority of N was composed of NO_2+NO_3. The average proportion of NO_2+NO_3 comprising TN was similar in all three distant-station regions; 0.71, 0.75, and 0.72 at the Bayfield, Maitland, and Saugeen study regions, respectively.

River concentrations of NO_2+NO_3 were 2 to 20 times higher than the average concentrations of the associated distant stations. Because of the relatively high NO_2+NO_3 concentrations in the Bayfield River, the difference between the river and the distant region stations of the Bayfield study area was the greatest of the three rivers. Averaged over the study dates, the Bayfield River was 13 times higher in NO_2+NO_3 than the distant station average; the Maitland River was 8 times higher, with the Saugeen River only 3 times higher.

Table 4: Total P, NO_2+NO_3, TN, turbidity and chlorophyll *a* concentration at intensive river monitoring stations, river mouth stations, distant region stations, and the lake offshore.

Parameter	Survey	Saugeen			Maitland			Bayfield			Offshore
		Intensive River	River mouth	Distant Region	Intensive River	River Mouth	Distant Region	Intensive River	River Mouth	Distant Region	
TP	Spring	15	17	4	20	18	3	13	20	3	7[a], 2[b]
($\mu g\ L^{-1}$)	Summer 1	26	19	4	24	21	2	18	25	4	3[a]
	Summer 2	14	16	3	13	12	3	52	54	3	2[b]
	Fall 1	9	13	4	N. A.[c]	N. A.[c]	N. A.[c]	21	26	3	6[a]
	Fall 2	46	50	8	36	35	13	93	92	12	N. A.
	mean	**21.7**	**22.7**	**4.2**	**23.3**	**21.7**	**5.2**	**39.4**	**43.6**	**4.9**	
NO_2+NO_3	Spring	1320	1332	385	8360	8380	1001	7930	7690	461	444[a], 330[b]
($\mu g\ L^{-1}$)	Summer 1	727	721	409	1170	1028	442	2440	1888	443	N. A.
	Summer 2	823	789	340	1650	1598	359	7840	7215	356	320[b]
	Fall 1	747	727	294	N. A.[c]	N. A.[c]	N. A.[c]	1610	1653	286	N. A.
	Fall 2	2280	2256	331	7590	7732	457	7420	7135	390	N. A.
	mean	**1179**	**1165**	**352**	**4693**	**4685**	**565**	**5448**	**5116**	**387**	
Turbidity	Spring	5.0	6.0	0.3	1.9	2.4	0.6	1.8	4.7	0.4	0.36[b]
(FTU)	Summer 1	8.8	6.9	0.2	5.7	3.8	0.2	2.5	9.9	0.2	N. A.
	Summer 2	5.2	7.1	0.2	4.0	2.7	0.4	27.4	36.0	0.2	0.32[b]
	Fall 1	3.6	6.2	0.2	N. A.[c]	N. A.[c]	N. A.[c]	4.5	16.1	0.4	N. A.
	Fall 2	15.1	17.4	5.3	1.9	2.9	18.4	18.9	29.3	14.6	N. A.
	mean	**7.5**	**8.7**	**1.3**	**3.4**	**2.9**	**4.9**	**11.0**	**19.2**	**3.1**	
Chl *a*	Spring	2.5	3.1	0.3	3.4	3.8	0.4	3.1	2.9	0.3	0.92[b]
($\mu g\ L^{-1}$)	Summer 1	3.5	2.3	0.6	5.0	5.2	0.3	3.5	5.2	0.2	N. A.
	Summer 2	1.0	1.1	0.3	2.8	2.0	0.4	6.3	7.4	0.3	0.93[b]
	Fall 1	1.2	1.3	0.5	N. A.[c]	N. A.[c]	N. A.[c]	4.4	2.4	1.2	N. A.
	Fall 2	3.5	3.5	0.8	3.0	4.3	1.0	5.8	10.3	1.8	N. A.
	mean	**2.3**	**2.3**	**0.5**	**3.6**	**3.8**	**0.5**	**4.6**	**5.6**	**0.8**	
TN	Spring	1945	1962	530	9150	9174	1187	8450	8233	598	N. A.
($\mu g\ L^{-1}$)	Summer 1	1350	1249	492	1980	1832	622	3110	2570	613	N. A.
	Summer 2	1298	1247	495	2300	2252	552	8240	7710	499	N. A.
	Fall 1	1067	1081	436	N. A.[c]	N. A.[c]	N. A.[c]	2160	2203	466	N. A.
	Fall 2	3050	3042	481	8290	8458	657	8060	7783	570	N. A.
	mean	**1742**	**1716**	**487**	**5430**	**5429**	**754**	**6004**	**5700**	**549**	

Offshore data are compiled from dates close to the corresponding survey period, and were not available for all survey periods.
[a] from Environment Canada
[b] from U.S. Environmental Protection Agency
[c] Fall 1 survey at Maitland River was not conducted

TP

The average offshore TP concentration of 5.0 μg L^{-1} was similar to that of the Saugeen (4.2 μg L^{-1}), Maitland (5.2 μg L^{-1}), and Bayfield (4.9 μg L^{-1}) distant regions. Total Phosphorus concentrations at the distant region stations were similar among the three study areas for most of the study periods ranging from 2 to 4 μg L^{-1}. However, during the second fall sampling period, concentrations were higher. Concentrations at this survey period ranged from an average of 8 μg L^{-1} at the Saugeen distant regions stations to 13 μg L^{-1} at the Maitland distant region stations. A contributing factor to the elevated concentrations of TP was the relatively high turbidity levels at the time due to energetic fall weather. It is likely that a portion of the phosphorus was associated with re-suspended particulate material. River TP concentrations were appreciably higher than those of the distant region stations at the time of the nearshore surveys, ranging from 12 to 92 μg L^{-1}; 3 to 18 times higher than at the distant stations.

Turbidity

Similar to TP, turbidity at the distant regions stations were similar, and generally low in magnitude, ranging from 0.2 to 0.6 FTU. Also similar to TP, the exception to this occurred on the second fall sampling date, at which average turbidity at the distant stations was much higher: 5.3, 18.4, and 14.6 FTU in the Saugeen, Maitland, and Bayfield rivers, respectively. River turbidity was typically much higher than that of the distant region. Excluding the second fall sampling date, river turbidity exceeded that of the distant stations by 4 to almost 200 fold at the time of the nearshore surveys.

As noted, turbidity was especially high in all three distant-station regions on the second fall survey. River turbidity exceeded that of the distant region by only 3-fold at the Saugeen study area, and 2-fold at the Bayfield study area. At the Maitland River, average turbidity at the distant stations exceeded that of the river by more than 6-fold on the second fall survey.

Chlorophyll *a*

Chlorophyll *a* concentrations at the distant region stations were typically well below 1 μg L^{-1} in all three of the study areas. During the second fall sampling period, average chlorophyll *a* concentrations were higher at the distant region stations than at other times; 0.77, 1.04, and 1.76 μg L^{-1} at the Saugeen, Maitland, and Bayfield distant regions, respectively. The only other occasion when slightly higher chlorophyll *a* concentrations were observed at the distant stations was during the first fall survey date at the Bayfield study area (1.2 μg L^{-1}). In the rivers, chlorophyll *a* was 2 to 23 times higher than that of the adjacent distant stations, spanning a large range, from 1.1 to 10.3 µg L^{-1}.

3.3.2 Lake Offshore in Area of the Nearshore Study Sites

Offshore lake data for the period and general locations of the nearshore study areas were sparse both seasonally and spatially, so comparisons should be made with caution. The limited offshore data that are available are generally similar to distant region values. Average offshore NO_2+NO_3 was 455 µg L^{-1}, while the average at the distant stations was 352, 565, and 387 µg L^{-1} at the Saugeen, Maitland, and Bayfield River regions, respectively. Average TP concentration was 4.9 µg L^{-1} in the offshore, and 4.2, 5.2, and 4.9 µg L^{-1} at the Saugeen, Maitland, and Bayfield River distant stations, respectively. The average offshore turbidity was 1.0 FTU, which was comparable to average turbidity at the Saugeen distant stations, which was 1.3 FTU. Average turbidity at both the Maitland and Bayfield distant stations was appreciably higher at 4.9 and 3.2 FTU, respectively. These averages were biased by a very high turbidity at the distant stations on the second fall survey.

3.4 Spatial Analysis of Variability in Nearshore Water Quality

3.4.1 Field conductivity as a Tracer of Tributary Discharge and Predictor of NO_2+NO_3 concentration

Electrical conductivity, a non-specific indicator of levels of ionic materials, is frequently used as a tracer of water discharged to the shores of Great Lakes. Ambient levels of conductivity within local areas of the Great Lakes are relatively constant over short durations of time. In contrast, usual sources of runoff (such as tributaries) typically have more variable, often elevated levels of conductivity relative to the lake. Conductivity is readily measured in the field and can be used to detect deviation from ambient lake conductivity as an indicator of the location and movement of inflowing water sources. The conductivity levels of the Saugeen, Maitland, and Bayfield Rivers are appreciably elevated relative to Lake Huron and conductivity measured in the areas of the nearshore adjacent to the river mouths can be used to track movement of the river discharge into the lake.

In general, nitrate concentrations in the Saugeen, Maitland, and Bayfield Rivers were elevated over ambient levels in the nearshore as inferred from results for the distant region.
On 10 of the 13 dates that field conductivity and NO_2+NO_3 data were collected, a strong, linear relationship was observed between NO_2+NO_3 and conductivity (Table 5; Fig. 14). The equations of the relationships varied greatly among surveys reflecting the empirical rather than functional relationship between the parameters. Since only a limited number of lab-based measurements of NO_2+NO_3 were made for the individual surveys, the survey-specific regression equations can be used to estimate NO_2+NO_3 from the more extensive set of field measurements of conductivity collected in each survey. The degree to which NO_2+NO_3 covaried with conductivity loosely corresponded with river discharge. During the summer, under reduced flow, the slope of the regressions declined.

Unexpectedly, a high degree of covariation was observed between conductivity and NO_2+NO_3 concentrations in the nearshore during some surveys suggesting that shoreline discharges, in particular the major tributaries were a key factor driving the appreciable variability in NO_2+NO_3 sometimes observed in the nearshore.

The typically strong relationship between conductivity and NO_2+NO_3 suggest that, like conductivity, NO_2+NO_3 acts as a conservative solute, and was not appreciably lost through processes other than dilution over the time frame from discharge to the lake and initial mixing.

Table 5: Linear regressions between NO_2+NO_3 concentrations ($\mu g\ L^{-1}$ N) and laboratory measurements of conductivity ($\mu S\ cm^{-1}$ at 25ºC) on corresponding water samples for the nearshore surveys.

Study Area	Survey period	NO2+NO3 vs. conductivity (lab)		
		equation	r^2	n
Bayfield	Spring	22.6x - 4617	>0.99	17
	Summer 1	4.0x - 412	0.36	16
	Summer 2	15.8x - 3081	0.93	17
	Fall 1	7.7x - 1425	0.87	17
	Fall 2	18.3x - 3552	≥0.99	16
Maitland	Spring	22.7x - 4465	≥0.99	21[a]
	Summer 1	2.7x-144	0.94	22
	Summer 2	3.8x - 474	0.87	23
	Fall 2	18.2x-3496	≥0.99	20[a]
Saugeen	Spring	2.9x - 273	>0.99	24
	Summer 1	0.96x -173	0.95	21
	Summer 2	1.3x+61	>0.99	17
	Fall 1	1.1x + 46	0.99	24
	Fall 2	5.9x - 901	≥0.99	21

a – one outlier removed from regression

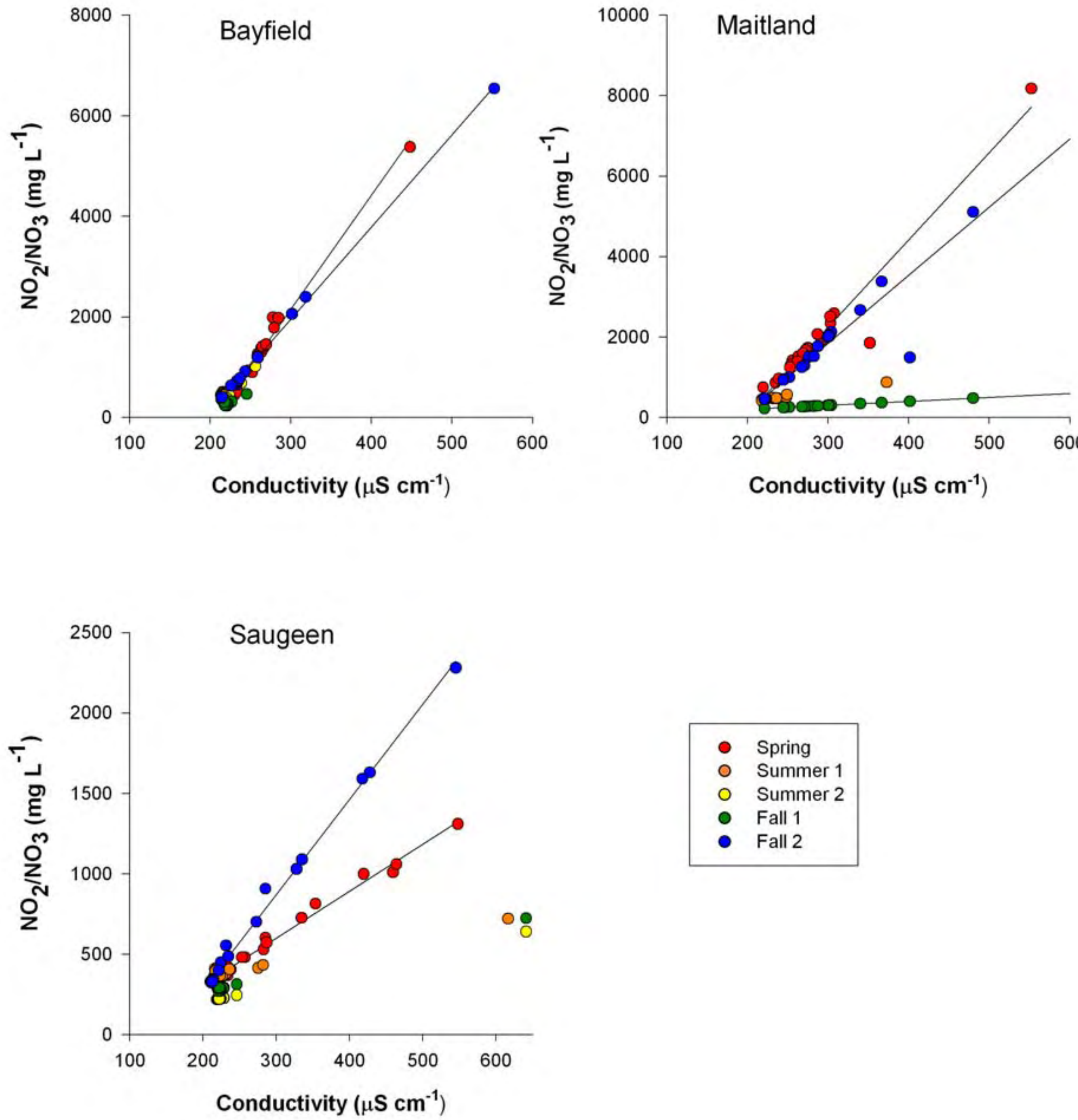

Figure 14: Linear regressions between NO2+NO3 concentration and field conductivity at the survey area. Field conductivity has been adjusted using survey-specific regressions of field against lab-measured conductivity to minimize the effects of variance in calibration of the field sensor over surveys and among study areas.

3.4.2 Estimation of Spatial Extent of Watershed Effect on the Nearshore

Discharge from the Saugeen, Maitland, and Bayfield Rivers appeared to be dominant sources of variability in water quality over the study areas. As inferred from surface measurements during field surveys, mixing areas associated with the discharge plumes typically remained close to the shoreline, and appeared to move in the direction of the alongshore surface currents. However, weaker, more diffuse discharge-affected areas in the opposite direction were often apparent; likely a remnant of earlier reversals of alongshore currents. This pattern was especially apparent at the Maitland River study area, where high current speeds, and frequent reversals in current direction were common in the proximate region.

Area of Nearshore Affected by River Discharge Plumes: 90% dilution areas

The discharge-affected areas of the nearshore adjacent to the Saugeen, Maitland, and Bayfield River mouths varied considerably. The area of nearshore where conductivity did not meet a value representing 90% dilution of the conductivity in the Saugeen, Maitland, and Bayfield River plumes was used to infer surface area affected by river discharge (see Section 2.4). The concentration boundary was calculated as: 90% Boundary = $0.1(R\mathit{c}-O\mathit{c}) + O\mathit{c}$ Where R*c* is the conductivity of river water and O*c* is the conductivity of the distant area of the nearshore.

At the Saugeen River study area, conductivity plume areas ranged from 0.2 km^2 (Fall 1) to more than 15 km^2 (Spring) (Table 6). Of the survey dates for which data were available, the Maitland conductivity plume areas were the largest, ranging from 0.5 km^2 (Summer 2) to 29.7 km^2 (Fall 2). A large range in conductivity plume size was observed adjacent to the Bayfield River, ranging from 0.005 km^2 at the Fall 1 survey, to 7.8 km^2 during the Spring survey. Across study areas and survey dates, three-day average river discharge explained 74% of the variation in the size of the estimated conductivity plumes (Fig. 15). Since this relationship is based on a limited number of surveys days, this result should be considered to be preliminary.

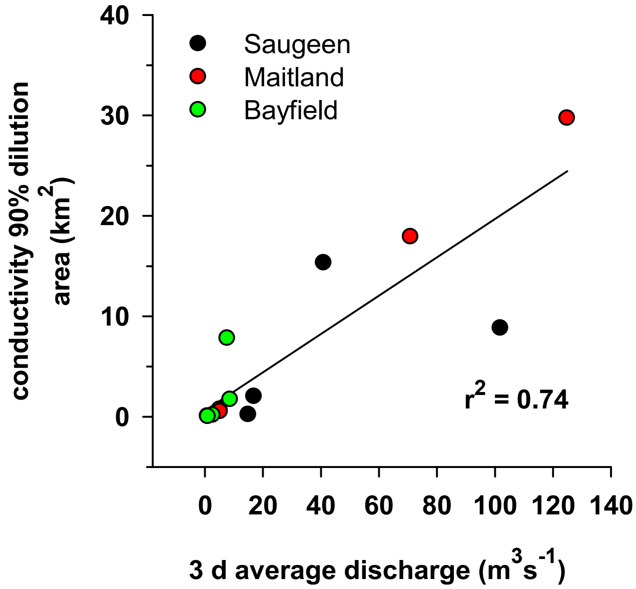

Figure 15: Linear regression between river plume size (conductivity 90% dilution area) and 3-day average river discharge across all rivers and survey dates (for which data were available)

Table 6: The 90% dilution areas (km^2) of river conductivity, at each of the study areas. See Table 1 for the size of survey areas.

survey period	parameter	Saugeen	Maitland	Bayfield
Spring	conductivity	15.3	17.9	7.8
Summer 1	conductivity	2.0	0.7	0.03
Summer 2	conductivity	N. A.[a]	N.A. [a]	0.13
Fall 1	conductivity	0.2	N. A.[b]	0.005
Fall 2	conductivity	8.8	29.7	1.7

[a] conductivity was not collected at the Maitland and Saugeen Summer 2 survey because of sensor failure

[b] Fall 1 survey was not conducted at the Maitland River study area

Area of Tributary and Shoreline Influence: ≥2x distant region concentration

The area of the nearshore where levels of water quality parameters were two or more times greater than the average of the distant region was used to estimate the spatial extent of shoreline and tributary effects on water quality over the study areas at the time of the nearshore surveys. Similar to the 90% dilution areas, the ≥2x concentration areas varied considerably among surveys (Table 7). While the 90% dilution areas were related to river discharge, a clear pattern in the sizes of the ≥2x areas for any of the parameters among surveys or among study areas was not apparent.

The ≥2x concentration areas for chlorophyll *a* were highest in the Maitland River study area, with an average of 5.4 km^2 (range = 0.2 to 14.8 km^2). The Bayfield and Saugeen River study areas had similar average ≥2x chlorophyll *a* areas at 2.6 km^2 (range = 0.4 to 7.7 km^2) and 2.7 km^2 (range = 0.02 to 6.7 km^2), respectively. NO_2+NO_3 average ≥2x area was the highest in the Maitland River study area (average = 15.9 km^2; range = 0.1 to 39.1 km^2). The Bayfield River study area average NO_2+NO_3 ≥2x area was 4.3 km^2 (range = 0 to 15.7 km^2), while it was an average of 3.0 km^2 in the Saugeen River study area (range = 0.04 to 6.2 km^2). The Saugeen River study area average turbidity ≥2x area was 16.3 km^2 (range = 7.0 to 25.6 km^2), while it averaged 18.1 km^2 (range = 6.8 to 26.0 km^2) at the Bayfield study area, and 21.6 km^2 (range = 0 to 49.5 km^2) at the Maitland study area.

Table 7: Areas (km^2) of the nearshore where chlorophyll *a* and NO_2+NO_3 concentration, and turbidity that were elevated more than twice that of the distant region at each of the nearshore study areas. See Table 1 for the size of survey areas.

survey period	Parameter	Saugeen	Maitland	Bayfield
Spring	chl *a* (μgL^{-1})	6.7	14.8	1.4
	NO_2+NO_3 (μgL^{-1})	2.8	8.4	15.7
	Turbidity (FTU)	9.5	36.4	22.0
Summer 1	chl *a* (μgL^{-1})	2.5	1.3	7.7
	NO_2+NO_3 (μgL^{-1})	N. A.[b]	0.1	N. A.[b]
	Turbidity (FTU)	25.6	49.5	26.0
Summer 2	chl *a* (μgL^{-1})	1.5	N. A.[a]	0.8
	NO_2+NO_3 (μgL^{-1})	N. A.[b]	N. A.[b]	0.2
	Turbidity (FTU)	22.4	0.3	10.7
Fall 1	chl *a* (μgL^{-1})	0.0	N. A.[c]	N. A.[b]
	NO_2+NO_3 (μgL^{-1})	0.0	N. A.[c]	0.0
	Turbidity (FTU)	17.0	N. A.[c]	6.8
Fall 2	chl *a* (μgL^{-1})	N. A.[a]	0.2	0.4
	NO_2+NO_3 (μgL^{-1})	6.2	39.1	3.2
	Turbidity (FTU)	7.0	0.0	25.0

[a] areas not generated because of inadequate relationship between continuous fluorescence measurements and laboratory-analysed chl *a* concentration

[b] areas not generated because of an inadequate relationship between field conductivity measurements and laboratory-analysed NO_2+NO_3 concentration

[c] Fall 1 survey was not conducted at the Maitland River study area

3.5 Summaries of Selected Nearshore Water Quality Surveys

Surveys of water quality were conducted in the nearshore of the three surveys areas on four to five dates in 2003 and provide snap-shots of environmental conditions at the time of survey. Extensive field measurements of a small suite of water quality variables, used as surrogates for a broader range of features, were used to interpolate water quality maps. These spatial maps of water quality features identify linkages between attributes of the shoreline and nearshore water quality. The water quality maps provide insight on the movement of river discharge plumes over the immediate lake-river mixing areas adjacent to the mouths of the three major rivers.

In this next section a representative set of the results collected over individual surveys is presented to illustrate features of water quality over the study areas and provide insight on the factors driving water quality at the time of survey.

The approach provides an approximation of true conditions and there are important limitations. Surveys were conducted over a small number of days and likely represent only a sub-set of conditions encountered over a full seasonal cycle. By design, data collection focused on the near-surface water mass and the bulk of the data reported here are for surface data. In general, vertical stratification of the water column in the nearshore is dynamic and often limited. It is recognized that at times there will be appreciable depth-related variability in water quality. However, it is technically difficult to quantify spatial features of water quality on a three dimensional basis. Extensive vertical profiles of a small suite of measures were collected as part of the surveys and are used to provide insight on the degree of vertical heterogeneity on each of the survey dates but these data are insufficient to characterize water quality. The size of the survey areas were limited by the time requirements of the field surveys. The spatial scale of variability of some features water quality in the nearshore extends beyond the study areas.

3.5.1 Bayfield Spring Survey

Physical conditions

Spring warming resulted in a distinct onshore-offshore pattern in surface temperatures. The four degree isotherm, the boundary of a possible thermal bar was well offshore of the study area by the time of the spring survey. In the days prior to and during the survey water temperature of the distant region ranged from 7.7ºC to 9.8ºC (Figure 16). The proximate region was warmer, ranging from 9.8ºC to 11.8ºC and the water column was unstratified. At the mouth of the Bayfield River, temperature fluctuated from temperatures near that of the proximate region, to several degrees warmer. The onshore-offshore stratification of surface temperature evident during the spring survey is likely a result of the rapid warming of shallower water towards the shoreline (Figure 17). The surface temperature map suggests only a faint thermal plume from the Bayfield River which is consistent with the limited temperature difference between the river and adjacent nearshore at the time of survey.

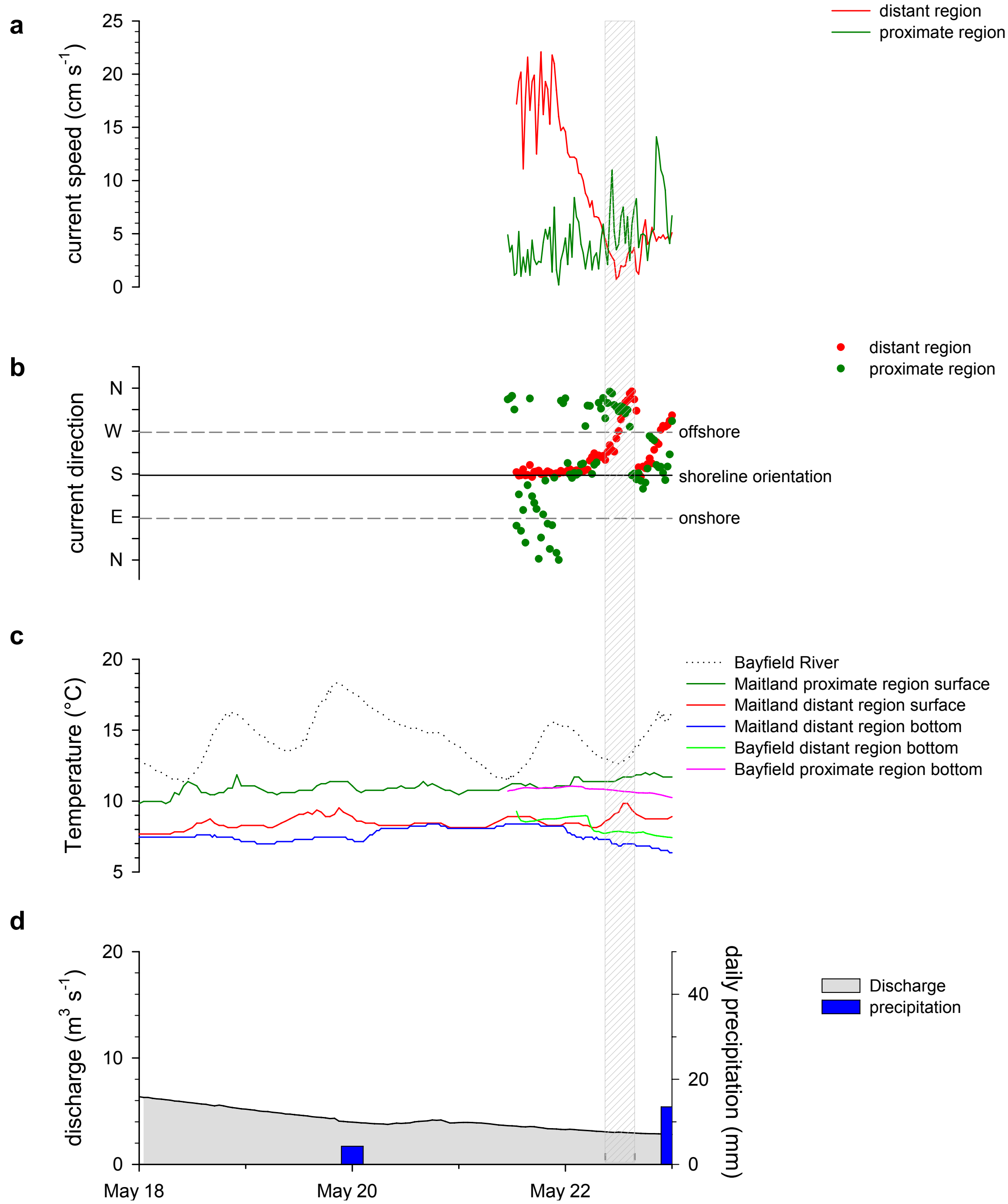

Figure 16: Bayfield study area Spring survey. Physical conditions in the days before and during the survey (hatched region). Near surface current speed (**a)** and direction (**b**) in the distant and proximate regions (Bayfield study area), temperature of the Bayfield River and the distant and proximate regions (**c**), Bayfield River discharge and local precipitation (**d**). Note that some temperature traces for the distant and proximate regions are from sensors at the Maitland study area. See sections 2.3 and 2.5 for details.

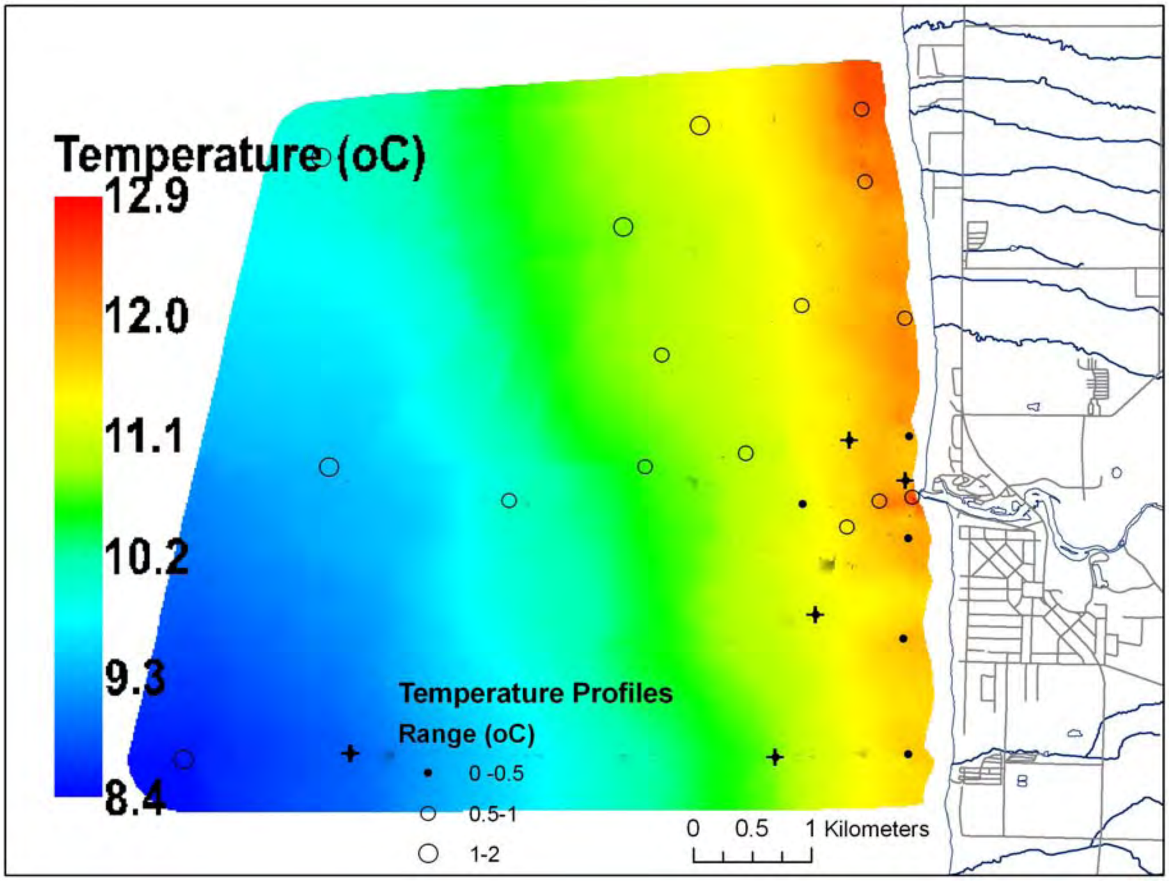

Figure 17: Surface water temperature (°C) at the Bayfield River survey area during the spring survey (May 22, 2003). The circles indicate locations of depth profiles of temperature with size proportional to temperature change with depth. The crosses indicate locations where water column was well mixed using a criterion of < 0.01 g cm^{-3} (density) change per meter drop.

The spring survey was conducted during declining flow towards the end of a high discharge event that had peaked at 36 m^3s^{-1} 10 days before. Discharge declined from approximately 6 m^3s^{-1} four days before the survey, to approximately 2.5 m^3s^{-1} during the survey. A small rainfall (2.25 mm) occurred two days before the survey.

Near surface current data for the days preceding the survey are limited to the day just before the survey, when ADCPs were deployed at the study area. During the day before the survey, there was a strong, south current in the distant region, which slowed just before the survey, and remained weak during the survey period. Currents in the proximate region were weaker than that of the distant region, but were increasing in an approximately alongshore direction to the NW during the survey period.

Water Quality

Conductivity

The discharge plume from the Bayfield River appeared to be of limited extent at the time of survey based on the area of elevated conductivity at the river mouth. Given the limited temperature difference between the adjacent lake and at the river mouth it is likely that the river plume mixed readily with the lake upon discharge (Figure 18). Additional patches of elevated conductivity, not contiguous with that of the river discharge, were observed south of the river mouth. It is unclear whether these zones are due to additional discharges along the shoreline or erratic, south-directed movement of the discharge from the Bayfield River over the period before the survey. A subtle onshore-offshore gradient in conductivity extended over the survey area. The basis of the gradient is uncertain. The increasing water density gradient moving offshore associated with the temperature gradient may have provided resistance to offshore mixing resulting in the accumulation and mixing of discharges along the shoreline.

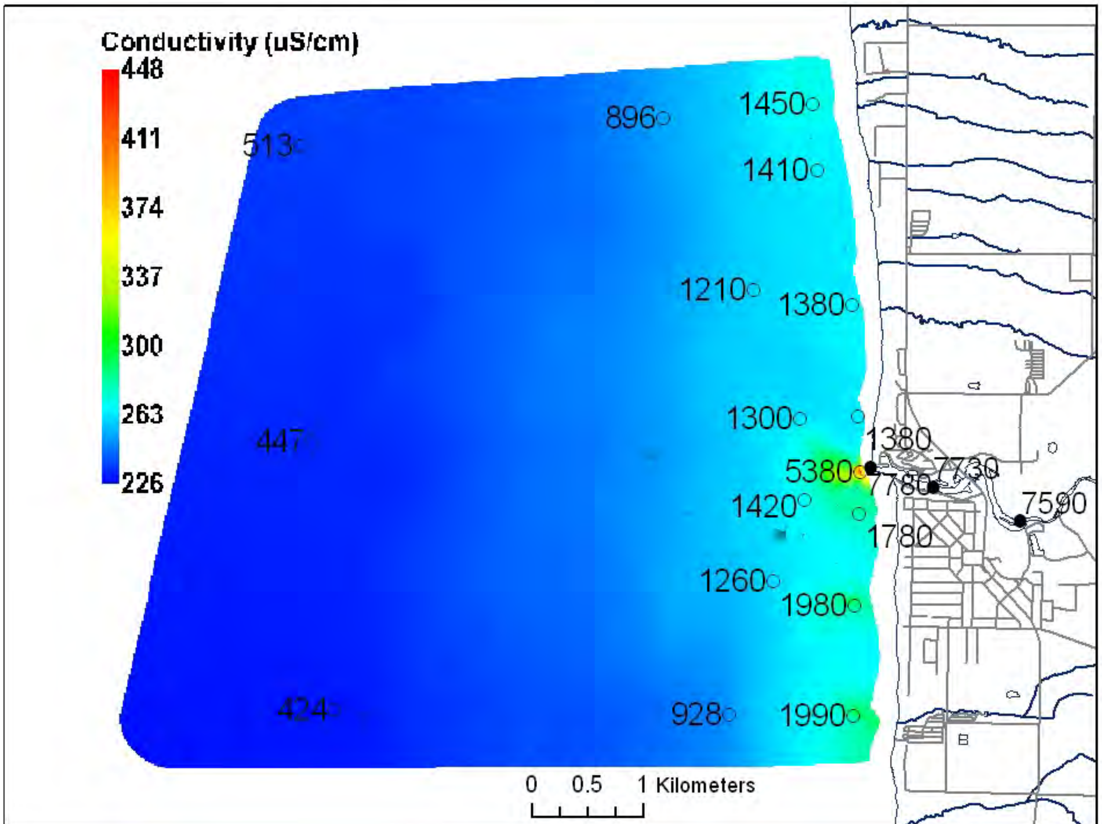

Figure 18: Surface conductivity (colour scale; µS cm^{-1} at 25°C) and NO_2+NO_3 concentrations (point samples; µg L^{-1} N) at the Bayfield River study area during the spring survey (May 22, 2003).

