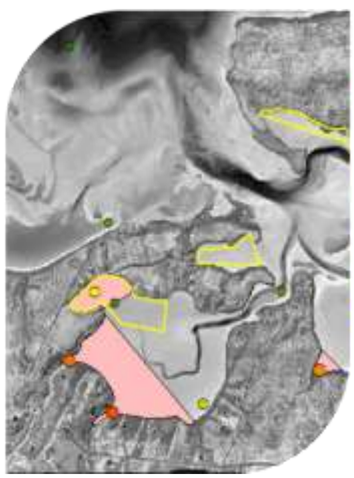
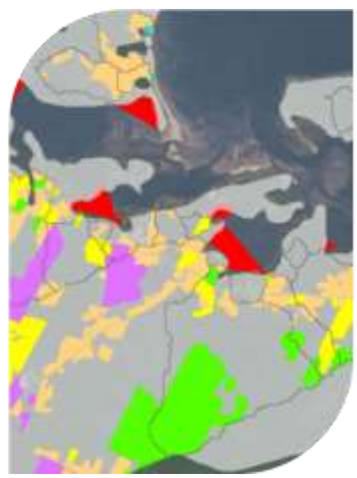
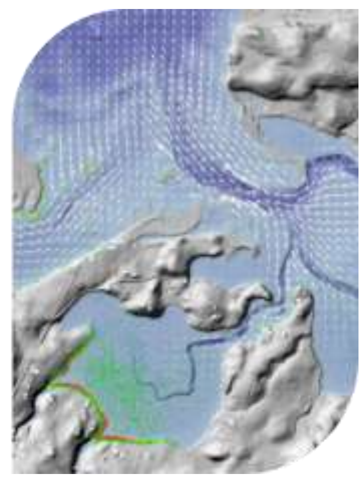
Optimizing oyster aquaculture in Little Harbour, NS using hydrodynamic modelling and bathymetric lidar

Prepared by

Tim Webster, PhD
Kate Collins, Nathan Crowell, Ariel Vallis
Applied Geomatics Research Group
NSCC, Middleton
Tel. 902 825 5475
email: tim.webster@nscc.ca

Submitted to

Paul Budreski
AquaDelights Seafood Ltd.

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Executive Summary

This project was an NSERC-funded partnership between AquaDelights Seafood Inc. and the Applied Geomatics Research Group. Research on water quality in Little Harbour, NS was undertaken in order to investigate the sources and circulation of bacterial contamination in the area that has been affecting recreational users as well as shellfish harvesters, both commercial and recreational.

Water quality data sampled at Little Harbour over the past 25 years received from Environment Canada was the subject of a spatial and statistical analysis. The fecal coliform data were sampled at various locations within the harbour and showed that contamination occurs frequently throughout the harbour, frequency of contamination is increasing with time, and the amount by which the threshold is exceeded is also increasing with time.

A spatial analysis of the land within the watershed surrounding Little Harbour revealed a steady increase in housing density in the area, concentrated mainly near the shoreline. The land within the watershed was mainly forested, with residential, agricultural and clear cut land use also present. The analysis did not reveal an obvious source of fecal coliform, but pointed mainly towards increased residential development and possible inappropriate handling of residential sewage as the sources of contamination.

A hydrodynamic model was developed and validated for Little Harbour to simulate circulation of water and particles through the area during a normal tidal cycle. The modelled simulations of particles representing fecal coliform showed minimal dispersion of particles away from their source, but rather a tendency to settle out on the shorelines.

The results of the water quality study, spatial analysis and hydrodynamic modelling were presented at a community meeting in Little Harbour on Sept. 1. The goal of the meeting was to raise community awareness on the issue of poor water quality and how it was affecting users of the harbour such as shellfish harvesters, boaters and swimmers. The meeting was successful in initiating a conversation on possible sources within the community and the process of identifying and assessing the sources in order to remediate them has begun. Only once clean water has been restored to Little Harbour can commercial aquaculture operators begin to expand and thrive, and the community was motivated to reach this goal through stewardship and remediation.

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1 Introduction

1.1 Background

Little Harbour, NS is a small rural community along the Northumberland Strait (Figure 1.1). It is enjoyed by various users, including recreational users like swimmers and boaters, shellfish harvesters, and commercial aquaculture operators. AquaDelights Seafoods Ltd. (ASL) has been operating a sustainable oyster production and export farm in Little Harbour, NS for over twenty years. The company collects oyster seeds, grows them on the seafloor in a low-impact, ecosystem sensitive method, and harvests the oysters when they reach market size. However, oyster demand greatly exceeds supply and expansion of this rural industry is inhibited by lack of easily accessible and clean growing areas. This lack of space is a product of water contamination by bacteria which are flushed into the system by heavy rainfall. The main source of this pollution is suspected to be residential septic fields.

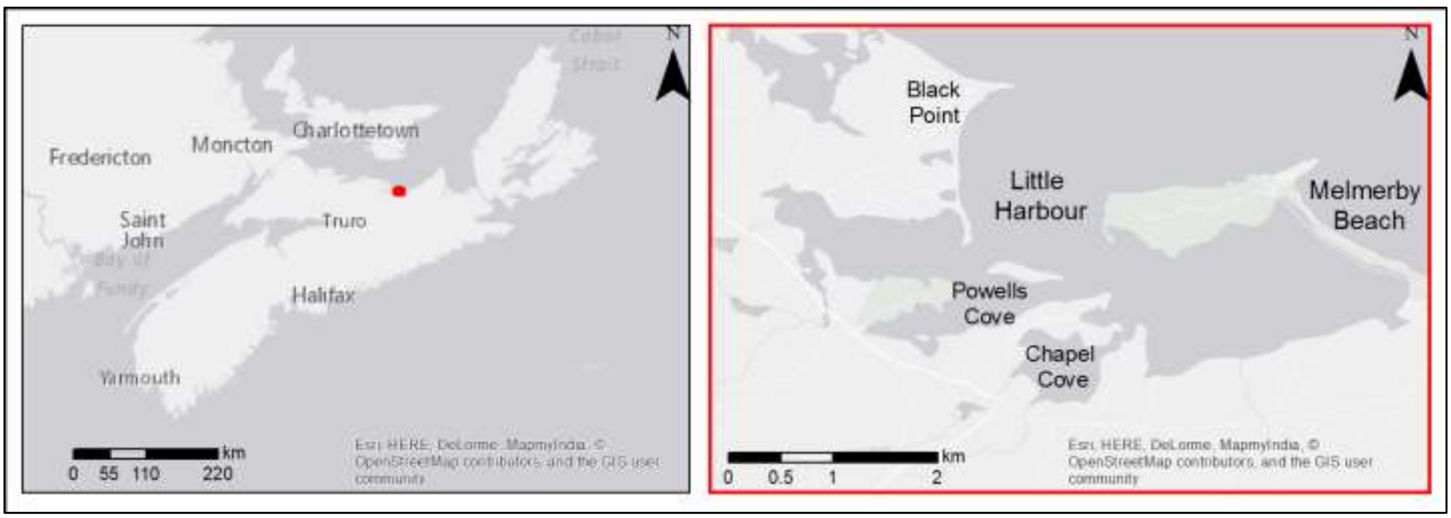

Figure 1.1: Little Harbour study area on the northern shore of Nova Scotia. The location of the right panel is indicated on the left map by the red symbol.

A partnership was established between the Applied Geomatics Research Group (AGRG) at the Nova Scotia Community College (NSCC) and ASL in order to investigate the water quality issue at Little Harbour. The project was funded for $25,000 over a six-month period by NSERC's Engage program. The goal of the project was to use existing remotely sensed data and a long time series of water quality data to research the level of contamination in Little Harbour, the locations where contaminants were entering the system, and how they were being circulated throughout the harbour. A Geographic Information System (GIS) was used to conduct a geospatial analysis on the water quality data, historical housing density information, and provincially available land use data. A hydrodynamic model was built to investigate the fate of bacteria in Little Harbour using existing topographic-bathymetric lidar data collected by AGRG in 2014.

AGRG and ASL partnered with the Aquaculture Association of NS to present the research results at a community meeting to initiate discussions on a watershed management strategy that would benefit all the users of Little Harbour, including homeowners, shellfish growers, and recreational users. A community stewardship group would begin the task of reducing the input of contamination into Little Harbour, which would allow existing aquaculture operators to expand, to reduce their product's exposure to contamination and therefore reduce costs associated with cleaning the product. A community stewardship group would make Little Harbour a cleaner place for new aquaculture operators to begin business, and a cleaner place for all users to enjoy.

1.2 Fecal Coliform and Water Quality

Fecal coliform is a bacteria found in feces and indicates the potential presence of disease-causing pathogens. Since both the bacteria and the pathogens can accumulate in shellfish tissue, fecal coliform is traditionally used as an indicator of sewage pollution in water and shellfish (Barrington et al., 2003). Potential point and non-point sources of fecal coliform into the coastal zone where shellfish grow can include municipal sewage, residential and agriculture runoff, and industrial waste (Government of Canada, 2009). Shellfish growing areas are temporarily closed to harvesting for a specific period of time when bacteria levels exceed prescribed thresholds following rainfall events to protect the public from these contaminates. The Canadian Shellfish Sanitation Program Manual describes the procedures followed in classifying shellfish growing areas and prohibiting harvesting (Government of Canada, 2015a). In general terms, samples which exceed 43 MPN/100 ml (Most Probable Number of fecal coliforms per 100 ml in each water sample) lead to restricted harvest. Permanent closures take place when routine water testing indicates the water quality has deteriorated and not recovered.

In the Atlantic region, closures have been on the rise in the past decades. In recent years 34% of shellfish growing areas have been classified as restricted, conditionally restricted, or prohibited. Shellfish aquaculture can operate in conditionally approved areas, as long as the live product is moved to a clean aquaculture lease as per Fisheries and Oceans Canada (DFO) protocols to ensure the product is clean; this process is called depuration. If the site is only temporarily closed to harvesting, harvesting is delayed for a prescribed period of time. The length of the closure can be reduced if site specific sampling confirms the area is free of contaminates. This sampling usually occurs a minimum of seven days following a rainfall event that contaminates the water (Government of Canada, 2013a). Both of these scenarios increase the cost of aquaculture operations and decrease profitability. Little Harbour has six active shellfish leases; two of these are in areas that are conditionally closed to harvesting requiring all shellfish product to be depurated at another approved location prior to harvest.

In Nova Scotia, public supervised beaches are monitored for contamination on a weekly basis (Government of Nova Scotia, 2013) and are closed by the Department of Health and Wellness to recreational activities if fecal coliform levels of 200 MPN/100 ml are detected (Government of Canada, 2012). In August 2015 Melmerby Beach was closed for the first time (CBC News, 2015).

This report describes the data used for the Little Harbour project and documents the methodology of the GIS Analysis and Hydrodynamic Modelling in Section 2. The results of the GIS analysis and the particle tracking modelling simulations are presented in Section 3. A Discussion of the results and the issues in Little Harbour follows, in Section 4, followed by conclusions.

2 Methods

2.1 Data Collection

2.1.1 Lidar Data and Aerial Photos

Little Harbour was surveyed on Sept. 25, 2014 using a Chiroptera II integrated topographic bathymetric lidar sensor equipped with a 60-megapixel multispectral camera. The system incorporates a 1064 nm near infrared topographic (topo) laser for collecting ground returns and a green 515 nm laser that penetrates the water column to collect hydrographic (hydro) returns (Figure 2.1). AGRG-NSCC does not own an aircraft, only the sensor, and thus partnered with our Canada Foundation for Innovation project partner, Leading Edge Geomatics (LEG) to assist in the operations of the survey and arranging the aircraft. For the September 2014 field campaign, a twin engine aircraft that was certified to carry the Chiroptera II sensor suite (Figure 2.2a). The lasers (Figure 2.2b, large red circles) utilize a Palmer scanner, which forms an elliptical pattern and enables the collection of more returns on vertical faces, causes less shadow effects in the data, and is less sensitive to ocean wave interaction. The depth at which the hydro laser is effective is limited by water clarity, and has a depth penetration rating of approximately 1.5 x the Secchi depth (a measure of turbidity or water clarity).

The Leica RCD30 60 megapixel camera (Figure 2.2b, lens on right) collects co-aligned RGB+NIR (Red Green Blue + Near-Infrared) motion compensated photographs which can be orthorectified and mosaicked into a single image in post-processing, or analyzed frame by frame for maximum information extraction. Along with the lasers and high resolution camera, the lidar system also includes a 5 megapixel quality assurance camera that the lidar operator is able to view during the flight (Figure 2.2b, lens on left). The aircraft had a hole cut in the bottom for the laser and cameras to image the ground and installation involved fitting the sensor head into the hole (Figure 2.2c).

Data collection occurred on Sept. 25, 2014 under clear skies and light wind; the sensor achieved complete coverage of the study area, with a maximum depth penetration of 6.5 m. A GPS base station was set up to use in processing the lidar data, and ground validation measurements were conducted simultaneously with the flight. Land-based GPS observations were collected to validate the topographic lidar returns, and depth measurements were made to validate the bathymetric lidar returns. In addition, measurements of water clarity and seabed type were conducted.

The lidar data and aerial photographs were processed and standard products were generated such as a Digital Elevation Model (DEM), Digital Surface Model (DSM) (Figure 2.3), depth-normalized intensity and true colour aerial photo mosaic

(Figure 2.4). The maximum depth, or minimum elevation, achieved was -5.8 m CGVD28. CGDV28 is the Canadian Geodetic Vertical Datum of 1928, and represents the orthometric height of the bathymetry. The geoid-ellipsoid separation model, HT2, from Natural Resources Canada was used to apply this conversion to the surface models.

An orthophoto mosaic and depth-normalized lidar intensity map were also generated (Figure 2.4). Lidar intensity is a measurement of the returning signal of the laser and provides information on bottom type; the process of depth-normalization of the lidar intensity is described in Webster et al. (2016). The aerial photographs reveal information about land use in the topographic area of the survey, and reveal information on the bottom type (e.g., eelgrass, sand) in areas where the water is clear. The depth-normalized intensity map also provides information on bottom type. Dark areas in Figure 2.4 can be interpreted as eelgrass or vegetation, while bright areas can be interpreted as sand. The depth-normalization process compensates for areas that appear dark due to light absorption in deeper water rather than bottom type.

The topographic lidar data were validated using GPS measurements of the land; the mean difference in elevation between GPS and the lidar was -0.05 m with a standard deviation of 0.04 m for the 3606 checkpoints. The bathymetric lidar data were validated by subtracting manual depth measurements from the water surface as measured by the lidar, and comparing these values to the DEM. The mean difference was 0.2 m (standard deviation 0.5 m). Additional data processing, sensor specification, and ground truth sampling details can be found in Webster et al. (2016).