NO_2+NO_3

Consistent with variability in field conductivity, the levels of NO_2+NO_3 in surface samples collected over the study area indicated both onshore-offshore and alongshore patterns of variability. Bayfield River NO_2+NO_3 concentrations were high (7690 µg L^{-1} averaged over the four stations closest to the river mouth), exceeding that of the distant region by more than 16-fold. Concentrations were also elevated among the shoreline sites and in the proximate region as a whole. Slightly higher levels were observed south of the Bayfield River consistent with the local areas of elevated conductivity. While loading of NO_2+NO_3 from Bayfield River was a contributor to the elevated concentrations along the shoreline, the extent of inputs from other shoreline sources or via alongshore transport cannot be determined. The ≥2x tributary and shoreline affected area (≥2x area) was large (15.7 km^2); the largest ≥2x area for NO_2+NO_3 observed for the Bayfield River study area. Concentration of NO_2+NO_3 in the distant region were similar among sites but slightly higher than observed in the offshore (see Table 4). It is difficult to estimate the distance that shore-based effects on water quality are experienced offshore. However, based on nitrate+nitrite levels, it conservatively extended at least 2 km from the shoreline at the time of survey.

Turbidity

A strong onshore-offshore gradient in turbidity also factored prominently in the variability over the study area (Figure 19). Similar to conductivity, several small, separated zones of elevated turbidity were observed along the shoreline south of the Bayfield River mouth. The ≥2x area of turbidity was high at 22 km^2. In addition to shoreline discharges and possible alongshore transport, shoreline erosion and bed sediment resuspension were likely contributors to the elevated turbidity along the shoreline.

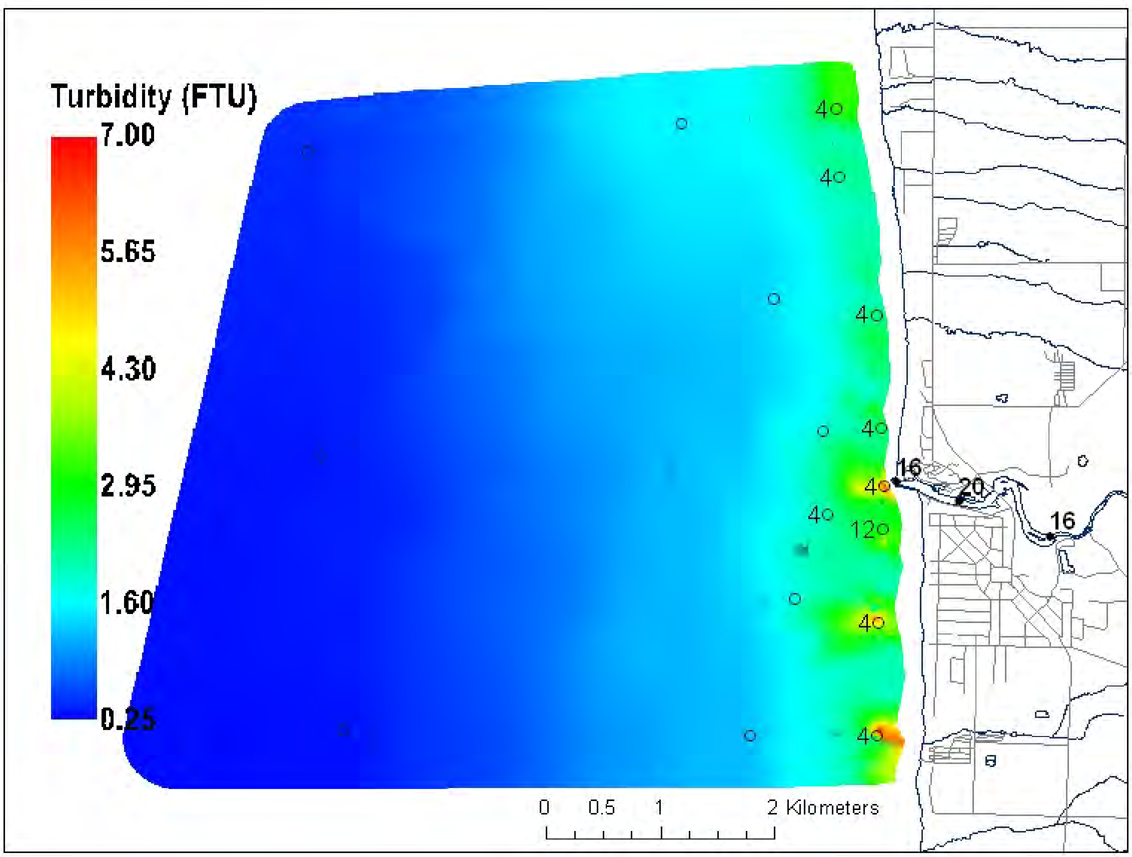

Figure 19: Surface turbidity (colour scale; FTU) and *E. coli* concentrations (point samples; CFU 100 mL^{-1}) at the Bayfield River study area during the spring survey (May 22, 2003). No samples were collected at points without numeric values.

E. coli

Despite the obvious watershed effects on water quality in the proximate area levels of *E. coli* were low with a maximum of 12 CFU 100 mL^{-1}. Sample collection for *E. coli* was limited to near the shoreline. Levels were low in the river at the time of survey (16-20 CFU 100 mL^{-1} near the river mouth).

Chlorophyll a

The chlorophyll *a* levels observed during the survey were low and did not exceed 2 µg L^{-1} and were <0.5 µg L^{-1} over the majority of the area (Fig. 20). A broad but subtle onshore-offshore gradient and localized areas of slightly elevated conductivity along the south shoreline were the main features of variability. Only 1.4 km^2 of the nearshore had chlorophyll *a* concentrations two or more times higher than that of the distant region. Chlorophyll *a* levels at the three most downstream river sites ranged from 2.9 -3.6 µg L^{-1}.

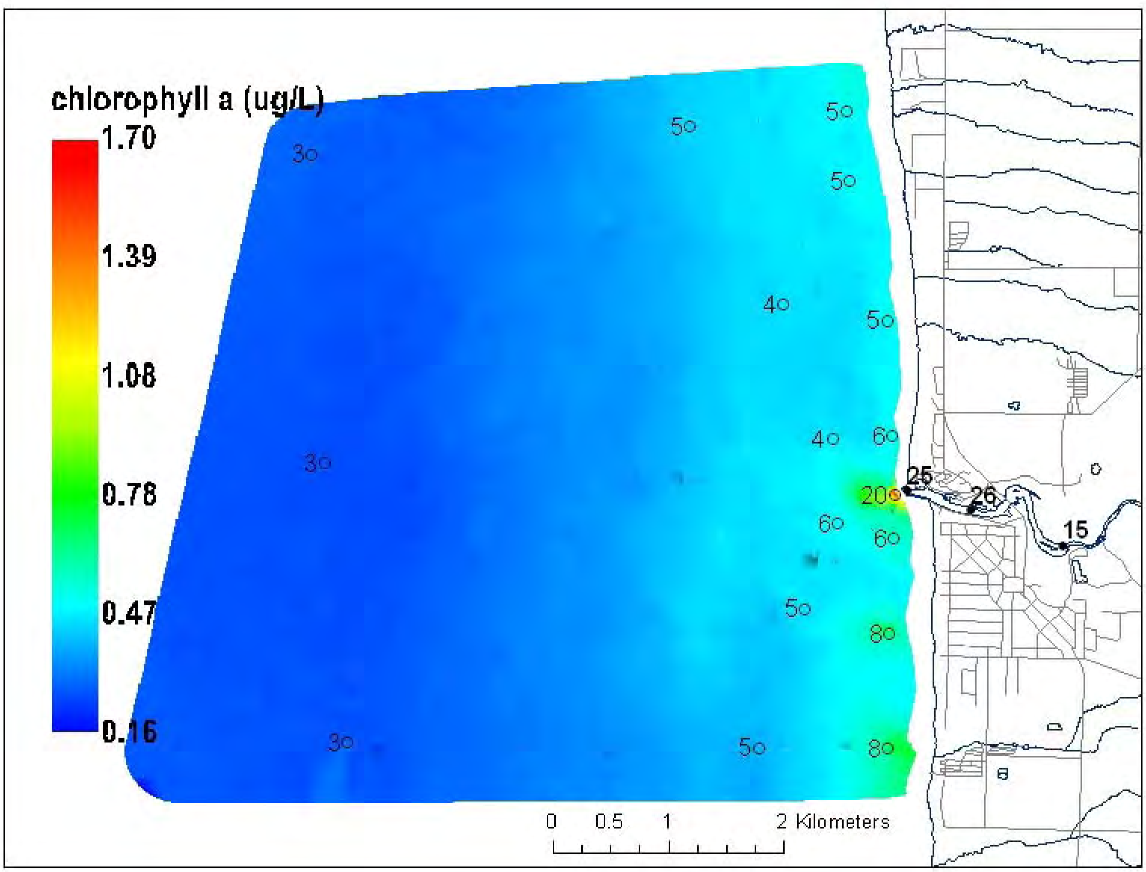

Figure 20: Surface chlorophyll *a* concentration estimated from fluorescence (colour scale; µg L^{-1}) and TP concentrations (point samples; µg L^{-1} P) at the Bayfield River study area during the spring survey (May 22, 2003).

TP

In contrast to NO_2+NO_3, there was limited enrichment of TP levels in the nearshore adjacent to the mouth of the Bayfield River. Concentrations ranged from 3 to 8 µg L^{-1} with the exception of a sample at the mouth of the Bayfield River (Figure 20). Slightly higher concentrations were observed in onshore areas and south of the Bayfield River as with other measures. Concentrations in the Bayfield River were moderate (25 µg L^{-1} at the river mouth). The distant region TP concentration of 3 µg L^{-1} was very close to that measured during the other surveys, with the exception of the second Fall survey when TP concentrations were higher.

General

The survey was conducted in late spring during dry weather at a time when tributary discharge levels were relatively low but had not yet declined to base flow. Despite this, and the expected relatively low runoff from other smaller tributaries and shoreline, there were obvious shore-based effects on water quality over the study areas. Patterns in the spatial variability of conductivity, turbidity, chlorophyll *a*, NO_2+NO_3 and TP suggested both broad-scale and local scale influences on nearshore conditions. Small, more affected areas at the mouth of the Bayfield River and at points along the shoreline south of the river mouth suggested locations affected by direct inputs from shoreline. A broad onshore-offshore gradient in water quality likely originated from the accumulation of discharges along the shoreline and mixed by alongshore currents suggested more diffuse land-based effects on water quality.

The spatial extent of patterns was broad for all parameters, however, the absolute ranges of values varied widely among the suite of features reported here. There was extensive enrichment of the nearshore with NO_2+NO_3 originating from the adjacent watersheds. The concentrations, however, did not exceed the CCME guideline for NO_2+NO_3 with the exception of sample near the mouth of the Bayfield River. Surprisingly, TP concentrations were low throughout the nearshore and, as supported by chlorophyll *a* concentrations, indicated that oligotrophic conditions prevailed over the study area. Levels of the fecal pollution indicator *E.coli* were low and suggestive of good conditions. Water clarity varied widely ranging from murky water along the shoreline to very clear conditions at the distant region.

3.5.2 Maitland Spring Survey

Physical conditions

The survey on May 28 was conducted during a period of declining discharge following a precipitation event on May 23 and rise in the Maitland River flow to 83 m^3s^{-1} on May 24. This discharge event itself was toward the end of a much longer period of high discharge, which had peaked approximately 10 days earlier. On the day of survey discharge was approximately 40 m^3s^{-1}, close to the annual average daily discharge of the Maitland River (Figure 21).

Thermal conditions were variable over the study area leading up to and during the survey. Surface temperature at the instrument site in the proximate region ranged from ~11 to 13ºC over the three days preceding the survey and were 1 to 4ºC warmer than the distant region. Surface temperature at the distant region instrument site ranged from 0.8 to 4.7ºC warmer than the bottom water (Figure 21). Water at the mouth of the Maitland River was 0.4 to 4.8ºC warmer than at the proximate region over the three days leading up to the survey. The surface temperature map for May 28 indicates a subtle onshore-offshore gradient and south-tending thermal plume at the Maitland River mouth (Figure 22).

A nearshore circulation pattern typical for the area was observed over the days leading up to the survey. Alongshore surface flow to the north prevailed for several days until reversing to the south the day before the survey. The southward flow was maintained over the survey period. Near-surface current speeds were variable reaching up to ~18 cm s^{-1} on occasion.

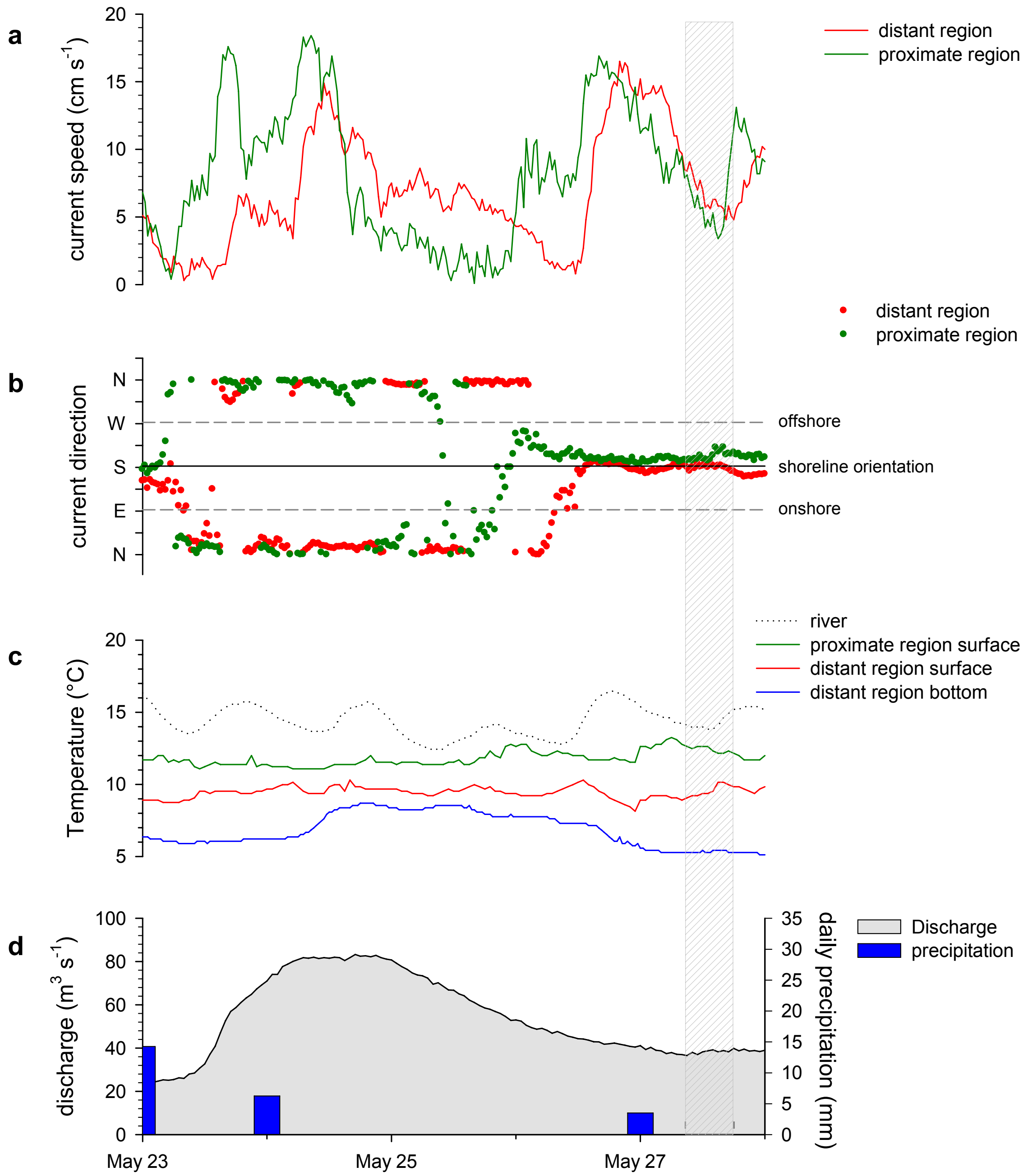

Figure 21: Maitland River study area spring survey. Physical conditions in the days before and during the survey (hatched region). Current speed (**a)** and direction (**b**) in the distant and proximate regions, temperature of the Maitland River and the distant and proximate regions (**c**), Maitland River discharge and local precipitation (**d**). See sections 2.3 and 2.5 for details.

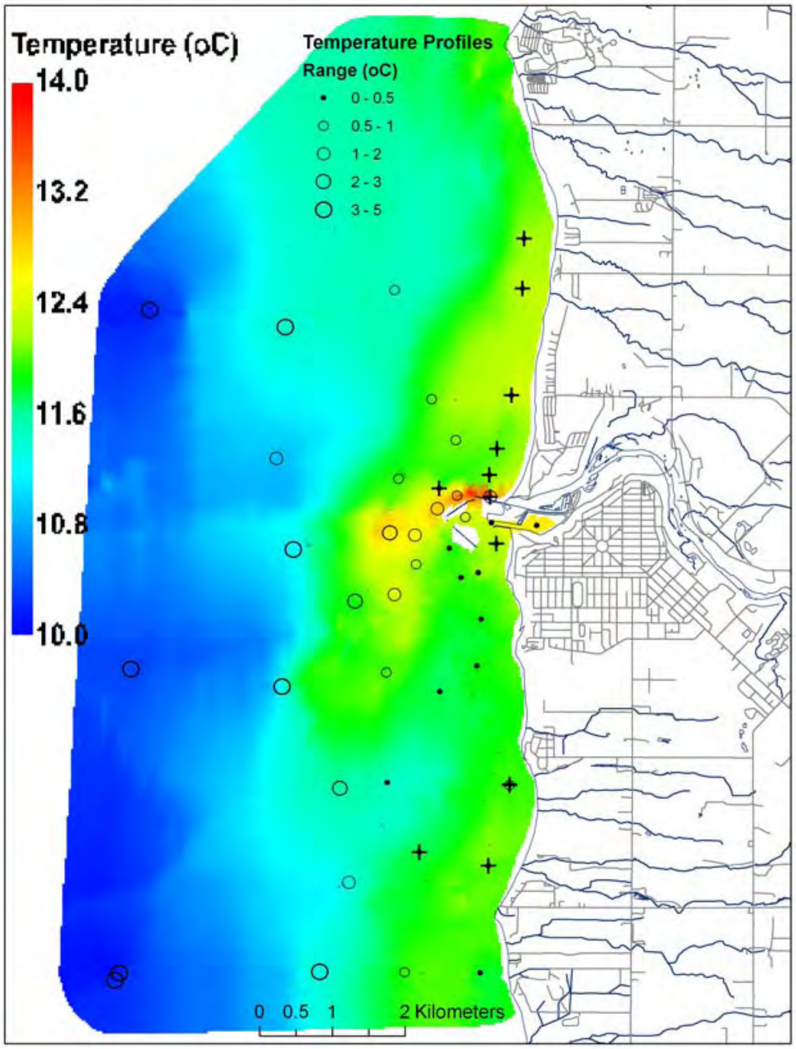

Figure 22: Surface water temperature (°C) at the Maitland River study area during the spring summer survey (May 27, 2003). The circles indicate locations of depth profiles of temperature with size proportional to temperature change with depth. The crosses indicate locations where water column was well mixed using a criterion of < 0.01 g cm^{-3} change per meter drop.

Water Quality

Conductivity

A feature of the variability in conductivity over the nearshore was a south-directed conductivity plume at the mouth of the Maitland River (Figure 23). The plume was deflected offshore at the river mouth but continued in a roughly shore-parallel orientation south of Goderich Harbour for several kilometres. Conductivity was moderately elevated over most of the shoreline south of the river mouth and appreciably less so north of the river mouth. It is uncertain whether the areas of elevated conductivity were solely due to discharge from the Maitland River or were due to a combination of river discharge and other inputs along the shoreline. Given the recent reversal of alongshore currents, it is likely that the area of weakly elevated conductivity north of the river mouth was due to the residual influence of previous northward movement of the Maitland River discharge. The overall onshore-offshore gradient in conductivity suggests that inputs to the lake remained close to the shoreline, rather than being dispersed toward the offshore.

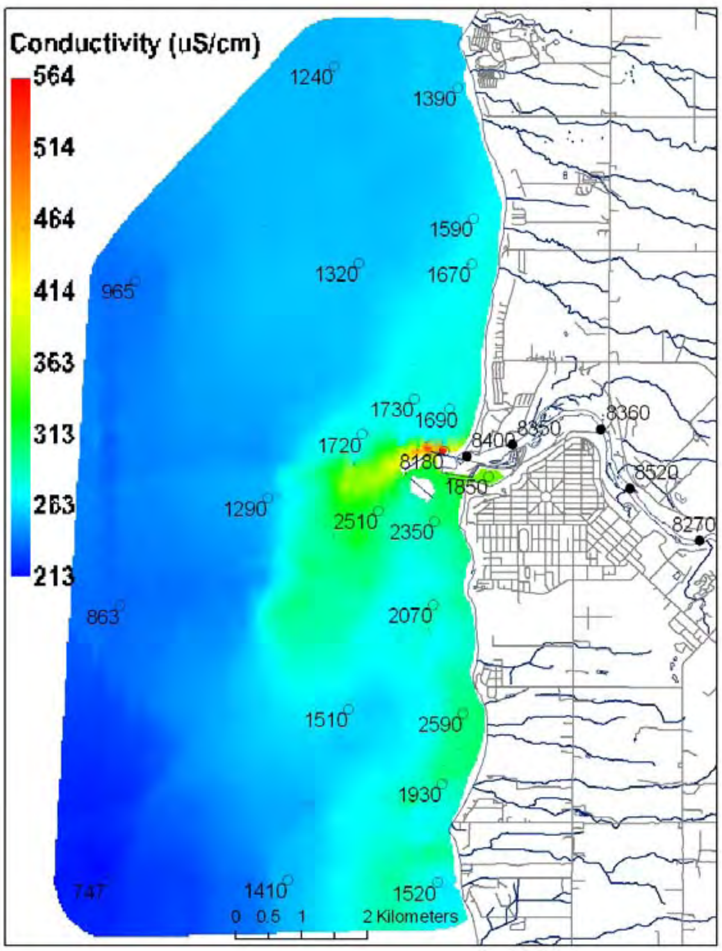

Figure 23: Surface conductivity (colour scale; µS cm^{-1} at 25°C) and NO_2+NO_3 concentrations (point samples; µg L^{-1} N) at the Maitland River study area during the spring survey (May 27, 2003).

NO_2+NO_3

Similar to the patterns of conductivity, the concentrations of NO_2+NO_3 in point samples were elevated along the shoreline, particularly within the conductivity plume, with lower levels in the distant region (Figure 23). The NO_2+NO_3 concentration near the mouth of the Maitland River exceeded 8000 µg L^{-1} and in combination with the strong river flow contributed an appreciable load of nitrogen to the nearshore at the time of survey. Concentrations were elevated ≥2x the distant region concentration over an area of 8.4 km^2. However, it is noteworthy that NO_2+NO_3 was elevated up to 2X the open lake concentrations in the distant region at distances of 5 km from the shoreline.

Turbidity

The spatial pattern in turbidity (Figure 24) was similar to that of conductivity, with a distinct plume from the Maitland River and areas of elevated turbidity along the entire shoreline. In contrast to conductivity, however, turbidity was not clearly different between the shoreline north and south of the Maitland River, suggesting that in addition to runoff, lakebed and shoreline erosion were contributors to turbidity along the shoreline. Of note was a small area of moderately elevated turbidity along the shoreline near the south end of the study. Given that conductivity was not correspondingly elevated in the area, this turbidity likely resulted from erosion of clay cliffs/shoreline adjacent to this location. The range in turbidity over the study area, was relatively small, from high clarity in the distant regions (0.6 FTU) to slightly turbid water along the shoreline (>1.5 FTU). Turbidity was elevated by ≥2x the distant region concentration over a large area of 36 km^2.

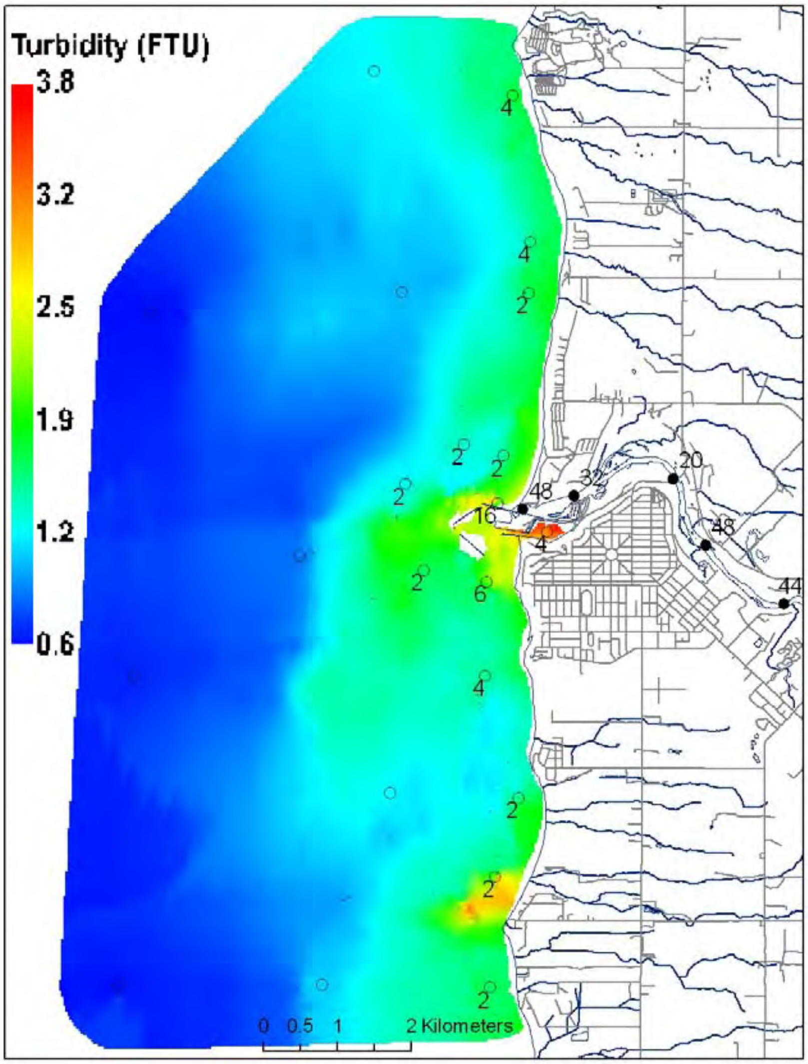

Figure 24: Surface turbidity (colour scale; FTU) and *E. coli* concentrations (point samples; CFU 100 mL^{-1}) at the Maitland River study area during the spring survey (May 27, 2003). Samples were not collected at points without numeric values.

E. coli

At the time of the spring survey *E. coli* levels were low throughout the study area (Figure 24). In the Maitland River near the lake, levels were < 50 CFU 100 mL^{-1}. The maximum concentration in the lake was 16 CFU 100 mL^{-1} at the mouth of the Maitland River. Otherwise, levels were $\leq$ 6 CFU 100 mL^{-1} at other lake stations.

Chlorophyll a

Despite the overall low concentrations of chlorophyll *a* over the study area there was appreciable relative variability among areas (Figure 25). An extensive area of very low chlorophyll *a* (<0.5 µg L^{-1}) prevailed over the area north of the Maitland River mouth and over a portion of the distant region south of the river. Loading of phytoplankton and/or of nutrients stimulating phytoplankton growth were clearly evident at the mouth of the Maitland River and possibly areas of shoreline south of the river mouth. The concentration gradient within the south-directed plume at the Maitland River mouth suggests that the plume may have, in large part, been driven by loading of phytoplankton from the river.

The more limited circulation of water within Goderich Harbour provides conditions in which growth response by algae to nutrient loading will be more persistent than on the open shoreline. While higher than that of the open lake, chlorophyll *a* concentrations within the harbour were not appreciably elevated, reaching a maximum level of 3.3 µg L^{-1}.

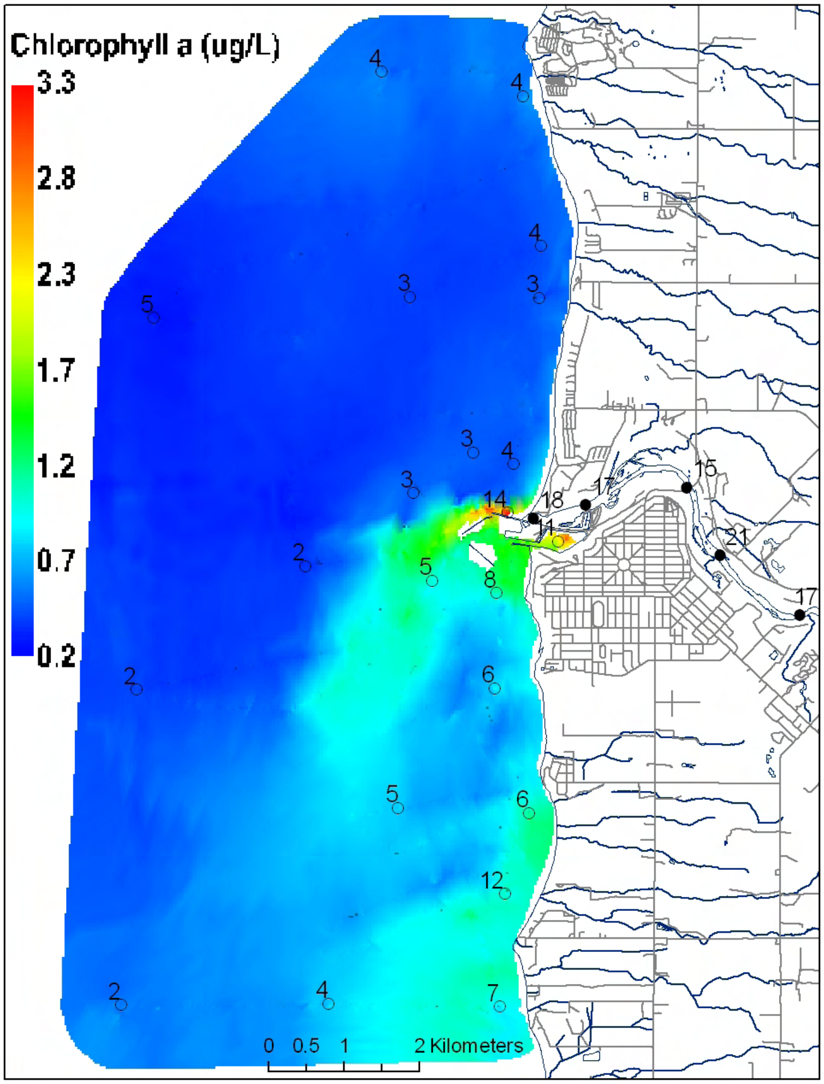

Figure 25: Surface chl *a* concentration estimated from fluorescence (colour scale; µg L^{-1}) and TP concentrations (point samples; µg L^{-1} P) at the Maitland River study area during the spring survey (May 27, 2003).

TP

Levels of TP observed during the spring survey suggested that oligotrophic conditions prevailed over the nearshore. During the spring survey, TP concentration at the mouth of the Maitland River was 18 µg L^{-1}, similar to that in the lower river. Concentrations of ≤ 5 µg L^{-1} TP were observed in the distant region. Total phosphorus concentrations at sites in the proximate region south of the Maitland River were elevated compared with corresponding sites to the north of the river mouth consistent with the flow regime at the time of survey. The extent of enrichment south of the Maitland River was modest and, with the exception of two samples, phosphorus concentrations were ≤ 8 µg L^{-1}. Goderich Harbour was more phosphorus rich than the open lake with a TP concentration of 14 µg L^{-1}.

General

The survey was conducted in late spring several days after rainfall. Tributary discharge was moderate and the survey fell within the period of declining river flow subsequent to elevated flow concurrent with the precipitation. There was weak alongshore flow to the south in the nearshore at the time of survey; however, there had been stronger southerly flows in the hours before the survey. The circulation pattern prior to and during the surveys shaped the patterns of water quality over the area. There was a southward-oriented plume at the mouth of the Maitland River extending for some distance along the shoreline. Levels of conductivity, turbidity, chlorophyll *a*, NO_2+NO_3 and TP were elevated in the mixing area of the discharge plume reflecting the differences in water quality between the river and distant region of the nearshore. The extent of the influence of the Maitland River discharge along the shoreline south of the river is uncertain. Areas of elevated conductivity, chlorophyll *a*, NO_2+NO and TP occurred towards the southern end of the study area, separated from the contiguous mixing area originating at the river mouth. It is uncertain whether the effects on water quality in these areas were due to inputs from the immediate shoreline (e.g. small creeks) or are a due to persistent (but variable) flow of the Maitland River plume in the southerly direction over a period of time. At a rate of flow of 15 cm s^{-1} (0.54 km h^{-1}), close to the maximum speed observed before the survey, it would take approximately 11 hours for the plume to move from the river mouth to the edge of the study areas ~ 6 km away.

The spatial extent of the mixing areas of discharge from the Maitland River was broad for all parameters. The ranges of variability and the environmental interpretation of these ranges varied among parameters. There was broad enrichment of the nearshore with NO_2+NO_3 originating from the adjacent watersheds, much of which appears to be delivered by the Maitland River. However, concentrations did not exceed the CCME guideline for nitrate for the protection of aquatic health. In contrast, TP levels were low throughout most of the nearshore. The shoreline south of the Maitland river mouth was slightly enriched with TP relative to other areas though concentrations remained low. The corresponding pattern of slightly higher concentrations of chlorophyll *a* to the south of the Maitland River is suggestive of a response to P loading, but may be in part driven by loading of phytoplankton to the lake from tributaries. Chlorophyll a levels at the Maitland River stations ranged from 3.2 to 4.5 µg L^{-1} on May 27. With the exception of the Maitland River Mouth and Goderich Harbour, even within the area of elevated chlorophyll *a*, levels did not exceed 2 µg L^{-1} (indicative of oligotrophic conditions). Levels of the fecal pollution indicator *E.coli* were low and suggestive of good conditions. Water clarity varied widely, ranging from slightly turbid water along the shoreline to very clear conditions at the distant region. Despite the strong connectivity between water quality in the nearshore and inputs from the watershed there was little evidence of adverse impacts on water quality as judged by conventional standards.

3.5.3 Saugeen Spring Survey

Physical conditions

The spring survey was conducted under relatively dry conditions but at a time of seasonally strong flow in the Saugeen River. There was moderate and stable flow in Saugeen River preceding the spring survey on May 28. Discharge ranged from 43 to 57 m^3s^{-1} at the stream flow gauge near the intensive river site. There was 3.6 mm of rainfall the day before the survey (Figure 26).

The temperature of the Saugeen River at the river mouth was 2ºC to 8ºC warmer higher than that of the proximate region of the lake over the period from four days before and during the spring survey. During this time, surface temperature at the instrument site in the proximate region increased gradually, diverging from the distant region surface temperature, and approaching that of the river. The water column at instrument site in the distant region was thermally stratified. Bottom temperature was near 4ºC with surface temperature 2ºC to 5ºC warmer than the bottom water. The surface water temperatures, measured more extensively on May 28, indicate a large thermal plume at the mouth of the Saugeen River oriented primarily along the shoreline NE of the river, but also extending some distance to the SW (Figure 27). The temperature range over the study area was wide, ranging from ~8ºC in the distant region to >15ºC at the mouth of the Saugeen River. Upon discharge of the warmer Saugeen River water to the lake it is likely that temperature-based density gradients would have affected the mixing and movement of the discharge plume within the nearshore.

Surface currents at the distant region measurement site preceding the spring survey varied in a roughly cyclical manner with seemingly strongest flows alongshore and to the south (Figure 26). Near to shore at the proximate region measurement site current speeds were weaker but widely variable in direction.

Over the day prior to the survey there were intervals of moderate (peak at ~8 cm s^{-1}) W to NW flow at the distant region and weak flow of variable direction at the proximate region site. During the survey period, currents were variable. At the distant site, current flow shifted from SW to NW over the survey period with current speed dropping as direction switched to the NE. At the proximate region flow ranged from E to NE direction. Current speed increased towards the later portion of the survey with flow in NE direction.

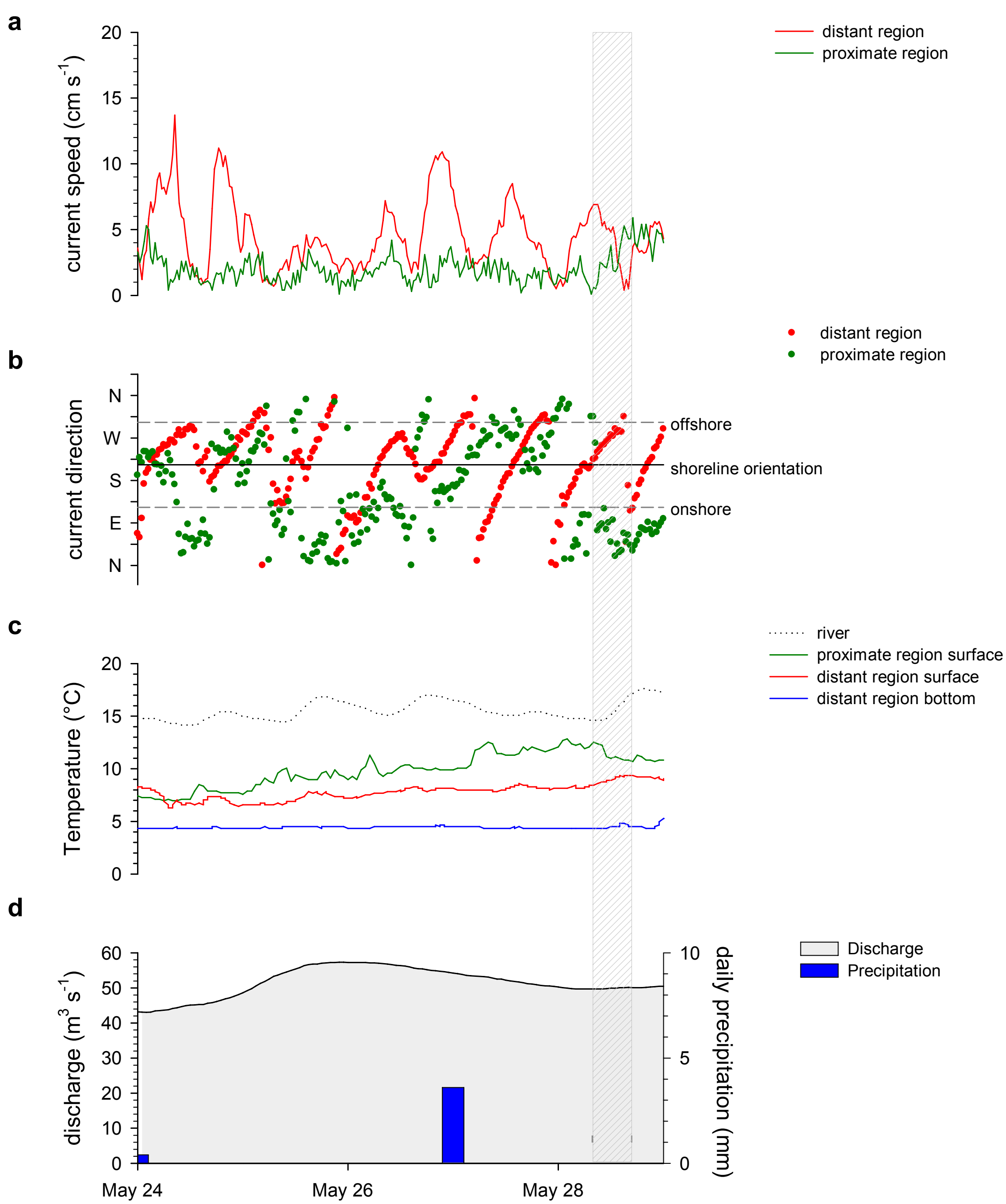

Figure 26: Saugeen River study area spring survey. Physical conditions in the days before and during the survey (hatched region). Current speed (**a**) and direction (**b**) in the distant and proximate regions, temperature of the Saugeen River and the distant and proximate regions (**c**), Saugeen River discharge and local precipitation (**d**). See sections 2.3 and 2.5 for details.

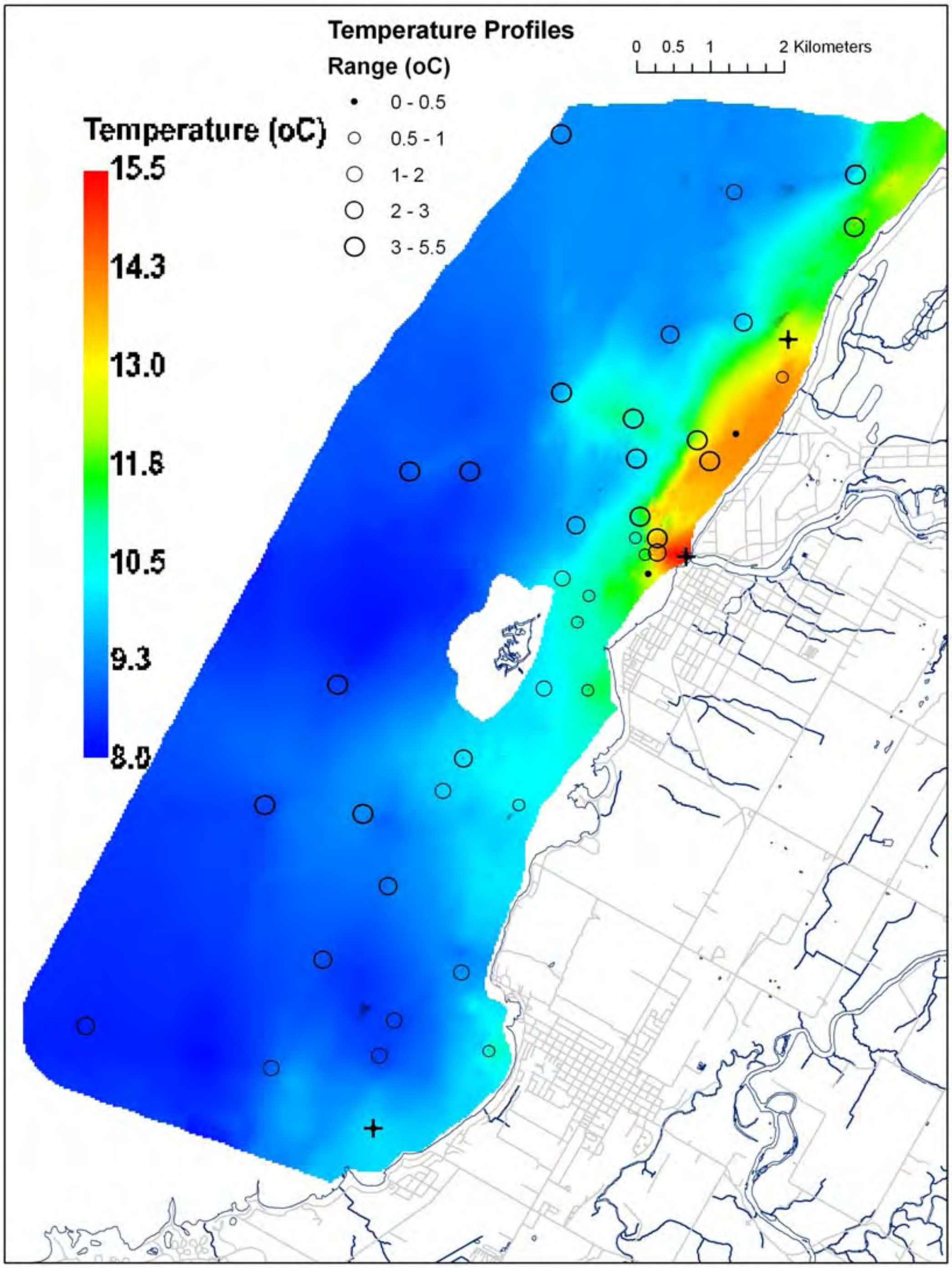

Figure 27: Surface water temperature (°C) at the Saugeen River study area during the spring survey (May 28, 2003). The circles indicate locations of depth profiles of temperature with size proportional to temperature change with depth. The crosses indicate locations where water column was well mixed using a criterion of < 0.01 g cm^{-3} change per meter drop.

Water Quality

Conductivity

A large conductivity plume originating at the mouth of the Saugeen River extended along the shoreline NE of the river, beyond the edge of the survey area, approximately six kilometres along the shoreline (Figure 27). A further area of elevated conductivity occurred for a limited distance along the opposite shoreline. The periods of flow in the opposing direction the day before the survey possibly account for the more limited elevation of conductivity in this area. The contiguous nature of gradient in conductivity along the shoreline suggests that the discharge from the Saugeen River was the primary source of input responsible for the elevated conductivity in the distant region. The conductivity plume size (90% dilution area) was 15 km^2. Conductivity was uniformly low along the shoreline south of Chantry Island including the shoreline along the town of Port Elgin.

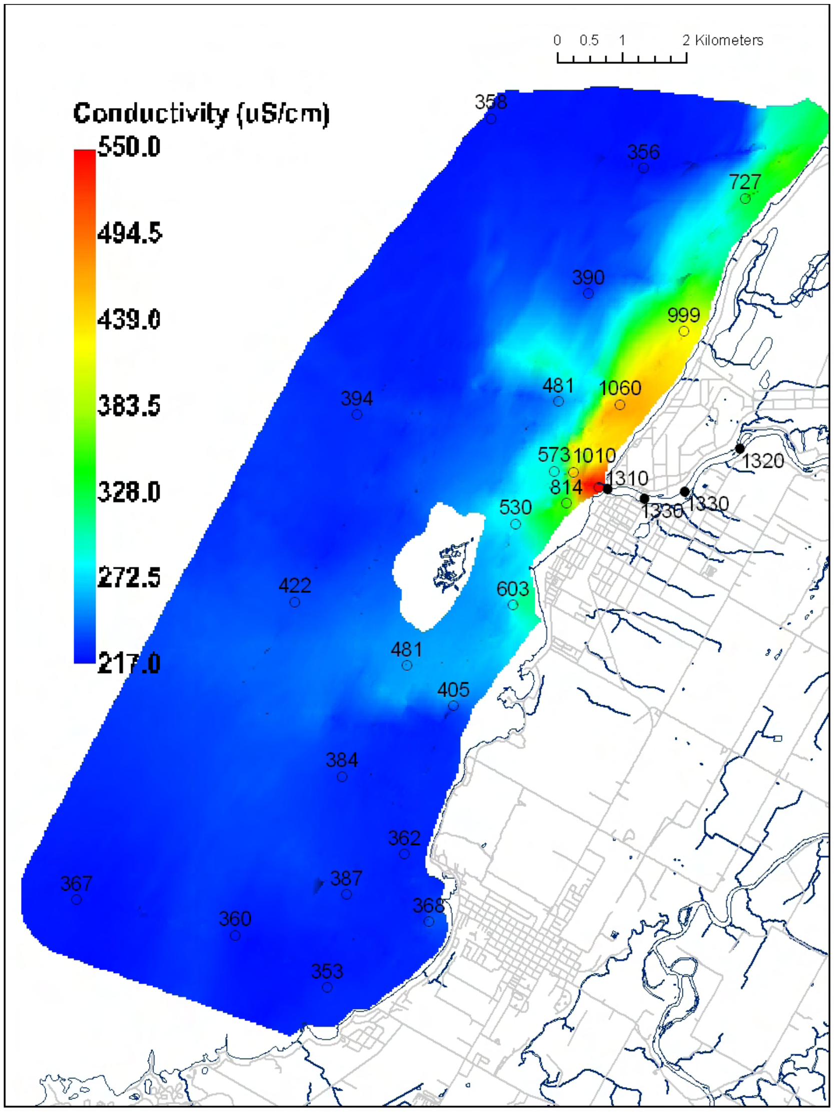

Figure 28: Surface conductivity (colour scale; µS cm^{-1} at 25°C) and NO_2+NO_3 concentrations (point samples; µg L^{-1} N) at the Saugeen River study area during the spring survey (May 28, 2003).

NO_2+NO_3

Levels of NO_2+NO_3 varied over the area in the same pattern as that of conductivity, with the highest NO_2+NO_3 concentrations in the conductivity plume NE of the river mouth (Figure 28). The degree of elevation of NO_2+NO_3 in the nearshore was more limited than observed at the more southerly study areas reflecting the lower NO_2+NO_3 concentration of the Saugeen River compared to the Maitland and Bayfield Rivers. At the time of survey, NO_2+NO_3 concentration at the mouth of the Saugeen River was

1310 μg L^{-1}. The NO_2+NO_3 concentrations at locations with low conductivity were < 400 μg L^{-1}. The ≥2x area for NO_2+NO_3 was limited in extent (2.8 km^2).

Turbidity

The spatial pattern in turbidity closely matched that of conductivity (Figure 29), suggesting that the discharge from the Saugeen River was the main source of turbidity in the nearshore during the spring survey. A 90% dilution area was calculated for turbidity (see Section 2.4). The 90% dilution area (7.3 km^2) for turbidity was appreciably smaller than that of conductivity (15 km^2). This suggests that turbidity was lost more rapidly from the water column than by dilution alone. It also corroborates the interpretation that the river was the primary source of turbidity at the time. A further implication is that the lakebed in the area of the conductivity plume is likely an area of deposition of river-derived sediment. Beyond the river-affected region, turbidity was low throughout the area (<1 FTU).

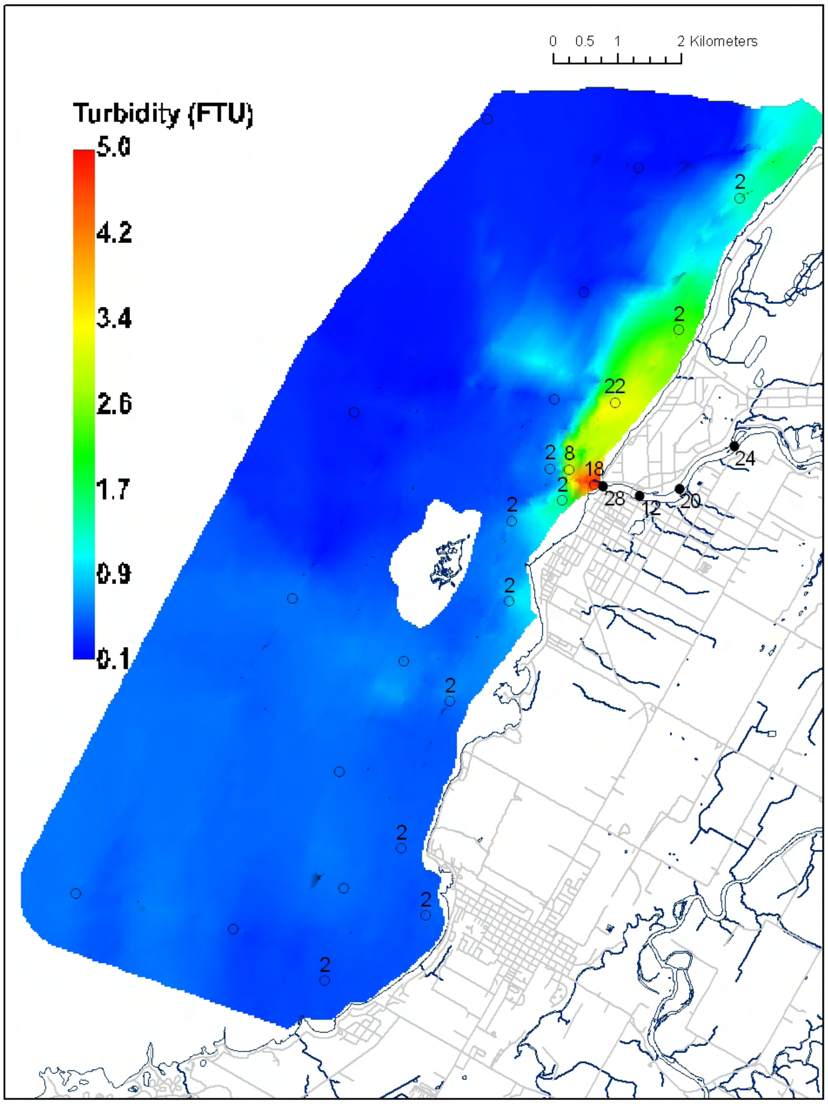

Figure 29: Surface turbidity (colour scale; FTU) and E. coli concentrations (point samples; CFU 100 mL^{-1}) at the Saugeen River study area during the spring survey (May 28, 2003). No samples collected at points without numeric values.

E. coli

There was little indication of fecal pollution at the time of survey as inferred from levels of the indicator *E. coli* (Figure 29). Highest levels were found at three stations very close to the river mouth (8, 18, and 22 CFU 100 mL^{-1}). Otherwise, nearshore levels were ≤ 2 CFU 100 mL^{-1}. Levels in the Saugeen River near the mouth were also low ≤ 28 CFU 100 mL^{-1}.

Chlorophyll a

Chlorophyll *a* concentrations followed a similar spatial pattern to the other measures (Figure 30) with elevated levels primarily along the shoreline NE of Saugeen River mouth. Despite the appreciable area affected by the Saugeen River, the magnitude of enrichment was limited. Chlorophyll *a* concentrations did not exceed 2 µg L^{-1} over the mixing area. Beyond this area, concentrations were < 1 µg L^{-1}; and < 0.5 µg L^{-1} over much of the nearshore. Concentrations in the Saugeen River ranged from 2.2 to 3.7 µg L^{-1}.

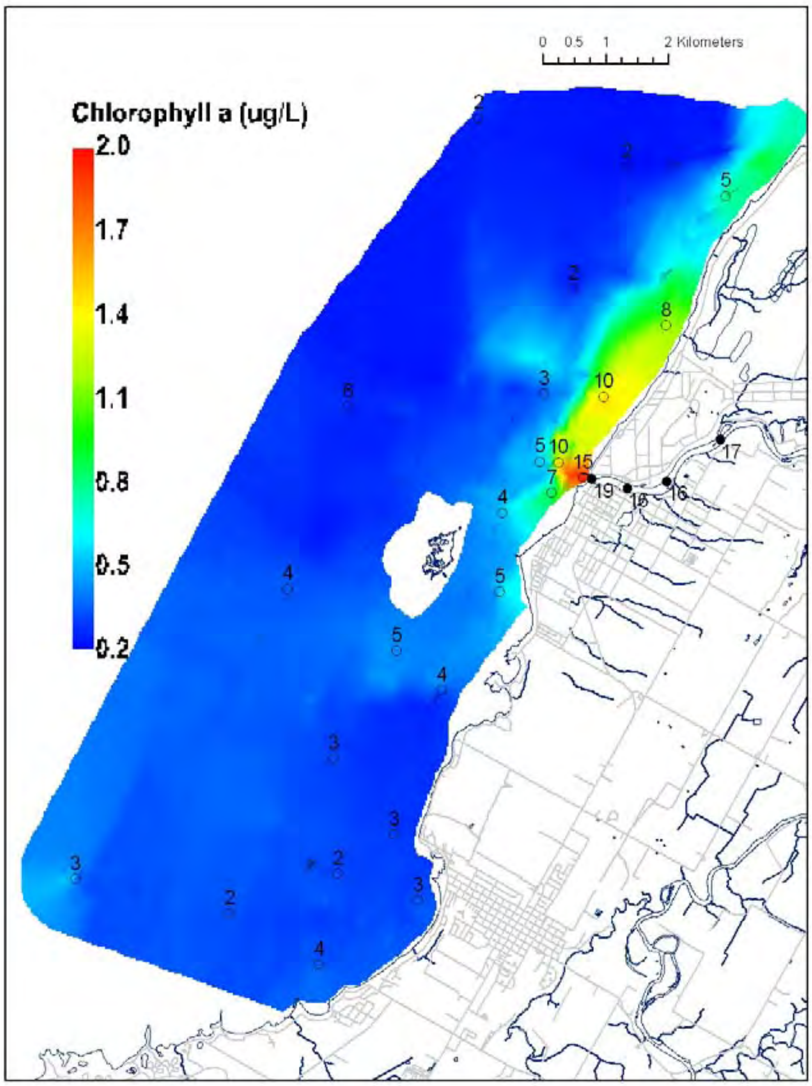

Figure 30: Surface chlorophyll *a* estimated from fluorescence (colour scale; µg L^{-1}) and TP concentrations (point samples; µg L^{-1} P) at the Saugeen River study area during the spring survey (May 28, 2003).

TP

Low phosphorus concentrations prevailed over the nearshore at the time of survey (Figure 30). Outside of areas with elevated conductivity, concentration of TP was <5 µg L^{-1}. Concentrations of TP in the plume-affected area were slightly higher (5-10 µg L^{-1}). At the mouth of the Saugeen River, TP concentration was 19 µg L^{-1}.

3.5.4 Saugeen Late Summer Survey

Physical Conditions

The late summer survey was conducted at a time of seasonally low watershed inputs to the nearshore. Dry weather preceded the survey with slight precipitation two days before the survey. Discharge from Saugeen River was at low (~16 m^3 s^{-1}) and in the range characteristic of baseflow. High winds on July 27, two days before the survey, are notable because of the potential of the resultant wave action and high current velocities to affect movement of materials in the nearshore.

A feature of surface currents during the days preceding the survey was an episode of strong alongshore flows at the distant region ADCP approximately two days before the survey (Figure 31). Current velocities in excess of 40 cm s^{-1} towards the NE were observed. During this time, currents at the proximate region ADCP were also to the NE but were comparatively weak (< 8 cm s^{-1}). Chantry Island and shallow waters lie SW of the proximate region ADCP and act as barriers to NE currents. During the day prior to the survey there was again N to NE flow at the more offshore ADCP but at low to moderate velocity. A similar flow pattern was maintained over the period of survey. Flows at the proximate region ADCP prior to and during the survey were weak in magnitude and variable in direction.

Surface temperature at both the distant and proximate region ADCP sites were <20°C and indicated recent intrusion and mixing of hypolimnetic water through the water column. Moderate offshore-directed flow components (at the surface) which occurred periodically through July likely contributed to the near chronic depression of water temperature in the nearshore subsequent to a downwelling event earlier in the month (see Figure 11). As surface water along the shoreline is pushed offshore there was a compensating flow of cooler bottom waters towards the shoreline resulting in the breakdown of thermal stratification and cooling of the water column. Water temperature near the lakebed at the distant region ADCP fluctuated appreciably over the days before the survey reflecting the instability of the thermal structure of the water column due to the interaction between warmer surface waters and cooler hypolimnetic water as the relative shoreward movement of the these thermal layers fluctuated. Periods with a wide range in temperature through the water column are interspersed with period of isothermal conditions.

Water temperature at the mouth of the Saugeen River was appreciably warmer than lake surface temperature during the survey (Figure 31) as it was much of the summer.

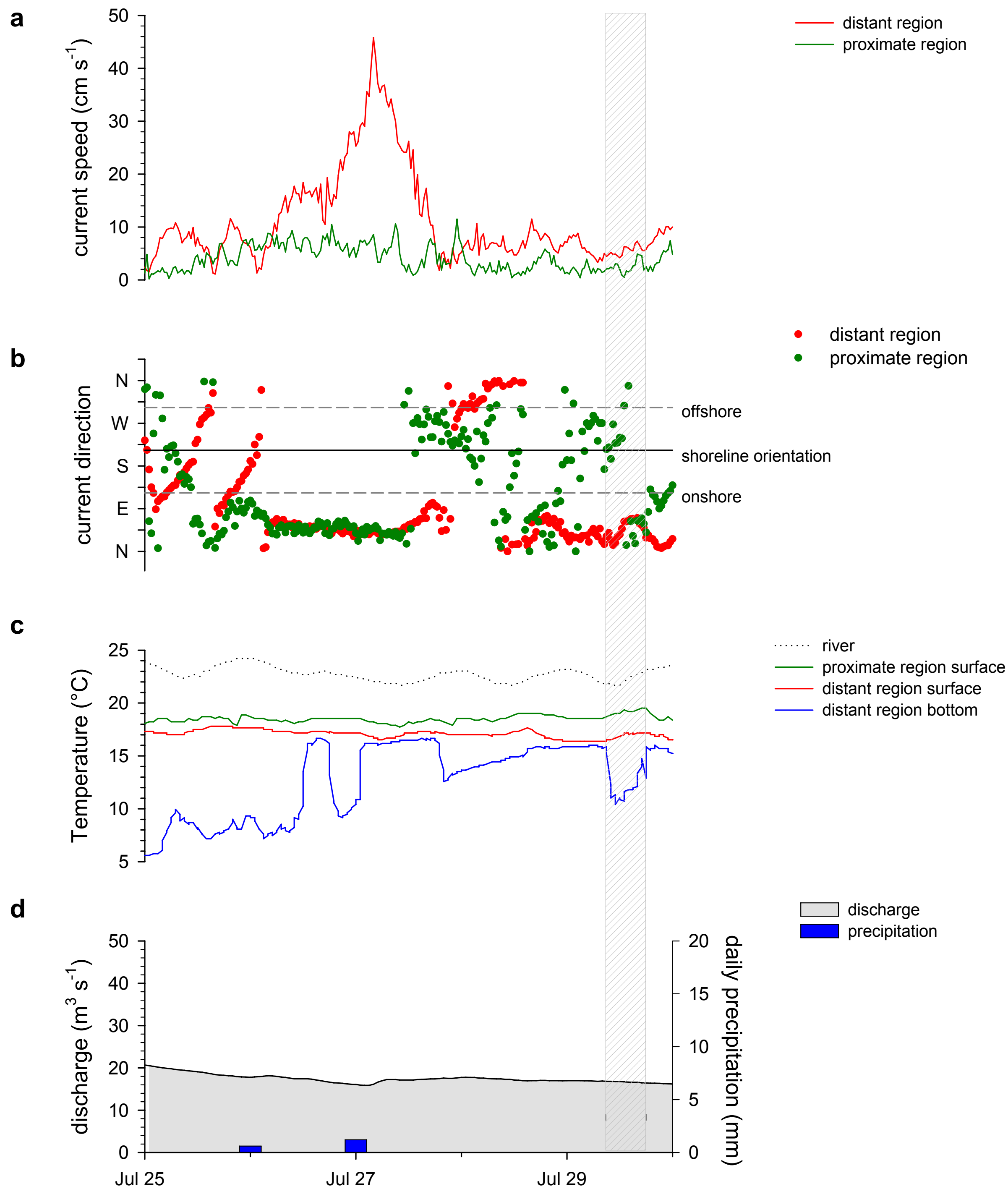

Figure 31: Saugeen River study area second summer survey (July 29, 2003). Physical conditions in the days before and during the survey (hatched region). Current speed (**a**) and direction (**b**) in the distant and proximate regions, temperature of the Saugeen River and the distant and proximate regions (**c**), Saugeen River discharge and local precipitation (**d**).

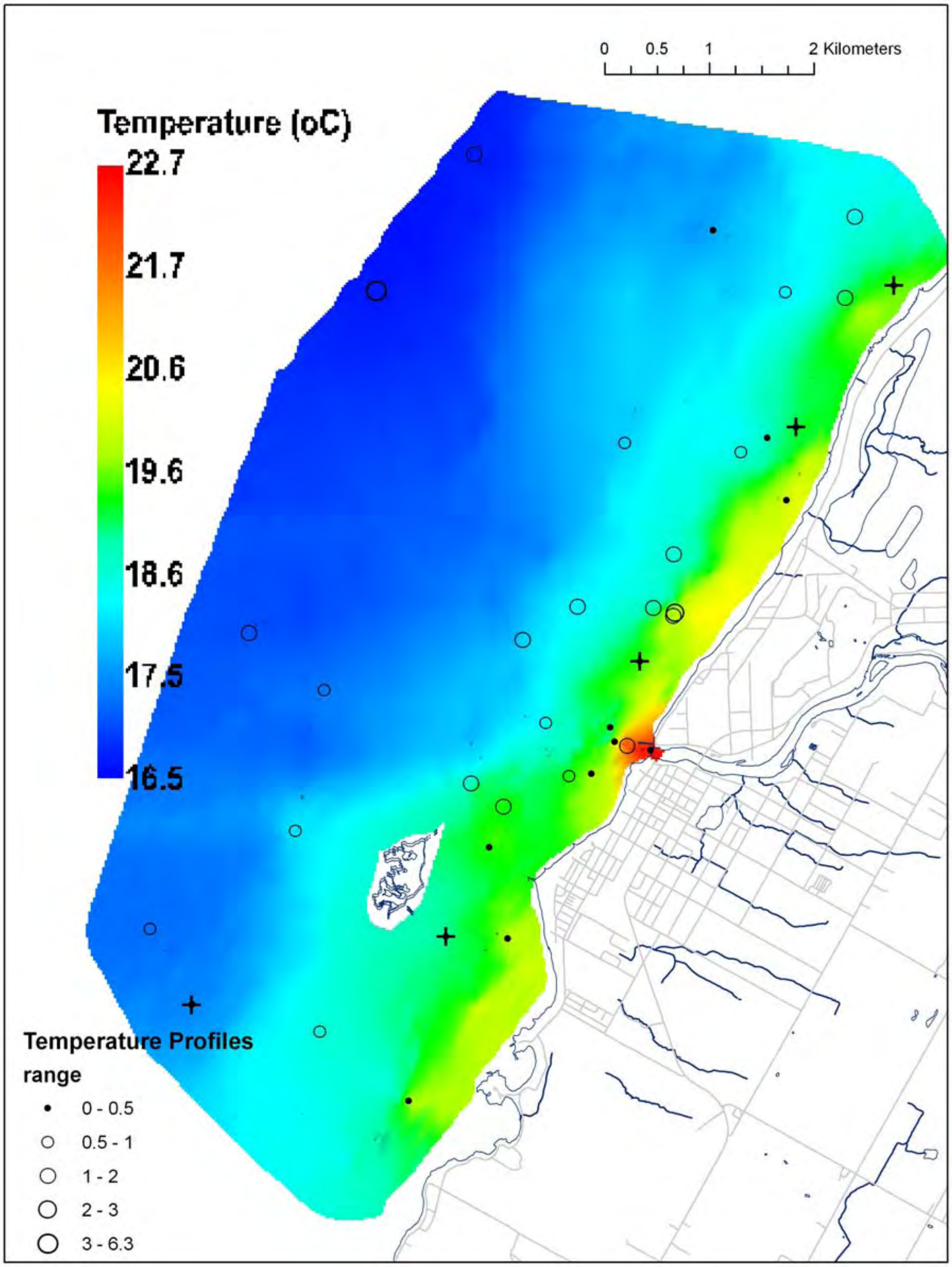

Figure 32: Surface water temperature (°C) at the Saugeen River study area during the second summer survey (July 29, 2003). The circles indicate locations of depth profiles of temperature with size proportional to temperature change with depth. The crosses indicate locations where water column was well mixed using a criterion of < 0.01 g cm^{-1} change per meter drop.

Water Chemistry

UV fluorescence of Hydrocarbons

Field conductivity data were not available for the late summer survey because of malfunction of the sensor. In situ measurements of UV-induced fluorescence in a range indicative of hydrocarbons (see Section 2.2.2) were used to identify the mixing area of discharge from the Saugeen River and other inputs along the shoreline. As with conductivity, hydrocarbon fluorescence of lake water is typically stable in the absence of exogenous inputs to the lake. Tributary water with a higher organic content usually exhibits a higher level of fluorescence which can be readily detected when discharged to the nearshore.

A broad area of elevated hydrocarbon fluorescence originating at the Saugeen River was detected along the shoreline north of the river mouth, extending to the edge of the study area (Figure 33). The source of the fluorescence was invariably the movement of water discharged by the Saugeen River moving and mixing with lake water along the NE shoreline. There was little variability in fluorescence along the shoreline SW of the river mouth suggesting little input of materials along the shoreline. The consistent low level of fluorescence of the distant region illustrates the consistency of fluorescence against which departures can be detected.

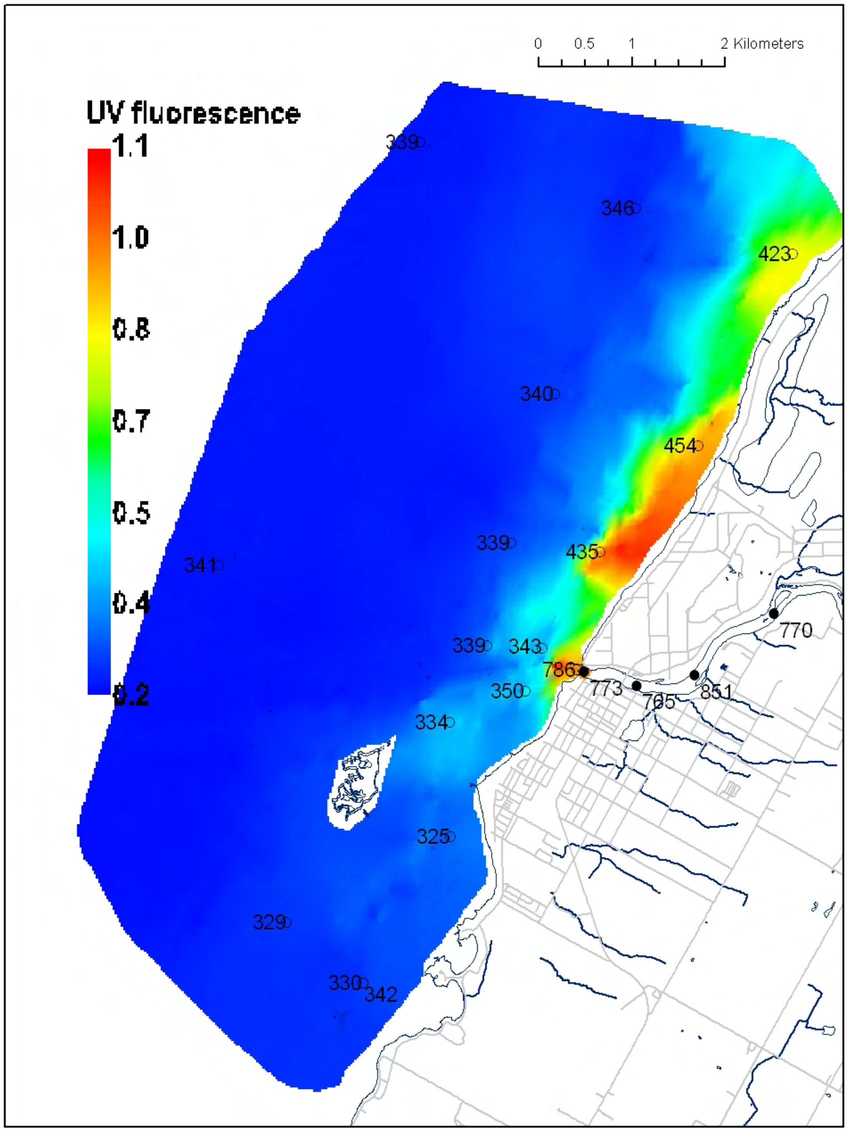

Figure 33: Surface UV fluorescence (colour scale; relative to µg L^{-1} of compound carbazole) and NO_2+NO_3 concentrations (point samples; µg L^{-1} N) at the Saugeen River study area during the second summer survey (July 29, 2003).

NO_2+NO_3

The levels of NO_2+NO_3 over the study area declined relative to the late spring survey. The average concentration of the lower Saugeen River sites of 789 µg L^{-1} was well below the CCME guideline. Three sites, north of the river mouth and within the area of elevated UV fluorescence, had marginally higher NO_2+NO_3 concentrations than elsewhere over the nearshore. Beyond the mixing area, levels ranged from 325 to 350 µg L^{-1}, concentrations typical of the lake offshore lake.

Turbidity

At the time of the late summer survey there was low turbidity throughout most of the nearshore with the exception of the shoreline affected by the discharge plume of the Saugeen River (Figure 34). Turbidity over the distant region was <0.5 FTU. A wide swath of more turbid water (1-4 FTU) occurred along the shoreline NE of the Saugeen River Mouth. The absence of elevated turbidity along the SW shoreline indicates that the source of the turbidity was the Saugeen River and not erosion and resuspension of bed sediments and shoreline. This is notable since river turbidity (7.1 FTU at the river mouth) was not particularly high at the time. The area of the lake that was elevated at least 2X compared to the distant region was 22.4 km^2.

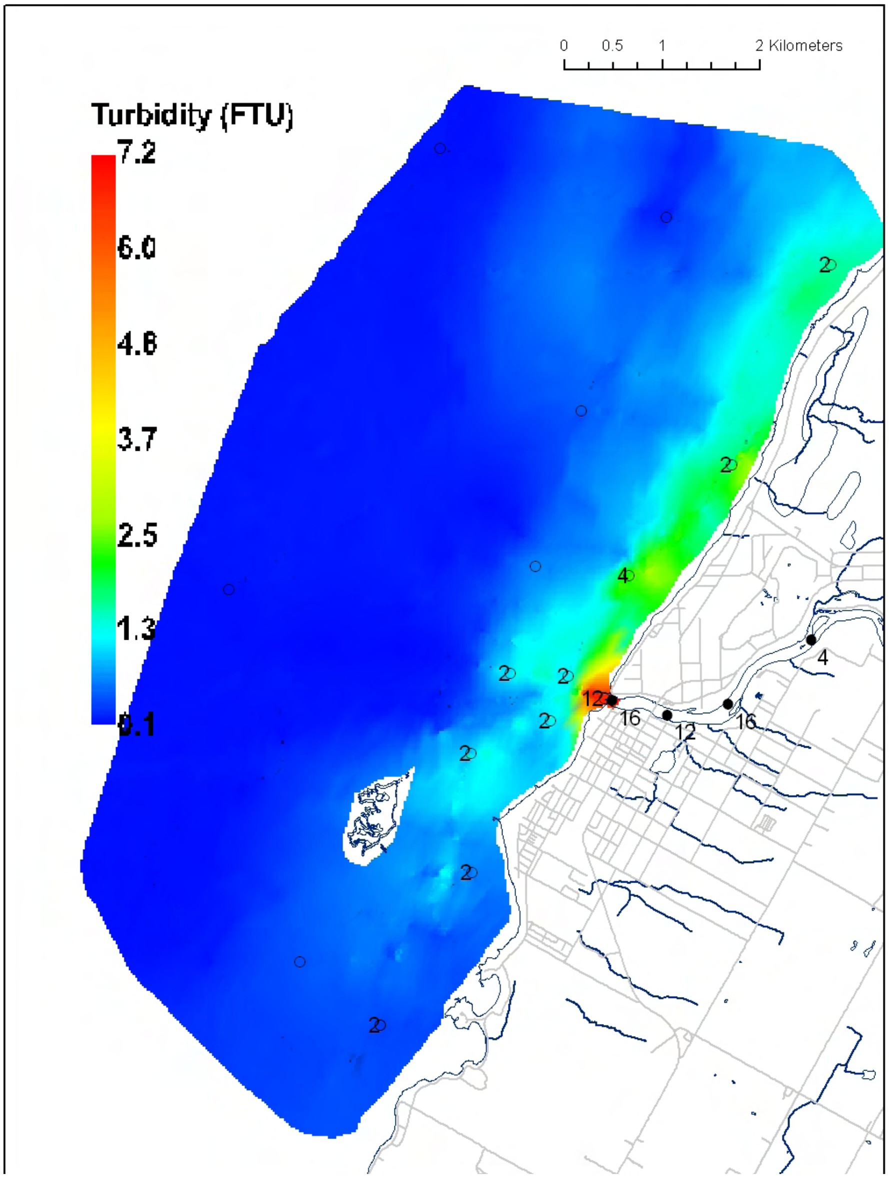

Figure 34: Surface turbidity (colour scale; FTU) and *E. coli* concentrations (point samples; CFU 100 mL^{-1}) at the Saugeen River study area during the second summer survey (July 29, 2003). No samples were collected at points without numeric values.