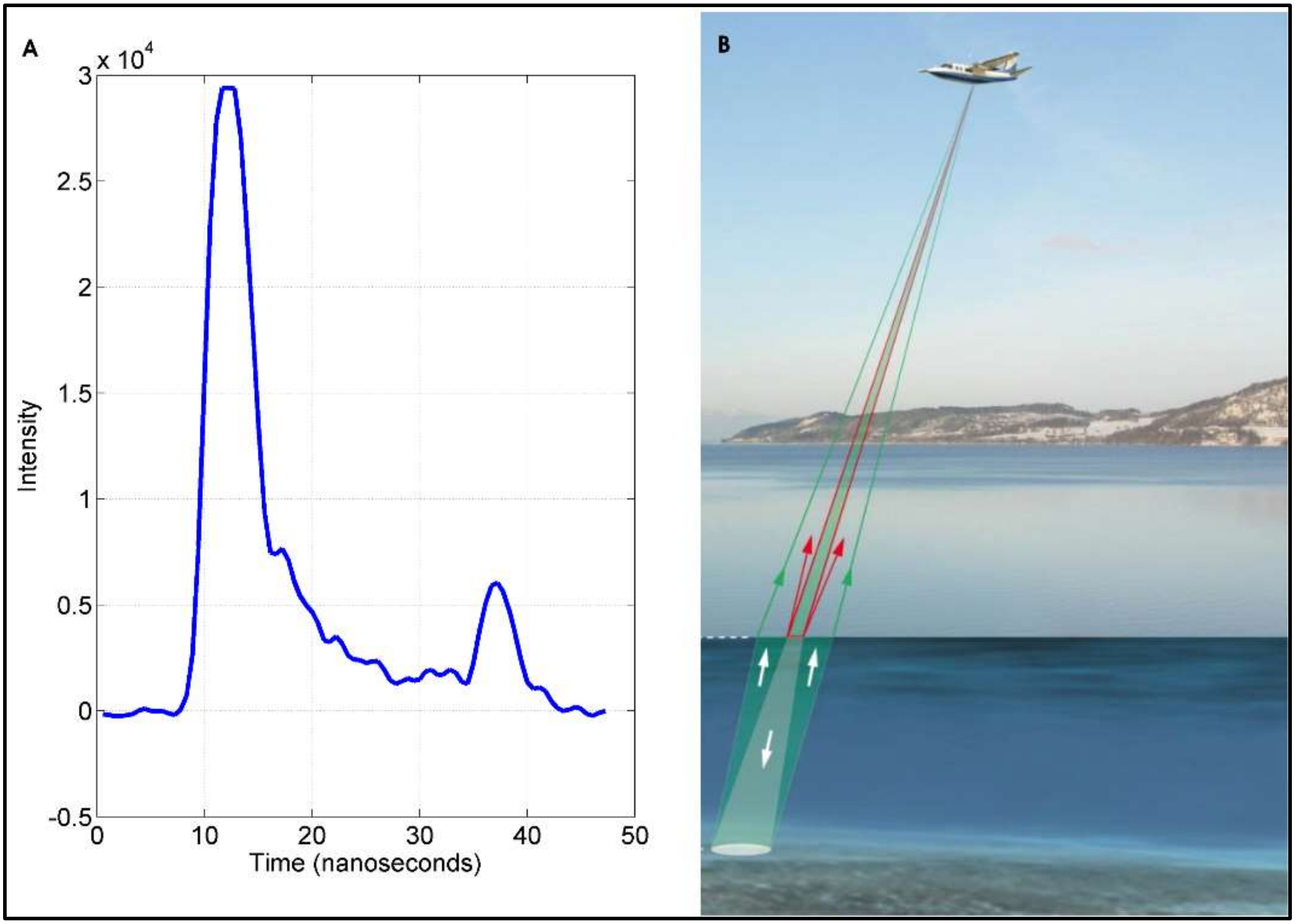

Figure 2.1: (A) Example of the Chiroptera II green laser waveform showing the large return from the sea surface and smaller return from the seabed. (B) Schematic of the Chiroptera II green and NIR lasers' interaction with the sea surface and seabed (adapted from Leica AHAB).

Figure 2.2: (a) Aircraft used for September 2014 lidar survey; (b) large red circles are the lasers; the RCD30 lens (right) and low resolution camera (left); (c) main body of sensor (left) and laser pointing through a hole cut in the bottom of the plane (right).

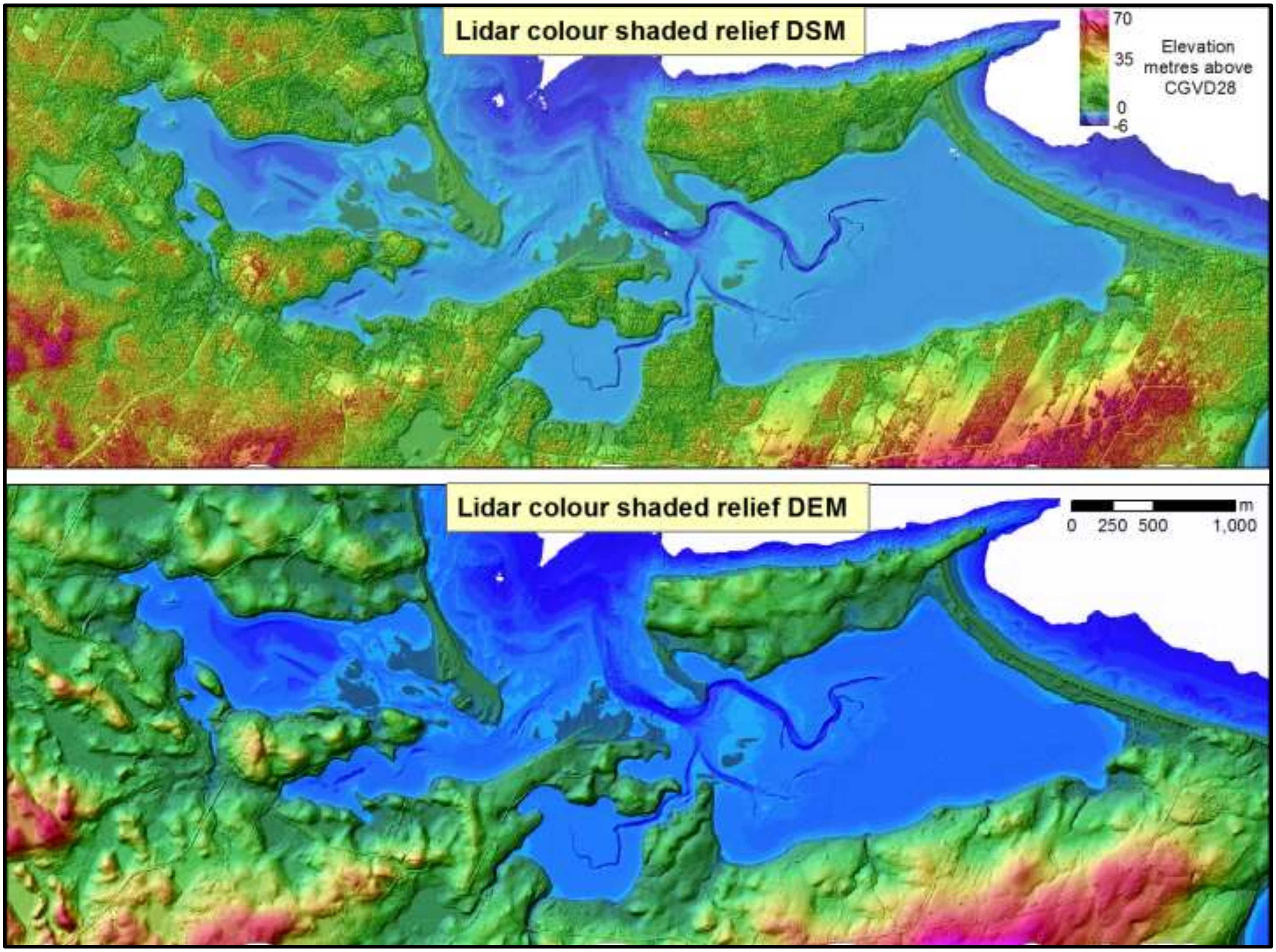

Figure 2.3: Lidar colour shaded relief DSM (upper panel) and lidar colour shaded relief DEM (lower panel). Areas coloured red indicate higher elevations and areas coloured dark blue indicate the lowest elevation, or deepest areas of the harbour.

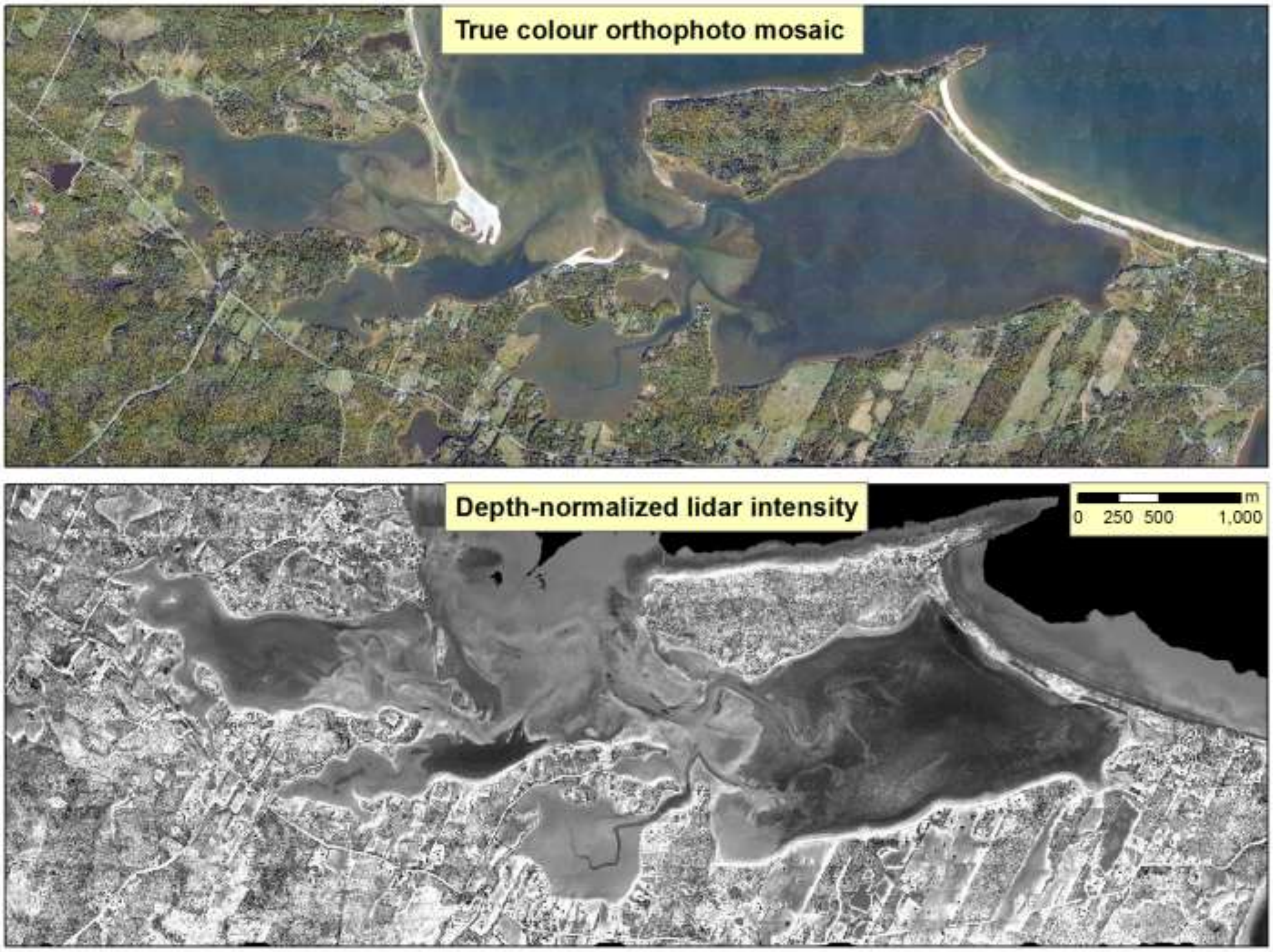

Figure 2.4: True colour orthophoto mosaic (upper panel) and depth-normalized lidar intensity (lower panel). Dark areas in the lidar intensity are typically representative of vegetation, where much of the laser energy is absorbed, and bright areas are representative of sandy areas, where much of the laser pulse is reflected back to the aircraft.

2.1.2 Water Quality Data

Water quality data for Little Harbour collected as part of the Canadian Shellfish Sanitation Program (Government of Canada, 2015b) for the period 1990-2015 were obtained from Environment Canada (EC) through personal communication (MacArthur, 2016). The dataset contained fecal coliform levels in Little Harbour at 22 stations (Figure 2.5) that were sampled five times per year during the late spring – early fall months, as well as a map showing the locations of the samples and current closures. Between 1991 and 2008 samples were taken approximately every three years, and from 2008 onward EC sampled Little Harbour annually. EC uses the dilution method to measure the Most Probable Number (MPN) of fecal coliforms per 100 ml in each water sample (Government of Canada, 2015a).

Information on historical and current Fishery Openings and Closures for Little Harbour were obtained using the online Orders Registry form (Government of Canada, 2013b). Searches for the keywords, "Little Harbour", and "Pictou County" displayed closures from 2015, 2012 and 2006, with links to older closures and their history.

To supplement the EC data, water samples were collected in Little Harbour by AGRG on three occasions between May and August 2016 (Figure 2.5, Table 2.1). The samples were processed at AGAT Laboratories in Dartmouth using membrane filtration, which reports fecal coliform in colony forming units (CFU) per 100 ml.

Sample Date	Sample numbers	Rain in past 24 hours (mm)	Rain in past 48 hours (mm)
May 02, 2016**	1-6	0	0
Jul 8, 2016**	1-6	31.6	33.1
Aug 16, 2016*	1-10	0.4	10.7

Table 2.1: AGRG sampling dates. * indicates single samples, ** indicates duplicate samples were taken. Sample locations are shown on Figure 2.5. Rain data are from EC meteorological station at Caribou (Environment Canada, 2016).

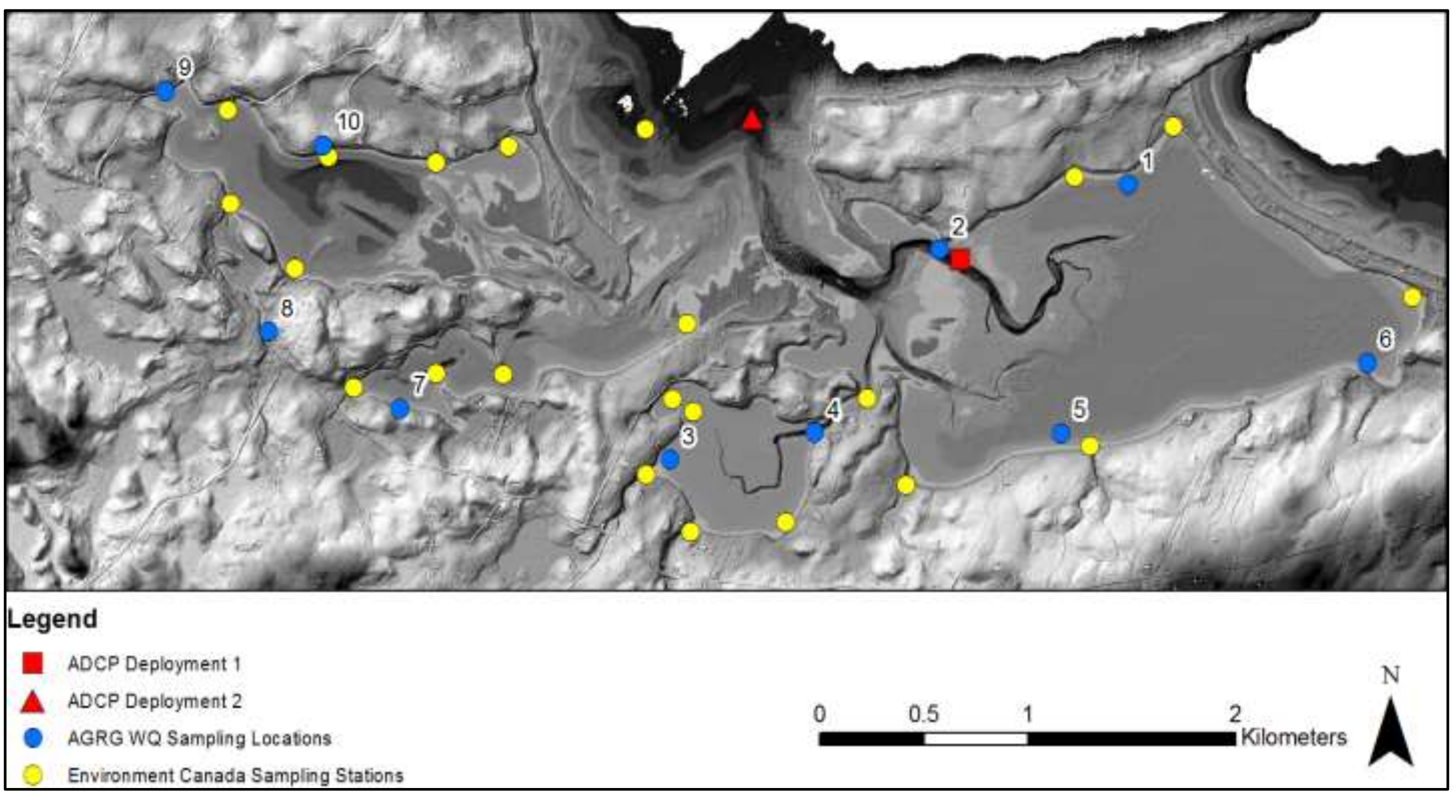

Figure 2.5: AGRG sampling locations (labelled blue circles), EC sampling locations (yellow circles) and ADCP deployment locations (red triangle and red square).