E. coli

Low levels of the fecal pollution indicator *E. coli* were detected in the lower Saugeen River and in the nearshore (Figure 34) . Lake levels along the shoreline were $\leq$ 4 CFU 100 mL^{-1} and only slightly higher in the lower river ($\leq$ 16 CFU 100 mL^{-1}).

Chlorophyll a

Chlorophyll *a* levels were slightly elevated in the mixing area of the Saugeen River discharge, however, levels were below concentrations suggesting appreciable enrichment (Figure 35). In the plume-affected areas, concentrations were < 2 μg L^{-1} and over much of the area remained below 1 μg L^{-1}. Chlorophyll *a* concentrations at the Saugeen River stations were low (0.8 to 1.3 μg L^{-1}). Over much of the nearshore, concentrations were < 0.5 μg L^{-1} and clearly suggestive of highly oligotrophic conditions.

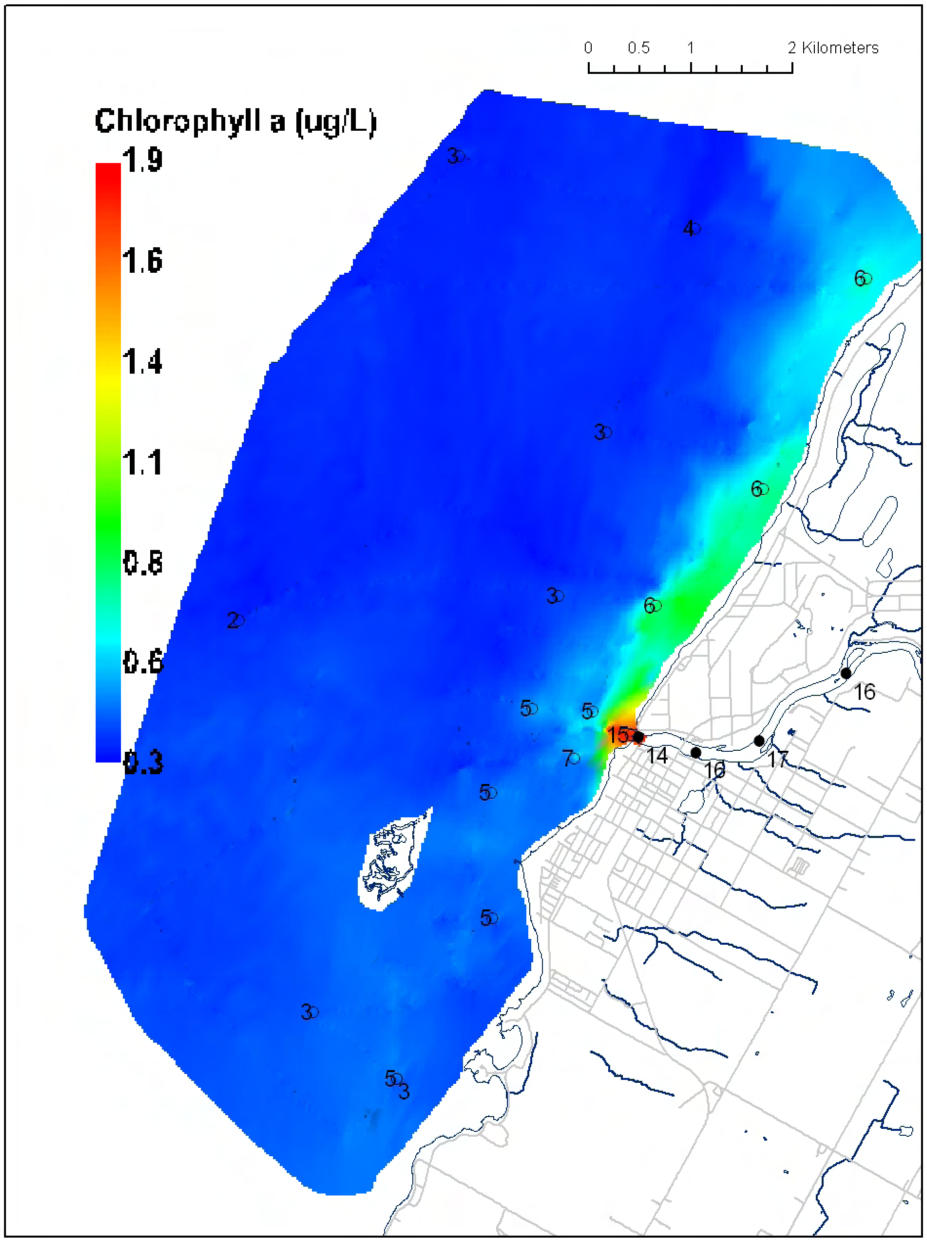

Figure 35: Surface chlorophyll *a* concentration estimated from fluorescence (colour scale; µg L^{-1}) and TP concentrations (point samples; µg L^{-1} P) at the Saugeen River study area during the second summer survey (July 29, 2003).

TP

Consistent with the chlorophyll *a* data, there were low levels of phosphorus throughout the study area including the lower Saugeen River (Figure 35). The average TP concentration in the lower Saugeen River of 16 µg L^{-1} was below the PWQO for phosphorus in streams (30 µg L^{-1}) . Levels in the lake ranged from 2 to 7 µg L^{-1}. There was a slight indication of a marginally higher TP concentration along the NE shoreline the differences were within the range of uncertain reliability for the analysis.

3.5.5 Maitland Late Summer Survey

Physical Conditions

The late summer survey was conducted at a time of seasonally low watershed inputs to the nearshore. Dry weather preceded the survey and discharge from Maitland River was low (~6 $m^3 s^{-1}$) and in the range characteristic of baseflow (Figure 36).

In the days before the survey, surface currents at the proximate and distant region ADCPs were approximately similar. Alongshore flow dominated 3-4 days before the survey in alternating north and south directions (Figure 35). Just before the survey, a weak onshore current developed in both regions, shifting to stronger alongshore flow in a N to NE direction during the survey period.

Distant and proximate region surface temperatures were similar before and during the survey, suggesting uniform surface temperatures over the nearshore (Figure 35). Bottom temperatures at the distant region ADCP were slightly cooler than at the surface. Temperature at the mouth of the Maitland was 2-5°C warmer than the lake. River temperature exhibited a diurnal temperature pattern, rising several degrees from the morning to late afternoon. Lake surface temperature was not mapped during the nearshore survey because of a malfunction of the sensor. Surface temperatures at profile sites are presented in Figure 37. There was a slight north to south gradient in surface temperature.

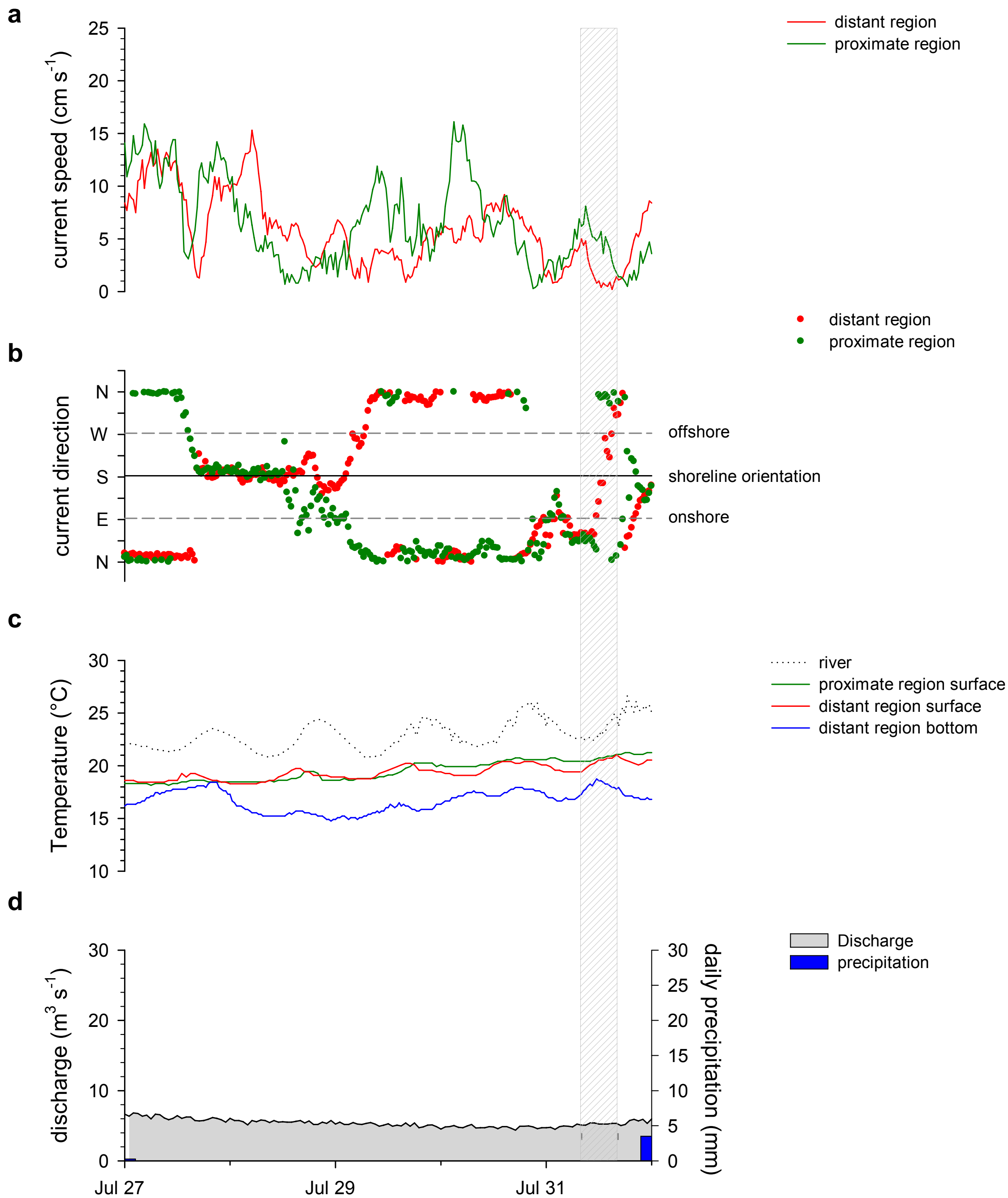

Figure 36: Maitland River study area second summer survey (July 31, 2003). Physical conditions in the days before and during the survey (hatched region). Current speed (**a**) and direction (**b**) in the distant and proximate regions, temperature of the Maitland River and the distant and proximate regions (**c**), Maitland River discharge and local precipitation (**d**).

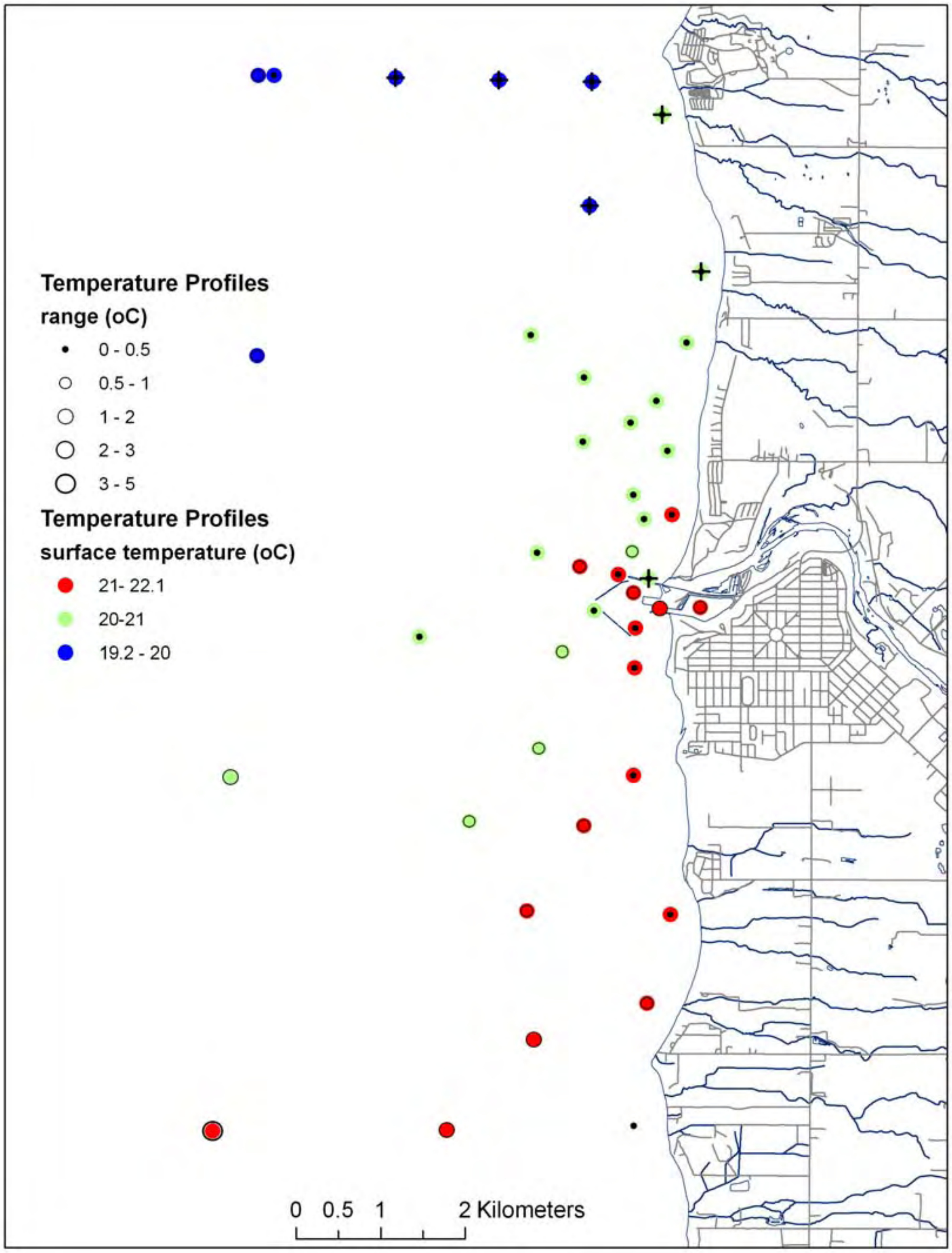

Figure 37: Surface water temperature (°C) at the Maitland River study area during the second summer survey (July 31, 2003). The circles indicate locations of depth profiles of temperature with size proportional to temperature change with depth. The crosses indicate locations where water column was well mixed using a criterion of < 0.01 g cm^{-1} change per meter drop.

Water Quality

UV fluorescence of Hydrocarbons

Field conductivity data were not available for the late summer survey because of malfunction of the sensor. In situ measurements of UV-induced fluorescence in a range indicative of hydrocarbons were used to identify the mixing area of discharge from the Maitland River and other inputs along the shoreline (see Section 2.2.2).

The fluorescence pattern indicated a discharge plume from the Maitland River and mixing area oriented along the shoreline north of the river mouth (Figure 38). Approximately 2 km north of the river mouth, the mixing area curved to the NW, in the same direction as surface flow at the beginning of the survey. Fluorescence levels south of the river mouth were uniformly low and similar to the proximate region, indicating little influence of the Maitland River at the time of the survey.

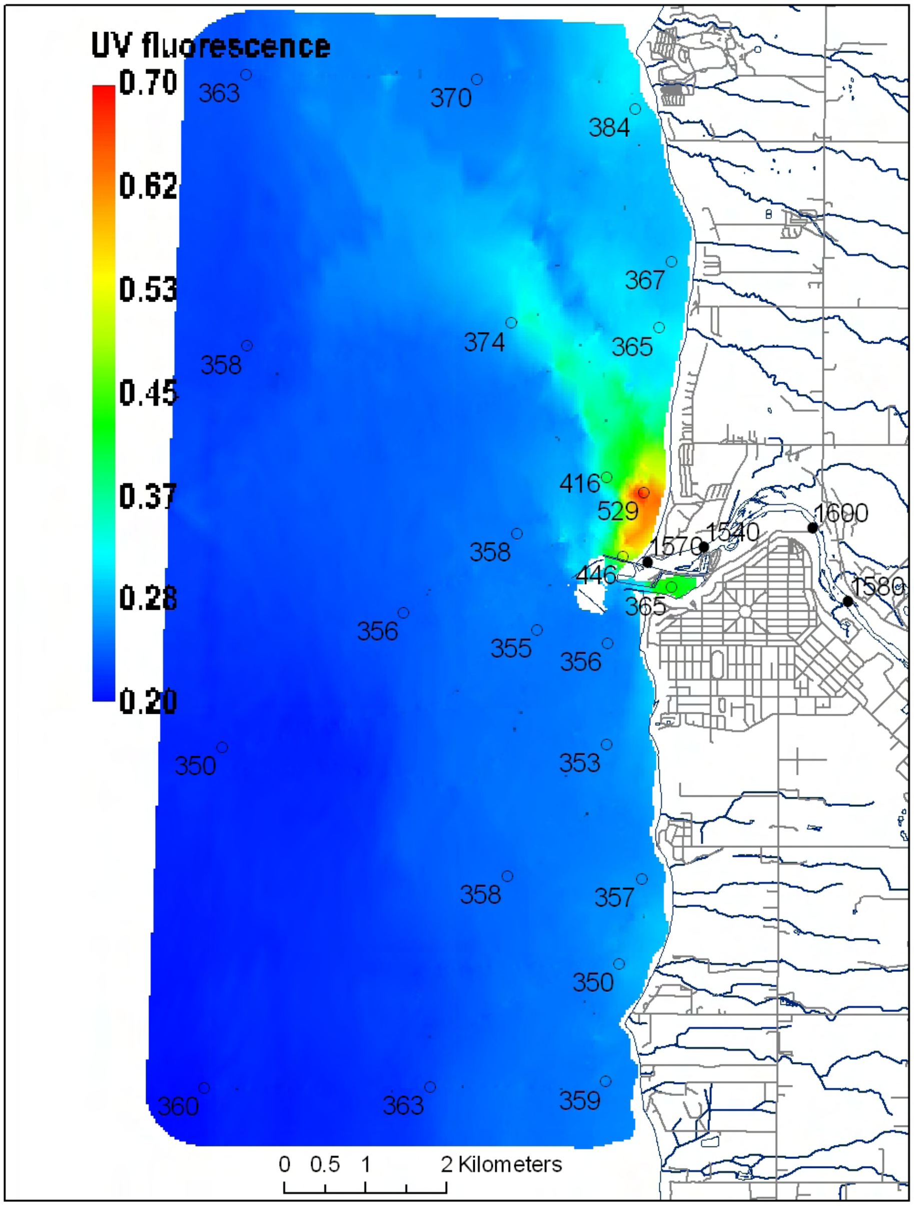

Figure 38: Surface UV fluorescence (colour scale; relative to µg L of compound carbazole) and NO_2+NO_3 concentrations (point samples; µg L^{-1} N) at the Maitland River study area during the second summer survey (July 31, 2003).

NO_2+NO_3

The portion of the nearshore with elevated NO_2+NO concentrations was limited and confined to the area identified as the mixing area of the discharge from Maitland River by UV fluorescence (Figure 38). Maitland River NO_2+NO_3 concentration had declined appreciably from the spring but remained approximately four times that of the distant region average concentration. The offshore NO_2+NO_3 concentration of 320 µg L^{-1} as measured by US EPA (Table 4) was very similar to the average of the distant region 359 µg L^{-1}. Over the study area south of the Maitland River concentrations ranged from 350 to 363 µg L^{-1} compared with a range of 358 to 529 µg L^{-1} north of the river.

Turbidity

Relatively low turbidity and clear water conditions prevailed throughout the nearshore (Figure 39). With exception of Goderich Harbour, turbidity was < 1 FTU over the study area. Turbidity was also low in the lower Maitland River (2.7 FTU). The position of the turbidity plume from the Maitland River closely paralleled the UV fluorescence plume (Figure 37). There was also a zone of slightly higher turbidity south of the river mouth adjacent to the shoreline that did not appear to correspond with areas of elevated UV fluorescence. Turbidity in this area was likely due to erosion of shoreline and lake bed.

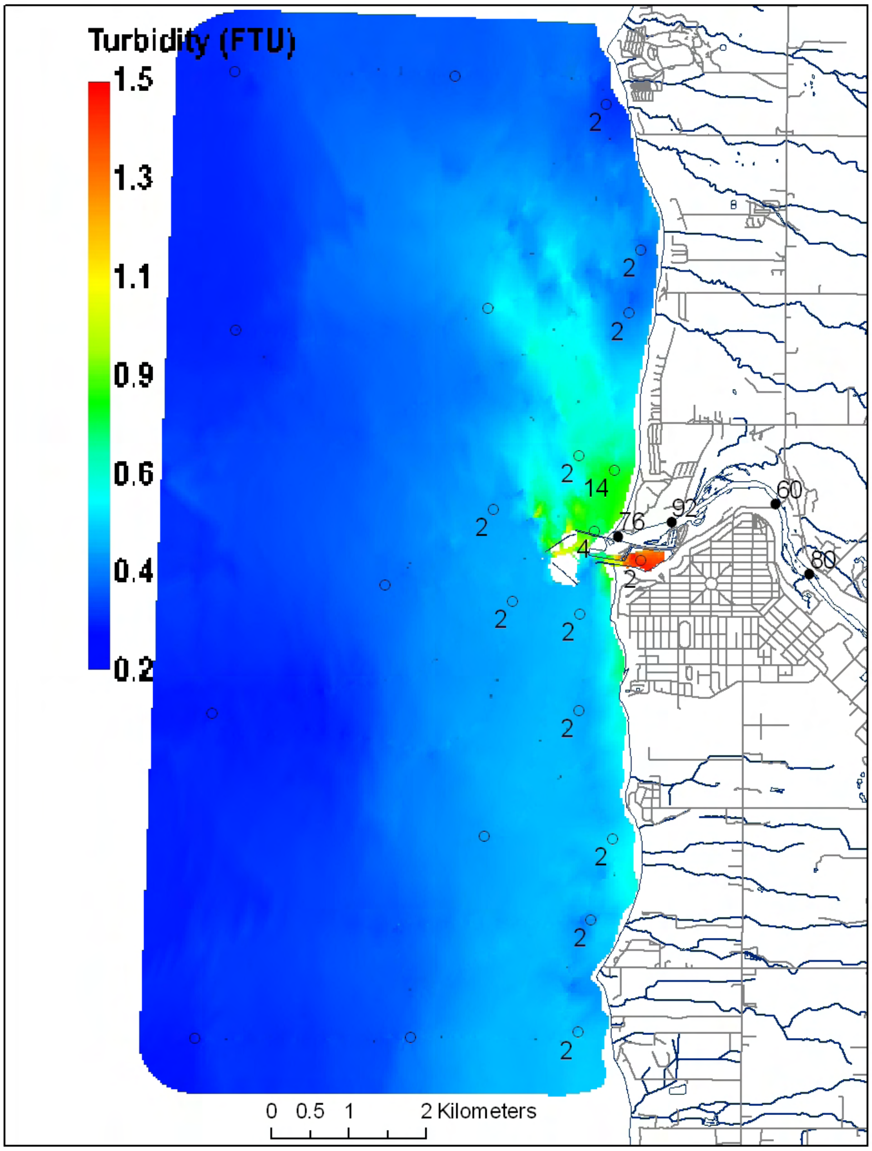

Figure 39: Surface turbidity (colour scale; FTU) and *E. coli* concentrations (point samples; CFU 100 mL^{-1}) at the Maitland River study area during the second summer survey (July 31, 2003). No samples were collected at points without numeric values.

E. coli

E. coli concentrations in the lower Maitland River were low (76 CFU 100 mL^{-1} - average of river stations). Maximum level of *E. coli* in the nearshore was 14 CFU 100 mL^{-1} and counts were ≤ 2 CFU 100 mL^{-1} in other samples with only one exception (Figure 39).

Chlorophyll a

Low levels of chlorophyll *a* were observed throughout the study area. Maximum levels in the nearshore did not exceed 1 μg L^{-1} with the exception of Goderich Harbour where, even under embayed conditions, concentrations did not exceed 2 μg L^{-1} (Figure 40). The average concentration in the lower Maitland River (2.0 μg L^{-1}) was the lowest measured over the four nearshore surveys. At the distant region, the average concentration (0.4 μg L^{-1}) was similar to those of other survey dates.

Despite the low levels of chlorophyll *a*, distinct patterns of variability were evident over the study area. An area of slightly elevated chlorophyll *a* concentration north of the Maitland River coincided with the area of elevated UV fluorescence (Figure 38). There were also small patches of elevated chlorophyll *a* south of the river mouth, one in the area of Goderich Rotary Beach, coincident with an area of increased turbidity. Nutrient inputs along the shoreline may have stimulated phytoplankton growth in these regions. However, evidence for this from other field measurements or chemical analysis of discrete water samples is lacking.

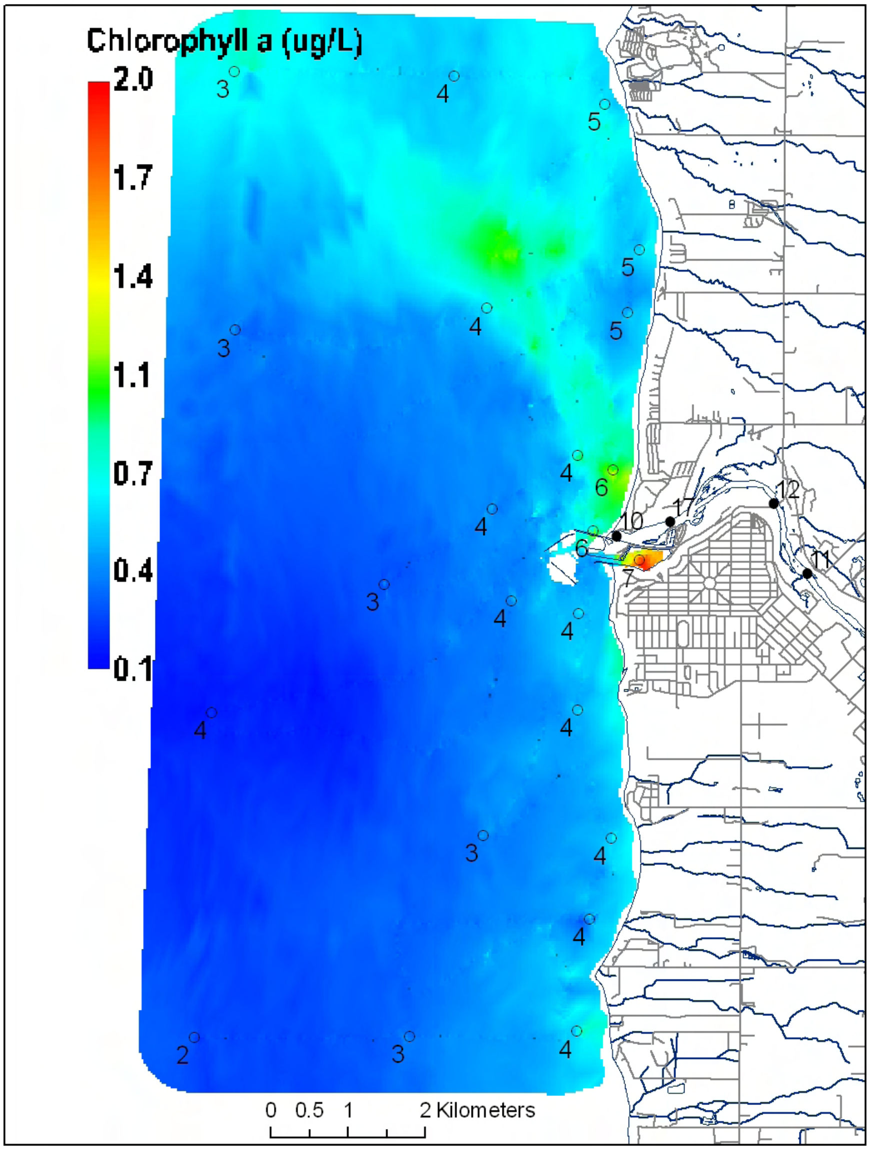

Figure 40: Surface chlorophyll *a* concentration estimated from fluorescence (colour scale; µg L^{-1}) and TP concentrations (point samples; µg L^{-1} P) at the Maitland River study area during the second summer survey (July 31, 2003).

TP

Low levels of TP prevailed over the nearshore study area with concentrations ≤ 6 µg L^{-1}. The average concentration in the lower Maitland River was 12 µg L^{-1}. In the distant region, the average concentration was 3 µg L^{-1}, similar to that of the offshore concentration of 2 µg L^{-1} measured by US EPA (Table 2).

3.5.6 Bayfield Late Summer Survey

Physical conditions

The late summer survey was conducted two days following a moderate rain event and during a period of elevated flow in Bayfield River driven by the precipitation. Prior to the rainfall on August 3, the flow at the downstream gauge on the Bayfield River was < 1 $m^3 s^{-1}$ and at baseflow. At the start of nearshore survey, river discharge was approximately 7 $m^3 s^{-1}$, having declined from a high of 14 $m^3 s^{-1}$ on August 4 (Figure 41).

Over the four days before the survey, lake surface currents fluctuated between weak onshore flows and much stronger alongshore southerly flows at the distant region ADCP (Figure 41). In the hours prior to and during the survey, there was near-consistent alongshore flow towards the south. Near-surface current speed increased progressively over the survey period reaching speeds of > 10 cm s^{-1}. Current data were not available for the proximate region due failure of the ADCP.

As inferred from temperature data collected at the Maitland study area, distant and proximate region surface temperatures were similar in the days preceding and during the survey. However, there was appreciable variability in thermal structure of the water column at the distant region. Bottom temperature rose during brief periods coincident with offshore (west) surface flow and fell with the return to southerly flow.

Temperature at the mouth of the Bayfield River was initially warmer than lake surface (as inferred from Maitland area data) but began to cool slightly after the rainfall on August 3. River temperature was similar to lake surface temperatures by the day of survey.

Lake surface temperatures at the time of survey varied over a small range (21.7 to 23.4°C) yet varied systematically over an onshore-offshore gradient likely due to more rapid warming of shallower water near the shoreline during the daytime (Figure 42).

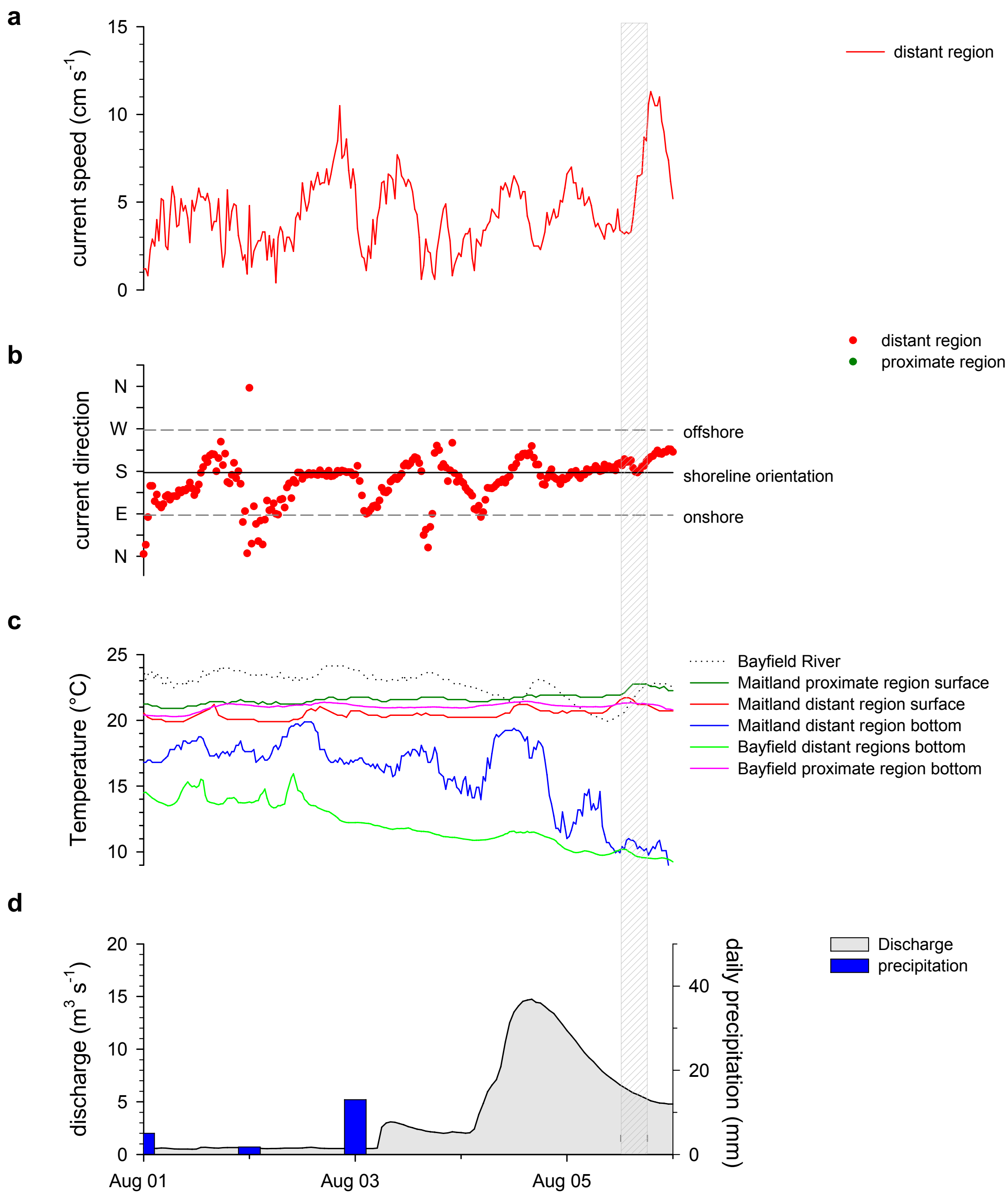

Figure 41: Bayfield study area second summer survey (August 5, 2003). Physical conditions in the days before and during the survey (hatched region). Current speed (**a**) and direction (**b**) in the distant region, temperature of the Bayfield River and the distant and proximate regions (note that some data are for the Maitland study area) (**c**) Bayfield River discharge and local precipitation (**d**). See sections 2.3 and 2.5 for details.