2.1.3 Historical Aerial Photographs

Three historical aerial photographs used as part of the geospatial analysis (Figure 2.6).

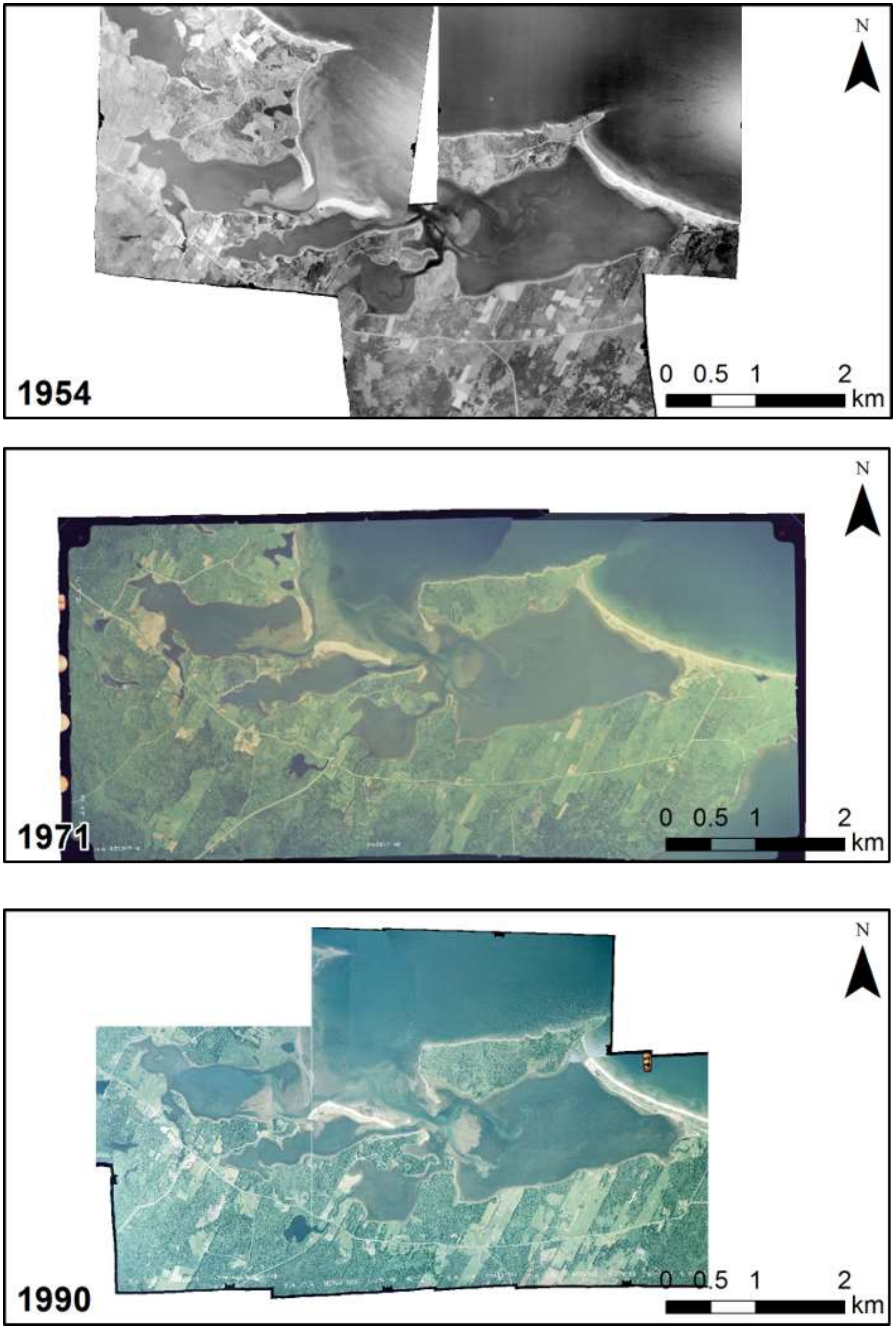

Figure 2.6: Aerial photographs from 1954, 1971 and 1990 that were used in the geospatial analysis.

2.1.4 Oceanographic Data

Two Acoustic Doppler Current Profilers (ADCP) were deployed at Little Harbour to use for hydrodynamic model validation as an in-kind contribution to the project from the NS Department of Fisheries and Aquaculture (Table 2.2, Figure 2.2). The Teledyne RDI 600 kHZ Workhorse upward-looking ADCPs were programmed to measure current speed, current direction, and waves for 35 days. A Conductivity Temperature Depth (CTD) instrument was used to measure temperature, salinity, and turbidity depth profiles at AGRG sampling locations 1-6 (Figure 2.5) on May 2.

	Deployed	**Recovered**	**Depth (m)**
ADCP 1 ■	June 30	Aug 5	4.0
ADCP 2 ▲	Aug 5	Sept 28	4.0

Table 2.2: ADCP deployment history. See Figure 2.5 for deployment locations, which are represented by a red square and a red triangle.

2.2 GIS Analysis

2.2.1 Water Quality Data

The map from EC showing sampling locations was digitized and georeferenced, resulting in a point shapefile, and the fecal coliform data from 1990-2015 were appended to the file. Using 43 MPN/100 ml as a threshold value, maps were generated that symbolized contamination (MPN) by colour and by size. The colour ramp was defined so that fecal coliform levels less than 43 ramped from green to yellow, and points with MPN greater than 43 were coloured red. The data were also symbolized using size, such that lower values were small and the highest values were largest. The mean MPN was calculated for each sample location.

Statistics and graphs were generated using Matlab software for the MPN data to quantify and visualize the number of times per year the threshold of 43 MPN/100 ml was exceeded at each station.

2.2.2 Watershed Land Use

The Little Harbour watershed and basins were derived in ArcGIS software using the 20 m DEM from the NS Topographic Database (NSTDB) of 2012 (Government of Nova Scotia, 2015a). A series of ArcGIS tools was used to derive stream order, delineate the watershed and basins by calculating flow direction and accumulation using the 20 m DEM. The resulting shapefiles were interpreted and verified using satellite imagery, and manually edited to merge small basins and remove basins where water drained outside Little Harbour. The NS Forest Inventory data (Government of Nova Scotia, 2015b) were used to examine land use within the Little Harbour watershed. The data were downloaded, clipped to the region of interest, and relevant land use codes were extracted (e.g., clear cut, agriculture, urban, etc.). Relevant codes for Little Harbour are defined in Table 2.3.

Land Use	Description
Agriculture	Any hay field, pasture, tilled crop, or orchard which contains no merchantable species.
Urban/Residential	Any area used primarily as residential or industrial and related structures such as streets, sidewalks, parking lots, etc.
Beach	That area of land between normal water line and the forest or non-forest category.
Plantation	A group of trees artificially established by direct seeding or setting out seedlings, transplants or cuttings.
Clear Cut	Any stand that has been completely cut and any residuals make up less than 25% crown closure and with little or no indication of regeneration.
Beaver Flowage	An area that is or has been occupied by beavers.

Table 2.3: Land use codes and descriptions relevant for Little Harbour (Government of Nova Scotia, 2015b).

2.2.3 Housing Analysis

Houses were digitized in ArcGIS for each aerial image: 1954, 1971, 1990, and the orthophoto mosaic from the 2014 lidar survey, resulting in a shapefile containing a point for each dwelling in the images. A 50 m buffer was applied to the points for each year, resulting in larger polygons for areas where houses existed closer together. The number of houses within each polygon was calculated and used to symbolize the polygons. This was done so that the resulting map could be interpreted for housing density in two ways: polygon size (smaller polygons = single dwellings with no close neighbours; larger polygons = more houses close together), and polygon colour (yellow polygons = single dwellings with no close neighbours; red polygons = more houses close together).

2.3 Hydrodynamic Model

2.3.1 Model Preparation

The model bathymetry grid was generated entirely from the 2014 topo-bathy lidar survey. The DEM was converted to an x,y,z grid and read into the modelling software, DHI's Mike 21, where the built-in tools were used to generate a functional model surface (Figure 2.7). The driving force of the hydrodynamic (HD) model in this case is the tide, as there is no large river that would influence flow and circulation. The tidal boundary was located at the seaward edge of the model domain (Figure 2.7, red line) and tidal values (Figure 2.8) were obtained from the DHI Global Tide Model Tidal Prediction toolbox (DHI, 2014). The model simulation period was the same as the deployment period for ADCP 1, June 30 – Aug. 5, 2016.

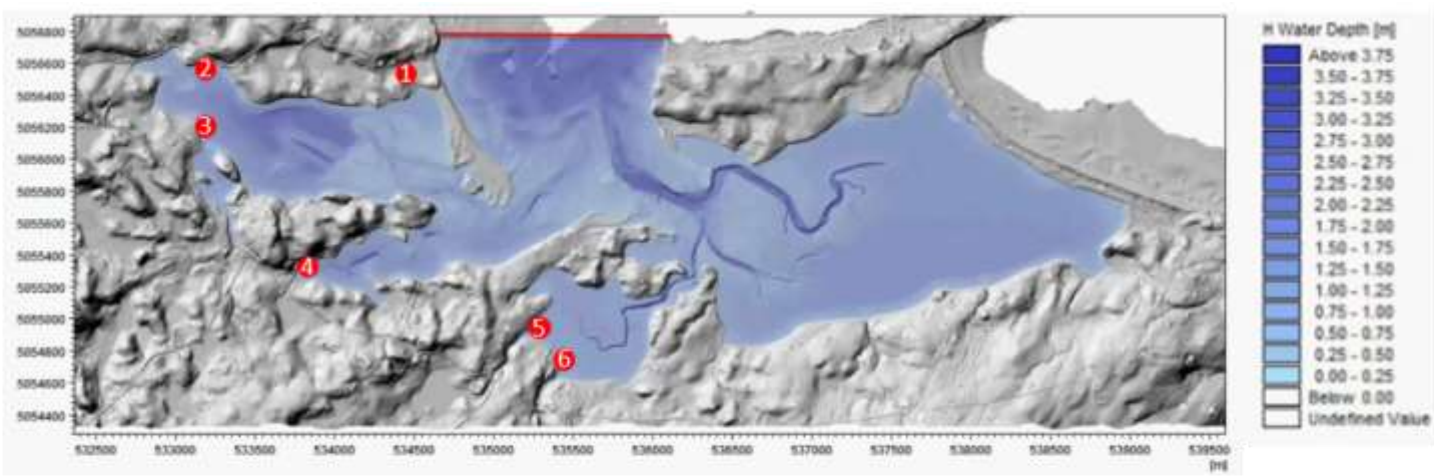

Figure 2.7: The modeled water depth, tidal boundary (red line), and particle tracking confluence points (red circles). The x-axis represents Easting (m) and the y-axis represents Northing (m).

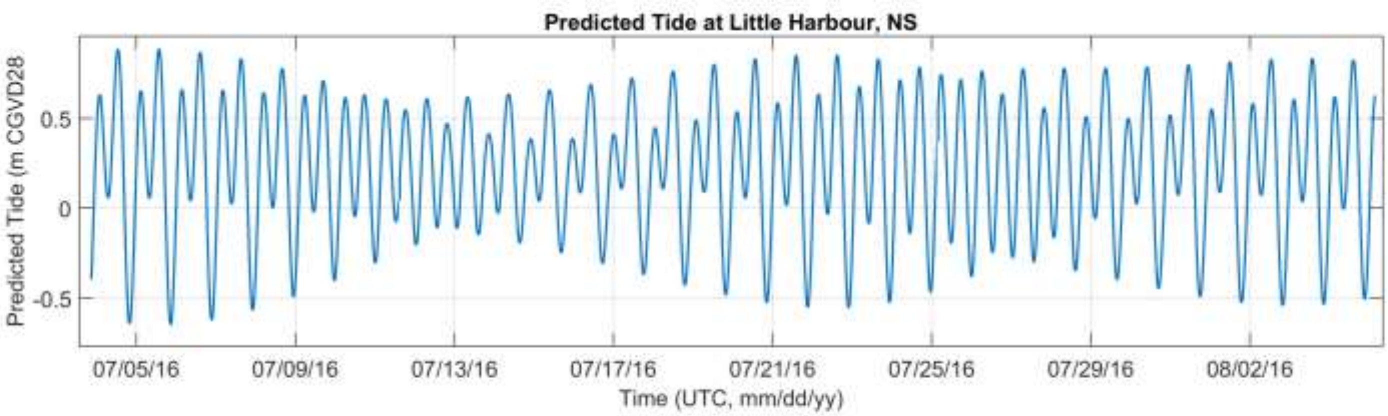

Figure 2.8: Predicted tide for Little Harbour during the model simulation; this time series was used as a boundary condition to force model circulation.

2.3.2 Particle Tracking

DHI's Mike 21 software includes a Particle Tracking module that facilitates the transport and fate of suspended or dissolved substances within an estuary. The particle tracking module is a Langrarian solver of the dispersion equations (DHI, 2016). The Little Harbour simulation was conducted using a generalized particle tracking scenario, without the inclusion of decay rates or varying initial concentrations; instead, the simulations included here present the visualization of how particles flow throughout Little Harbour, how they might settle on the shore, and their fate after several tidal cycles. The points of entry of the simulated bacteria, e.g. "point sources", were determined using the mean MPN values from the 1990-2015 EC fecal coliform data (red stars, Figure 2.7).

3 Results

3.1 AGRG Sampling

The AGRG water quality sampling over the summer of 2016 showed clean water when little or no rain had fallen, and contamination following a rain event (Figure 3.1). Sample results were 4 CFU/100 ml or less in May when there had been no rain in the past 48 hours, and clean again in August (with the exception of one: 667 CFU/100 ml) following a light rain event. Following a heavy rainfall of 33.1 mm during the 48 hours prior to sampling on July 8 the fecal coliform levels ranged from 3.5 CFU/100 ml behind Melmerby Beach to 2000 CFU/100 ml at the mouth of Chapel Cove.