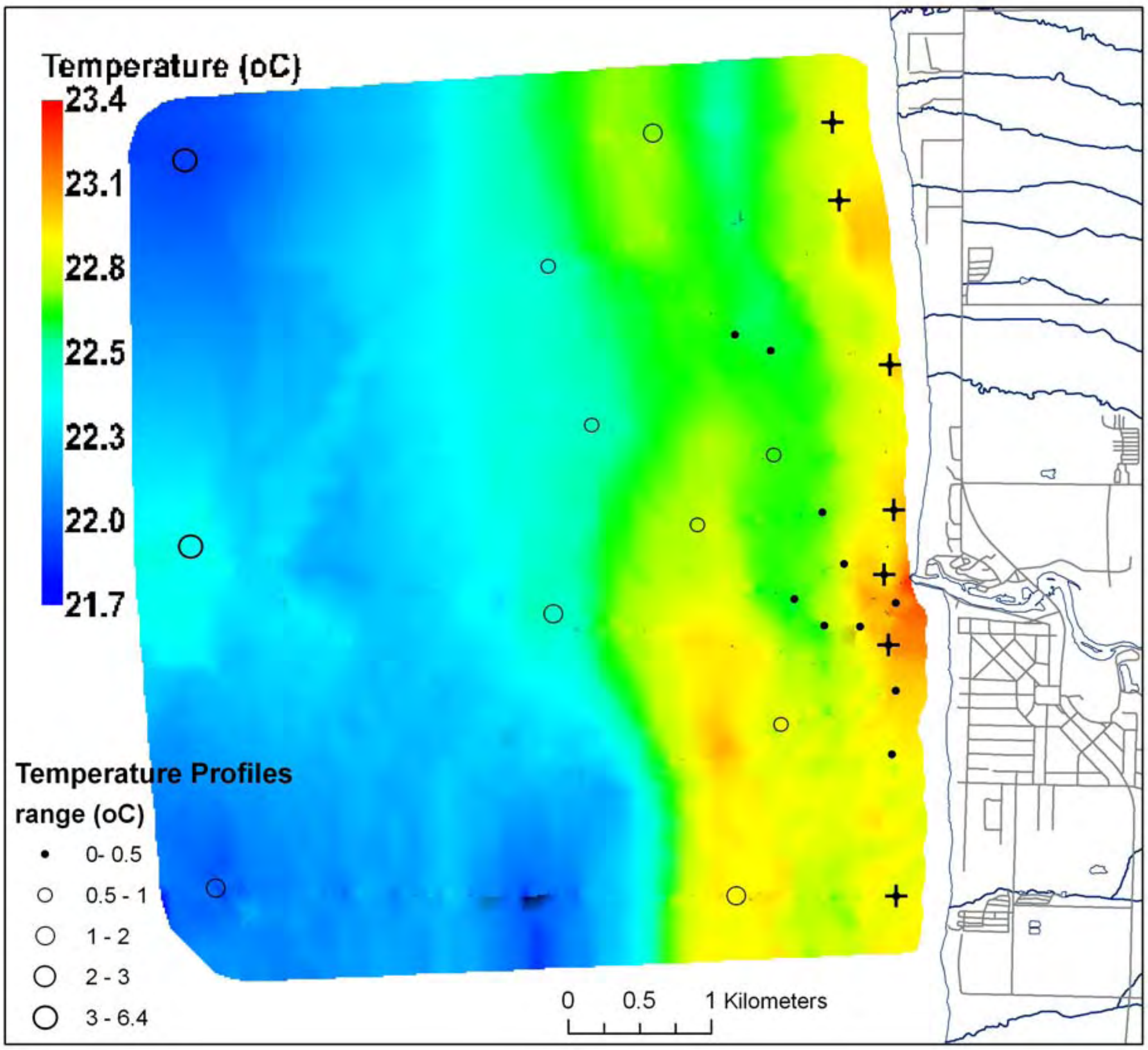

Figure 42: Surface water temperature (°C) at the Bayfield River Survey area during the late summer survey (August 5, 2003). The crosses indicate locations where water column was well mixed using a criterion of < 0.01 g cm^{-3} change per meter drop.

Water Quality

Conductivity

There was a conductivity plume at the mouth of the Bayfield River oriented primarily along the shoreline to the south (Figure 43). The marginally elevated conductivity directly west and to the NW to N of the river mouth is likely due to residual effects of movement of river discharge during the brief period of offshore surface flow in the day prior to the survey. The size of the 90% dilution area of conductivity was 0.13 km^2. Conductivity was uniformly low at levels indicative of the lake background for the nearshore beyond the area affected by discharge from the Bayfield River.

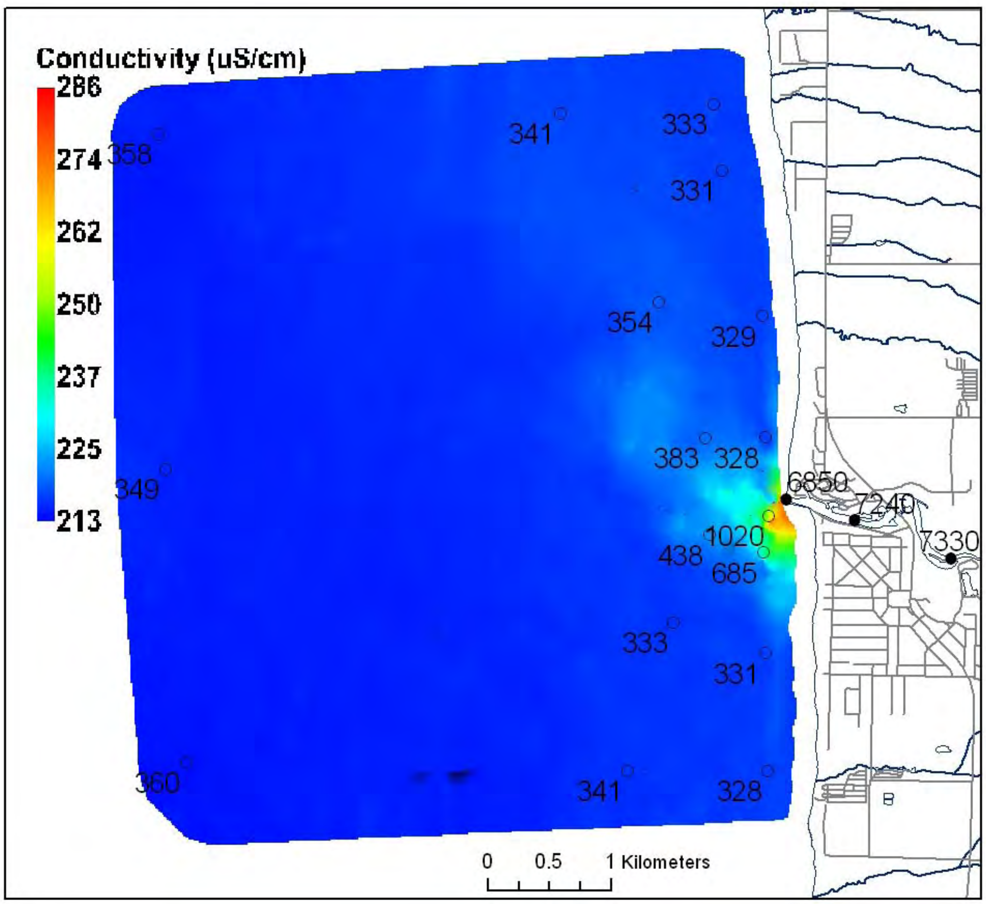

Figure 43: Surface conductivity (colour scale; µS cm^{-1} at 25°C) and NO_2+NO_3 concentrations (point samples; µg L^{-1} N) at the Bayfield River study area during the second summer survey (August 5, 2003).

NO_2+NO_3

River NO_2+NO_3 concentration was high (7215 µg L^{-1} –average of river stations) (see Figure 7). Distant region NO_2+NO_3 concentration was typical of other surveys for the Bayfield study area (356 µg L^{-1}) and comparable to the offshore concentration of 320 µg L^{-1}, indicating that the distant region reflected offshore concentrations of NO_2+NO_3. The proximate region results for NO_2+NO_3 demonstrated that, as with other surveys, NO_2+NO_3 concentration dropped very rapidly away from the river mouth. Only three sites within the mixing area of the discharge plume (as inferred from conductivity) had higher levels of NO_2+NO_3 than in the distant region (Figure 43). Interestingly, the lowest levels of NO_2+NO_3 occurred immediately along the shoreline. It is possible that the slight depression of NO_2+NO_3 stemmed from biological uptake and could suggest more concentrated biological activity along the shoreline. In general, there appears to be a seasonal reversal in direction of NO_2+NO_3 onshore-offshore concentration gradients. The spring period was marked by decreasing concentrations offshore driven by shoreline loading. This contrasts with more subtle increasing concentrations offshore during the summer gradient possibly driven by within lake biological uptake of nitrate.

Turbidity

Despite the elevated turbidity of the Bayfield River at the time of survey, low turbidity levels were observed over the nearshore with the exception of the mixing area of the river plume near the river mouth (Figure 44). Turbidity in the lower Bayfield River (36 FTU) was the highest observed during any of the nearshore surveys. The area of elevated turbidity in the nearshore was appreciably smaller than the conductivity plume, providing some evidence that turbidity was lost from the water column faster than was conductivity, presumably via sedimentation. In the distant region, turbidity (0.2 FTU) was low. Offshore turbidity (0.32 FTU) was similar to the distant region. The spatial map of turbidity did not suggest an appreciable contribution of turbidity from shoreline sources or resuspension in the proximate region in this survey.

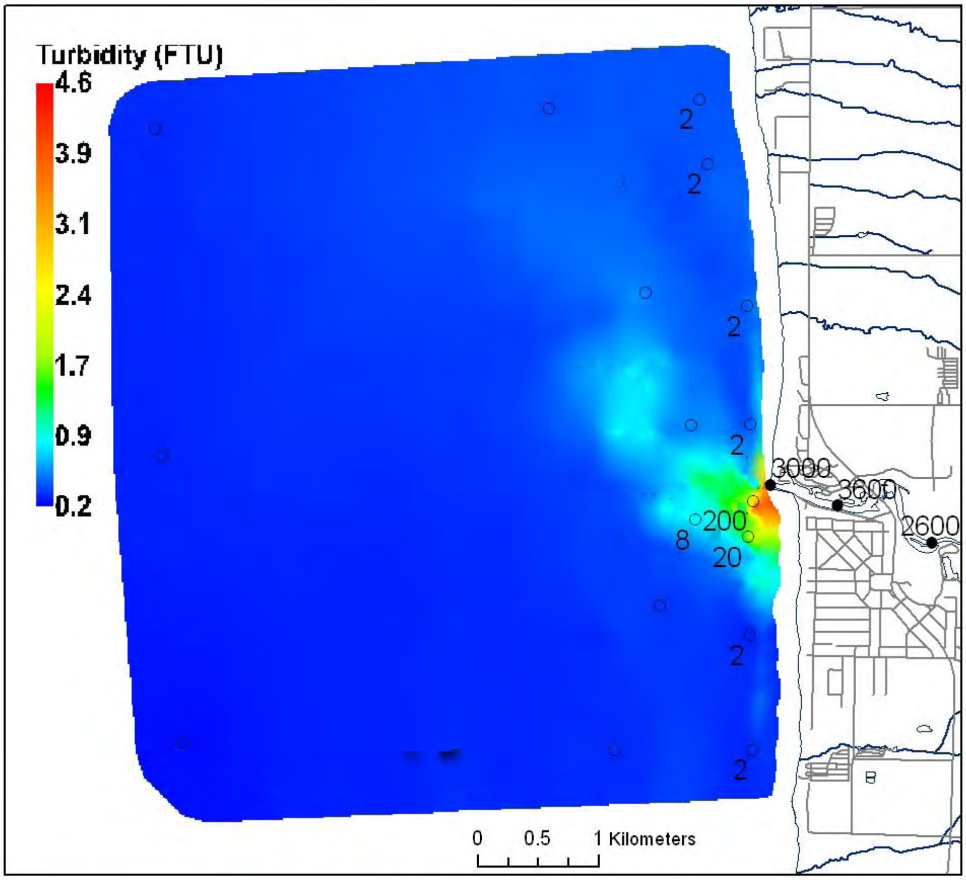

Figure 44: Surface turbidity (colour scale; FTU) and *E. coli* concentrations (point samples; CFU 100 mL^{-1}) at the Bayfield River study area during the second summer survey (August 5, 2003). No samples were collected at points without numeric values.

E. coli

The late summer survey is notable in that it was the only nearshore survey conducted when *E. coli* levels in the Bayfield River were appreciably elevated (Figure 44). Levels of *E. coli* (3000 CFU 100 mL^{-1}) were high concurrent with the recent precipitation and elevated flow in the river. At the shoreline sites within the mixing area of the river plume, *E. coli* levels were variably elevated, consistent with the dilution of the plume (as inferred from conductivity). The highest level (200 CFU 100 mL^{-1}) occurred in a sample near the Bayfield River mouth. Beyond the mixing area, *E. coli* was ≤ 2 CFU 100 mL^{-1}.

These results illustrate both the power and limitations of the nearshore survey approach. They clearly identify the location of the mixing area of the Bayfield River plume and illustrate the adverse effect of the plume on the nearshore within the mixing area (and the limited extent of the impact). A limitation of the approach is that due to operational constraints data were not collected in water of < 3m depth. The mixing gradient on August 5 likely extends to the shoreline south of the river mouth (location of Bayfield Main Beach) but was not captured.

Chlorophyll a

Typical of all surveys, trophic status as inferred from concentrations of chlorophyll *a* was low throughout the nearshore with the possible exception the area of the mixing area at the mouth of the Bayfield River (Figure 45). Chlorophyll *a* concentration in the lower Bayfield River was suggestive of mesotrophic conditions (average of 7.4 µg L^{-1}) in contrast to highly oligotrophic conditions over the distant region (average of 0.3 µg L^{-1}). Offshore chlorophyll *a* concentration (obtained from the USEPA) was measured at 0.9 µg L^{-1}. The apparently higher offshore chlorophyll *a* concentration may be, in part, due to differences in methods, especially at these very low chlorophyll *a* concentrations. Another possible factor was removal of phytoplankton by filter feeding of dreissenid mussels (exclusively *Dresissina polymorpha*) in the nearshore. Nevertheless, it is a strong indication that, like the other measures, chlorophyll *a* concentration in the distant region was similar to that of the offshore.

The chlorophyll *a* 90% dilution area was similar in size to the conductivity 90% dilution area, suggesting that the source of elevated chlorophyll *a* within the mixing zone was due to loading of algae from the river and not growth of phytoplankton in the lake in response to nutrient stimulation. Beyond the mixing area there appeared to be a large area north of the Bayfield River mouth where chlorophyll *a* levels appeared to be marginally elevated but with concentrations < 1 µg L^{-1} throughout (Figure 45). It is possible that levels over this area are due to phytoplankton growth in the lake stimulated by nutrient loading in the recent past.

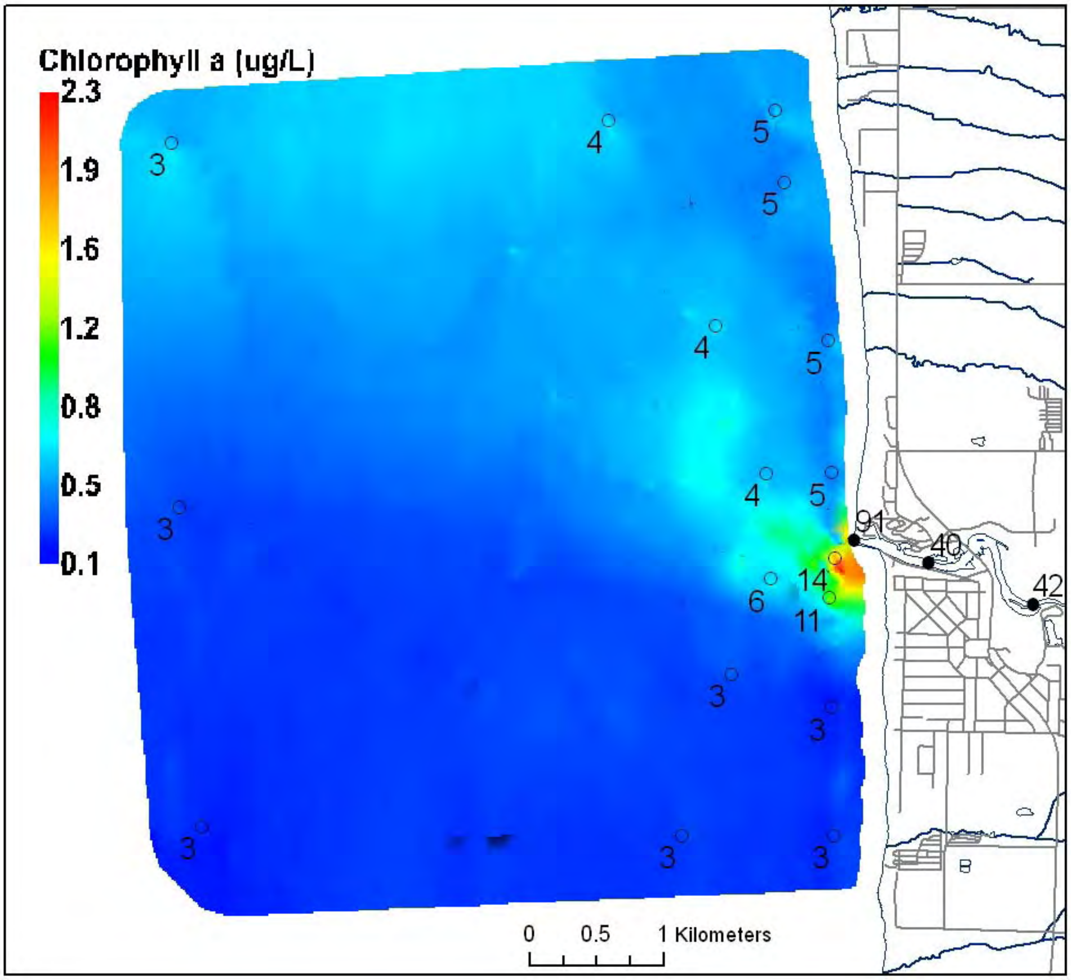

Figure 45: Surface chl *a* concentration estimated from fluorescence (colour scale; µg L^{-1}) and TP concentrations (point samples; µg L^{-1} P) at the Bayfield River study area during the second summer survey (August 5, 2003).

TP

The elevated TP concentration in the lower Bayfield River (54 µg L^{-1}) contrasted with the low TP concentration of the distant region (3 µg L^{-1}). Offshore TP concentration (2 µg L^{-1}) was the same as that of the distant region. Concentrations of TP were slightly elevated within the mixing area at the mouth of the Bayfield River mouth (6-14 µg L^{-1}). Otherwise, TP concentrations were ≤ 5 µg L^{-1} throughout the nearshore. The explanation for the high TP concentration (91 µg L^{-1}) within the river mouth is uncertain, but a similar pattern of elevated TP at the mouth station was observed in four out of five nearshore surveys suggesting that there are sources of phosphorus input to Bayfield Harbour (below the bridge at Highway 21).

3.5.7 Saugeen Late Fall Survey

Physical conditions

The late fall survey was conducted during a period of wet weather and increasing flow in the Saugeen River. Discharge of the Saugeen River at the downstream gauge ranged from 110 to 130 m^3 s^{-1} in the days preceding the survey. There was limited rainfall (< 5 mm) on 3 of the 4 days before the survey, as well as 12 mm of precipitation on the day of survey (Figure 46).

In the days preceding and during the survey, the water column was isothermal at the ADCP site in the distant region with temperature varying between approximately 7 to 9ºC. The surface temperature at the proximate region ADCP was similar to that of the distant region. Saugeen River temperatures were, however, 3 to 4ºC lower than that of the lake for the days preceding the survey. This was evident in the surface temperature map for the day of survey, which showed the colder river water entering the lake and the cooling effect of the river discharge on the lake (Figure 47).

Lake currents were dynamic in the days preceding the survey. High winds on November 13 resulted in periods of atypically high flow in the nearshore on November 13 and 14. On November 13, currents were strong at the distant region ADCP (reaching > 40 cm s^{-1} for brief periods) and moving alongshore approximately to the NE.

This dynamic and complex pattern in nearshore lake circulation continued during the survey period. Surface currents in the proximate region were weak and mostly onshore-directed from November 16 up to, and including, the survey period. At the distant region ADCP, moderate to weak alongshore currents towards the NE dominated the two days prior to the survey and the survey period.

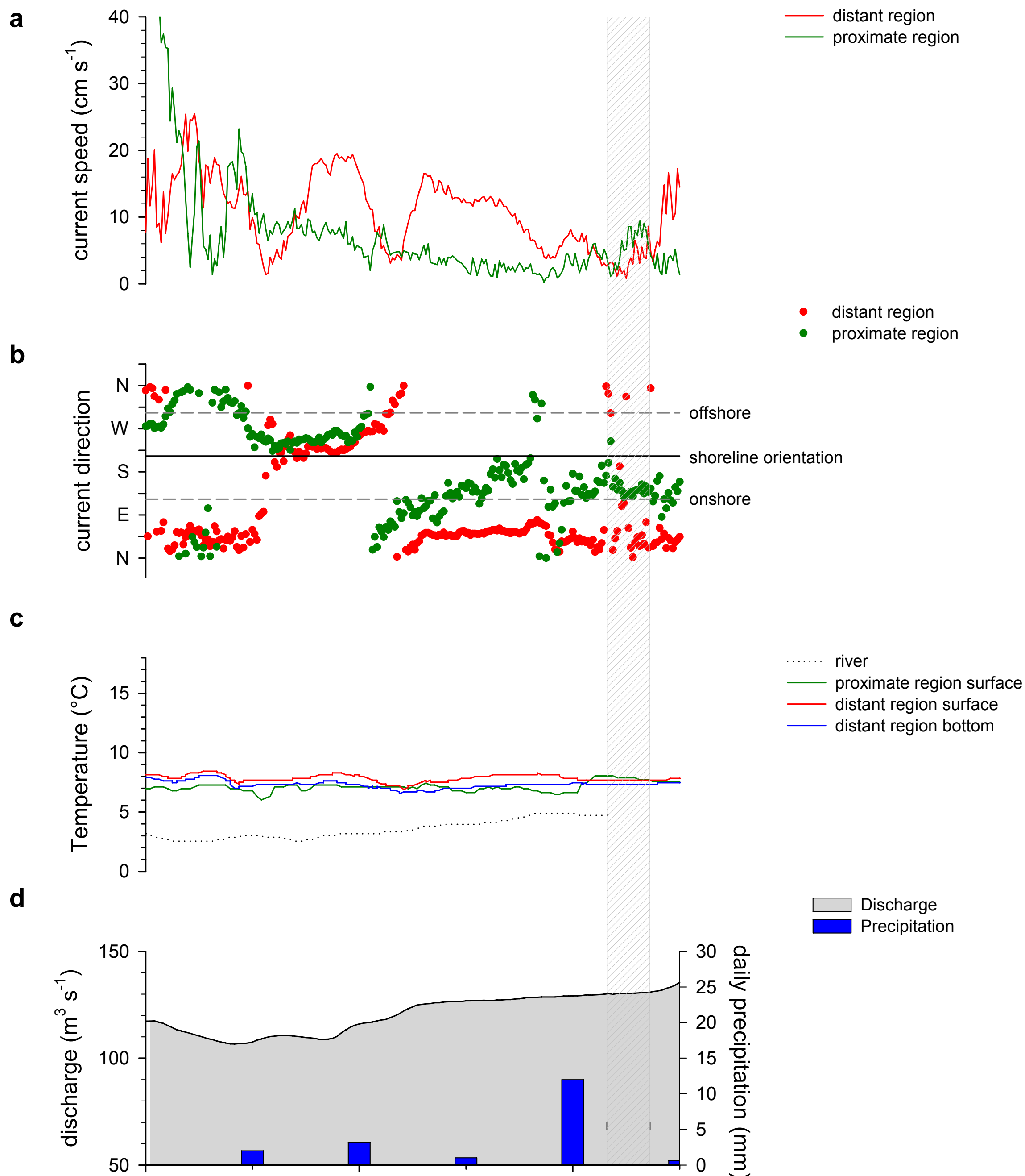

Figure 46: Saugeen Fall 2 survey. Physical conditions in the days before and during the survey (hatched region). Current speed (**a**) and direction (**b**) in the distant and proximate regions, temperature of the Saugeen River and the distant and proximate regions (**c**), Saugeen River discharge and local precipitation (**d**). See sections 2.3 and 2.5 for details.

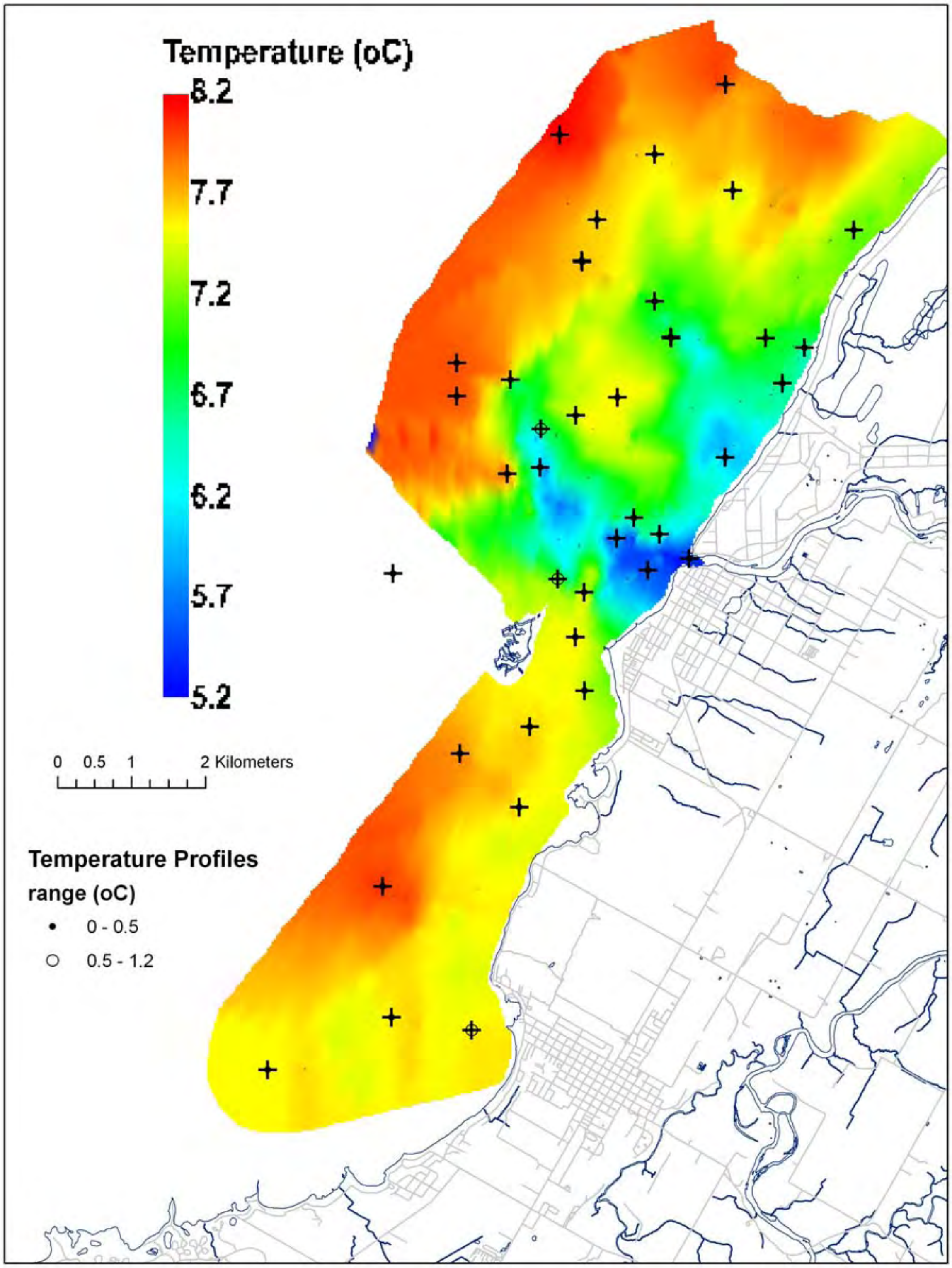

Figure 47: Surface water temperature (°C) at the Saugeen River study area during the second fall survey (November 18, 2003). The crosses indicate locations where water column was well mixed using a criterion of < 0.01 g cm^{-3} change per meter drop.

Water Quality

Conductivity

Consistent with the high discharge of the river at the time of survey, conductivity was elevated in comparison to lake background over a large area offshore and to the NE of the Saugeen River mouth (Figure 48). Unlike previous surveys, the mixing area of the discharge from the river extended an appreciable distance offshore from the river mouth. The areas of elevated conductivity formed two offshore-oriented arms, one of which extended from the river mouth and the second positioned approximately 2-3 km NE of the river mouth. This unusual pattern was likely the result of the recent currents, influenced by the heterogeneous bathymetry of the lakebed near the river mouth. There is a shallow ridge just north of the river mouth that may impede offshore flow, resulting in stronger flow to the deeper water SW and NE of the ridge.

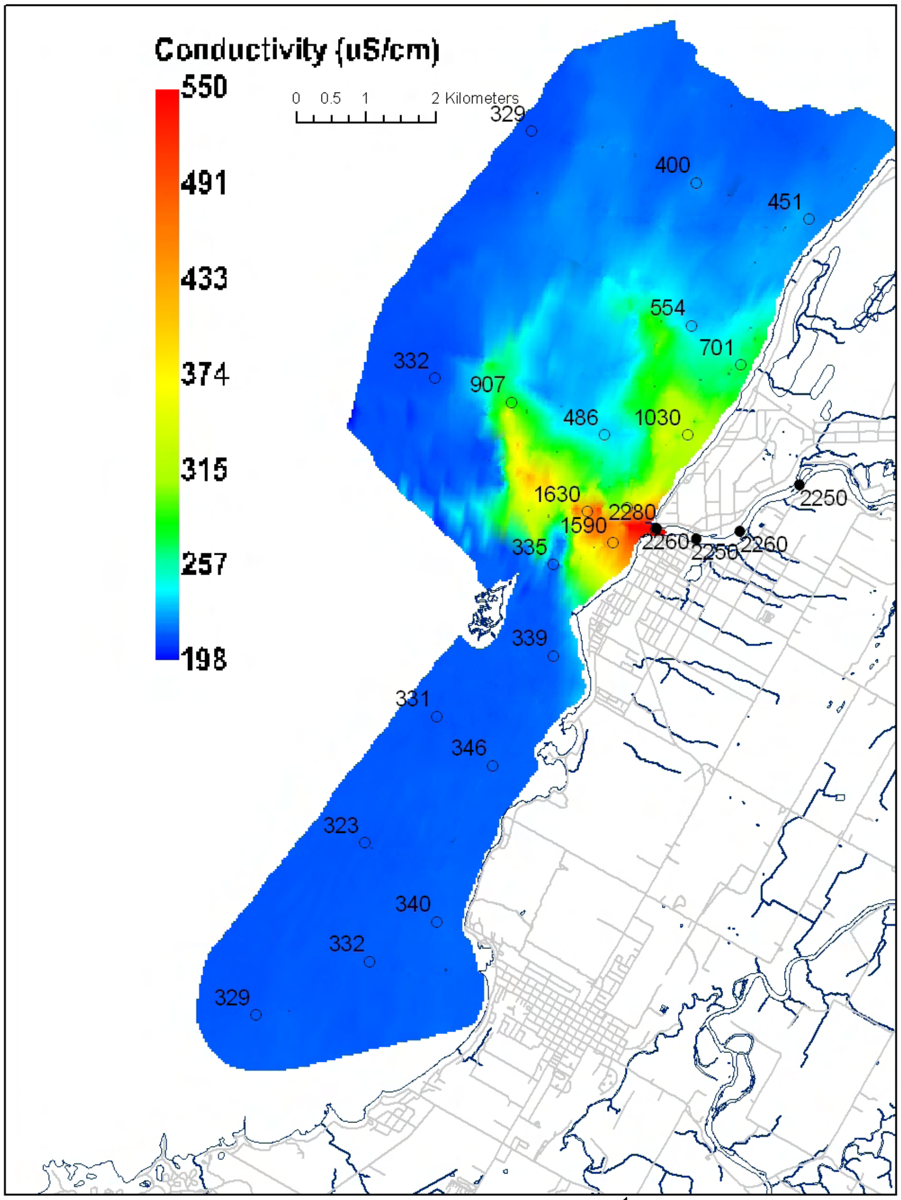

Figure 48: Surface conductivity (colour scale; µS cm^{-1} at 25°C) and NO_2+NO_3 concentrations (point samples; µg L^{-1} N) at the Saugeen River study area during the second fall survey (November 18, 2003).

NO_2+NO_3

The NO_2+NO_3 concentration of the lower Saugeen River (2256 µg L^{-1}) was high relative to the other survey dates. This combined with the recent high river discharge, resulted in NO_2+NO_3 concentrations close to 1000 µg L^{-1} more than 2 km from the river mouth (Figure 48). NO_2+NO_3 concentrations ranged from 323 to 339 µg L^{-1} to the SW of the Saugeen River mouth and outside the discharge mixing area.. The nearshore area ≥2x higher than the distant region NO_2+NO_3 concentration was 6.2 km^2.

Turbidity

The nearshore was appreciably more turbid during the second fall survey than previous surveys (Figure 49). Average turbidity of the distant region was ~8 FTU in contrast with ~0.2 and ~0.3 FTU during the spring and second summer surveys. The ≥ 2x area of turbidity was 25 km^{-2}. Given the elevated turbidity of the distant stations, the extent of nearshore with elevated turbidity relative to the open lake is underestimated by the ≥ 2x area calculation. The turbidity of the lower Saugeen River was also elevated (50 FTU). The surface turbidity map indicates a turbidity plume at the river mouth. However, turbidity was elevated throughout the survey area, with areas of high turbidity far from the river mouth. There was an especially turbid area several kilometres to the north of the river mouth along the shoreline. The area is at the edge and slightly beyond the mixing area of the Saugeen River conductivity plume. The elevated turbidity is not likely due to loading from the Saugeen River. This area coincides with, and lies outside, a shallow ridge on the lakebed that is parallel to the shoreline. It is possible that the area is exposed to more wave action and lake current resulting in more erosion and particle resuspension than that the area to the south of this ridge. The general elevation of turbidity over the nearshore is likely due to erosion of the lakebed and shoreline due to strong winds and wave action.

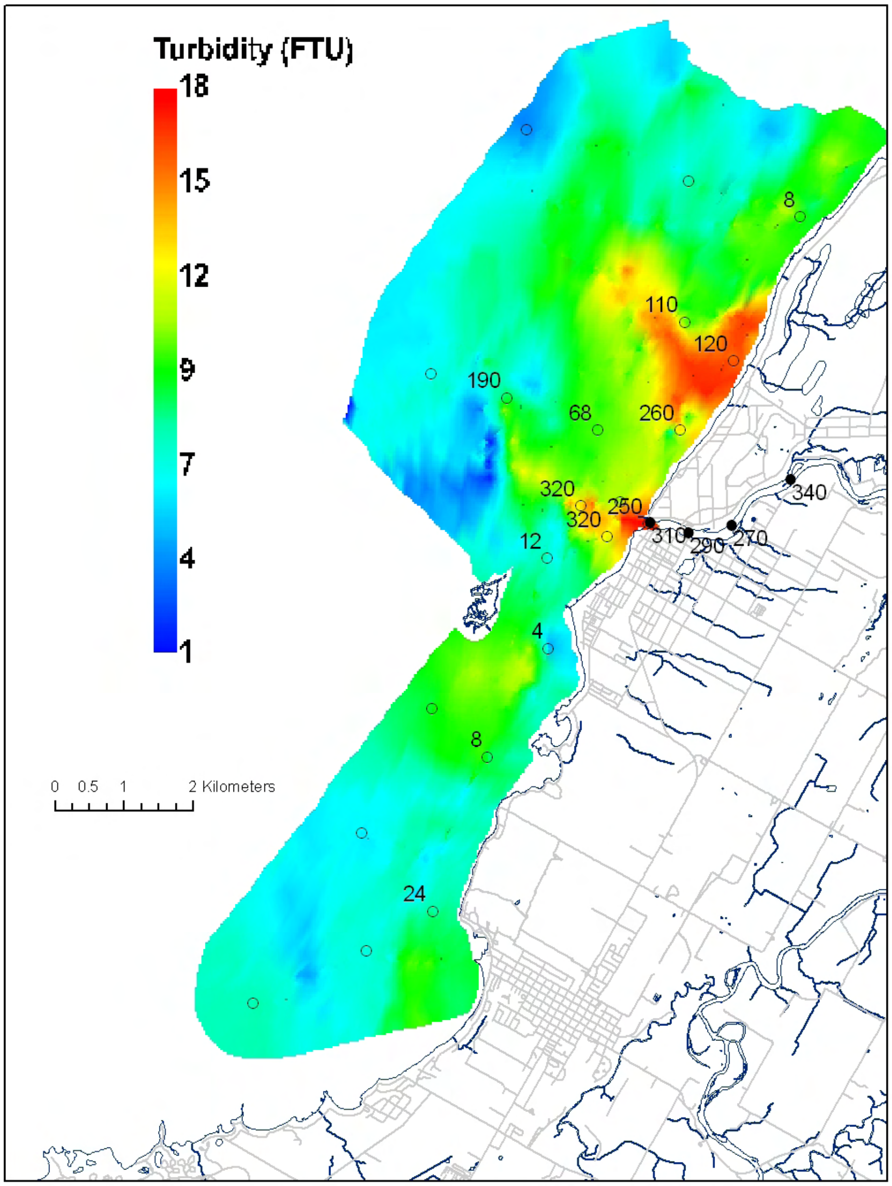

Figure 49: Surface turbidity (colour scale; FTU) and *E. coli* concentrations (point samples; CFU 100 mL^{-1}) at the Saugeen River study area during the second fall survey (November 18, 2003). No samples were collected at points without numeric values.

E. coli

Levels of *E. coli* in the lower Saugeen River (310 CFU 100 mL) were slightly elevated and higher than observed at the time of any previous nearshore survey. Levels similar to the lower river were detected in the lake mixing area as inferred from conductivity (Figures 48 & 49). Levels in the nearshore ranged from 4 to 320 CFU 100 mL and exceeded 100 CFU 100 mL in seven samples. The results stand out due to the extent to which elevated levels of *E. coli* were detected away from the shoreline. By comparison to other surveys, including those conducted at the other study areas, elevated *E. coli* were limited to samples collected near the shoreline. The correspondence between the locations of elevated *E.coli* and the Saugeen River mixing area suggested that river discharge was the source of much of the *E. coli* detected in the nearshore.

Chlorophyll a

The pattern of chlorophyll a concentration in the nearshore was similar to that of the conductivity, with an offshore-directed gradient and another along the shoreline originating at the mouth of the Saugeen River (Figure 50). Levels over the distant region and proximate region outside the mixing area of the Saugeen River discharge were low (<1 μg L^{-1}) as in previous surveys. There was moderate enrichment over the mixing area with concentrations > 3 μg L^{-1}. Concentrations in the lower Saugeen River varied from 3.3 to 3.8 μg L^{-1} at the time of survey.

TP

Distant region TP concentrations were relatively elevated (~8 μg L^{-1}); levels were approximately twice the average of the other survey dates (Figure 50). Along the shoreline levels ranged from 8 to 47 μg L^{-1}. The higher levels, and wide range in concentrations, likely resulted from a combination of enriched runoff to the nearshore and weather-related turbidity in the nearshore.

Total phosphorus concentration in the lower Saugeen River was high (50 μg L^{-1}) relative to the other surveys at the Saugeen River study area. The highest concentrations in the nearshore were observed in the mixing area of the river discharge and were likely due to loading from the river. The more general enrichment of TP observed more broadly over the study area is possibly due to the higher concentrations of particulate material in the water column due to physical resuspension. Inorganic and organic particles such as clay, organic debris and benthic algae typically have an associated phosphorus content which will affect measurements of water column TP.

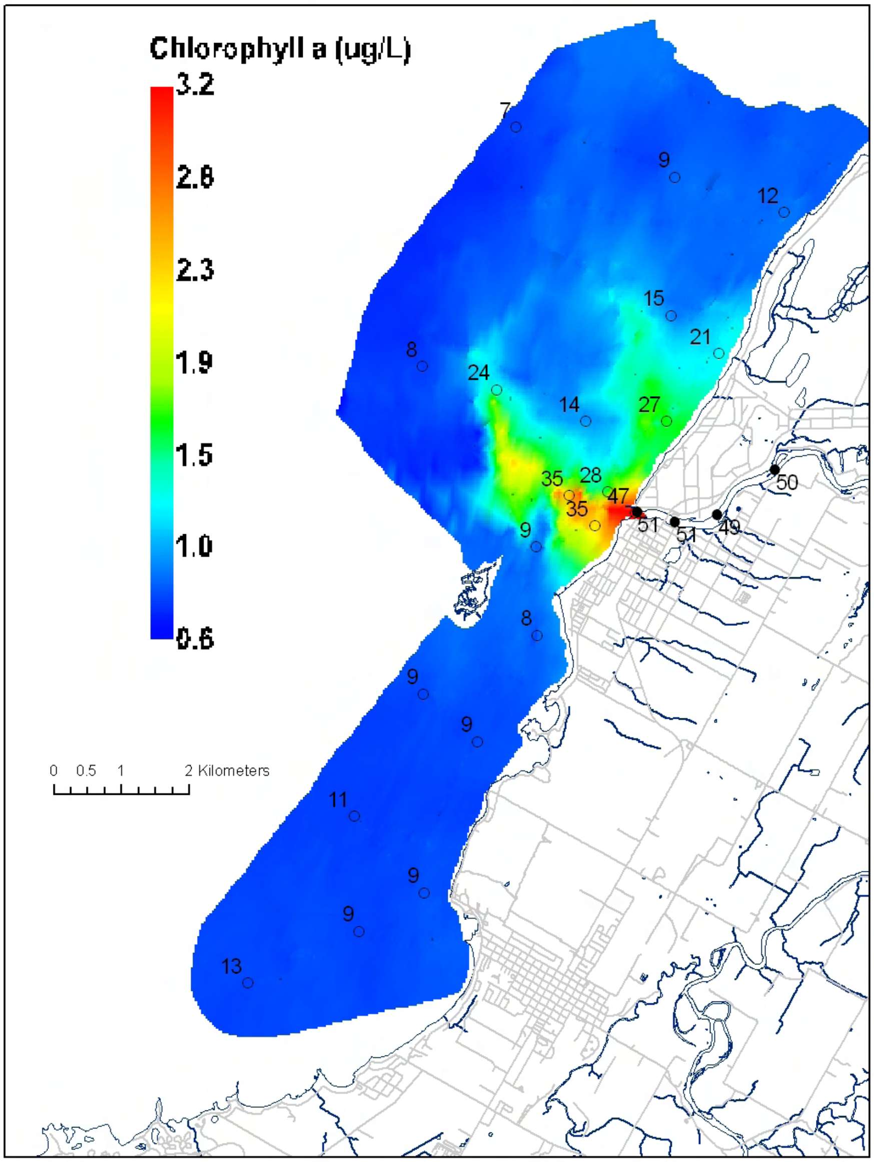

Figure 50: Surface chl *a* estimated from fluorescence (colour scale; µg L^{-1}) and TP concentrations (point samples; µg L^{-1} P) at the Saugeen River study area during the second fall survey (November 18, 2003).

3.5.8 Bayfield Late Fall Survey

Physical conditions

The second fall survey was conducted during late fall at a time of wet weather and moderate and rising flow in the Bayfield River. Over the days preceding the survey the discharge from the Bayfield River as inferred from the downstream gauging station was 6 to 8 m^3s^{-1}, in a range similar to the spring survey (Figure 51). Discharge increased appreciably (exceeding 15 m^3s^{-1}) during the day of survey in response to precipitation events. There were varying amounts of rainfall over each of the eight days preceding the survey with approximately 5 and 6 mm falling the day before and of the survey, respectively (Figure 51).

The water column was likely isothermal in the distant region preceding and during the second fall survey based on results for the Maitland distant ADCP site (water temperature of approximately 8ºC) (Figure 51). Water temperature was cooler towards the shoreline reflecting the more rapid cooling of the shallower water. Over the four days preceding the survey, temperature of the Bayfield River increased from approximately 4 to 8ºC.

An onshore–offshore gradient in surface temperature was observed during the survey which appeared to be the result of the variable nature of fall cooling of surface water as a function of depth (Figure 52). Unlike the spring the cooler water is on the shore side of the temperature gradient during the fall reflecting the more rapid cooling of shallower water. However, the coolest water temperatures were observed at intermediate depths and not along the shoreline as might be expected with progressive cooling of the lake into the fall. It is likely that a shift in weather from cool to warmer conditions over the preceding days resulted in a switch from a cooling to warming trend in the nearshore resulting in a degree of warming along the shoreline despite the broader cooling trend. The temperature rise in the Bayfield River is consistent with a change in weather conditions.

Strong north-directed alongshore currents dominated much of the day before the survey and just prior to the survey at both ADCP sites (Figure 51). The survey was conducted during a period of transition of alongshore flow from north to south directed. There was initially a period of weak flow but with increasing current speed at the proximate region over the course of the survey. Over the five days depicted in Figure 51 there are two periods of reversal of alongshore current with appreciable variability in the intensity of flow, ranging from weak to strong flows of > 20 cm s^{-1}.

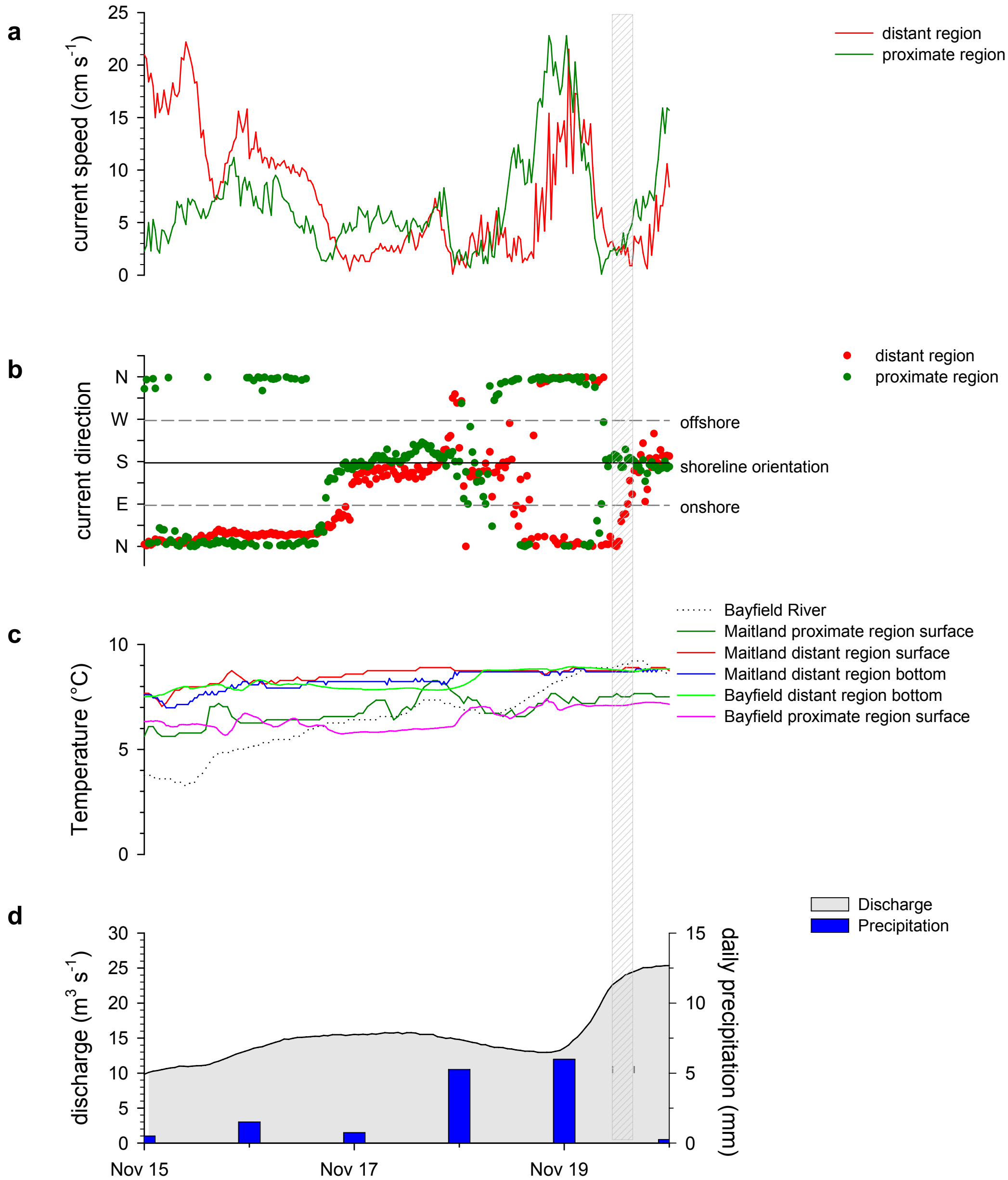

Figure 51: Bayfield second fall survey (November 19, 2003). Physical conditions in the days before and during the survey (hatched region). Current speed (**a**) and direction (**b**) in the distant and proximate regions, temperature of the Bayfield River and the distant and proximate regions (note that some data are for the Maitland study area) (**c**), Bayfield River discharge and local precipitation (**d**). See sections 2.3 and 2.5 for details.

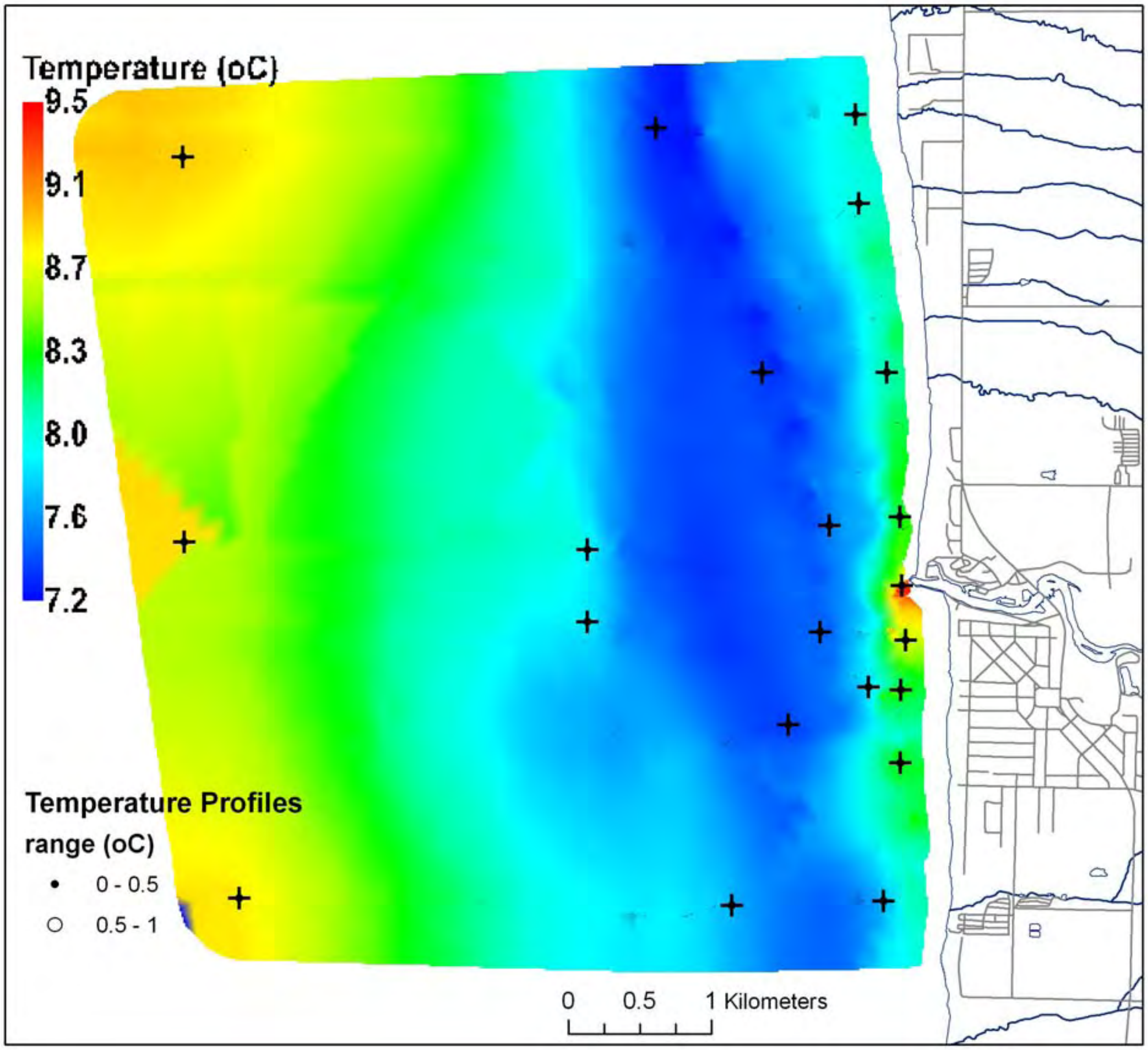

Figure 52: Surface water temperature (°C) at the Bayfield River study area during the second fall survey (November 19, 2003).

Water Quality

Conductivity

A broad area of elevated conductivity south of the river mouth, oriented in the direction of the alongshore current, indicated the mixing area of the discharge of the Bayfield River (Figure 53). There were also small, seemingly isolated, patches of weakly elevated conductivity along the shoreline north the Bayfield River. The elevated conductivity at these locations may have been due to discharge from the Bayfield River during the earlier period of northward flow prior to the most recent current reversal. There are also several small creeks and drains along the affected shoreline which may have contributed to the elevated conductivity. The area of 90% dilution of conductivity was 1.7 km^2, the second largest observed among the five surveys over the Bayfield River study area.

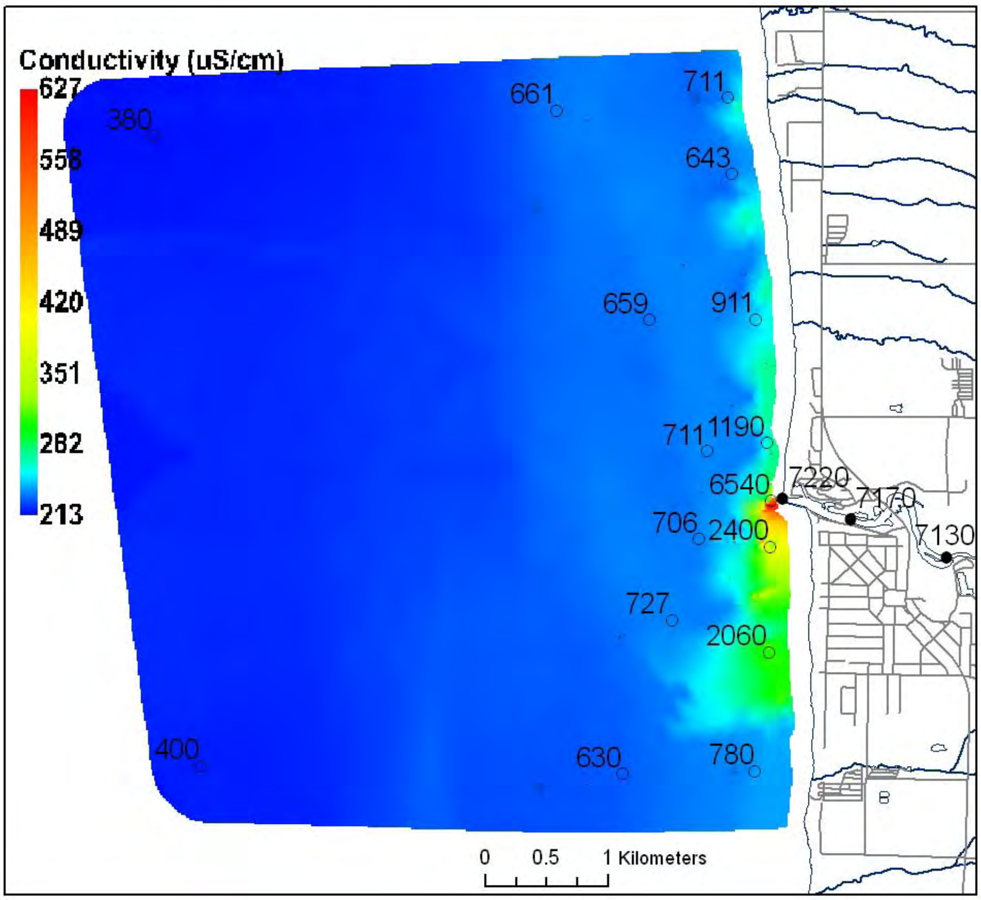

Figure 53: Surface conductivity (colour scale; µS cm^{-1} at 25°C) and NO_2+NO_3 concentrations (point samples; µg L^{-1} N) at the Bayfield River study area during the second fall survey (November 19, 2003).

NO_2+NO_3

Concentrations of NO_2+NO_3 were slightly to moderately elevated over much of the proximate region during the late fall survey, reflecting the high concentrations in the lower Bayfield River and the moderate discharge volume of the river. In the lower Bayfield River, concentrations of NO_2+NO_3 were in excess of 7000 µg L^{-1}, compared to

380-400 μg L^{-1} in the distant region (Figure 53). The impact of the Bayfield River discharge on nitrate+nitrite levels is corroborated by the elevated concentrations of nitrate+nitrite in the area of elevated conductivity along the shoreline south of the river mouth; NO_2+NO_3 concentration was 2060 μg L^{-1} in the discharge mixing area more than 1 km from the river mouth. An area of 3.2 km^{-2} in the proximate region was elevated ≥ 2x the NO_2+NO_3 concentration of the distant region, which was approximately one-fifth the area of the spring survey, but much larger than the other surveys at the Bayfield River study area.

Turbidity

Turbidity was elevated to varying degrees over the full extent of the nearshore study area. Unlike other surveys, turbidity in the lower Bayfield River was lower than that of the proximate region of the lake. The ≥ 2x area of elevated turbidity was large relative to nitrate+nitrite (25 vs 3.2 km^{-2}) and is consistent with a large proportion of the turbidity originating from a within-lake process, which in all likelihood was weather-driven erosion of the lakebed and shoreline and suspension of particles in the water column.

Similar to surface temperature, a complex onshore-offshore pattern in turbidity was observed (Figure 54). The least turbid water was found in the distant region; however, turbidity still exceeded 15 FTU five kilometres from the shoreline. Turbidity increased towards the shoreline until approximately within 1-1.5 km of the shoreline where it declined and then increased upon approaching the shoreline. Maximum turbidity in excess of 40 FTU was observed both at areas along the shoreline and over a broad area approximately 2 km from shore, north of the Bayfield River. The explanation for the band of relatively lower turbidity positioned slightly offshore is unclear, though it is likely due to sub-surface movement of clearer offshore water towards the shoreline which occurred briefly during the surface flow reversal observed at the distant region ADCP at the start of the survey period (see Figure 51).

The high turbidity observed in the nearshore was likely due to agitation of the lakebed and shoreline during a storm and high winds on November 13 and 14 (5-6 days prior to the survey). At the distant region ADCP, a strong N-NW current developed on November 13, which then switched to approximately southerly later in the day and into

November 14, but again shifted to a northerly direction during the day. Current speeds in excess of 50 cm s^{-1} were observed at points over this period.

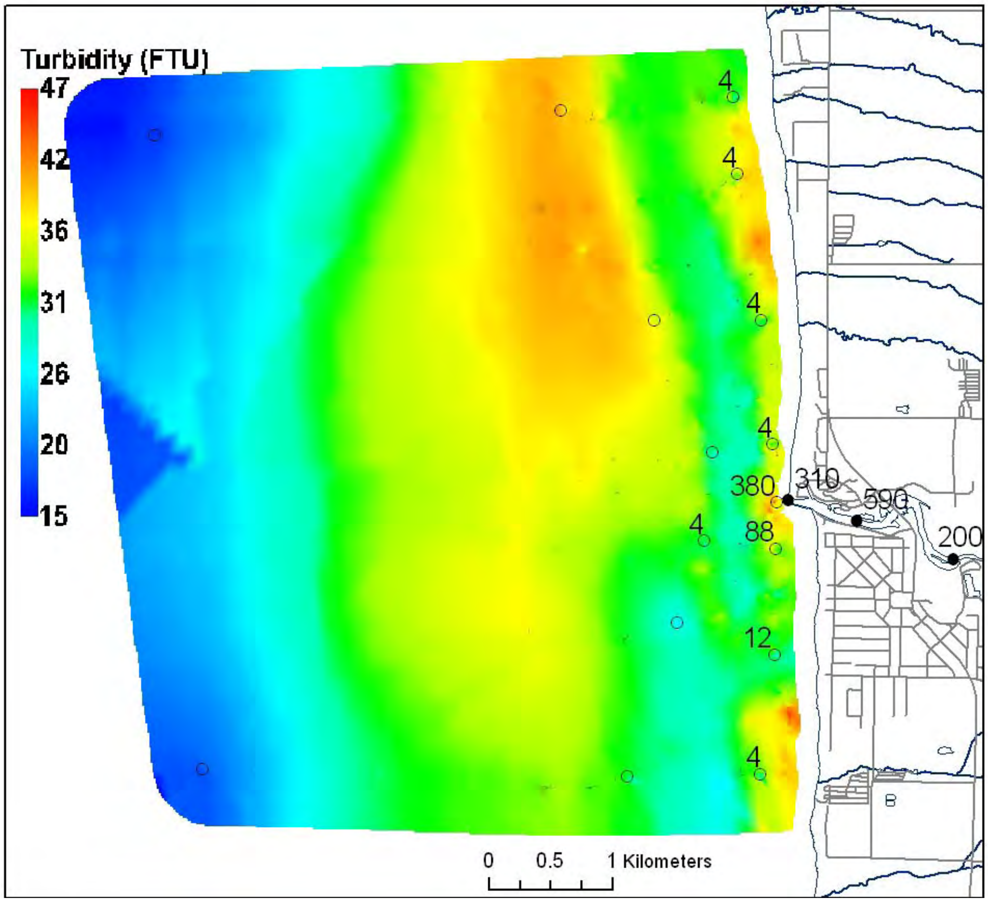

Figure 54: Surface turbidity (colour scale; FTU) and *E. coli* concentrations (point samples; CFU 100 mL^{-1}) at the Bayfield River study area during the second fall survey (November 19, 2003). No samples collected at points without numeric values.

E. coli

Despite the recent precipitation and elevated flow in the Bayfield River, *E. coli* levels in the nearshore appeared to be little impacted by the discharge from the river at depths sampled in this study. Levels were < 100 CFU 100 mL^{-1} in the nearshore with the exception of a sample collected directly offshore of the Bayfield River mouth in the discharge plume (380 CFU 100 mL^{-1}). The levels in the lower Bayfield River were moderately elevated, ranging from 200-590 CFU 100 mL^{-1}, among the three river stations nearest the lake.

Chlorophyll a

Unexpectedly, chlorophyll *a* concentrations were higher in the nearshore during the late fall survey than at any other time over the study though concentration over most of the study area remained low (< 2 µg L^{-1}) (Figure 55). There were several areas along the shoreline where higher levels of chlorophyll *a* were detected, suggesting stimulation of phytoplankton growth in response to nutrient (presumably phosphorus) inputs. With the exception of the immediate mixing area of the discharge from the Bayfield River where the highest concentrations were observed, it is difficult to interpret the patterns in chlorophyll *a* concentration. At the mouth of the Bayfield River, concentrations of 7 to 13 µg L^{-1} indicated productive conditions in the lower river and loading of phytoplankton to the shoreline over the mixing area. The areas of slightly elevated chlorophyll *a* (~2-4 µg L^{-1}) in the proximate region beyond the mixing area of the Bayfield River discharge south of the river mouth are suggestive of areas of stimulated growth but may also be artefacts of inputs of phytoplankton during the previous mixing of Bayfield River water along the shoreline north of the river. The cool water temperatures and declining light levels in November are unlikely to be conducive to strong phytoplankton growth. Another possibility is that weather-driven erosion of the benthic microbial layer (periphyton) and suspension of algae normally attached to the lakebed in the water column might have been contributing chlorophyll a to the water column.

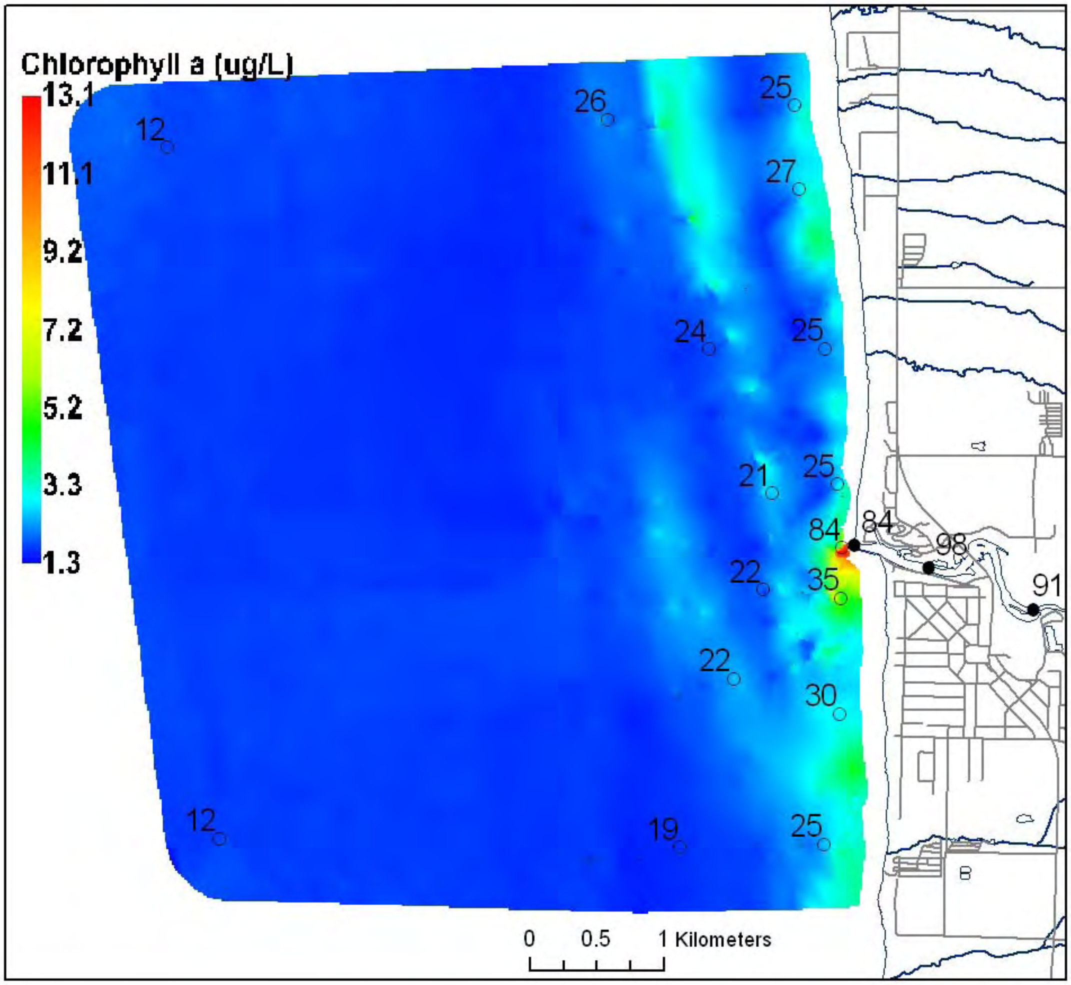

Figure 55: Surface chlorophyll *a* estimated from fluorescence (colour scale; µg L^{-1}) and TP concentrations (point samples; µg L^{-1} P) at the Bayfield River study area during the second fall survey (November 19, 2003).

TP

The TP concentrations detected during the late fall survey were appreciably elevated over levels detected in previous surveys. In the distant region, TP concentration was 12 µg L^{-1} and 3-4 times higher than other surveys. In the proximate region, TP concentrations were higher, ranging from 19 to 30 µg L^{-1}, with the exception of two sites near the mouth of the Bayfield River. Concentration of TP in the lower Bayfield River was also high, ranging from 84 to 98 µg L^{-1}, at the three most downstream sites. Concentrations of TP appeared to be only slightly higher in the area of elevated conductivity south of the Bayfield River than in the proximate region in general. This suggests that a portion, possibly a large portion, of the TP in the proximate region was from the suspension of particle-bound P upon erosion of the lakebed and shoreline, which are known to be typically P-rich (Wetzel 1983).

3.5.9 Maitland Late Fall Survey

Physical conditions

The late fall survey at the Maitland River study area was conducted during a period of moderate but declining discharge from the Maitland River following a period of wet weather days earlier (Figure 56). Discharge of the Maitland River at the downstream gauge was 140 m^3s^{-1} two days before the survey but declined to 60 m^3s^{-1} on the day of the survey. There was no rainfall over the three days preceding the survey. While there was limited rainfall (~ 6-7 mm) on the day of the survey, it had no apparent effect on river discharge during the survey.

Temperature at the distant region ADCP site was approximately 8ºC and uniform through the water column in the days before and during the survey (Figure 57). The proximate region was 1 to 2ºC cooler than the distant region and the temperature in the lower Maitland River was similar to the proximate region in the days before the survey. The map of surface temperature on the day of survey suggested little variability beyond that noted in the comparison of the temperatures among the deployed sensors above. There was broad area of marginally cooler along the shoreline north of the Maitland River in the area of mixing of the slightly cooler river discharge with the lake (Figure 57).

During the survey period there was a strong north-directed alongshore flow at both the distant and proximate region ADCP sites (Figure 56). Over the four days prior to the survey there was a series of reversing alongshore currents with two periods each of northward and southward flow along the shoreline (not including the day of survey) with limited periods of more variable flow between reversals. Also notable were several periods of strong flow, and to the north in particular (>20 cm s^{-1}), at the proximate region ADCP.

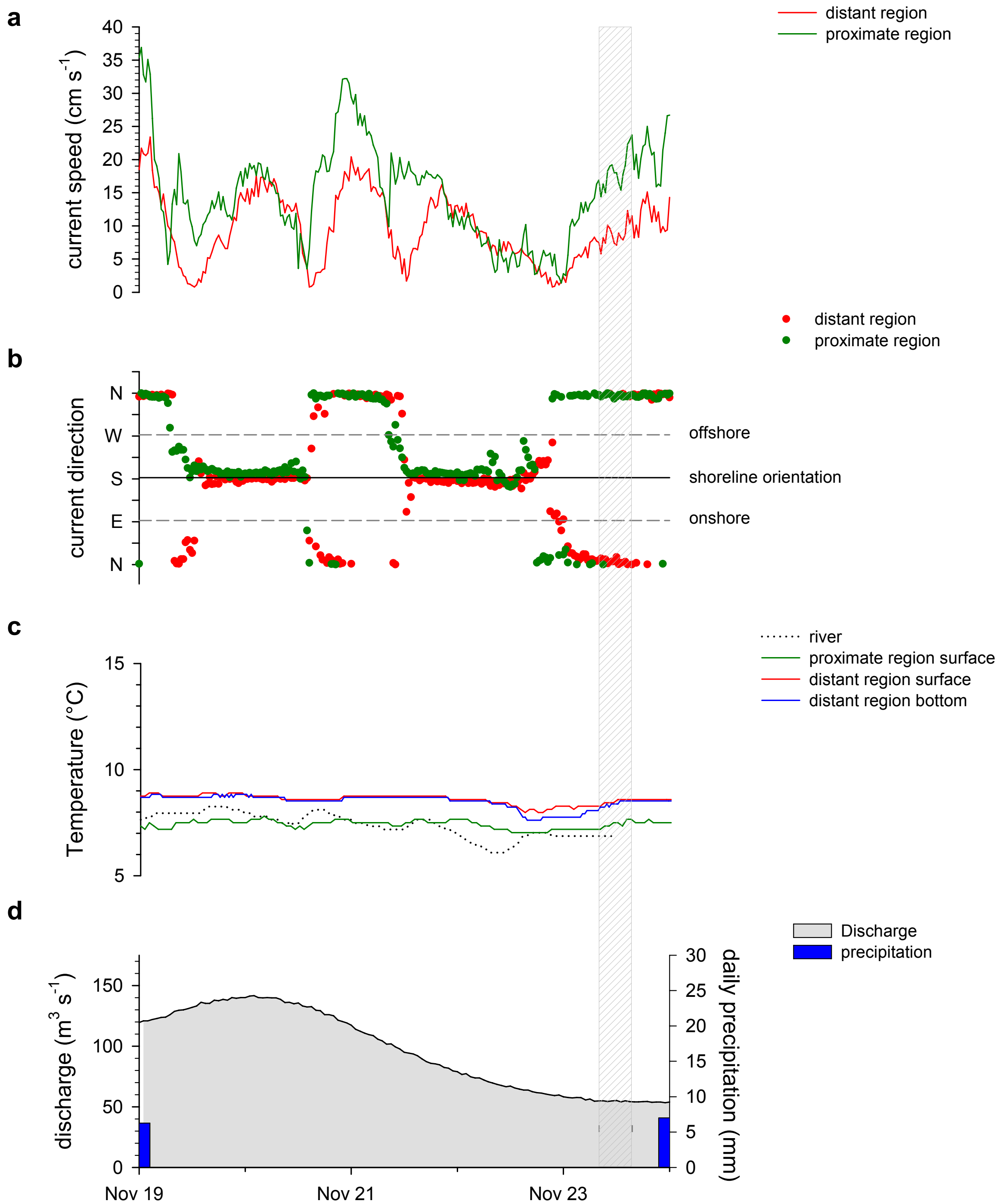

Figure 56: Physical conditions in the days before and during the second fall survey of the Maitland study area (November 23, 2003). The hatched region shows the survey period. Current speed (**a**) and direction (**b**) in the distant and proximate regions, temperature of the Maitland River and the distant and proximate regions (**c**), Maitland River discharge and local precipitation (**d**). See sections 2.3 and 2.5 for details.