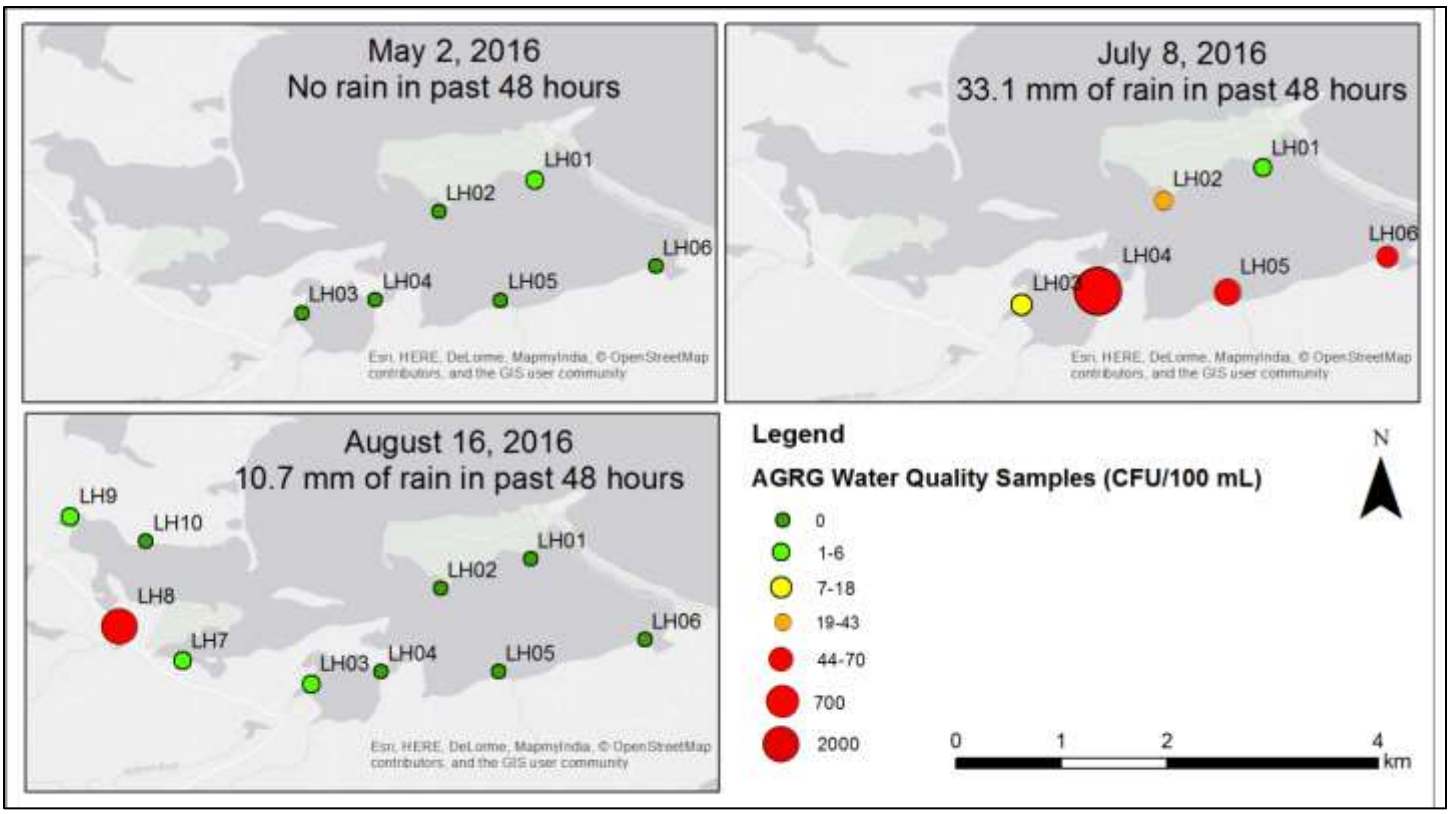

Figure 3.1: AGRG water quality sampling results for May 2, July 8, and Aug. 16, 2016.

Conductivity Temperature Depth (CTD) profiles were measured at sampling locations LH1-6 on May 2 (Figure 3.2). The water at LH3 (at mouth of stream in Chapel Cove) was the freshest, warmest, and shallowest. LH2 was located in the channel near the mouth of the harbour and was the most saline and coldest water, appearing to be well-mixed from the surface to the bottom. LH4, located in the channel at the neck of Chapel Cove, was the most stratified and deepest water, exhibiting a fresh, warm layer in the top 1.5 m, and appearing well-mixed below. The surface salinity at LH3 and LH4 were similar, suggesting that the freshwater signal from the streams entering Chapel Cove extends through the cove and out as far as the neck of the cove, even on a rising tide.

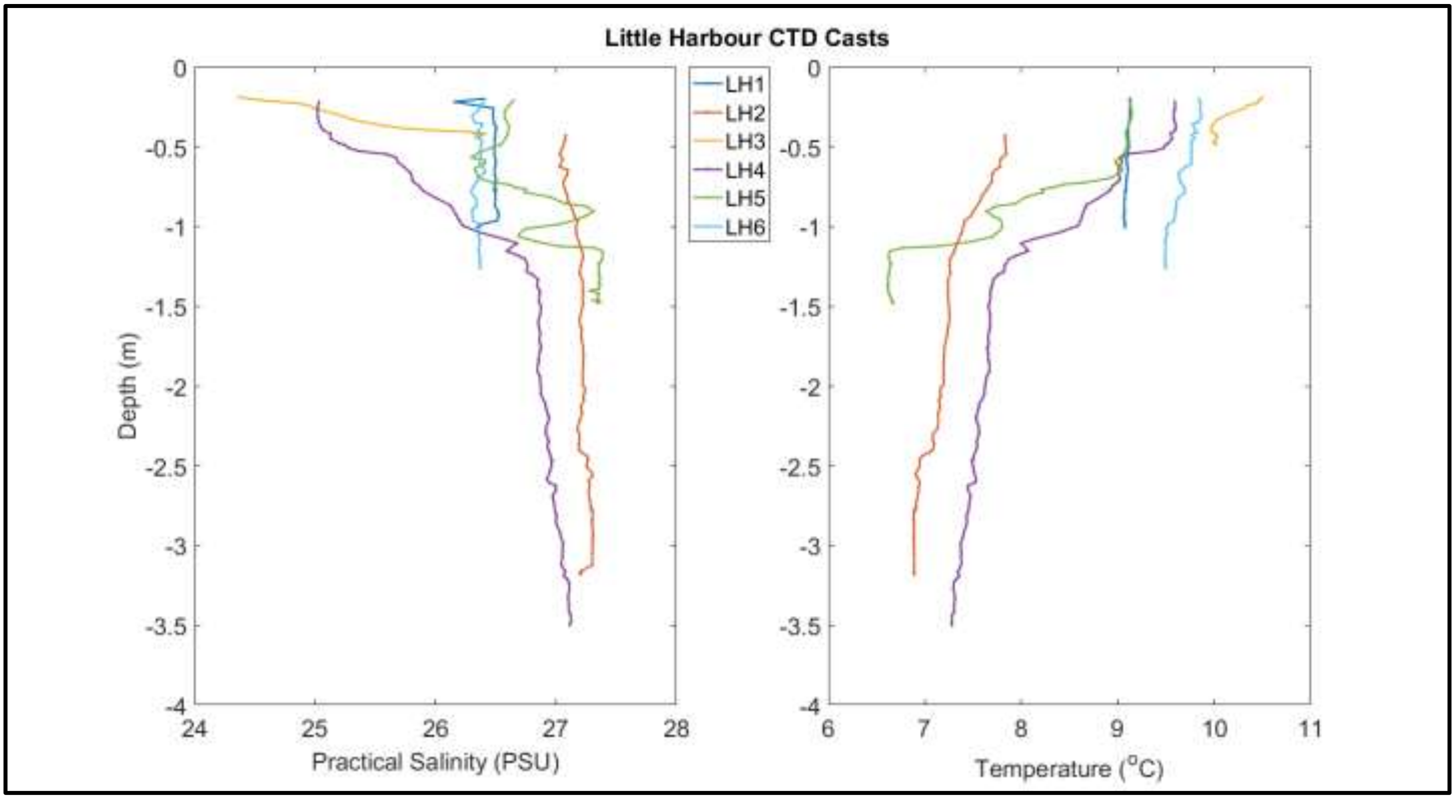

Figure 3.2: Temperature and salinity measured on May 2 at the six AGRG water sampling locations.

3.2 GIS Analysis

3.2.1 Water Quality

The DFO Orders Registry (Government of Canada, 2013b) lists closures in Little Harbour beginning in 1991 and as recent as 2015 (Figure 3.3). The closures in Powells Cove and Chapels Cove have existed for the longest time, although the Powells Cove closure extent was reduced in 2015 after a sampling location was added in 2012 in mid-Powells Cove. The numbered closures in Figure 3.3 represent the present-day closures. The closures will be referred to for the remainder of this report by their closure number as per Figure 3.3, e.g., 1-5.

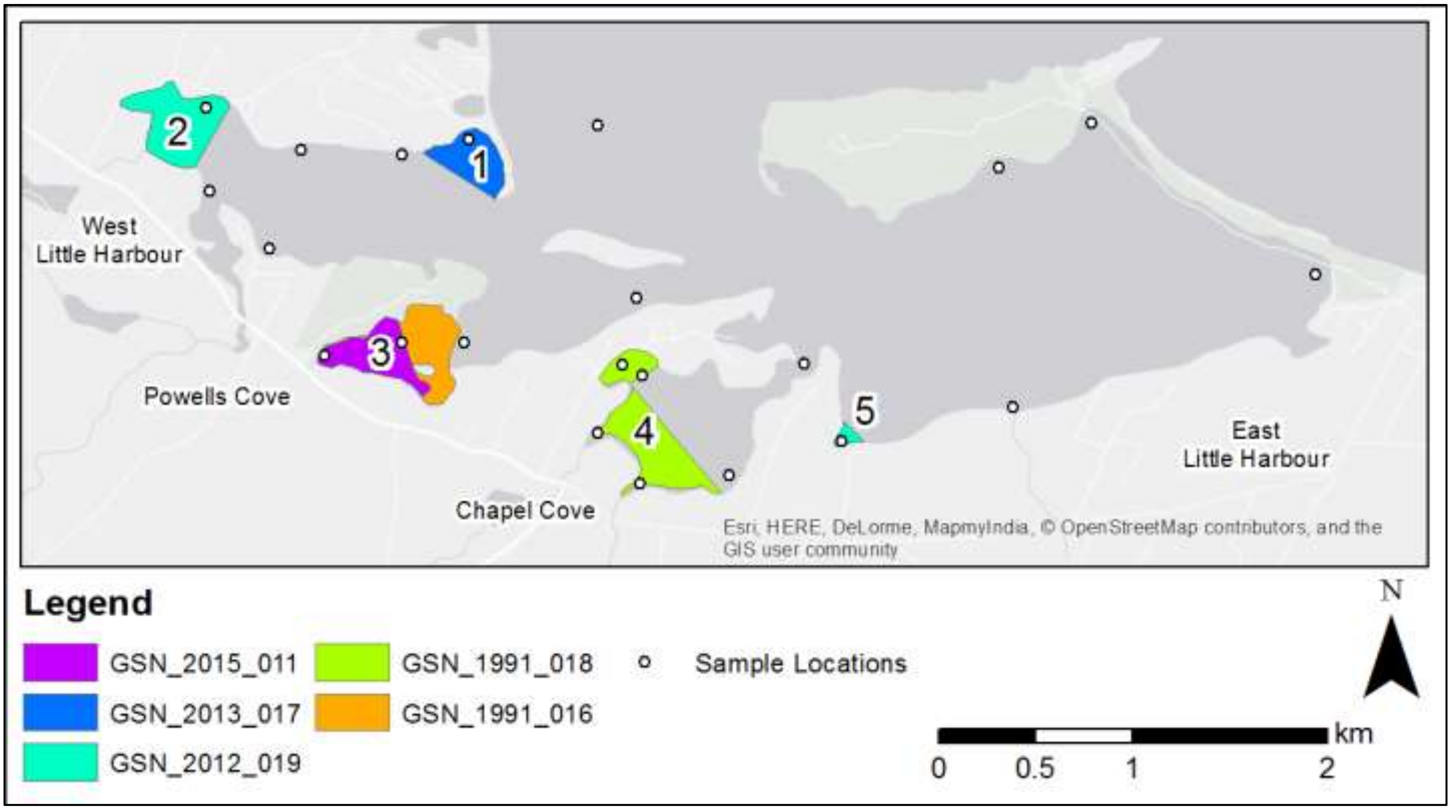

Figure 3.3: Shellfish closures in Little Harbour coloured by Order Number. The numbered orders represent the currently closed areas, and Closure 4 refers to both closures in Chapel Cove.

Mean fecal coliform count for the 25 years of water quality data was calculated for each of EC's sampling locations (Figure 3.4). Two sampling locations had mean values higher than the 43 MPN/100 ml shellfish threshold (65 MPN/100 ml in Powells Cove and 45 MPN/100 ml in Chapel Cove) and two more had mean values near the threshold (36 MPN/100 ml in Chapel Cove and 32 MPN/100 ml in East Little Harbour). The sampling locations with the highest values were located within areas that are currently closed to shellfish harvesting (Figure 3.4); the only exception was near the western side of Little Harbour at the mouth of a small stream, where Egypt Road crosses Pictou Landing Road. At that location the mean was 20 MPN/100 ml but the station was not contained within a closure area. A closer examination of the 25 years of data there revealed one anomalously high result that caused a high mean, but the long-term record at that station indicates clean water. Two aquaculture leases overlap with closure areas in Powells Cove (Closure 3) and Chapel Cove (Closure 4) (Figure 3.4).

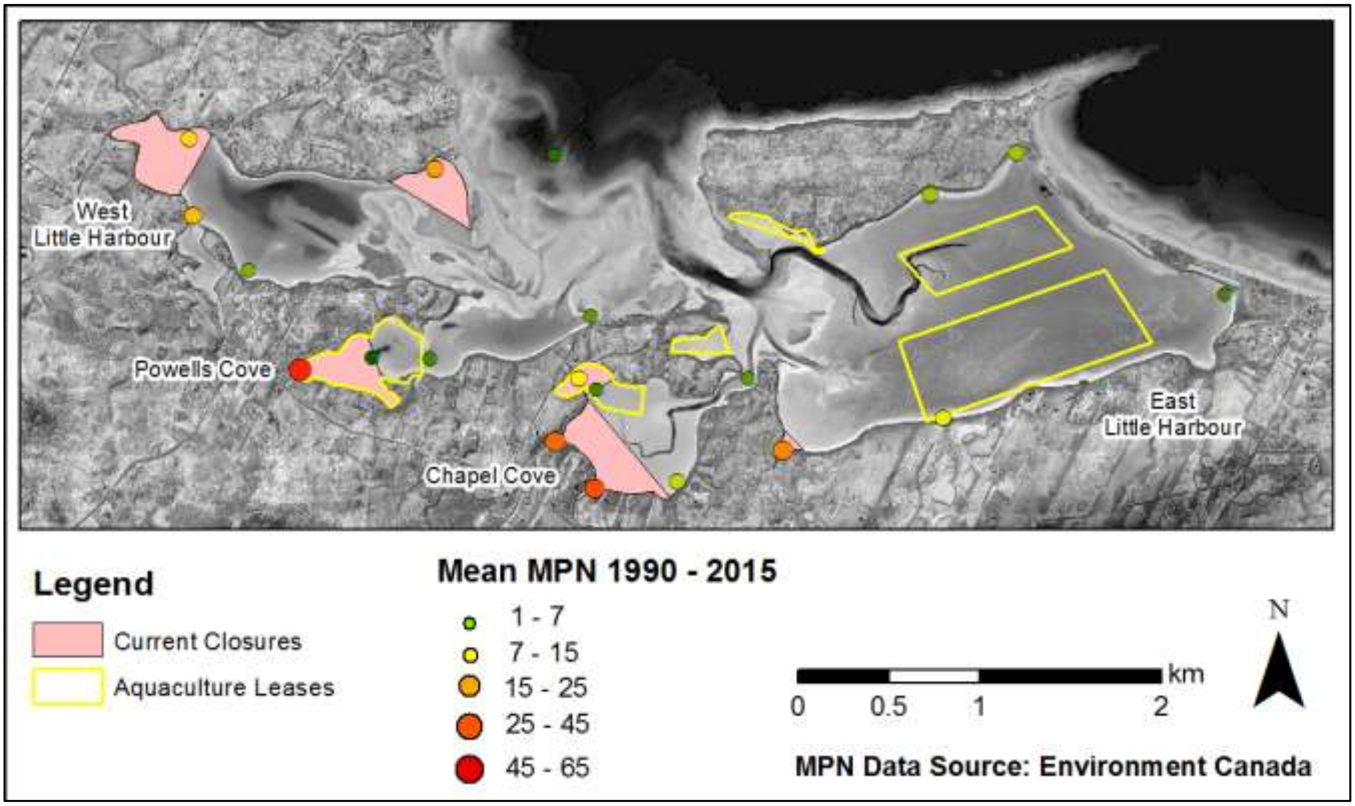

Figure 3.4: Mean fecal coliform count for the 25 years of water quality data, measured in MPN/100 ml: small green symbols have the lowest means (cleanest water) and large, red symbols have the highest means and represent the most frequently contaminated water. Prohibited shellfish growing areas are shown in pale red polygons and shellfish aquaculture leases as yellow outlines.