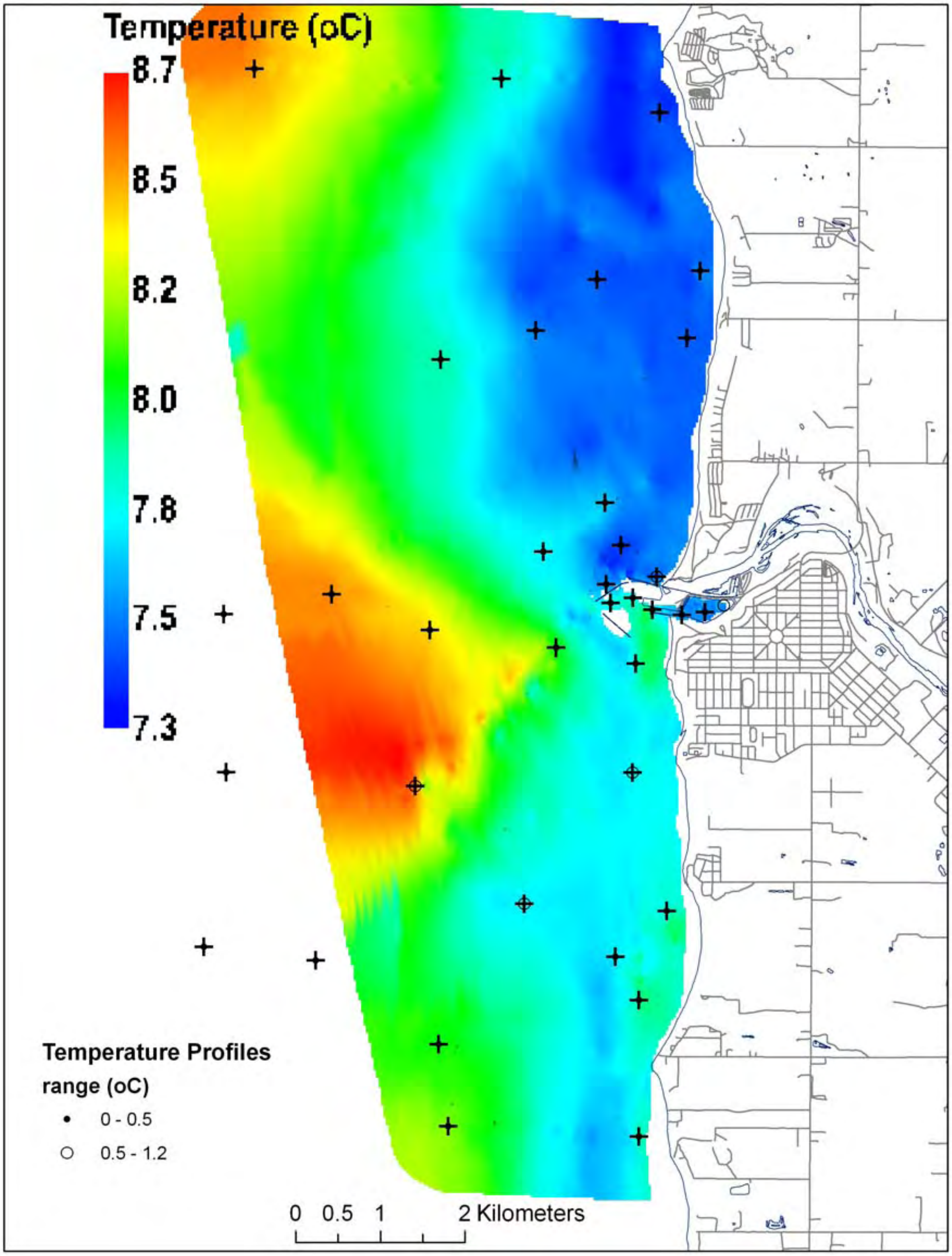

Figure 57: Surface water temperature (°C) at the Maitland River survey area during the second fall survey (November 23, 2003). The crosses indicate locations where water column was well mixed using a criterion of < 0.01 g cm^{-3} change per meter drop.

Water Quality

Conductivity

There was a large conductivity plume along the shoreline north of the Maitland River mouth indicating the mixing area for the discharge from the Maitland River (Figure 58). The orientation of the mixing area corresponded with the direction of surface currents at the time of the survey. Conductivity was elevated to a degree along the whole of the shoreline north of the river mouth, a distance of roughly 6 km. A weaker and more diffuse area of elevated conductivity was present to the south of the river mouth and is likely a remnant from the previous south-directed current flow. The 90% dilution area of the Maitland River plume for conductivity was 30 km^2. Given the pervasive influence of the Maitland River discharge on the shoreline it is difficult to detect other more localized areas where discharges to the lake may be affecting conditions.

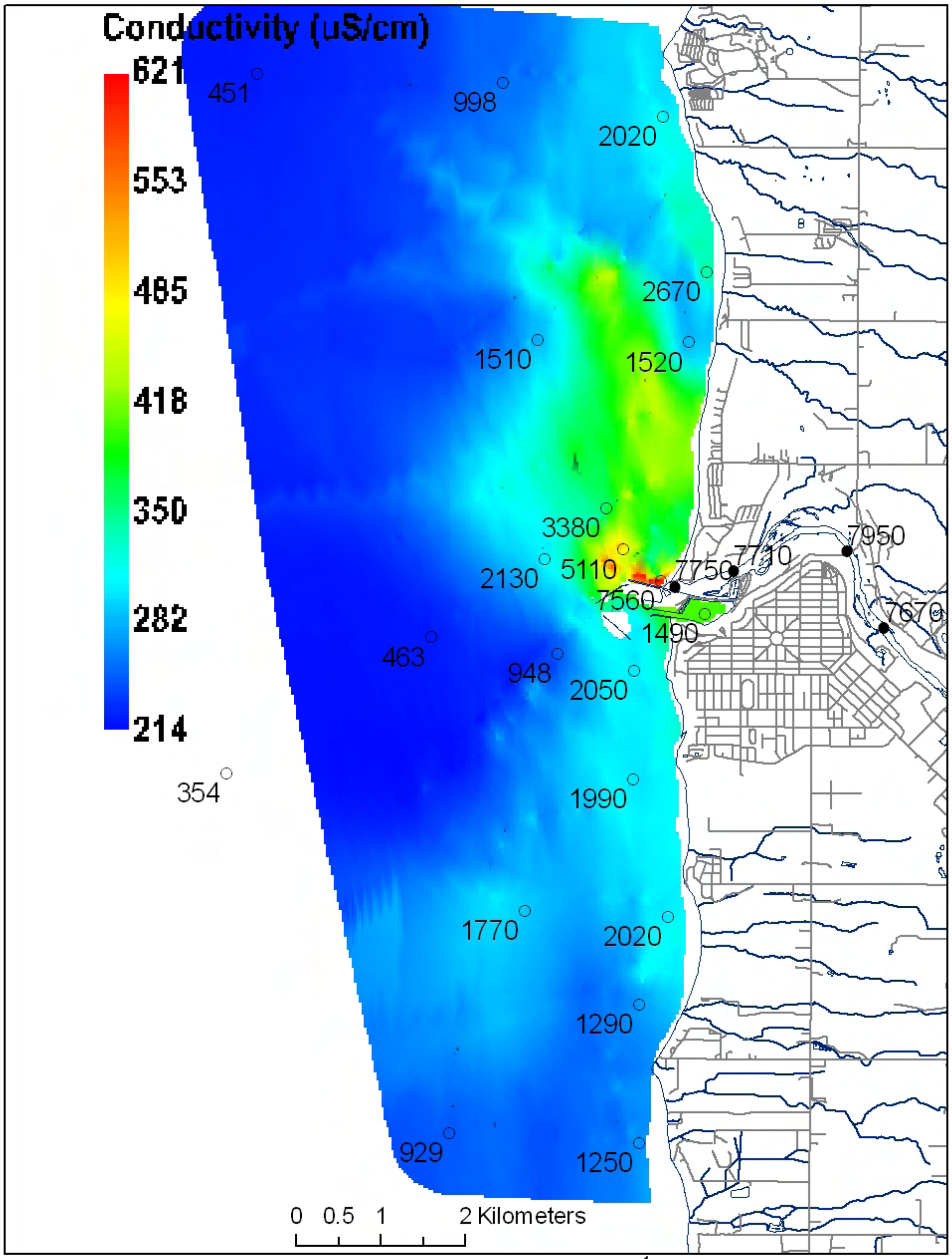

Figure 58: Surface conductivity (colour scale; µS cm^{-1} at 25°C) and NO_2+NO_3 concentrations (point samples; µg L^{-1} N) at the Maitland River study area during the second fall survey (November 23, 2003).

NO_2+NO_3

The levels of NO_2+NO_3 was elevated over much of the study area in comparison to ambient lake concentrations (Figure 58). The combination of high discharge volume and high concentration of NO_2+NO_3 in the Maitland River at the time of the survey resulted in an appreciable loading of nitrate+nitrite to the nearshore. In the lower Maitland River, NO_2+NO_3 concentration was 7732 µg L^{-1} (averaged over the river stations) and was almost 17 times higher than that of the lowest levels of the distant region. The ≥ 2x area for NO_2+NO_3 was 39 km^2. Concentration at all shoreward sample points exceeded 1000 µg L^{-1}.

Turbidity

As observed earlier at the Saugeen and Bayfield late fall surveys there were high levels of turbidity throughout the nearshore (Figure 59). The distant region was more turbid than the river (~2.9 FTU), and was more than 30 times higher than any previous survey date. As noted previously, the source of much of the turbidity is likely wind-driven erosion of the lakebed and shoreline resulting in suspension of particles into the water column. In addition to the strong lake currents on November 13 and 14 as described for the Bayfield area survey, there were also less dramatic but strong currents on November 19 and 21 indicating periods of strong wind.

Turbidity was slightly lower at the mouth of the Maitland River and over the area of strongest mixing of river discharge with the lake due to the unusual situation where river water was diluting turbidity in the lake. While turbidity was elevated everywhere there were also localized areas along the shoreline (and for up to 1 km away from the shore) with higher turbidity. These are possibly locations with higher clay content or rates of erosion.

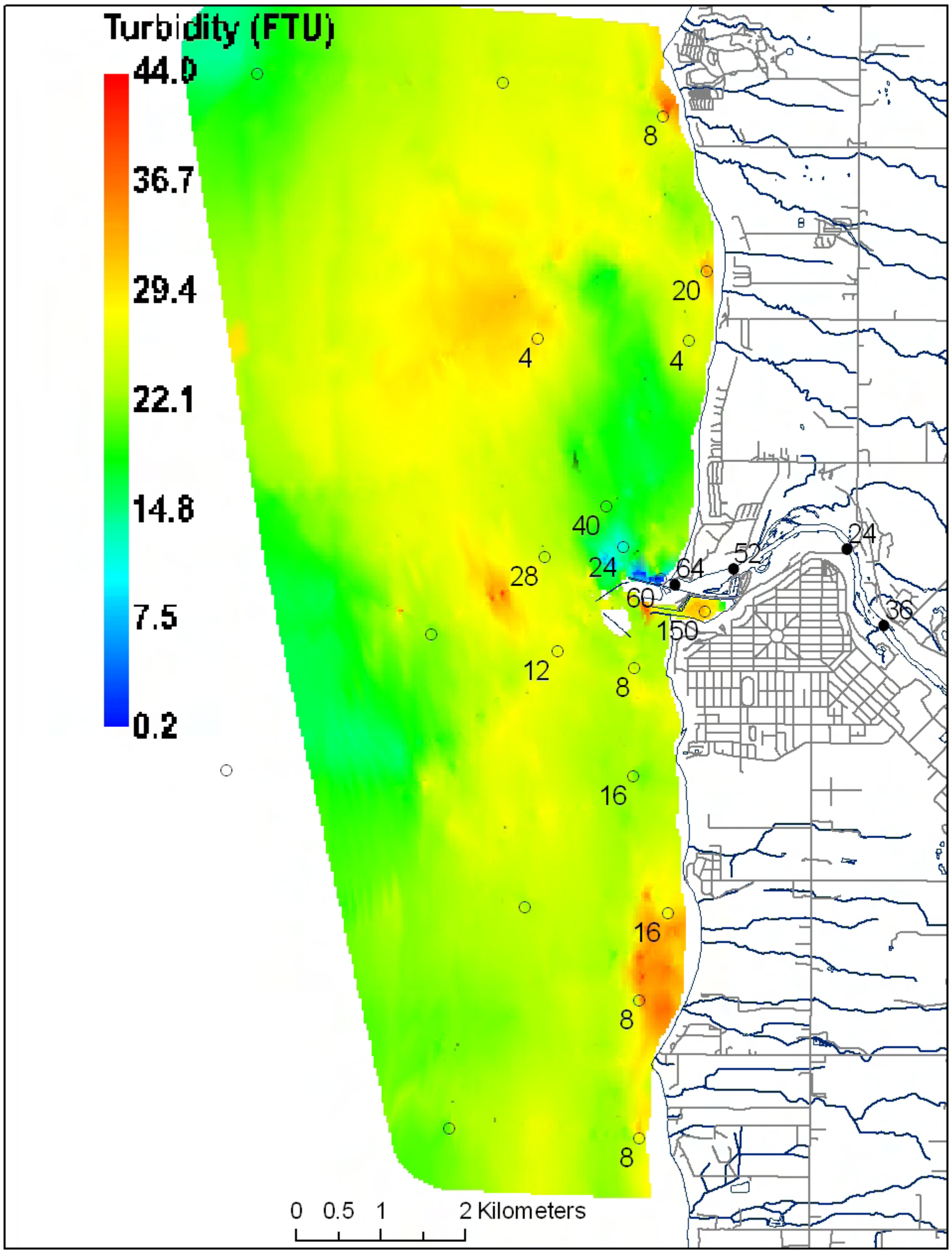

Figure 59: Surface turbidity (colour scale; FTU) and *E. coli* concentrations (point samples; CFU 100 mL^{-1}) at the Maitland River study area during the second fall survey (November 23, 2003). No samples were collected at points without numeric values.

E. coli

E. coli concentrations were marginally elevated (8-60 CFU 100 mL^{-1}) at most proximate region sample points with the exception of Goderich Harbour. There were 150 CFU 100 mL^{-1} in the single sample from the harbour. The broad pattern of variability in concentrations among stations did not suggest that discharge from the Maitland or any other shoreline location was a predominating source. Rather, it suggested a broader source such as the resuspended sediment.

Chlorophyll a

Despite the cool water temperatures with the advancing fall weather, the levels of chlorophyll *a* in the nearshore were at or above levels observed earlier in the year (Figure 60). The chlorophyll *a* concentration over the distant region (~1.0 µg L^{-1}), while low, was more than twice that observed on any other survey. The spatial variability of chlorophyll *a* over the proximate area resembled that of conductivity, suggesting that loading of phytoplankton from the Maitland River was likely a contributing source of chlorophyll *a* to the nearshore. With the exception of the area near the Maitland River mouth, concentrations in the plume-affected areas did not exceed 2 µg L^{-1}. Average chlorophyll *a* concentration over the lower river stations was 4.3 µg L^{-1}, and in the range of other survey. The range in chlorophyll *a* concentration between the proximate and distant region was slight, resulting in a ≥ 2x area of only 0.2 km^2, suggesting that nutrient inputs to the nearshore were having little impact on productivity.

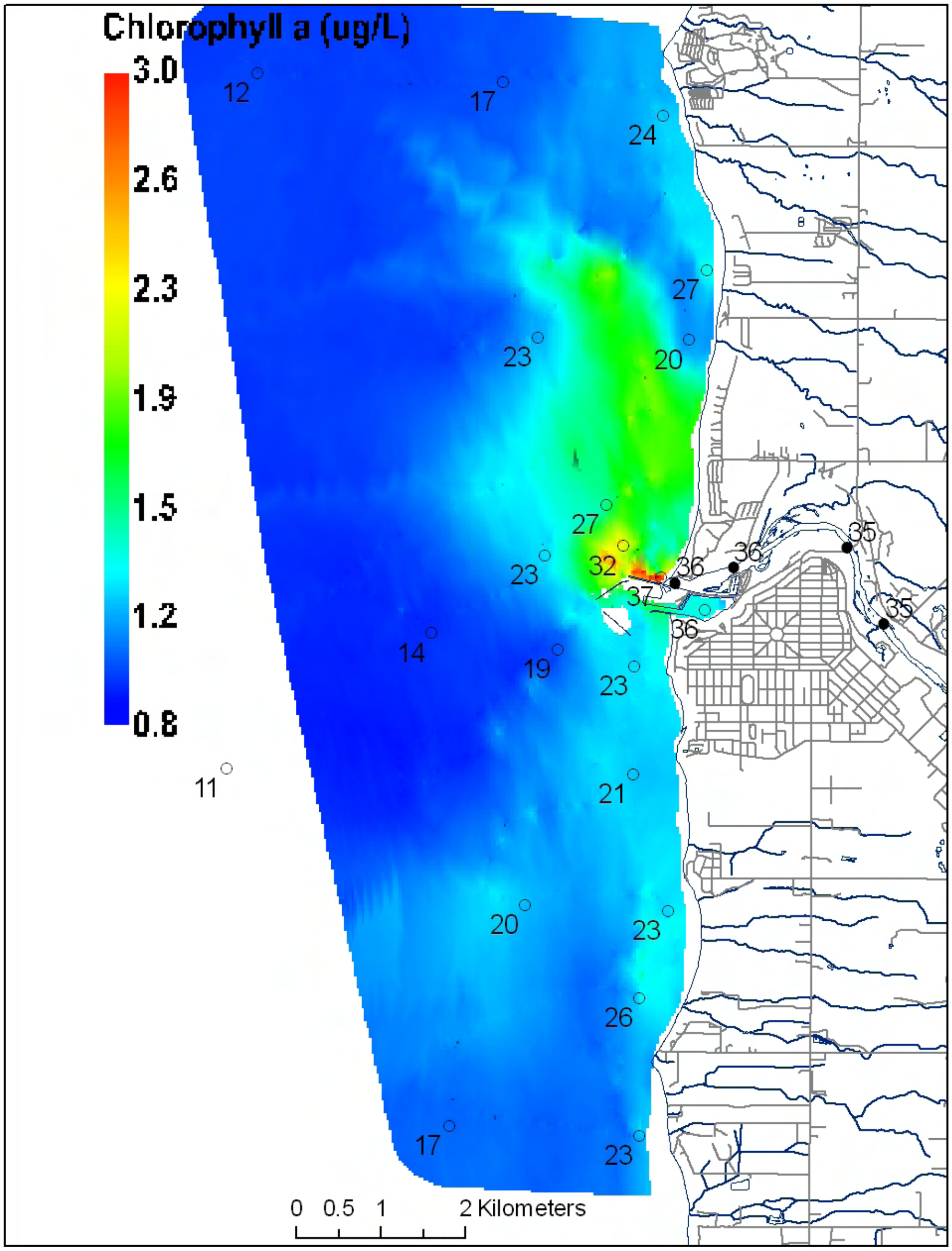

Figure 60: Maitland River study area during the second fall survey (November 23, 2003) showing [chl *a*] and [TP]. Surface chlorophyll *a* estimated from fluorescence (colour scale; µg L^{-1}) and TP concentrations (point samples; µg L^{-1} P).

TP

As seen in the late fall surveys at the Saugeen River and Bayfield River study areas, TP levels were appreciably elevated in the nearshore. In the proximate region, concentrations ranged from 14 to 28 µg L^{-1} with the exception of a site near the mouth of the Maitland River. Concentrations in the lower Maitland River were moderate, ranging from 35 to 36 μg L^{-1}. The pattern of TP concentrations in the proximate region were dissimilar to the orientation of the mixing area of the discharge from the Maitland River, indicating that additional sources of phosphorus were contributing to observed levels. As noted previously, it is probable that suspension of particles into the water column was contributing to the elevated levels of phosphorus.

4.0 Discussion

The offshore waters of Lake Huron are considered to be of high quality, however, environmental conditions in the nearshore of the lake are not well understood. There is longstanding debate as to the extent that loading from watersheds around the perimeter of the lake impacts water quality along the coastline (LHCCC 2005). Contributing to mixed perceptions of environmental quality is the potentially wide range of physical, chemical, and biological conditions that may occur over an area of the nearshore. A descriptive interpretation of environmental conditions in the nearshore based on observational data are fraught with difficulty because of the extent of observations that may be required to represent the range of conditions. The qualitative but mechanistically-focused analysis which follows attempts to provide a basis for integration of the study results over time and location and is meant to facilitate the interpretation of causes of variability in water quality.

4.1 Variability in Nearshore Water Quality

4.1.1 Quality and Quantity of Discharge From Saugeen, Maitland and Bayfield Rivers

The discharge from the Saugeen, Maitland, and Bayfield Rivers to the nearshore of Lake Huron was responsible for much of the variability in physical-chemical conditions observed over the three respective study areas. This was expected given that these three large river systems were selected for monitoring because of their high relative potential to affect the nearshore having the largest watersheds on the Canadian side of Lake Huron with the exception of the Bayfield River.

Recognizing the qualitative difference in water quality between the open waters of Lake Huron and water in the tributaries to the lake is critical to interpreting environmental conditions in the nearshore. Water discharged to the lake from the Saugeen, Maitland, and Bayfield Rivers in general contained appreciably higher levels of nutrients, particulate material, fecal pollutants (as inferred from *E.coli*), chloride, DOC and phytoplankton (as inferred from chlorophyll *a*) than the receiving lake water. Consequently, river discharge results in the creation of concentration gradients in the nearshore over the area of mixing as well as loading of pollutants to the lake, the extent being dependent on the volume of discharge, the river: lake concentration ratio and nearshore circulation.

Mapping of conductivity in the nearshore appeared to be an effective way of identifying the river plumes and broader pattern of mixing of tributary discharge with the lake. Nitrate+nitrite levels were consistently elevated in the rivers in comparison with the nearshore and nitrate+nitrite concentrations gradients in the lake generally corroborated the conductivity-based inferences on mixing areas.

The extent to which tributary discharge affected the shoreline as inferred from the size of the mixing areas in the nearshore was widely variable over time and roughly corresponded with fluctuations in river discharge. Large areas with elevated conductivity, contiguous with the discharge plumes from the Maitland and Saugeen Rivers, were noted during the spring and late fall surveys during periods of moderate to high relative discharge. On several occasions, the affected areas extended beyond the study areas approximately 6 km from the respective river mouths. More spatially limited mixing areas were detected during summer surveys when river discharge had declined to near base flow. The contrast in the extent of the discharge-affected areas between the Bayfield River and the two larger rivers illustrates the importance of discharge volume in determining the spatial scale over which the river directly affects the nearshore. Despite the appreciable drainage area of the Bayfield River, the direct influence of the river discharge was limited (1-2 km of shoreline) in comparison to the Maitland and Saugeen Rivers.

There were broad fluctuations in the physical-chemical composition of the water discharged from Saugeen, Maitland, and Bayfield Rivers over the study and these changes were typically concurrent with alteration of river flow. Inherent variability in riverine water quality associated with spring runoff and wet weather events is well recognized. The implications for nearshore water quality are obvious in concept but difficult to assess in practise. High relative effect on the nearshore and the potential for adverse impacts are anticipated when concentration gradients between the river and lake are large and the quantity of discharge is high. In many cases, concentrations must exceed a threshold (guideline or objective) to be considered a concern (e.g. 10 µg L TP). Under conditions where the concentration gradient is large but the discharge volume is low, the concentration gradient at the river mouth will be steep with a limited area in the nearshore where the threshold is exceeded. The results of the late summer survey at the Bayfield study area are a good illustration of this point. Despite appreciably elevated levels of nitrate+nitrite and *E.coli* in the river in response to wet weather, the impacted area in the nearshore was limited to a steep gradient over a relatively small mixing area near the river mouth. With increasing discharge, the gradients extend further into the lake as the larger volume of river water retards dilution by lake. The pattern of nitrate+nitrite concentrations during the spring survey over the Goderich area demonstrate the potential scale of effect when concentration gradients and discharge volume are high. Nitrate+nitrite levels were elevated at least 2X lake background over the immediate mixing area which, at its extremes, was 6 km from the river mouth.

The daily discharges from the Saugeen, Maitland, and Bayfield Rivers varied by about an order of magnitude over 2003. The nearshore surveys were conducted over the low to medium ranges of river discharge. Maximal discharge typically occurs in early spring during snow melt when it is impractical to conduct lake-based work. Similarly, storm-related pulses in discharge were not well captured by the pre-scheduled lake-based surveys.

Periods of wet weather associated with heavy or prolonged precipitation can be expected to impact water quality in rivers draining the developed watersheds bordering the three study areas. The results of the regular water quality sampling at downstream sites on the Saugeen, Maitland and Bayfield River illustrate that there were periods of reduced water quality concurrent with weather events in the lower rivers that were outside of the times of the nearshore surveys. As with the lake surveys, the tributary sampling effort, while more temporally extensive, was insufficient to capture the full range of conditions experienced in 2003.

4.1.2 Shoreline Runoff and Discharge from Small Tributaries and Point Sources

There were a diversity of features along the shoreline of the study areas, in addition to the large rivers (Saugeen, Maitland, and Bayfield River), where water was discharged to the lake with potential to affect water quality. Notable were the small tributaries and drains along the shoreline of the Bayfield and Goderich area, several of which flowed through clay-based ravines. On multiple occasions, spatial patterns in conductivity and turbidity along the shoreline suggested that runoff from small tributaries was affecting water quality. However, on the scale of the study areas, the affected areas were limited in extent, difficult to conclusively interpret, and frequently difficult to separate from the more pervasive effects of the discharge from the large rivers.

Storm sewers servicing the communities of Bayfield, Goderich, Port Elgin, and Southampton discharged to the shoreline over the study areas. Again, on the scale of the survey areas no impact was detected that could be conclusively interpreted as resulting from storm water discharge. A possible exception to this was the spring survey at Bayfield study area. During this survey, conductivity was slightly elevated over localized areas approximately offshore two storm sewers south the Bayfield River at this time, however, a causal connection was not established.

There was a single point-source discharge to the lake over the three study areas, which is consistent with the relatively few direct discharges along the shoreline of Lake Huron. The Goderich sewage treatment plant discharges to the shoreline approximately 1.5 km south of the Maitland River mouth. No effect of the shore-based discharge was detected over the study, though it should be recognized that shallow water offshore of the discharge limited the ability to effectively survey near the site. The sewage treatment plant for Southampton and Port Elgin discharges to the Saugeen River and potential effects on the lake are blended with those of the river. At the time of survey, there was no communal sewage treatment plant operating at Bayfield.

4.1.3 Shoreline Erosion and Resuspension

Physical disturbance of the lakebed and shoreline by water movement and wave action at times, exerted a strong influence on water quality in the nearshore by the entrainment of particulate material into the water column. High water clarity is an expected characteristic of the Lake Huron coastline, however, areas of elevated turbidity were common in shallow water and on occasion over wide areas of the nearshore. The resuspension of particulate material originating within the lake into the water column was inferred from broad areas of elevated turbidity along the shoreline independent of river mouths. Frequently, there was an area-wide gradient in water clarity with turbidity decreasing with depth and distance from the shoreline. Notable was the wide range in turbidity over the study period, with exceptional levels of water clarity at some times, and murky conditions at others.

Reduced water clarity is the most obvious effect of resuspension of particulate material on water quality. Chemical and biological constituents are also potentially affected depending on the characteristics of the bed and shoreline sediments. The suspension of fine clay particles loads, mineral-bound phosphorus (usually apatite), to the water column may give the impression of anthropogenic phosphorus enrichment until the particles settle out of the water column (Palmateer and Huber 1984). Since clay-associated phosphorus has limited biological availability, it does not stimulate the same degree of algal growth, as would a more biologically available form such as those associated with fertilizers or manure (Reynolds and Davies 2001). The elevated levels of total phosphorus observed during the late fall survey were likely in large part due to resuspension of inorganic particles. Organic particles resulting from breakdown of biological materials deposited on the lakebed and from periphyton, (attached growth consisting of bacteria, fungi, micro- algae, micro-invertebrates) contribute nutrients (phosphorus and nitrogen), algae and other micro-organisms when eroded from the lakebed and areas of accumulation on the waterline and foreshore of the beach. Total phosphorus levels and organic nitrogen are frequently elevated along the shoreline in shallow water in samples containing any amount of particulate material of organic origin. Bioavailability of phosphorus bound within organic particulate materials is variable but again tends to be of low biological availability.

Diagnosing the sources of turbidity and its potential effects on water quality can be challenging. An approximate separation of particulate materials originating from runoff to the lake from in-lake generation by resuspension is possible by determining if dissolved chemical constituents such as chloride, nitrate, phosphate, or DOC are also elevated in the area. However, mixing areas of external loading and areas of resuspension will invariably overlap to varying extents. In this study the relative spatial patterns in conductivity and turbidity were used to distinguish situations where runoff was contributing particulate material to the water column from situations where in-lake processes were the source of elevated particulate levels. Predominance of within-lake loading of inorganic particles from organic materials can be inferred to a limited extent by examining the relative elevation of total phosphorus to organic nitrogen. Attention to the origins of particulate materials is necessary when assessing water quality problems where bioavailability of nutrients is a factor.

Temporal patterns in nearshore turbidity as a function of lake energy are well known. Seasonal variability in wind and wave energy account for increased turbidity during the spring and fall (Gregor and Ongley 1978). Calm weather occurs 75% of the time in June and <40% of the time in November (Gregor and Ongley 1978). Inorganic turbidity is greatest in the fall, the season of greatest wave energy (Gregor and Ongley 1978; based on 1967 to 1973).

For the areas of the present study, inorganic turbidity of natural origin (erosin of shore bluffs) was considered to be a serious problem along the Canadian shoreline resulting in reduced aesthetic quality (Gregor and Ongley 1978). On a longer time frame, changing lake levels may affect nearshore turbidity with greater erosion of shoreline bluffs and more turbidity during high water levels (Gregor and Ongley 1978).

4.1.4 Lake Circulation in the Nearshore

Lake currents strongly affect how materials loaded from watersheds or generated within the lake affect the nearshore on exposed shores of Lake Huron. On a basin-wide scale and over seasons, currents in the nearshore follow a counter-clockwise gyre with prevailing flow tending northward along the SE shores of the lake. However, it is the short-term circulation patterns that most strongly influence observable water quality conditions at a point in time. Short-term currents in the nearshore on the scale of hours to days were dominated by alongshore flows with frequent reversals of current direction.

Alongshore flow most frequently shaped the spatial features of water quality observed. The orientation of the mixing area of the discharge from the Maitland and Bayfield Rivers were often parallel to the shoreline extending away from the river mouth in the direction of the surface currents. A further, common feature was evidence of residual effect of river discharge on water quality along the opposing shoreline that was likely the result of the current flow in the opposing direction at a time preceding the most recent current reversal. In contrast to the approximately linear shoreline of the Maitland and Bayfield Rivers study areas, the shoreline of the Saugeen River study areas was more varied, as was the bathymetry of the nearshore, contributing to greater variability in the orientation of mixing areas as the predominately alongshore currents were deflected by various shoreline and bathymetric features.

Short-term current speeds measured at the ADCP sites were appreciable at times, resulting periodically in conditions where discharges to the nearshore could be moved appreciable distances along the shoreline under the influence of sustained unidirectional alongshore flow. Evidence of the capacity for movement of materials along the shoreline comes from dimensions of the mixing area of river discharge which, on occasion, extended beyond the bounds of the study areas, up to 6 km from the river mouth, in the case of the Saugeen and Maitland Rivers.

The frequent changes in current direction and magnitude, which characterize the nearshore, contributes appreciably to the persistent variability in water quality in the nearshore. The influence of circulation on environmental conditions becomes more apparent as the volume of watershed discharge increases and the quality of the discharge declines.

4.1.5 Seasonality and Weather

The striking difference in physical-chemical conditions observed from one survey period to the next where due, in large measure, to fluctuations in weather conditions on times scales ranging from seasons to hours.

There is an approximate seasonality in water quality corresponding with the degree to which water is discharged from watersheds. During the spring and fall, when there is more water discharged because of reduced evapotranspiration (cooler temperatures and diminished plant growth), the effects of the adjacent lands to the lake becomes more apparent. The higher levels of nitrate+nitrite and broader areas of elevated conductivity observed during spring and late fall surveys is evidence of the more extensive effects of lake-shoreline interaction on water quality at these times, compared with the summer and early fall months. There also is the possibility that seasonal changes in frequency of high winds, notable more in the fall, contribute to broadly changing levels of lakebed/shoreline erosion resulting in patterns in sediment resuspension over the seasons.

Seasonal and roughly predicable changes in temperature regimes in the lake and the rivers discharging to the nearshore alter the spatial dimensions of the shoreline-lake interaction through temperature-driven density gradients, which affect mixing patterns over a range of spatial scales.

In spring, temperature was a major driver affecting the spatial patterns in the river plumes of all three regions. Differential water temperatures between the river, the proximate region, and distant region resulted in the river water, as well as shoreline inputs, to be trapped close to the shore. These observations demonstrate that seasonal and physical effects can have strong influences on plume dynamics. By holding river and shoreline inputs in the region adjacent to the shore, current reversals may spread the potential impact of these further in the nearshore region. At the Maitland and Bayfield study areas, a band of high turbidity, nutrients, and conductivity parallel to the shore was evident during the spring survey. This effect was attenuated at the Saugeen river region, again because of the shallow area to the south that inhibited the spread of the river plume in that direction.

4.1.6 Water Quality Concerns in SE Lake Huron

Typical of many developed areas on the Great Lakes, there has been a history of concern of how human activities on the shores of the lake are affecting environmental quality of the lake as a whole and, more specifically, the more heavily used nearshore area. In recent years two issues have dominated concerns expressed by the public: i) nutrient enrichment leading to eutrophication and excessive amounts of algae, and, ii) fecal pollution resulting in impairment of recreational water quality and beach postings (Lake Huron Centre for Coastal Conservation 2004). In both cases, the most sensitive areas of the lake where impacts are potentially greatest (and most apparent) are the coastal waters or nearshore as referred to in this report.

4.1.7 Watershed Nutrient Loading and Nearshore Trophic Status

The patterns of nutrient levels and trophic indictors documented in this study describes a paradoxical condition where, at times, there was strong evidence of land-based nutrient enrichment, most notably in nitrates, yet loading of the primary limiting nutrient, phosphorus, was seemingly insufficient to appreciably alter trophic status in the nearshore as inferred from levels of chlorophyll a. Phosphorus is thought to be the primary nutrient limiting growth of phytoplankton in southern Lake Huron (Lin and Schelske 1981).

Nowhere was the connection between watersheds, major rivers, and the nearshore more evident than in the patterns of variability in NO_2+NO_3 concentrations. The river concentrations of NO_2+NO_3 were high relative to the lake and strongly responsive to hydrological events in the watershed. In the open lake, NO_2+NO_3 concentrations were generally many times lower than river concentrations. Consequently, river discharge invariably elevated NO_2+NO_3 levels over the mixing areas in the nearshore. On occasions when river discharge was high, appreciable areas of the nearshore were affected because of the broad areas over which the discharge was transported in the nearshore before being diluted to ambient lake levels.

In oligotrophic areas of the Great Lakes, including Lake Huron, nitrogen is thought to rarely limit primary production of phytoplankton. While it is possible that N can become transiently limiting, at least for some groups of organisms, extensive N-limitation is thought unlikely in highly oligotrophic systems such as lake Huron. The often strong correspondence in decline in NO_2+NO_3 concentration with conductivity over mixing areas of river discharge indicates that dilution was primarily responsible for the attenuation of NO_2+NO_3 with little uptake of NO_2+NO_3 and limited biological utilization suggested.

Loading of nitrogen compounds to tributaries in watersheds with concentrated agriculture resulting in elevated nitrate+nitrite levels in surface water has been appreciated for many years (Neilsen et al. 1978, Lefebvre et al. 2005). The Saugeen watershed was one of the Canadian intensive study areas in the PLUARG study of 1970s (Hore and Ostry 1978), a major Great Lakes–wide study to examine non-point source pollution effects on the Great Lakes from urban and agriculturally impacted watersheds. A conclusion of the study was that agriculture and point sources were the major sources of nitrogen pollution. Agriculture (general) was ascribed a 77% contribution to total estimated load and combined municipal and industrial point sources 12.5% of total estimated load of nitrate+nitrate at the outlet of the Saugeen River watershed.

Over much of the Great Lakes P is thought to be the primary controllable limiter of algae growth and to generally control production of algae biomass (IJC 1980). Concentrations of TP in the rivers were typically elevated relative to lake ambient levels; however, the spatial extent and magnitude to which levels were elevated in the nearshore above ambient were qualitatively lower than compared with NO_2+NO_3. There are at least three contributing factors for the seemingly more limited influence of the watersheds and shoreline on the nearshore. Firstly, the degree of enrichment in the rivers compared with ambient lakes level was usually lower than that of nitrates. Secondly, much of the P delivered to the lake by river discharge is likely associated with particulate material, which would be removed from the water column as particulate materials settles out of the water on reaching the typically less energetic conditions of the lake. Evidence of this is in the correspondence between TP and turbidity levels over discharge mixing area was sometimes observed. In contrast, NO_2+NO_3 is largely in dissolved form and not attenuated by sedimentation of particles. Finally, because P is likely the growth-limiting nutrient, there will likely be much stronger biological uptake and attenuation of concentration over the discharge mixing area.

The area of nearshore over which levels of nutrients and chlorophyll *a* were greater than 2x that of the offshore edges of the study area (distant region) were estimated among surveys as an indicator of shoreline/watershed effect. The ≥2x areas were large on multiple occasions over each of the study areas for NO_2+NO_3 and chlorophyll *a* concentration. The spatial patterns leave little doubt of nitrate+nitrite enrichment. The interpretation of the chlorophyll *a* data are, however, less obvious. The finding of large ≥2x areas on occasion implies nutrient enrichment sufficient to stimulate phytoplankton growth. Chlorophyll *a* concentrations were typically higher in the river compared with the lake, and it is possible that, at times an appreciable portion of the additional chlorophyll *a* was due to input of phytoplankton to the lake by river discharge. It is not possible to distinguish between chlorophyll *a* discharged to the lake from chlorophyll *a* produced in the lake as a result of growth of phytoplankton stimulated by nutrients discharged to the lake. The fluorescence-based approach used to survey chlorophyll *a* is sensitive at low concentrations and while it was technically possible to detect small changes, the absolute concentrations were, with limited exception, in the low range of concentration characteristic of the Great Lakes.