The maximum fecal coliform count between 1990 and 2015 was 1700 MPN/100 ml at the head of Powells Cove (Figure 3.5). The sampling location with the lowest maximum (14 MPN/100 ml) also occurred in Powells Cove (Figure 3.5, green symbol) but it should be noted that this sampling location was added in 2012 to reduce the extent of the closure there and therefore the value doesn't represent the same long-term statistical analysis as the other stations.

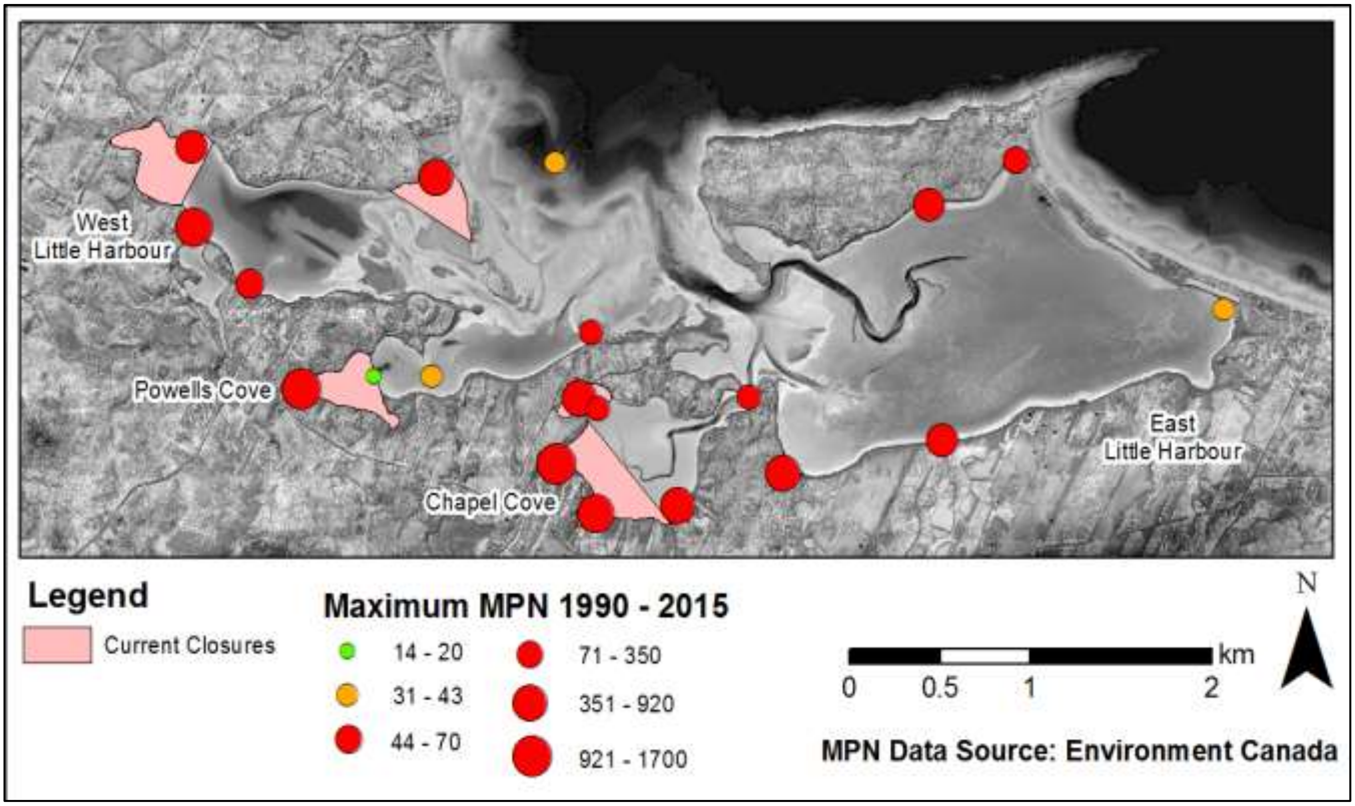

Figure 3.5: Maximum fecal coliform count for the 25 years of water quality data, measured in MPN/100 ml. The small green symbol has the lowest maximum, but note that this location has only been sampled since 2012; large, red symbols have the highest maximums and represent the most frequently contaminated water. Prohibited shellfish growing areas are shown in pale red.

To examine the inter-annual differences in water quality a stacked histogram was generated (Figure 3.6). The graph shows that 17 samples exceeded 43 MPN/100 ml in 2011. The colours on the graph indicate different sampling dates. Each year EC sampled Little Harbour five times, but during some visits there were no sample results > 43 MPN/100 ml; in 2011 the "dirty" samples occurred on three dates. Figure 3.6 suggests a trend of more samples resulting in fecal coliform levels > 43 MPN/100 ml in the 2000s than in the 1990s, but any strong relationship is difficult to determine because of the inconsistent sampling regime and the resulting denser data available in the 2000s compared to the 1990s.

An examination of water quality data values over time shows the increasing frequency of high coliform counts in the past decade (Figure 3.7). Little Harbour was sampled during nine summers between 2005 and 2015, and with the exception of 2005, the swimming threshold (200 MPN/100 ml) was exceeded at least once per summer. Before 2005, Little Harbour was sampled eight times, and the swimming threshold was exceeded three times. This information adds strength to the suggestion that there is a trend towards poorer water quality in Little Harbour. Between 1990 and 2015 the samples exceeded the shellfish threshold (43 MPN/100 ml) 94 times and the swimming threshold on 30 occasions. Figure 3.8 shows the spatial distribution of the incidences of both shellfish and swimming threshold exceedance. The southern sampling location in Chapel Cove exceeded the shellfish threshold most frequently (14 times in 25 years), and the sampling location at Closure 5 in East Little Harbour exceeded the swimming threshold most frequently (6 times in 25 years).

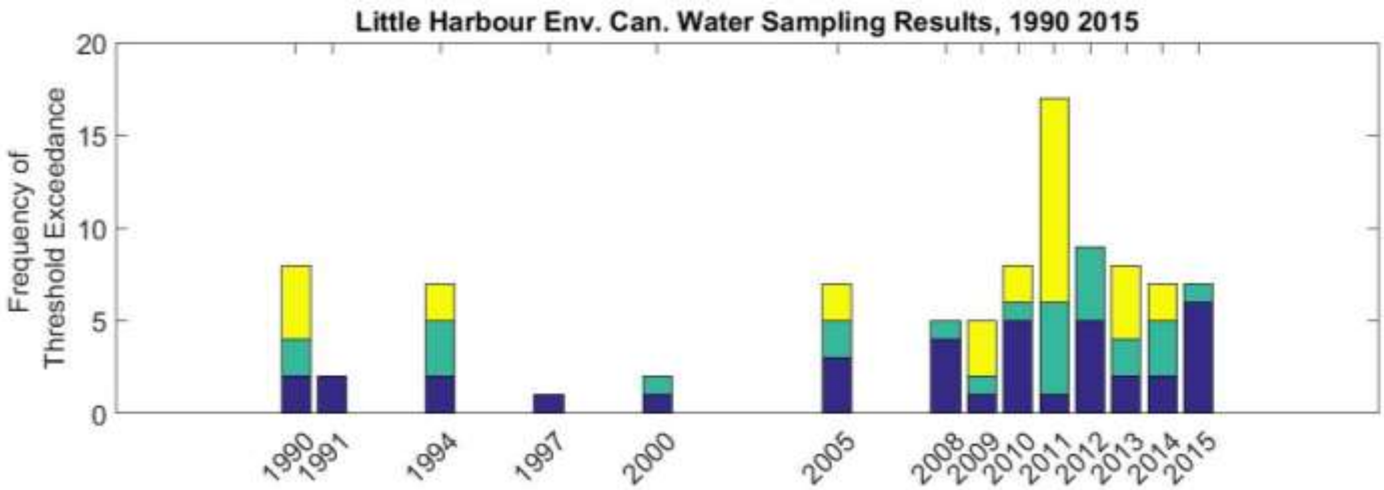

Figure 3.6: The stacked bars represents the number of times per summer that a sample result (from any sampling location) exceeded 43 MPN/100 ml; colours show different visits throughout the summer. 17 samples exceeded 43 MPN/100 ml in 2011.

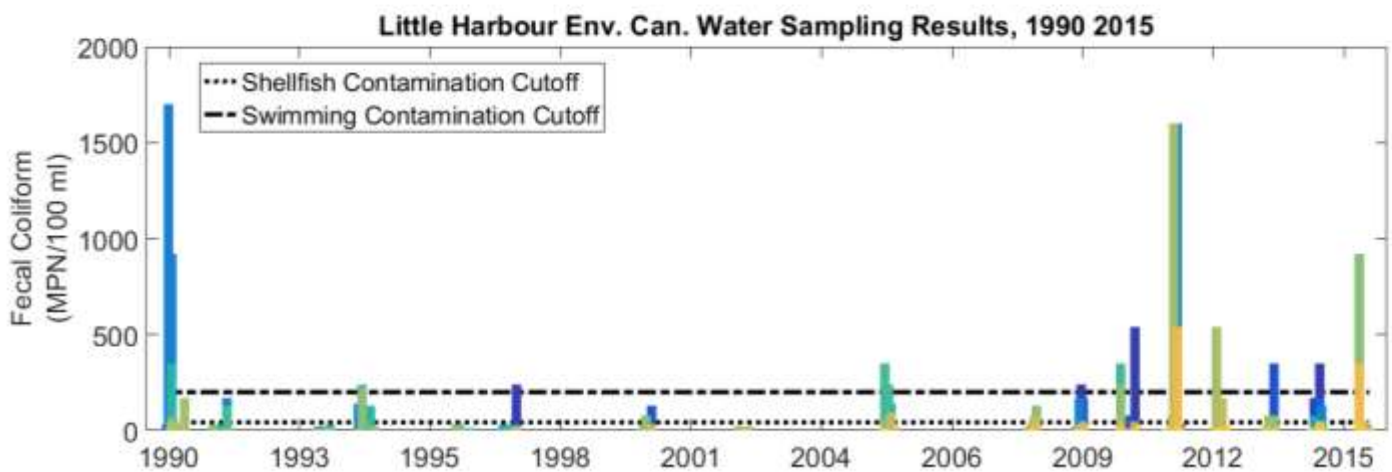

Figure 3.7: Water quality data at all stations, 1990 – 2015; each different coloured line is a different station. The shellfish contamination cutoff and swimming contamination cutoffs are shown.

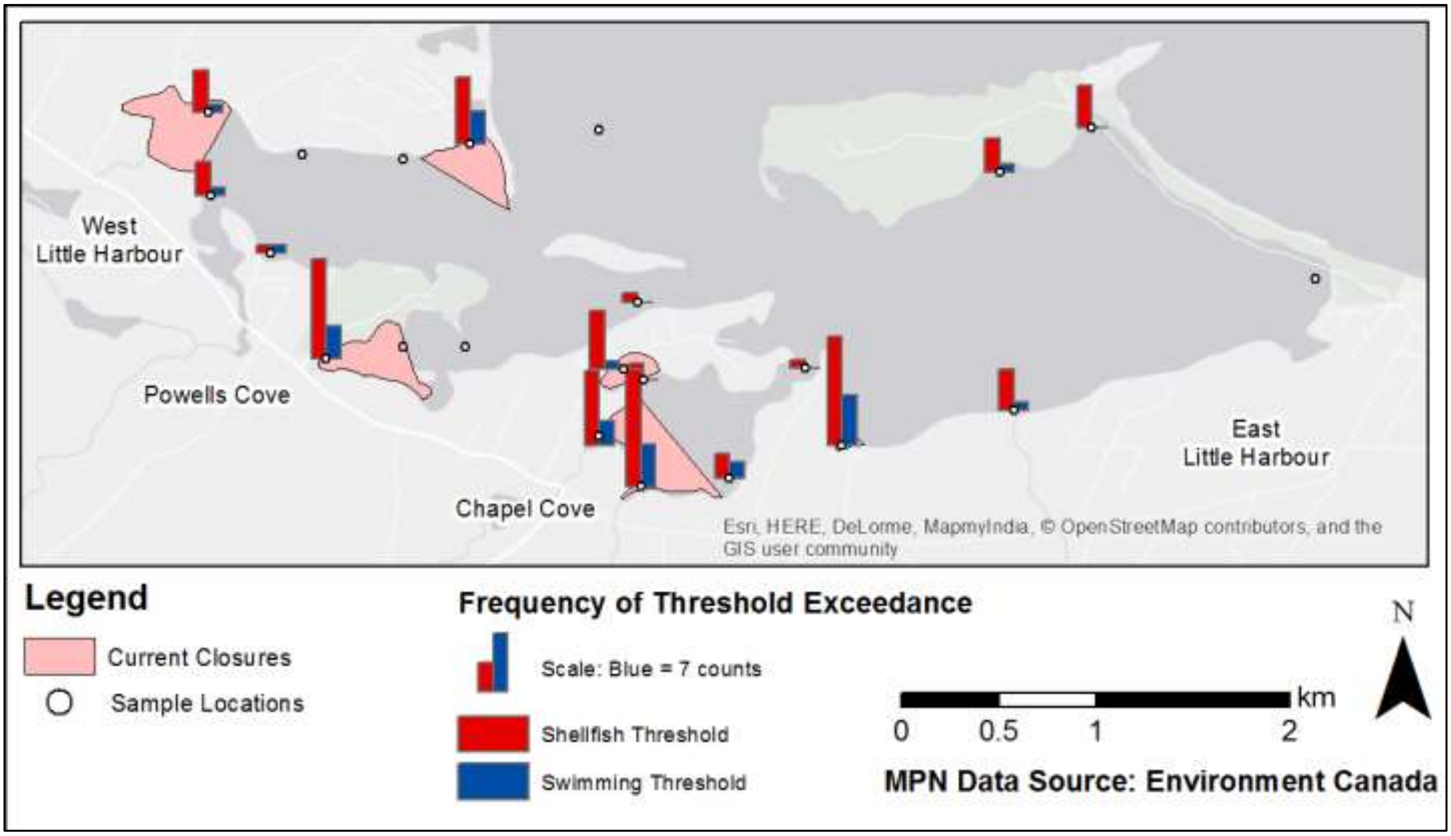

Figure 3.8: Red bars represent the number of times between 1990 and 2015 that a sample result exceeded the shellfish threshold of 43 MPN/100 ml; blue bars are analogous for the swimming threshold (200 MPN/100 ml). The southern sampling location in Chapel Cove exceeded the shellfish threshold most frequently (14 times in 25 years), and the sampling location at Closure 5 in East Little Harbour exceeded the swimming threshold most frequently (6 times in 25 years).

3.2.2 Watershed Land Use

The watershed delineation resulted in 32 basins ranging in size from 0.05 km^2 to 8.8 km^2, with a mean size of 0.7 km^2 and a total area of ~21 km^2 (Figure 3.9). The largest basin contains ~15 km of large streams while many of the smaller basins contain very small and short streams. The land classification analysis revealed that the majority of the Little Harbour watershed is forested areas, shown here as undefined (Figure 3.10). Urban/residential land use makes up 13% of overall land use (2.7 km^2), while agriculture and clear cut each make up ~8% of overall land use (1.6 km^2 each). Examination of the aerial photographs in areas defined as agricultural land use appear to be mainly fields rather than pasture.

The largest and third-largest basins drain into Chapel Cove, where the shellfish closures have been in effect since 1991 (Figure 3.10). The second largest watershed drains into Little Harbour where Egypt Road crosses Pictou Landing Road, in the western arm of the harbour. There is no closure directly at the mouth of that stream but it is adjacent to Closure 2. The non-forest land use in these basins is mainly classified as clear cut and urban (Table 3.1).

	Area (km^2)	Agricultural	Urban/Residential	Clear Cut
Chapel Cove (two basins)	10.8	5.4%	8.4%	11.2%
Egypt Road	4.4	1.3%	7.1%	6.3%

Table 3.1: Land use classification breakdown for the largest basins.

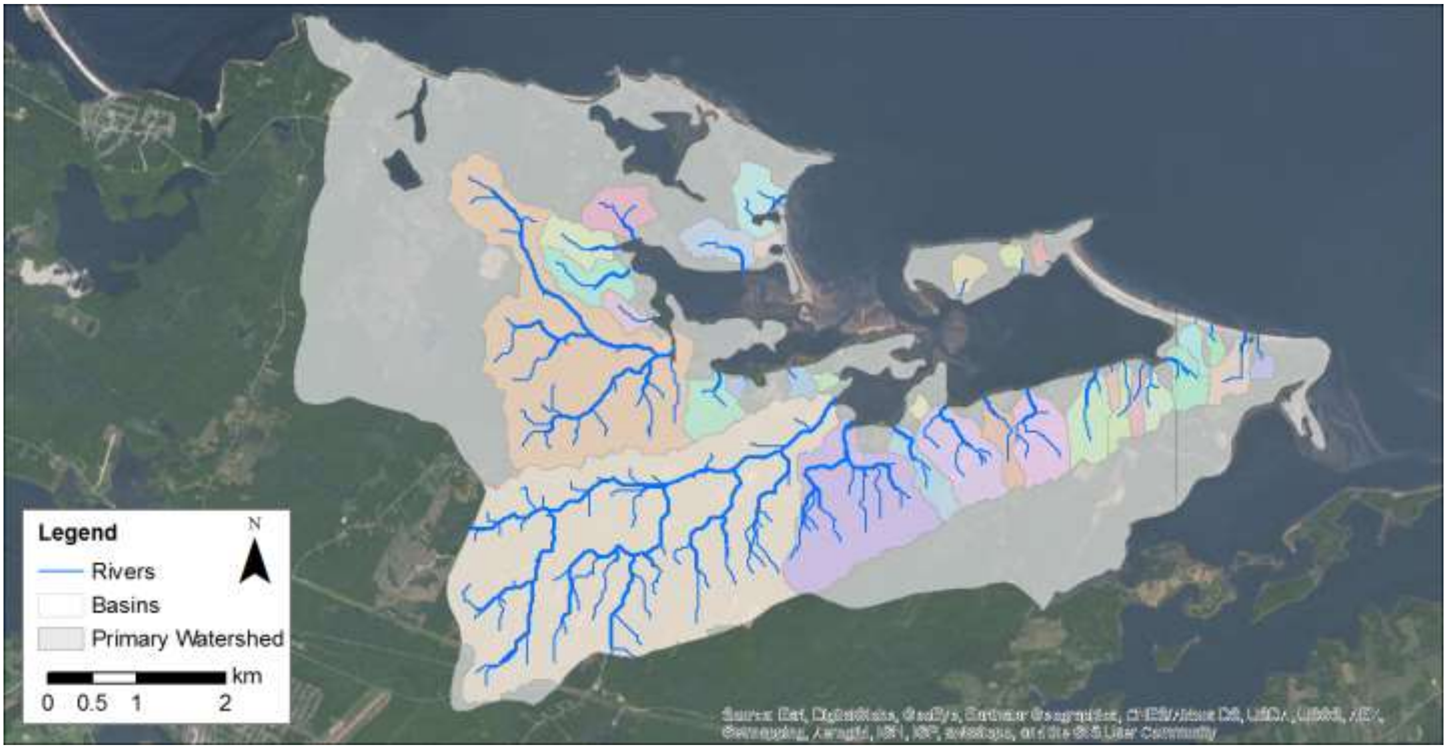

Figure 3.9: Little Harbour primary watershed, basins and streams. The largest watershed is 9 km^2 and the total area is 22 km^2.

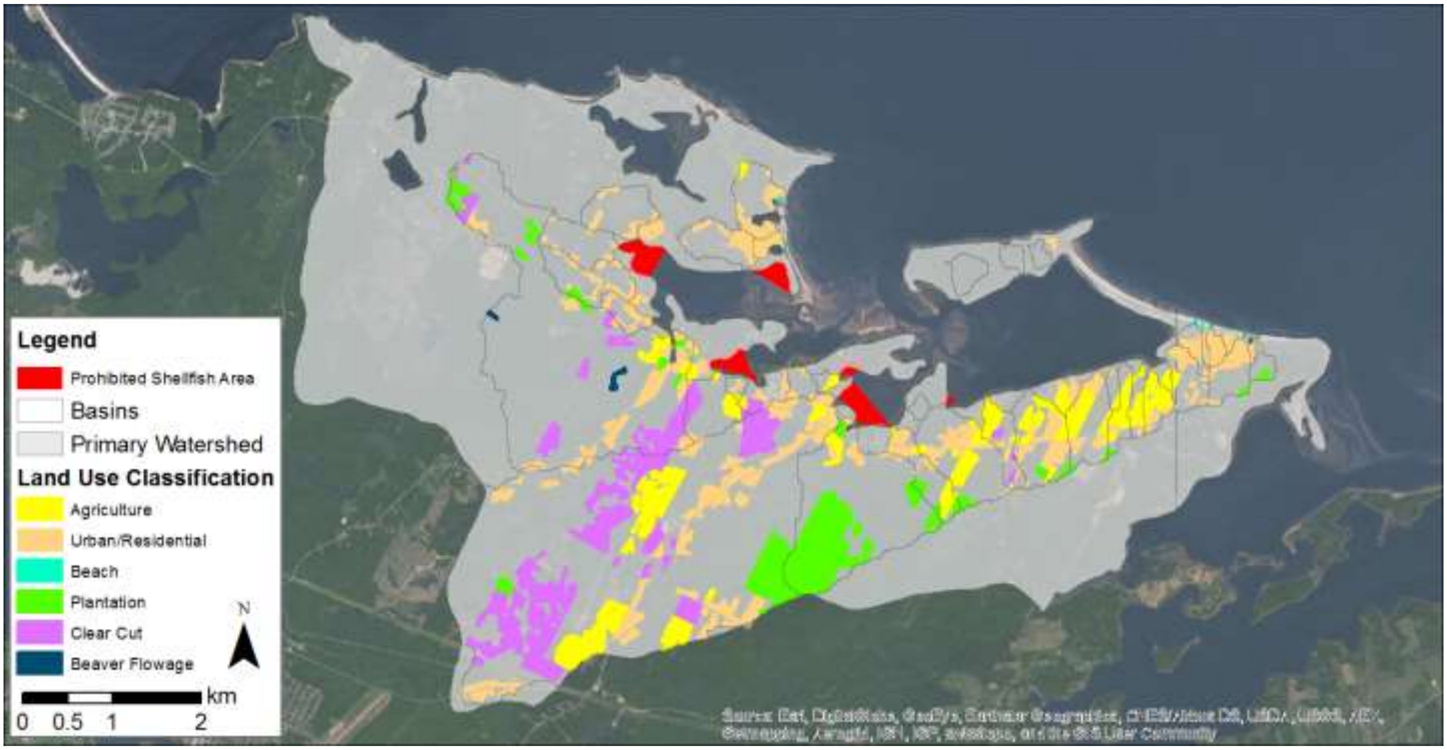

Figure 3.10: Land use classification from NS Forest Inventory data (Government of Nova Scotia, 2015b) and prohibited shellfish areas.

3.2.3 Housing Analysis

The housing analysis of digitized dwellings from 1954, 1971, 1990 and 2014 aerial images showed that the number of dwellings (houses, cottages, permanent trailers, etc.) increased six fold between 1954 and 2014, from 106 dwellings to 666 (Table 3.2). Dwellings in Little Harbour are clustered near the shoreline and the densest development during the past 60 years occurred near Melmerby Beach and Black Point (Figure 3.11, Figure 3.12). Note that the blue polygons that represent the aerial photograph extents explain why it appears as though there has been negative development between 1971 and 1990 near Melmerby Beach in Figure 3.11; this is unlikely but no dwellings were digitized outside of the aerial photograph extents. Although there is a high density of housing near Melmerby Beach in 2014 there is no issue with water quality in that area of Little Harbour; however, the area near Black Point has a high housing density adjacent to Closure 1. The western end of Little Harbour has also seen increased housing density but it appears as though most of the dwellings along the shore near Closure 2 have existed since the 1971 photo, raising the possibility of older septic systems that could be contributing to water quality issues and the prohibition there.

Year	Number of Dwellings
1954	106
1971	272
1990	317
2014	666

Table 3.2: Number of dwellings digitized from aerial photographs.

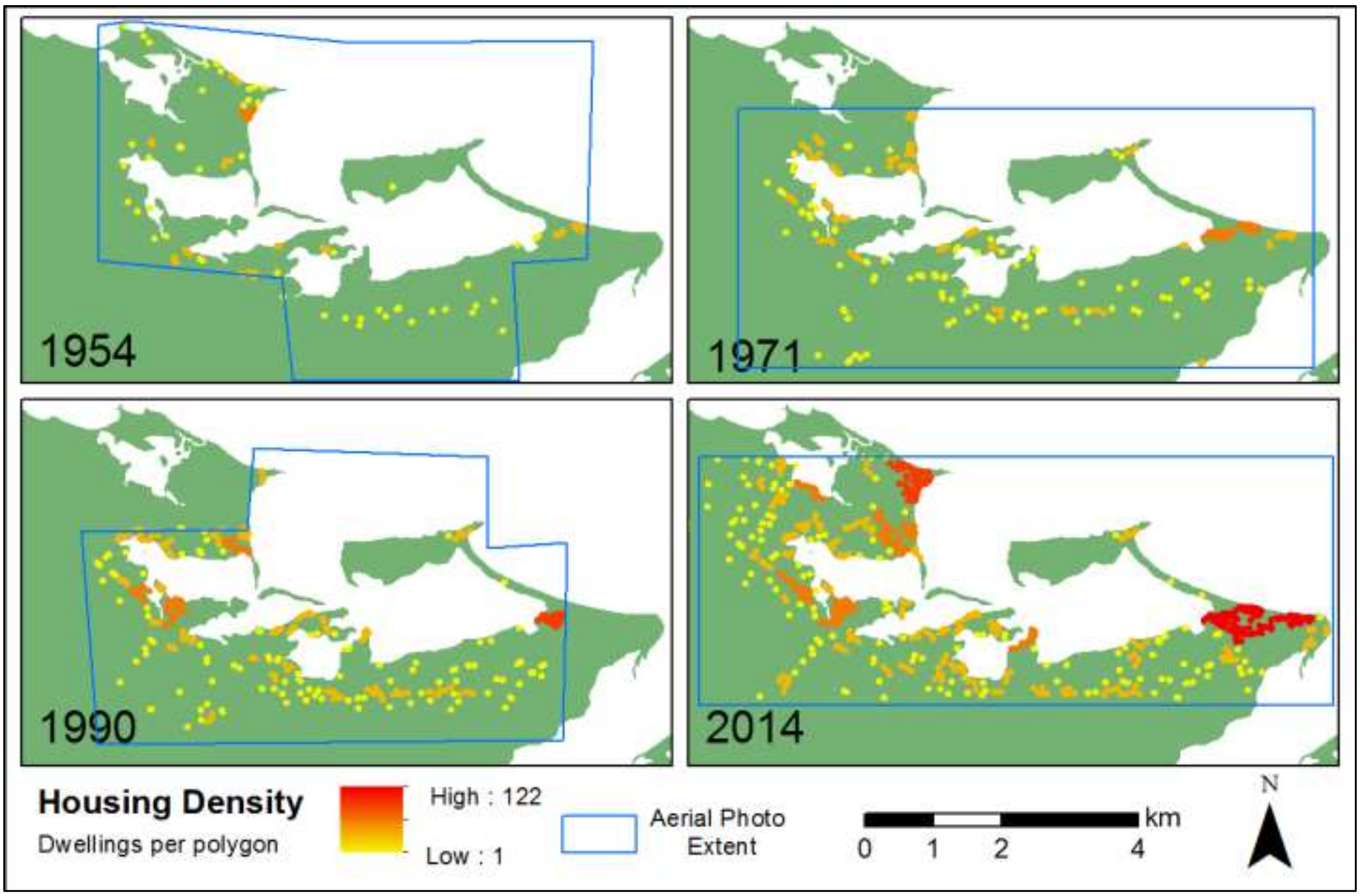

Figure 3.11: Housing density for the four aerial photographs: 1954, 1971, 1990 and 2014. Each polygon represents dwellings that were digitized from the aerial photographs; small yellow polygons represent fewer dwellings in close proximity to one another, while larger, redder polygons represent more dwellings closer together. The red polygon near Melmerby Beach in 2014 has the highest "housing density", with 122 dwellings contained within the red polygon. Blue polygons represent the extents of the aerial photographs used to digitize dwellings.