There were, however, occasions (Bayfield and Maitland second summer surveys) that chlorophyll *a* appeared to be elevated in the direction of movement of river discharge along the shoreline over areas beyond the locations with elevated conductivity and direct effect of mixing areas. Importantly, while chlorophyll *a* concentrations appeared to be elevated 2-4 fold in the plume region, the chlorophyll *a* concentration in the plume generally did not exceed 1 $\mu g\ L^{-1}$ (excluding the area directly adjacent to the river mouth). In terms of absolute concentrations, this is well within the range of an oligotrophic body of water (0.3-4.5 $\mu g\ L^{-1}$; Wetzel 1983). The direct (locally expressed) effect of the rivers on eutrophication in the pelagic zone is therefore likely to be limited.

Average summer chlorophyll *a* levels are frequently used to infer trophic status and overall level of biological productivity in an area. Differing concentration boundaries have been used to infer trophic status. Neilson et al. (1995) used a boundary of 2 $\mu g\ L^{-1}$ to distinguish mesotrophic from oligotrophic conditions in the Great Lakes. Rarely did concentrations exceed 2 $\mu g\ L^{-1}$ in the nearshore. In contrast, mesotrophic conditions prevailed in the Saugeen, Maitland and Bayfield Rivers based on chlorophyll *a* levels over the study.

Nutrient and chlorophyll *a* levels have been monitored in raw water collected at the Goderich Water Treatment plant for many years on a roughly weekly interval as one of eighteen water intakes monitored in the MOE Great Lakes Water Intake Biomonitoring Program. A primary objective of the program is to track nutrient levels and trophic status around the Great Lakes. Nicholls et al. (2001) report on trends in nutrients over the period 1976 to 1999 as detected by the monitoring of raw water at these Water Treatment Plants including the Goderich WTP and two plants further south along the Lake Huron shoreline outside the study area, Grand Bend and Lambton, respectively. A decreasing long-term trend in phosphorus was reported for the three Lake Huron plants reflecting the phosphorus management initiatives of the Great Lakes Water Quality Agreements of 1972 and 1978. The rate of decline in total phosphorus over the period 1976 to 1992 was given as 1.0 µg L^{-1} per year. However, over the most recent 10 to 12 years no statistical significant trend was reported. The average phosphorus concentrations at the Goderich site were 2 and 4 times higher than observed at the Grand Bend and Lambton locations. Direct comparison among locations is biased by the influence of the Maitland River on water quality in the vicinity of the Goderich intake (as evident in this study) and the differences in susceptibility to resuspension of bed sediment owing to the varying depths and distances from shore. The five year mean total phosphorus at the Goderich site for 1996 to1999 was 22 µg L^{-1} (as approximated from figure 3 in Nicholls et al. 2001). Seasonally, TP concentrations at the Goderich site were elevated in the spring and fall, consistent with the periods of more energetic weather and the seasonal pattern of discharge from the Maitland River.

Gregor and Ongley (1978) report on trends and state of water quality information available for the nearshore of Lake Huron over the period 1967 to 1973. Due to minimal amounts of data and limited seasonal data (single summer cruises in many years) they remark that there were major limitations to interpretation of spatial and temporal trends. Water quality was described as good to fair with minimal variation along the coastline but with a slight decrease in quality towards the south. Concentrations of chlorophyll *a* were described as small or minimal and in contrast to the impression of quality based on secchi depth, which was impacted by inorganic turbidity (erosion of clay bluffs along the coastline).

In 1974 and 1975, MOE undertook a series of water quality surveys at a number of embayments on the shores of Lake Huron and Georgian Bay including sites on the shoreline of Goderich, Port Elgin and Southampton within the present study area. Water quality was considered to be generally good but with some localized areas exhibiting signs of impairment (Ross and Chatterjee 1977). The Goderich harbour and adjacent nearshore was assessed as exhibiting mesotrophic conditions, which was attributed primarily to discharge from the Maitland River and watershed-derived nutrient sources. Increasing loading of total nitrogen, again from the Maitland River, was also flagged as a concern, and predicted to continue into the future. Three sites in Goderich inner harbour and seven sites in the adjacent nearshore described as being under the influence of the Maitland River were visited seven times from May 1974 to May 1975. Unfortunately, the locations of the nearshore stations were not reported, limiting the direct comparison of results with the present study. The locations of two of the earlier three harbour stations are similar to stations surveyed in 2003 permitting direct comparison. Several general observations on limnological conditions by Ross and Catterjee (1977) bear resemblance to observations in 2003. Notable is the overall influence of discharge from the Maitland on the nearshore and the strong variability in river influence as a function of seasonal changes in discharge. The authors also comment on the elevated levels of turbidity and suspended solids observed in the nearshore, which they attributed to the combination of shoreline erosion, lakebed resuspension, and loading from the Maitland River. Overall nutrient levels observed in 1974 and 1975 suggest contrasts with 2003. Overall, chlorophyll *a* levels and TP concentrations appear higher than in 2003 (see Table 8 for summary of 1974/1975 data). This is not surprising since the study preceded the phosphorus management actions of the Great Lakes Water Quality Agreement of 1978.

Seven sites were surveyed in the Port Elgin and Southampton areas, extending from MacGregor Point to north of the Saugeen River, and extending to about 1 km offshore and an additional site that was located at the mouth of the Saugeen River. Four surveys were completed over the period May 1974 to May 1975. The nearshore in the areas of Port Elgin and Southampton were considered to be oligo-mesotrophic with the discharge from the Saugeen River noted as an important nutrient source (see Table 9). Direct comparison of the 1974/1975 results are difficult because of the limited assessment of spatial variability over the study areas conducted in the earlier study.

Table 8: Summary of water quality measures over the 1974-75 study period at monitoring stations in the Goderich area. Seven sites were surveyed in the nearshore and three sites in Goderich Harbour.

Measure	Goderich Area	Study mean	Seasonal Period Averages min[1]	Seasonal Period Averages max	Single sample min	Single sample max	Harbour Site 2003 Mean (min-max)
Chlorophyll *a*	Nearshore[2]	2.6	0.91	4.9	0.5	6.5	
($\mu g\ L^{-1}$)	Harbour[3]	3.4	2.0	4.8	1.3	8	
Total Nitrogen	Nearshore	712	259	906	222	1350	
($\mu g\ L^{-1}$ N)	Harbour	554	320	747	213	1080	1331 (555-2150)
NO_3	Nearshore	NA	NA	NA	20	960	
($\mu g\ L^{-1}$ N)	Harbour	NA	NA	NA	19	610	1059 (361-1850)
TP	Nearshore	26	18	32	9	39	
($\mu g\ L^{-1}$)	Harbour	41	28	64	5	140	15 (7-36)
Turbidity	Nearshore	11.3	6.4	17.2	1.7	27	
(FTU)	Harbour	23.0	19.7	25.0	0.4	67	9.6 (1 – 33)
Conductivity	Nearshore	236	207	257	204	294	
(uS cm^{-1})	Harbour	323	274	367	192	488	312 (235 - 411)
Fecal Coliform	Nearshore	2	2	3	1	280	
(cfu/100mL)	Harbour	22	16	21	1	112	7 (2-150)[4]

1- Survey results were reported as aggregated result for three seasonal periods (May 1974, September 1974 and April 1975). 2-The nearshore stations were considered by the authors to be under the influence of the Maitland River; at least one of the stations was > 1 km offshore. 3-The harbour stations extended from the channel to the inner harbour to the east end of the harbour. 4-in 2003 data are for *E.coli*.

Table 9: Summary of water quality measures over the 1974-75 study period at monitoring stations in the Port Elgin-Southampton area. Seven sites were surveyed in the nearshore and one sites in mouth of the Saugeen River. Results are also presented for a similarly placed station in 2003.

Measure	Port Elgin - Southampton Area	Study mean	Seasonal Period Averages min[1]	Seasonal Period Averages max	Single sample min	Single sample max	River Mouth Site 2003 Mean (min-max)
Chlorophyll *a*	Nearshore	1.1	0.82	1.3	0.4	2.3	
($\mu g\ L^{-1}$)	River Mouth	1.9	1.5	2.2	1.5	2.2	NA
Total Nitrogen	Nearshore	476	440	511	372	598	
($\mu g\ L^{-1}$ N)	River Mouth	850	604	1090	564	1100	1808 (1093-2980)
NO_3	Nearshore	NA	NA	NA	250	330	
($\mu g\ L^{-1}$ N)	River Mouth	NA	NA	NA	140	444	1158 (716-2270)
TP	Nearshore	11	8	14	6	20	
($\mu g\ L^{-1}$)	River Mouth	34	28	40	27	40	22 13-47
Turbidity	Nearshore	2	1.6	2.4	0.95	7.4	
(FTU)	River Mouth	31	20	41	19	43	8.3 4.4-16.8
Conductivity	Nearshore	208	205	211	202	233	
(uS cm^{-1})	River Mouth	496	391	600	390	600	562 534-602
Fecal Coliform	Nearshore	2	1	2	1	12	
(cfu/100mL)	River Mouth	34	20	48	12	48	40 (12-250)[2]

1-Survey results were reported as aggregated result for two seasonal periods (nearshore May 1974, May 1975; river mouth May1974 and September 1974). 2- In 2003 results are for *E.coli* (cfu/100mL).

During the open water season of 1980, MOE undertook water quality surveys at nearshore areas adjacent to Grand Bend, Goderich and Southampton. These were done to assess the extent of eutrophication in response to earlier reports by the Upper Lakes Reference Group of the IJC, which suggested there were localized nearshore water quality problems at the mouths of some tributaries and embayments (Jackson et al. 1985). Multiple locations spread along the shoreline and into the lake were surveyed on three occasions from early summer to early fall. While the spatial distribution of stations was generally similar to the present study, the survey duration was more limited. Quantitative comparison of findings is not possible because there is insufficient information reported to integrate data to arrive at comparable spatial basis for comparison. There was appreciable spatial variability observed along the shoreline in 1980, notably decreasing gradients in concentration of chlorophyll *a*, TP, and nitrate+ nitrite from the shoreline into the open lake. The extent of the gradients varied among surveys with generally less variability during the mid-summer survey than the early summer and fall survey.

Qualitative comparison of results suggests both similarities and contrasts. The ranges in nitrate+nitrite concentrations observed in 1980 appear lower than that found in 2003 (Table 10). This, to some extent, likely reflects the more limited sampling during periods of enhanced watershed runoff in 1980. Increasing lakewide (Neilson et al. 1995) and tributary levels of nitrate+nitrite (Bronte-Gelok and Joy 1999) in the intervening period contribute to the discrepancy. In contrast, levels of TP and chlorophyll *a* appear to be in a similar range between surveys.

Of note are the results for the fall survey at the Goderich area, which followed a period of stormy weather. The authors (Jackson et al. 1985) indicate that uniformly turbid water extended for 5 km into the lake. The ranges in nutrients, chlorophyll *a* and chloride concentrations exceeded other surveys at this time.

Jackson et al. (1985) concluded that nearshore areas examined showed signs of eutrophication and conditions were tending towards mesotrophy (moderate enrichment) with the nearshore adjacent to Goderich more impacted than Southampton. No criterion was given for the assignment of trophic status.

Table 10: Summary of water quality measures over the 1980 study period at monitoring stations on the Saugeen and Maitland Rivers.

Measure	Study Area	Study mean	Single sample min	Single sample max
Chlorophyll *a*[1] ($\mu g\ L^{-1}$)	Nearshore - Saugeen River Mouth	0.67	0.1	2.9
	Nearshore - Maitland River Mouth	0.97	0.1	3.3
	Lake Huron nearshore - S	NA		
	Lake Huron nearshore - N	NA		
NO_2+NO_3 ($\mu g\ L^{-1}$ N)	Nearshore - Saugeen River Mouth	241	160	430
	Nearshore - Maitland River Mouth	355	220	1720
	Lake Huron nearshore - S	260	225	293
	Lake Huron nearshore - N	265	240	281
TP ($\mu g\ L^{-1}$)	Nearshore - Saugeen River Mouth	6	1	25
	Nearshore - Maitland River Mouth	10	2	48
	Lake Huron nearshore - S	4	3	6
	Lake Huron nearshore - N	4	3	7
Conductivity ($uS\ cm^{-1}$)	Nearshore - Saugeen River Mouth	229	202	424
	Nearshore - Maitland River Mouth	226	200	403
	Lake Huron nearshore - S	202	189	210
	Lake Huron nearshore - N	201	191	212

1- corrected chlorophyll *a*

A lake-wide perspective on trends in nutrient and trophic status in Lake Huron can be gleaned from the report (Depinto et al. 2006) of a technical committee examining the status of progress towards the objective of Annex 3, the phosphorus management annex, of the Great Lakes Water Quality agreement of 1978. With respect to meeting the prescribed target loads of phosphorus, the committee concluded that it appeared that the target has been met with the caveat that phosphorus load estimates have not been available since 1991. Load targets were consistently met since 1985, based on available data. The open lake TP concentration target of 5 $\mu g\ L^{-1}$ was being met to the end of the data record at 2005, with no apparent trend in concentrations from the 1970s through to 2005. Similarity, open lake levels of chlorophyll *a* were below the Lake Huron target of 1.3 $\mu g\ L^{-1}$, and were indicative of oligotrophic conditions to 2005, the end of the data examined. Summer chlorophyll *a* concentrations have been in the range of approximately 0.3 to 1.3 $\mu g\ L^{-1}$ since about 1993 with no apparent trend in concentrations.

Neilson et al. (1995) in a synopsis of nutrient trends in the Great Lakes prepared for the 1994 SOLEC conference, drew attention to a long-term trend of increasing levels of nitrate+nitrite around the Great Lakes, advising continued monitoring but concluding that it was not of itself a cause for concern at the time. Concentrations were below well below drinking water objectives (the only relevant objective at the time) and a trend of increasing N to P served to shift competitive advantage away from cyanobacteria in the plankton. Multiple causes of increasing nitrogen levels were suggested, including trends in chemical fertilizer use. Atmospheric deposition was suggested as the major cause in the upper Great Lakes.

In a 2004 review of nearshore water quality information for southeastern Lake Huron, LHCC (2004) indicated that nutrient enrichment appeared to be increasing, however, support for this interpretation appears to have been based on incidence of shoreline fouling by algae in recent years and ongoing evidence of nutrient enrichment in tributaries to the lake.

4.1.8 Fecal Pollution as Inferred from the Indicator *E. coli*

The contrasting occurrence of the fecal pollution indicator *E.coli* among the Saugeen, Maitland, and Bayfield Rivers and the corresponding nearshore areas provides a seemingly contradictory picture of fecal pollution. River levels of *E. coli* varied widely, periodically reaching levels suggestive of loading of fecal pollutants to the rivers. In contrast, levels of *E.coli* at the nearshore sampling positions were almost always near or below method detection. While levels elevated over lake background (seemingly non-detectable), suggestive of loading from river discharge or shoreline sources, were occasionally observed, only rarely did estimates exceed 100 CFU 100 mL^{-1}, the Provincial Water Quality Objective for recreational water use. The second summer survey at the Bayfield River study area provides a striking example of this contrast. The survey followed wet weather and concentrations of *E. coli* in the lower Bayfield River were elevated (on the order of 10^3 CFU 100 mL^{-1}). Yet, *E.coli* levels in samples beyond the immediate vicinity of the Bayfield River mouth were near or below the detection limit for *E. coli*. (1-4 CFU 100 mL^{-1}).

The disparity between the lake and river likely lies in a mixture of explanations depending on the time and location. Fundamental to the explanation is that ambient levels of *E.coli* in the water column of the nearshore at the depths sampled in this study

(>2.5-3 m) appear to be low and below the method detection of the analysis. Consequently, away from the immediate shoreline (depths >2.5-3m) discharge from the large rivers and other shoreline sources may be expected to affect levels in proportion to mixing gradients and orientation of mixing areas in the nearshore.

The study results under-represent the effects of river discharge because, with the exception of the second summer survey at the Bayfield area, *E.coli* levels in the river were low at the time of the nearshore surveys. In the case of the second summer Bayfield survey, while concentrations were high in the river the volume of discharge was relatively low. The transient nature of *E.coli* loading, and presumably fecal materials, to rivers makes it difficult to assess impacts on the nearshore of the lake using a lake-based survey approach such as in this study. However, the results for the intensive river stations provide a basis to predict that more appreciable effects of fecal pollution on the nearshore are likely at times over each of the survey areas. The spatial extent and severity cannot be easily predicted.

Other factors may contribute to declines in *E. coli* concentrations in the lake water beyond simple dilution of river and shoreline discharges. It is thought that *E. coli* do not survive well in the water column, especially when the nutrient concentrations are low and upon exposure to sunlight. Another way that *E. coli* may be lost from the water column is through sedimentation. *E. coli* are often associated with small particles; pattern of loss through sedimentation over mixing areas may have similarity to that of turbidity.

Periodic beach postings because of elevated *E.coli* is a longstanding concern in south eastern Lake Huron. It is important to recognize, however, that sampling for *E.coli* in beach monitoring programs occurs at depth of ~1m, and closer to the shoreline than in this study. Effects of loading from the shoreline at depths of 1 m will be more direct with less opportunity for attenuation by dilution than at 2.5-3 m depths surveyed here. A short coming of the present study is that it does provide insight on water quality over the shallow band of lake water adjacent to the shoreline where water recreation is concentrated.

Wide-scale surveys of levels of indicator bacteria were conducted along the coastline of Lake Huron on single occasions in May and October 1974 and April 1975 by MOE

(Young et al. 1977). No information is provided on site characteristics; however, sampling appears to have been vessel based making the results more comparable with the present study than shore-based monitoring at recreational beaches. The results for sites within geographic areas were aggregated and reported as geometric means. Considering the geographic groups bracketing the present study (groups C, H, D [vicinity of Maitland River], E and stations 62 [vicinity of Bayfield River],15-005 [vicinity of Saugeen River] the levels of fecal coliform ranged from 1 to 72 CFU 100 mL^{-1} among the three surveys and with the exception of group D did not exceed 28 CFU 100 mL^{-1}.

4.2 Improving the Understanding of Nearshore Water Quality

It has long been appreciated that environmental conditions in the nearshore of the Great Lakes are heterogeneous and dynamic, especially over areas where large rivers discharge and areas adjacent to developed shoreline. Variability originates both from factors external to the lake as inputs from the watersheds as well as from within the lake from physical and biological processes. This study provides demonstration of a variety of known features of spatial and temporal variability in nearshore water quality. The points of departure of this study from typical nearshore monitoring approaches are to two-fold. Firstly, the design attempts to link dynamics in the nearshore of the lake with drivers originating in the adjacent watershed through integrated monitoring of the lake and adjacent major rivers. Secondly, through a series of spatially-detailed surveys spanning a range of seasons, information is accumulated with which to begin the critical task of developing an integrating framework for environmental conditions such that norms and extremes, sensitive areas and problem features can be interpreted. Significant logistical, technical and theoretical challenges make it difficult to achieve an integrated understanding of conditions and arguably make it difficult to effectively monitor the nearshore. Selected aspects of where development of study design and monitoring approach may be beneficial are described in this next section.

4.2.1 Lake-Scale Physical Dynamics and Basin-Scale Variability in Water Quality

The nearshore study areas extend over only 25-60 km^2 of the lake. Processes extending over broad areas of the lake influence physical and chemical features of the nearshore on what may be interpreted at times as a more local scale. A limitation of the present study design is that it is can be difficult to relate the findings for an individual survey to the processes that may be operating on scales larger than the survey area and may at times be contributing substantively to the observations within the study area. The physical data collected using current meters and temperature recorders to an extent provides insight on broader physical processes, however, there is no corresponding information on broader water quality features with which to discern local from regional influences. An example of this difficulty comes from the early season survey at the Bayfield River study area. Strong onshore-offshore gradients in water clarity (suspended solids and nutrients) extended over the survey area. It is likely that spatial structure resulted from mixing of multiple inputs along an undefined stretch of shoreline in combination with limited offshore circulation. With the available information it was not possible to determine the extent of shoreline that had contributed to conditions within the study, nor determine how the spatial structure had been created. Coordination of nearshore-scale studies with broader basin-scale surveys and data collection among monitoring agencies and research groups could be beneficial in linking local observations to wider-scale driving processes.

4.2.2 Fine-scale Variability in Environmental Conditions at the Shoreline

The collection of water quality data in the nearshore was limited to depths exceeding 2.5-3 m for practical reasons. A water intake for collection of analytical samples and field sensors were deployed at ~1.5 m below surface, restricting the minimum depth of survey. The lakebed sloped gently over each of the study areas. At places, minimum sampling depth was at 0.5 to 1 km from the shoreline.

For several reasons, the relatively shallow water at the interface of the lake and shoreline is important to understand more fully. The waterline fringe, the area extending from the shoreline to depths of 1.5-2 m, is often the area of most concentrated recreational use and can be the basis of people's perspectives on environmental conditions in the lake. Conditions in this area can be at variance with the adjacent waters further offshore. Small volume discharges to the shoreline such as storm sewers or creeks may, at times, affect water quality over localized areas adjacent to the point of discharge. It is probable that multiple such occurrences did not extend sufficiently away from the shoreline to be detected with the present survey design. A case in point is the shore-based discharge from the Goderich sewage treatment plant. Nutrient enrichment at the shoreline as evidenced by growth of benthic algae in proximity of the discharge was observed from the shoreline, yet, the lake-based surveys did not detect any effects on water quality that could be unequivocally attributed to the discharge. A further distinction between the broader nearshore and the waterline fringe that contributes to disparity in water quality is the effect of wave-driven disturbance of the lakebed/shoreline. The effects of sediment resuspension are more frequent and more concentrated at the waterline fringe due to the closer proximity of the lakebed/shoreline and the more limited volume of water. It may be argued that shoreline fringe represents only a small portion of the nearshore, however, if affected areas are coincident with areas of high resource value, then impacts on water quality are of concern and require elucidation.

Known features of recreational water quality provide rationale for the need to consider the waterline fringe in nearshore study design. Beach monitoring studies in Lake Huron and other areas of the Great Lakes have reported a tendency for levels of *E.coli* to increase with decreasing depth towards the shoreline. It is also common for levels of *E.coli* to decline to low levels a short distance from the shoreline in relatively shallow water. The seemingly poor resolution of fecal pollution concerns in this study is likely due to the lack of sampling at the waterline fringe. On one hand. the results strongly suggest that levels of fecal pollution as inferred from the indicator *E.coli* is low over the nearshore as a whole, yet the study provides little insight for the areas in proximity to the shoreline where fecal pollution is a documented concern.

Integrated collection of water quality information for the waterline fringe and the nearshore is a recommended for future monitoring designs where the objective is to relate water quality information to resource use and water quality concerns in coastal areas.

4.2.3 Short-term, Seasonal and Inter-annual and Changes in Water Quality

In this study, patterns in water quality were described over a time scale of a few hours-essentially producing an approximate ‘snapshot’ of conditions in the nearshore. The frequent changes in water currents on scales of hours to days and the sometimes strong fluctuations in tributary discharge rates, again on the scale of hours to days, provides a basis for expecting that conditions will be dynamic and features of water quality will likely be changeable over short intervals of time. The finding for an individual day of survey represents one of a potentially large population of possibilities.

Possibly the most challenging type of short-term variability to assess through lake-based monitoring are the potentially extreme changes associated with episodic events. Sporadic high-tributary discharge events associated with periods of wet weather are of particular interest because of their potential for adverse impacts on water quality. In addition to weather-related events, irregular occurrences of anthropogenic origin with potential to impact water quality such as spills and STP by-passing are likely from time to time.

This study was conducted over the open water period of single annual cycle. The relatively coarse sampling through time indicated appreciable changes in conditions among surveys, elements of which appeared to correspond with expected seasonal changes. However, the limited number of sampling events in the lake precludes analyses of trends among seasons and, at best, provides insight on the range of variability likely to be encountered. Practically speaking, it would be highly difficult to increase the frequency of surveys within seasons to the point that temporal analyses would be robust because of the extent to which physical and chemical conditions vary over the short-term and within seasons.

Features of water quality will vary from year to year in both the ranges of conditions and the nature of the predominating conditions. The potential for inter-annual changes in environmental and anthropogenic factors that potentially affect water quality is diverse and largely unpredictable.

There is a need for the development of a predictive framework with which to assist in the interpretation and ultimately management of water quality in the anthropogenically-developed coastal areas of the Great Lakes. In this regard initiatives to apply nearshore hydrodynamic models to more fully understand and quantify circulation regimes and mixing features and watershed water quality models to predict pollutant inputs to the shoreline may provide a means for more fuller interpretation and prediction of water quality. As a step in this direction a hydrodynamic and mixing model has been applied for the 2003 study year over the Maitland River nearshore survey area in a companion study (Nettleton 2008 draft). Patterns in concentrations of nitrates, conductivity and *E.coli* over the nearshore as influenced by discharge from the Maitland River and lake circulation were evaluated over the time-course of selected limnological events and integrated over periods of time to better infer event and longer-term conditions.

5 Conclusions

Periodic elevation of nearshore nitrate+nitrite concentrations was the most overt indicator of anthropogenic effects on Lake Huron over the study areas. Adverse outcomes of the nitrogen pollution were not obvious. Nearshore phytoplankton levels, as inferred from extensive measurement of chlorophyll a, were low with few exceptions and did not suggest eutrophication of the nearshore. From a correlative basis, primary production appears to be strongly phosphorus limited and unresponsive to elevated nitrogen. The CCME guideline for nitrate to protect aquatic health was infrequently exceeded in the nearshore. However, the nitrate+nitrite data demonstrates a strong connectivity between adjacent lands, land-based activities and nearshore water quality and reinforces the need to be vigilant of the potential for changes in land-use to impact on the adjacent lake. For example the highly oligotrophic state of Lake Huron as demonstrated in this study indicates a strong potential for increased discharge of phosphorus to the shoreline to stimulate growth of algae on a local basis.

The focused manner in which discharge from the study rivers generally moved along the shoreline indicates that nearshore water quality is both variable along the shoreline, and that at any point in time that there are areas which are likely to more impacted than other areas by discharges to the shoreline. While intuitively obvious, the implications may be far reaching. An understanding of the spatial and temporal dynamics patterns of water quality in the nearshore may contribute to the citing and management of water-based resources along the shoreline.

A 2004 review of water quality information for southeastern Lake Huron by the Lake Huron Centre for Coastal Conservation concluded that nearshore water quality monitoring along Lake Huron lacked coordination, consistency and needed re-evaluation with respect to completeness (LHCC 2004). Since about 2003 the coordinating efforts of the Lake Huron South East Shores Working Group, an ad hoc committee of representatives from federal, provincial and area agencies with environmental protection functions, have increased the degree to which monitoring efforts are shared and discussed among independent groups, and in many cases lead to cooperative projects. However, there remains the challenge of how to effectively under take water quality monitoring in the nearshore of a very large lake with a diverse shoreline.

The monitoring strategy employed in this work, while with acknowledged limitations, has provided insight on the ambient water quality conditions and on a diversity of factors which interact to yield environmental conditions along the coastline of Lake Huron. This report has also highlighted short comings in approach where further development of study design and methodology is needed. Primary in this regard is the need for further information to support evaluation of environmental concerns which are situated in very shallow water at the shoreline, at depths not easily assessable in lake-based studies. This study makes progress with the challenge of temporal and spatial integration of information over a dynamic coastline when assessing water quality but falls short of an adequate methodology. Development and application of predictive models will be needed to achieve more robust assessments of conditions over a period of time and over regions of shoreline, as well as to support the task of assessing water quality conditions under extreme events, natural or otherwise.

Our ability to predict, manage, and mitigate known and emerging stressors on the nearshore environment is improved when we understand present day conditions and can detect if those conditions have changed from the past, or are changing today. A conclusion of this report is that there is inadequate historical information to determine if nearshore water quality conditions in 2003 have changed from past conditions.

The focus of this study was the nearshore of Lake Huron, however, effort was devoted to water quality sampling of the lower reaches of the large rivers discharging to the study areas. Water quality in the lower Maitland, Saugeen and Bayfield Rivers was periodically impacted as evidenced by elevated levels of suspended solids, nutrient and the fecal pollution indicator *E.coli*. Anthropogenic stress on these rivers adversely affecting water quality is a longstanding concern. Efforts to protect and improve environmental quality within these rivers will serve to not only advance the ecological and resource values of these rivers but will also impact positively on the nearshore of Lake Huron.

6 Acknowledgements

The efforts of the Great Lakes field group and Greg Hobson, Wendy Page, Lance Boyce and Dave Supper are greatly appreciated. Paul Weidman contributed to an earlier draft of this report.

7 References

Beeton, A. M, and J. H. Saylor. 1995. Limnology of Lake Huron. *In* The Lake Huron ecosystem: Ecology, fisheries, and management. M. Munawar, T. Edsall, and J. Leach, Editors. pp. 1-37. SPB Academic Publishing. Amsterdam, The Netherlands.

Bronte-Gelok, S. and D.M. Joy. 1999. Final report. Huron County water quality data study (Project #30HS1) to Huron Farm Environmental Coalition.

Depinto, J.V., Lam, D., Auer, M., Burns, N. Chapra, S., Charlton, M., Dolan, D., Kreis, R., Howell, T., Scavia, D. Rockwell, D., Van Bochove, Eric and Looby, Tom. 2006. Examination of the status of the goals of Annex 3 of the Great Lakes Water Quality Agreement. Report of Annex 3 Technical sub-group of RWG D.

Dobson, H. 1971. Nutrient in Lake Huron. Preliminary report, Canada Centre for Inland Waters. Burlington, Ontario, 54 pages.

Dolan, D.M., Warry, N.D., Rossman, R., Reynoldson, T.B., Swain, W.R. 1986. Lake Huron Intensive Survey Summary Report. Report to the Surveillance Work Group of the Water Quality Board, International Joint Commission Windsor, Ontario

Elfrink, B and Baldock. T. 2002. Hydrodynamics and sediment transport in the swash zone: a review and perspectives. Coastal Engineering 45: 149-167.

GLISP 1986. Great Lakes International Surveillance Plan. Volume II. Lake and Connecting Channels Plans. Surveillance Workgroup of the Great Lakes Water Quality Board. IJC.

Gregor, D.J. and Ongley, E.D. 1978. Analysis of nearshore water quality in the Canadian Great Lakes , 1967-1973, Part 1. International Reference Group on the Great Lakes Pollution from Land Use Activities. International Joint Commission

Hore, R.C. and Ostry, R.C. 1978. Suageen River, Ontario summary of pilot watershed report. International Reference Group on Great Lakes Pollution from Land Use Activities, International Joint Commission. 56p.

Howell, T. and G. Hobson. 2003. Water quality on the Lake Erie shores of Wainfleet township in 2002. Technical Memorandum, Ontario Ministry of the Environment, Environmental Monitoring and Reporting Branch, Water Monitoring Section. 66 p.

Hydat 2005. Surface water and sediment data. Water Survey of Canada, Environment Canada.

IJC 1980. Phosphorus management for the Great Lakes. Final report of the phosphorus management strategies task force to the International Joint Commission's Great Lakes Water Quality Board and Great Lakes Science Advisory Board.

Jackson, M.B., Nakamoto, L.K., and Wong, S.L. 1985. The nearshore water quality of southeastern Lake Huron. Water Resources Branch, Ontario Ministry of the Environment. 35pp.

Lefebvre, A, W. Eilers and B. Chun (editors). 2005. Environmental Sustainability of Canadian Agriculture. Agri-Environmental Indicator Report Series. Report #2.. Agriculture and Agri-food Canada. Ottawa.

Lake Erie Lakewide Management Plan (LaMP) 2006.

Lake Huron Binational Action Plan 2004.

Lake Huron Centre for Coastal Conservation. 2004. Nearshore Water Quality. A preliminary report on historical nearshore water quality information for southeastern Lake Huron. Sauble Beach to Sarnia. The Coastal Centre, Blyth, Ontario.

Lake Huron Science Committee Interim Report. 2005. Sources and Mechanisms of Delivery of *E.coli* (bacteria) Pollution to the Lake Huron Shoreline of Huron County. Interim Report: Science Committee to Investigate Sources of Bacterial Pollution of the Lake Huron shoreline of Huron County. April 8, 2005. 270pp. Report to Ontario Ministry of the Environment.

Lake Ontario Lakewide Management Plan (LaMP) 2006.

Lawrence P.L. and Davidson-Arnott, R.G.D.1997. Alongshore wave energy and sediment transport on southeastern Lake Huron, Ontario, Canada. Journal of Coastal Research 13(4) 1004-1015.

Lee, C. and Hawley, N. 1998. The response of suspended particulate material to upwelling and downwelling events in southern Lake Michigan. Journal of Sedimentary Research. 68:819-831.

Lin, C.K. and Schelske, C.L. 1981. Seasonal variation of potential nutrient limitation to chlorophyll a production in southern Lake Huron. Can. J. Fish. Aquat. Sci. 38: 1-9.

MOE 1990. Canadian Great Lakes Basin Intake-Outfall Atlas Volume 3. Lake Huron and Georgian Bay. By Kleinfeldt Consultants Limited & M. Griffiths(ed). ISBN 0-7729-5507-7

Moll, R. A., C. O. Davis, and C. L. Schelske. 1980. Phytoplankton productivity and standing crop in the vicinity of the Lake Huron-Saginaw Bay front. Journal of Great Lake Research 6:232-246.

Murthy, C. R., and D. S. Dunbar. 1981. Structure of the flow within the coastal boundary-layer of the great-lakes. Journal of Physical Oceanography 11: 1567-1577.

Nicholls, K.H., Hopkins, G.J., Standke, S.J. and Nakamoto, L. 2001. Trend in total phosphorus in Canadian near-shore waters of the Laurentian Great Lakes: 1976-1999. J. Great Lakes Res. 27: 402-422.

Neilson, M., L'Italien, S. ,Glumac, V., Williams, D., Bertram, P. 1995. State of the Lakes Ecosystem Conference. Nutrients: trends and system response. Environment Canada, US Environmental Protection Agency. EPA 905-R-95-015

Neilsen, G.H., J.L.Culley and D.R. Cameron. 1978. Nitrogen loadings from agricultural activities in the Great Lakes basin. Integration report on nitrogen agricultural watershed studies. Task C (Canadian Section) – Activity1. International Reference Group on Great Lakes Activities. IJC.

Nettleton, P. 2008 Draft. Modeling of water quality impacts from the Maitland River within the Lake Huron nearshore in the vicinity of Goderich in 2003; in support of the Great Lakes Nearshore Monitoring and Assessment Program. Environmental Monitoring and Reporting Branch, Ontario Ministry of the Environment.

Palmateer,G. and Huber, D. 1984. Lake Huron beaches –factors affecting microbiological water quality in 1984 summary report. Southwest Region, Ontario Ministry of the Environment

Rao, Y. R., and Schwab D.J. 2007. Transport and mixing between the coastal and offshore water in the Great Lakes: a review. J. Great Lakes Res. 33: 202-218.

Report to Great Lakes Binational Executive Committee. 2007. Agreement review committee (ARC). Review of the Canada-US Great Lakes Water Quality Agreement.

Reynolds, C.S. and Davies, P.S. 2001. Sources and bioavailability of phosphorus fractions in freshwaters: a British perspective. Biological Reviews 76: 27-64.

Ross, D.I. and Chatterjee, R.M. 1977. Water quality assessment of some Ontario embayments on Lake Huron, including Goderich, Port Elgin, Southampton, Tobermory, Owen Sound, Collingwood and Parry Sound. ULRG Project Report D-27. Water Resources Branch, Ontario Ministry of the Environment. 109 pg.

Seip, K. L. 1994. Phosphorus and Nitrogen Limitation of Algal Biomass Across Trophic Gradients. Aquatic Sciences 56: 16-28.

Singer, S.N., C.K. Cheng and M.G. Scafe. 2003. The hydrogeology of southern Ontario, second edition. Hydrogeology of Ontario Series (Report 1), Environmental Monitoring and Reporting Branch, Ontario Ministry of the Environment.

Spectranalysis Inc. 1999. Ontario land cover data base revised user's manual. Report to Ontario Ministry of Natural Resources. Unpublished.

Statistics Canada. 2001 census data

Stevens, R.J.J, Neilson , M.A.T. and Warry, N.D. Water Quality of the Lake Huron - Georgian Bay system. 1985. Environment Canada. Scientific Series No. 143, Inland Waters Directorate, Ontario Region. 43pp.

Wetzel R. G. 1983. Limnology. W.B. Saunders Company, Toronto.

Young, M., Toth, A. and Janhurst, S. 1977. A bacteriological study of the Ontario nearshore areas of Lake Huron 1974-75. Microbiology Section. Ontario Ministry of the Environment. 14pp.

Vanderploeg, H. A., Johengen, T. H., Lavrentyev, P. J., Chen, C., Lang, G. A., Agy, M. A., Bundy, M. H., Cavaletto, J. F., Eadie, B. J., Liebig, J. R., Miller, G. S., Ruberg, S. A., McCormick, M. J. 2007. Anatomy of the recurrent coastal sediment plume in Lake Michigan and its impacts on light climate, nutrients, and plankton. Journal of Geophysical Research- Oceans 112 C03S90, doi:10.1029/2004JC002379