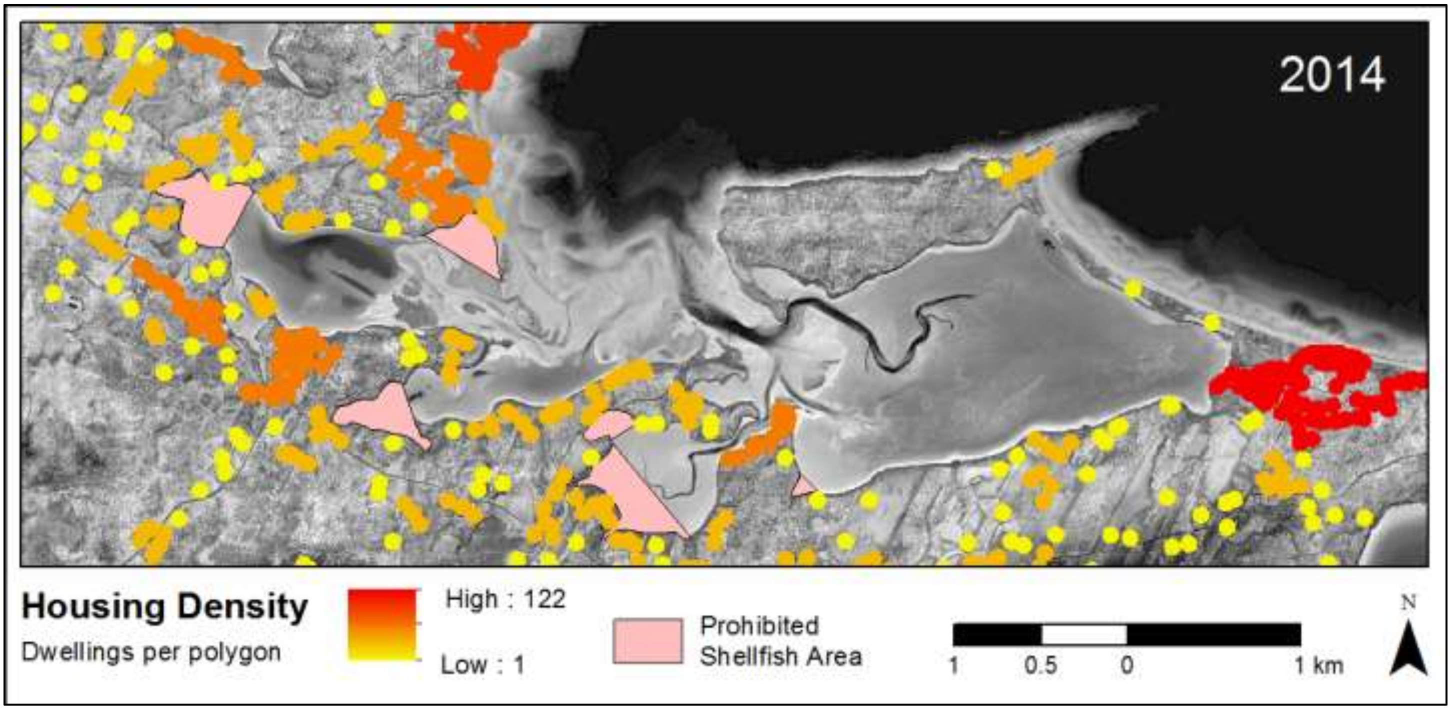

Figure 3.12: Housing counts for 2014 coloured by sparse (yellow) to dense (red), and prohibited shellfish growing areas.

3.3 Hydrodynamic Model

3.3.1 Validation

The hydrodynamic model generated water level and depth-averaged current data for each model cell. To validate the model and ensure that the circulation patterns it simulated were an accurate representation of real circulation in Little Harbour, water level and current data were extracted from the model at the two ADCP deployment locations and the modelled data were compared to the observed (ADCP) data (Figure 3.13, Figure 3.14). The coordinates for the ADCP deployment locations were obtained using GPS units with 3-5 m resolution, and a mismatch was observed between modelled and observed depth that can likely be explained by extracting the modelled depth from a cell that was deeper in the channel than the ADCP actually was. To accommodate this, a -0.60 m offset was applied to the modelled depth for Deployment 1 (Figure 3.13), and a -1.2 m offset was applied to the modelled depth for Deployment 2 (Figure 3.14). Once this adjustment was made it is clear that the model, observations, and predicted tide agree very well for Deployment 2, and moderately well for Deployment 1.

At Deployment 1, the model does not capture the mixed semidiurnal nature of the tidal cycle, but instead predicts a scenario where successive high and low tides are more closely matched. The model also does poorly at predicting the timing of the high tide following a higher low tide (an example is marked by the red line in Figure 3.13), likely because of the mismatch in amplitude prediction. However, the model “catches up” by the next high tide in both amplitude and phase. The modelled and observed currents during Deployment 1 (Figure 3.14) exhibit the same mismatch in amplitude and phase as the depth. The model over predicts currents on the flood tide following the higher low tide, because it is modelling a larger volume of water coming into the harbour than is observed.

During Deployment 2, the observed tide was in a more ‘regular’ semidiurnal phase and the model matched observations and predictions well in both amplitude and phase (Figure 3.14). Currents at Deployment 2 are not shown because the ADCP was not set up suitably for the depth of water in which it was deployed. The ADCP can only begin measuring currents a certain distance away from the sensor, and observations too close to the water surface are also typically rejected due to interference with the surface. Due to the shallow deployment and the size of the bins that the ADCP was set to measure, there was not enough good data to compare with the model.

A possible explanation for the mismatches in modelled depth and current during Deployment 1 is that the model boundary was located too close to the inner harbour. It was placed at the outer extent of the lidar bathymetry data, but it is possible that the tidal signal forcing the model is not performing well this close to the shore. It is expected, however, that the small mismatches in depth and current predictions are insignificant to the general performance of the model and its role as a mechanism for particle tracking. The effect of the model predicting a low tide that is lower than the observed tide would not affect the movement of particles in the model in a way that would alter their course from the scenarios presented in the next section, and it is concluded that the model has been validated within the scope of this project.

Figure 3.13: Deployment 1 depth and current validation. A -0.6 m offset was applied to the modelled depth, as described in the text (top panel). Current flowing in the East-West direction (*u*) are shown in the middle panel and current flowing in the North-South direction (*v*) are shown in the lower panel. The red line marks a higher low tide when the model over-predicts the tidal amplitude and east-west currents.

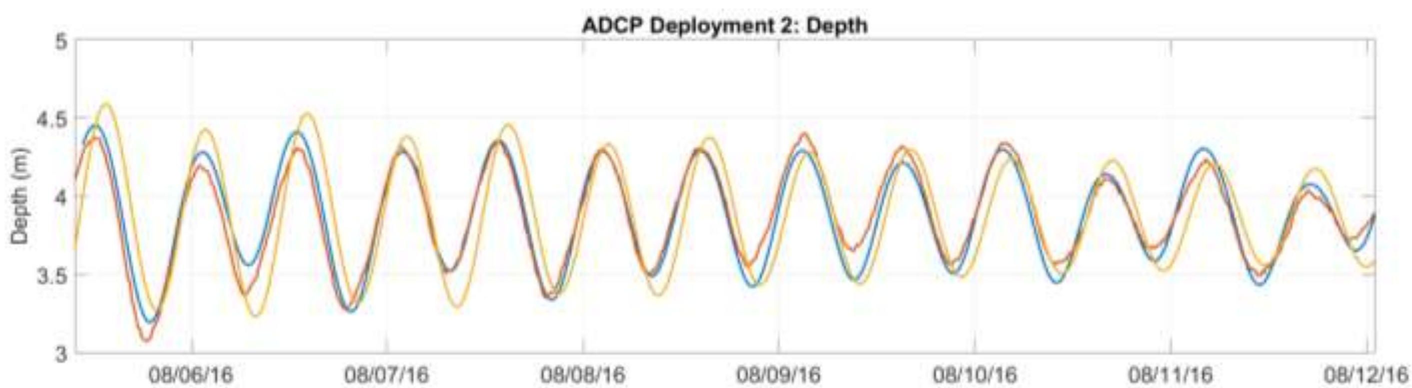

Figure 3.14: Model depth validation for ADCP Deployment 2. A -1.2 m offset was applied to the modelled depth, as described in the text.

3.3.2 Particle Tracking

Particles were released into the model at the six locations associated with high contamination levels. Dispersion concentartions and extents of the particles were exported at various model timesteps (Figure 3.15). After two hours, during which the tide was falling, the particles have remained close to their source. After four hours particles at Sources #2-6 (see bottom right inset for source labelling) have not been transported any significant distance from shore and concentrations remain high, as indicated by the dark red; but after four hours the particles at Source #1 have been dispersed out of the western arm of Little Harbour at a low concentration, and remain at a moderate concentration at the source. At six hours, just before the tide changes to an rising tide, the particles reach their maximum transport distance away from their sources; Sources #2,4-6 have been transported a few hundred meters, Source #3 has been transported to the back of the island, and Source #1 has been transported nearly to the model boundary at the mouth of the harbour. After eight hours the incoming tide has pushed the particles at Source #1 back towards their source and is spreading them along the shoreline there at a low concentration. Sources #2,4-6 have been pushed back towards the shore and remain at moderate concentrations; Source #3 remains at a high concentration behind the island. After 12 hours the particles that entered the model at Source #1 have been dispersed west of the original source, and some have settled on the shoreline there. Between 12 and 24 hours after the start of the simulation Source #2 has settled out completely onto the shoreline near its point of origin and does not change significantly. Particles at Sources #3-6 do not disperse any further after six hours, the particles do not leave their coves of origin but remain at low concentrations near their sources with some higher concentrations of contamination becoming deposited on the shoreline. The low concentration of contaminates originating from Source #1 continue to move around the estuary between 12 and 24 hours after the model began, remaining mainly in the western arm of Little Harbour.

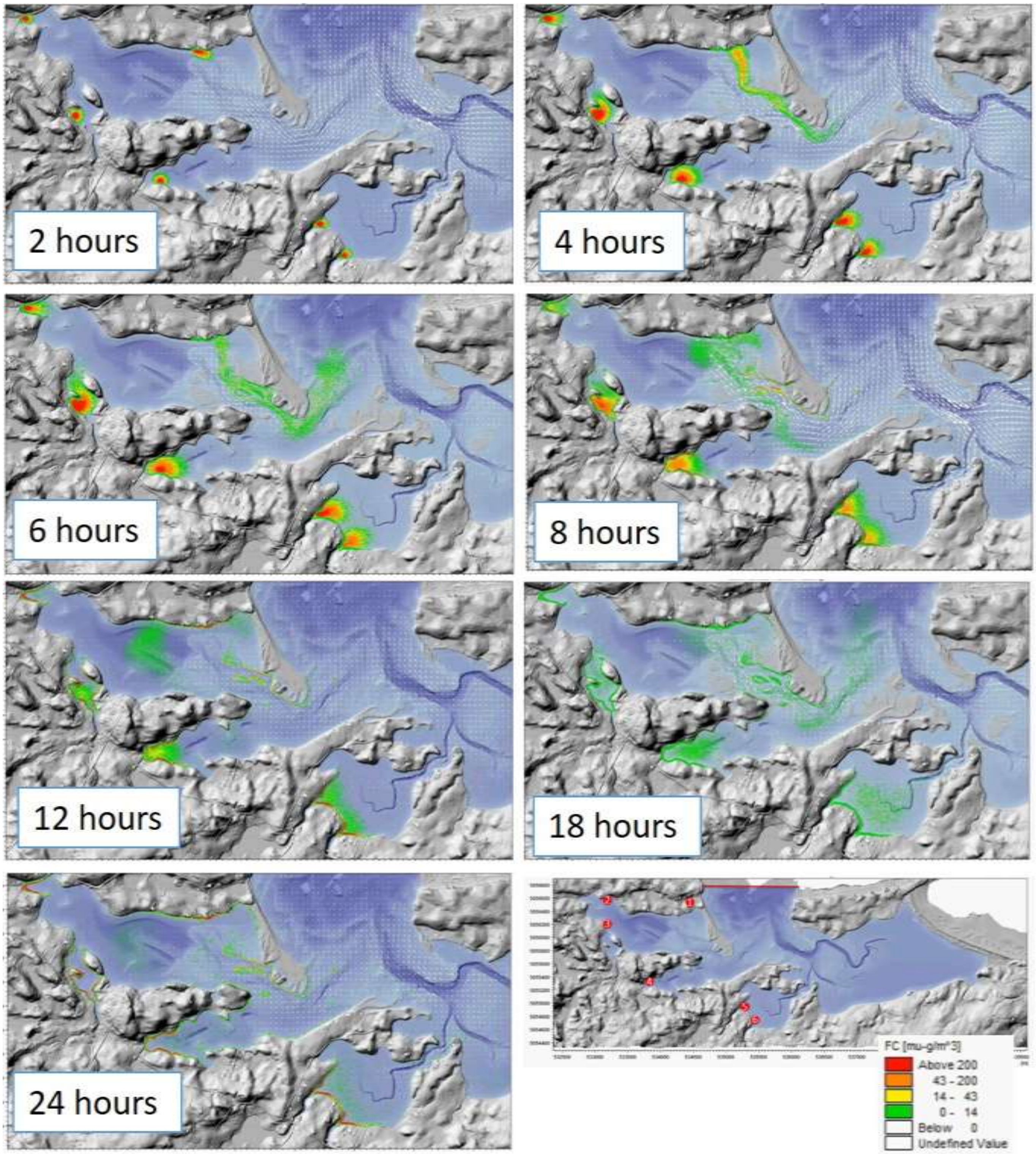

Figure 3.15: Model results showing particle dispersion at 2, 4, 6, 12, 18, 24, and 36 hours after particle release. Bathymetry is shown in shades of blue, where dark blue indicates deeper water and light blue indicates shallower water, and fecal coliform concentrations (modelled particles) are shown as green, yellow, orange or red (low to high concentration).

4 Discussion

4.1 Analysis

The lidar DEM was scaled to a narrow depth range to emphasize changes in bathymetry in Little Harbour, including location of the channels and deeper areas, sandbars, and the steepness of the back bays and inlets (Figure 4.1). In most of the figures for this section of the report, the true colour orthophotos are displayed for the land, and bathymetry is shown by the DEM scaled to show white for 1 m CGVD28 elevation, and red for any depths greater than -2 m CGVD28. Rivers and streams, and shellfish closure areas are also displayed on the maps as a visual aid to the analysis of water quality in Little Harbour. The main channel extends into the eastern arm of Little Harbour, with a small channel branching off and splitting into two narrower channels near Closure 4 and 5; these channels are at least -2 m CGVD28 (Figure 4.1). The channel that leads from the mouth of the harbour to Powells Cove is much shallower (~-1 m CGVD28) and less well-defined. The channel leading to the western arm where Closure 1 and 2 are located is not well-defined, and passes between several sand deposits and bars before entering a deeper area near Closure 2. The 1990 aerial photograph with delineated coastline shows that the coastline and bathymetry in this area were quite different when EC began their sampling program at Little Harbour in 1990 (Figure 4.2). Black Point has been extending across the former channel over the past 24 years and a tiny clump of trees is all that remains of an island that once blocked the mouth of Powells Cove. These changes in bathymetry would no doubt have played a role in circulation within the estuary and the transport of bacterial contamination.

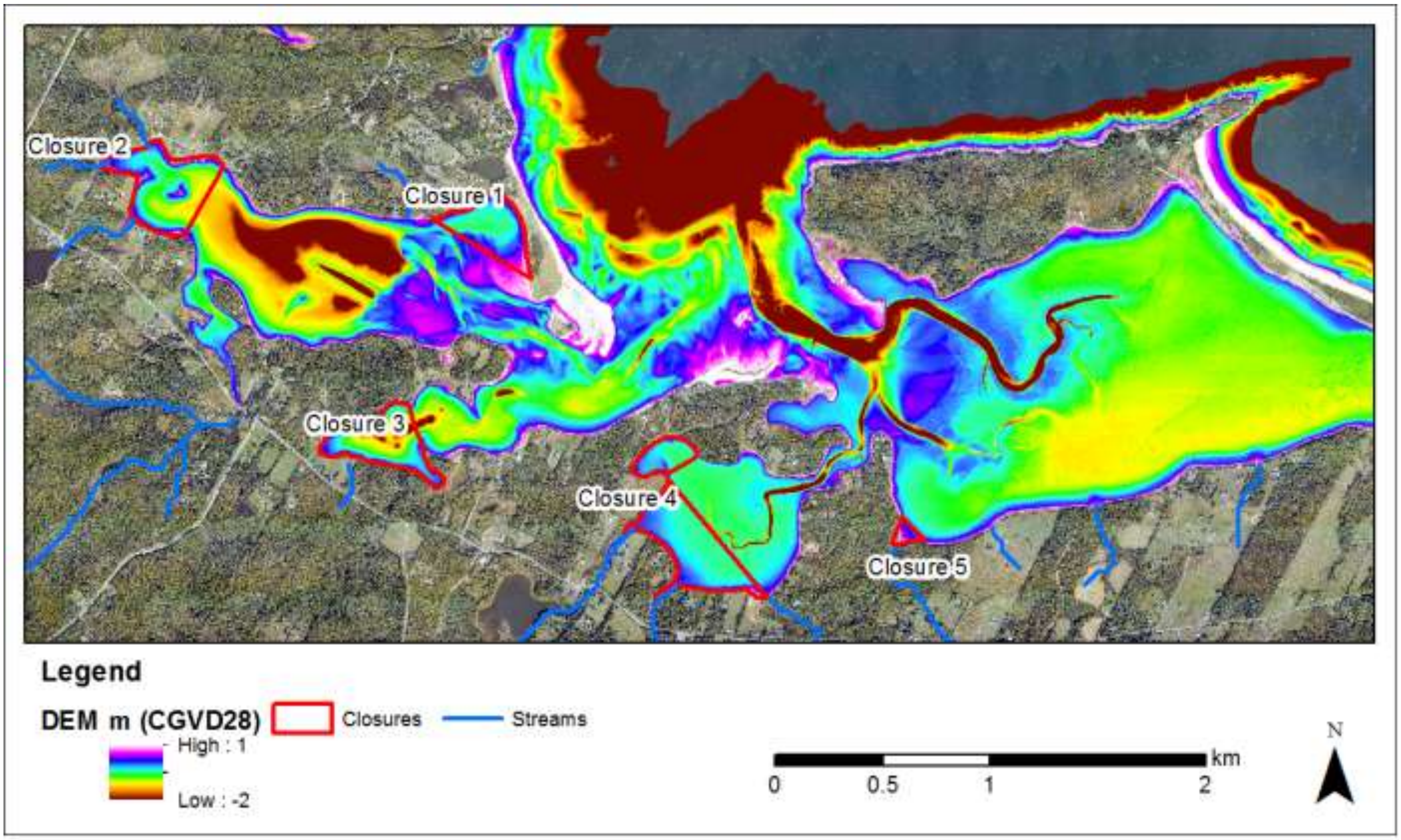

Figure 4.1: Lidar DEM scaled to emphasize bathymetry in Little Harbour on true colour orthophoto showing shellfish closure areas.

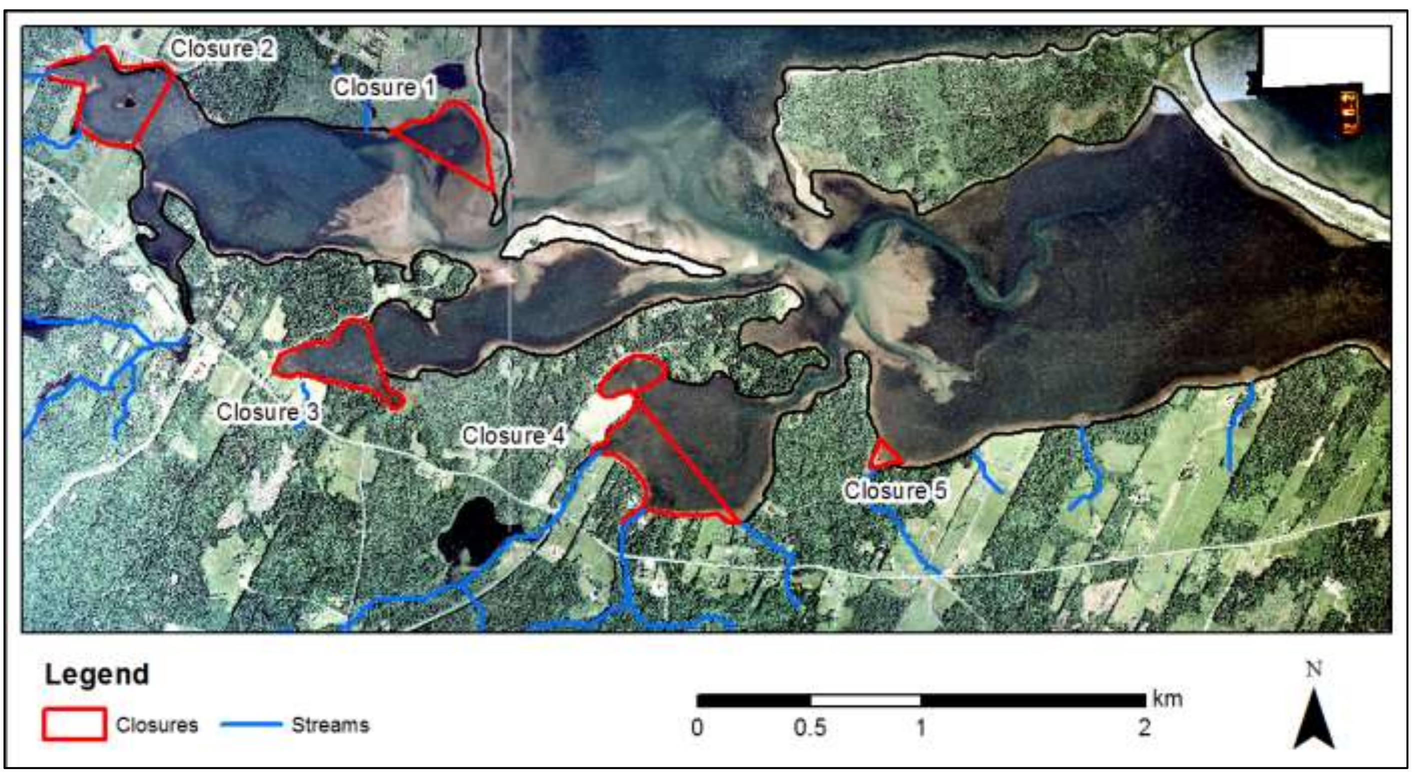

Figure 4.2: Current-day closures and streams overlaid on 1990 aerial photograph.

Shellfish Closure 1 at Black Point has existed since 2013 and has a mean contamination level of 25 MPN/100 ml. The housing development there, as determined using the aerial photographs, has been steady since 1954, and includes a trailer or RV park that was built sometime in the 1970s or 1980s (Figure 4.3). There is a small stream at Closure 1 draining a small watershed which is 27% residential land use. The bathymetry within the closure is relatively flat and has elevation of approximately -0.5 m CGVD28. The bathymetry does not show a wide or deep channel leading to Closure 1, but the hydrodynamic and particle tracking models shows that there is flow to Closure 1, a significant enough flow to move particles out from behind Black Point on an ebb tide. The aerial photographs showed the southward migration of Black Point and the change in the opening to the western arm of Little Harbour which may have contributed to circulation of contaminants there.

Closure 2 was established in 2012 at the head of the western arm of Little Harbour (Figure 4.3). Three streams drain approximately one square kilometer of land classified as a combination of residential, forested, and agricultural land. The watersheds in this area also contain small ponds. The number of dwellings in this part of Little Harbour increased between 1954 and 2014, mostly within 100 m of the shoreline, but property sizes are larger here than in other parts of Little Harbour such as Black Point and Melmerby Beach, resulting in more longer-established, less dense housing. The bathymetry in Closure 2 slopes gently away from the shoreline and has elevation of between -0.5 m and -1.2 m CGVD28. The bathymetry between Closures 1 and 2 is as deep as -3 m CGVD28.

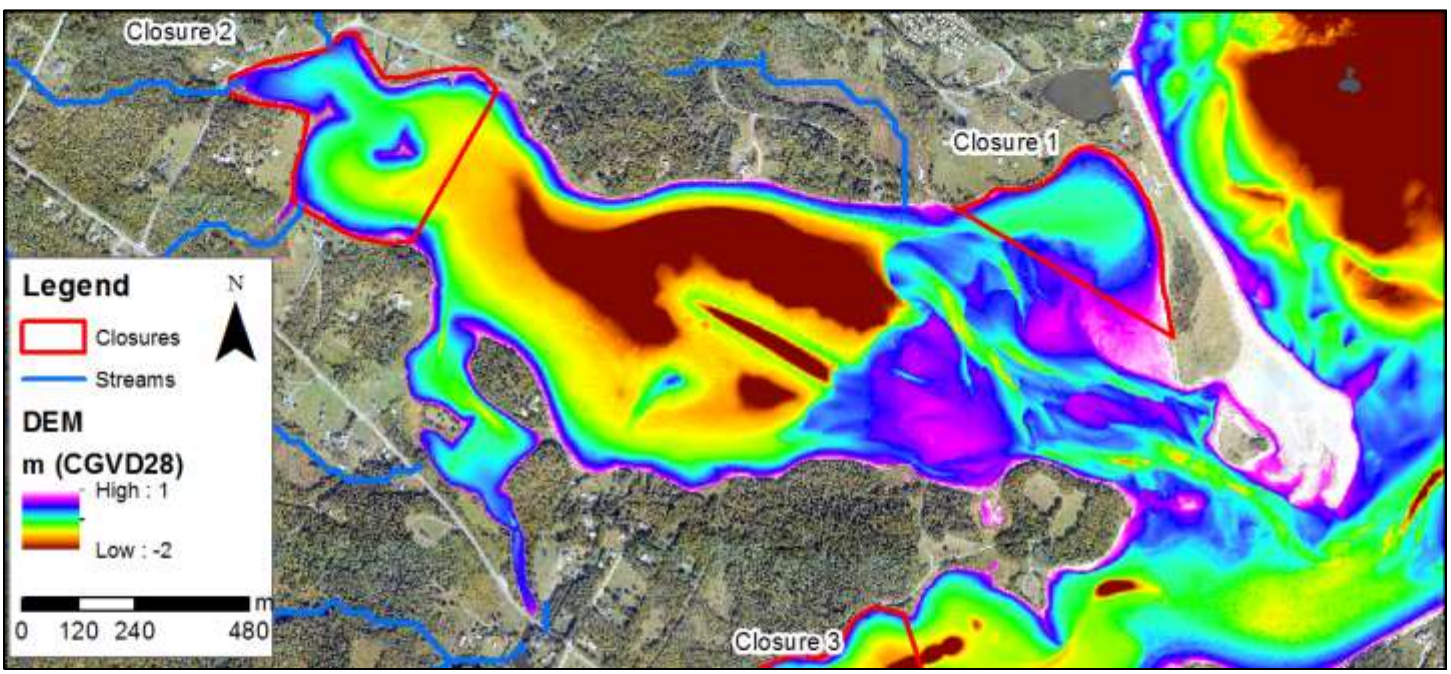

Figure 4.3: Shellfish closure areas 1 and 2 on lidar DEM bathymetry and true colour orthophoto on land.

Closure 3 and 4 in Powells Cove and Chapel Cove, respectively, are the longest-established closures in Little Harbour, having been in effect for 25 years. At Powells Cove, the watershed is small, and doesn't drain a significant stream, and the housing density is relatively sparse (Figure 4.4). The bathymetry within Closure 3 slopes gently from the shore and reaches an elevation of -3 m, and the rest of Powells Cove is typically -1 m elevation. As noted above, the circulation in Powells Cove since the shellfish closure was established in 1990 has likely changed as the island that once blocked the mouth of the cove has been reduced and the shoreline changed markedly. The particle tracking model showed that contaminants that entered Powells Cove were not dispersed more than a few hundred meters away from the shore, so regardless of their source, they pose a problem to water quality in that area.

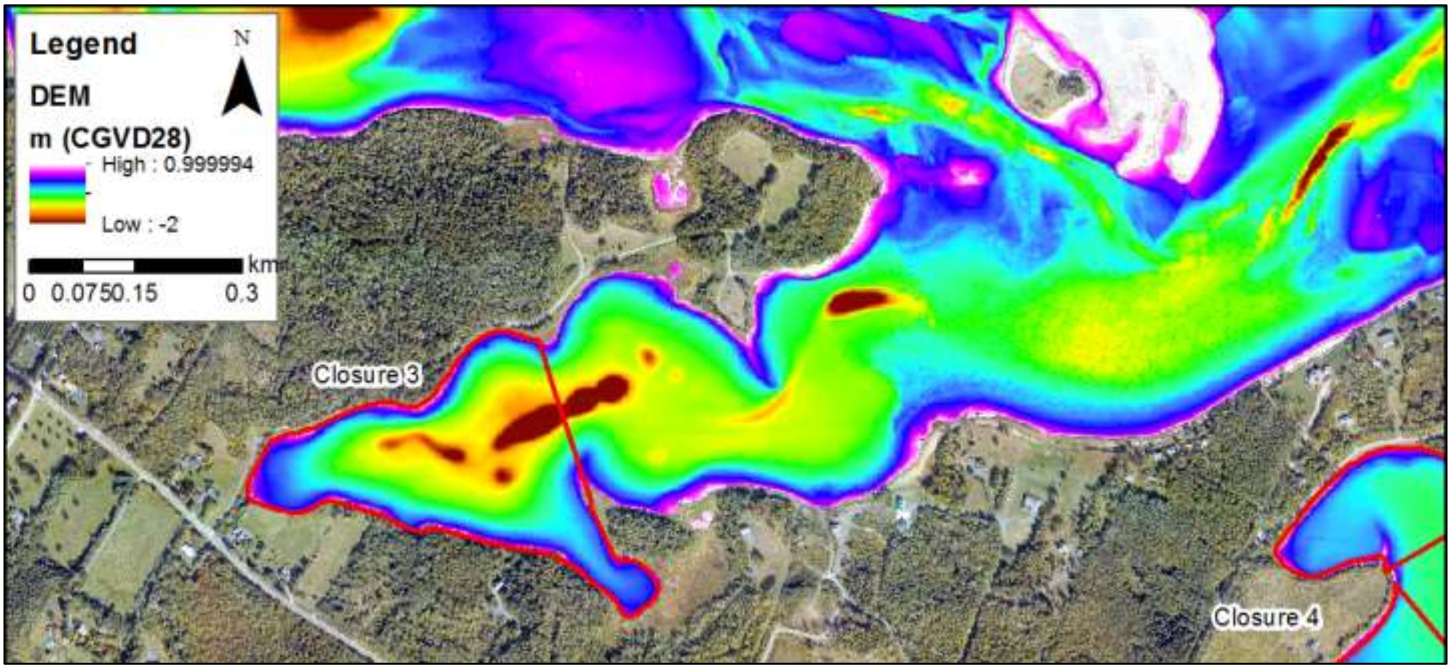

Figure 4.4: Shellfish closure area 3 on lidar DEM bathymetry and true colour orthophoto on land.

Chapel Cove drains ~11 km^2 of land via two large streams, so the potential for non-point contamination in the upper watershed is great (Figure 4.5). Housing density increased in the Chapel Cove area greatly in the past 25 years. Chapel Cove has a narrow entrance to a wide, flat basin, rarely over half a meter deep outside the channel. The model showed minimal dispersion of particles within the cove, and no transport of particles out of the cove.

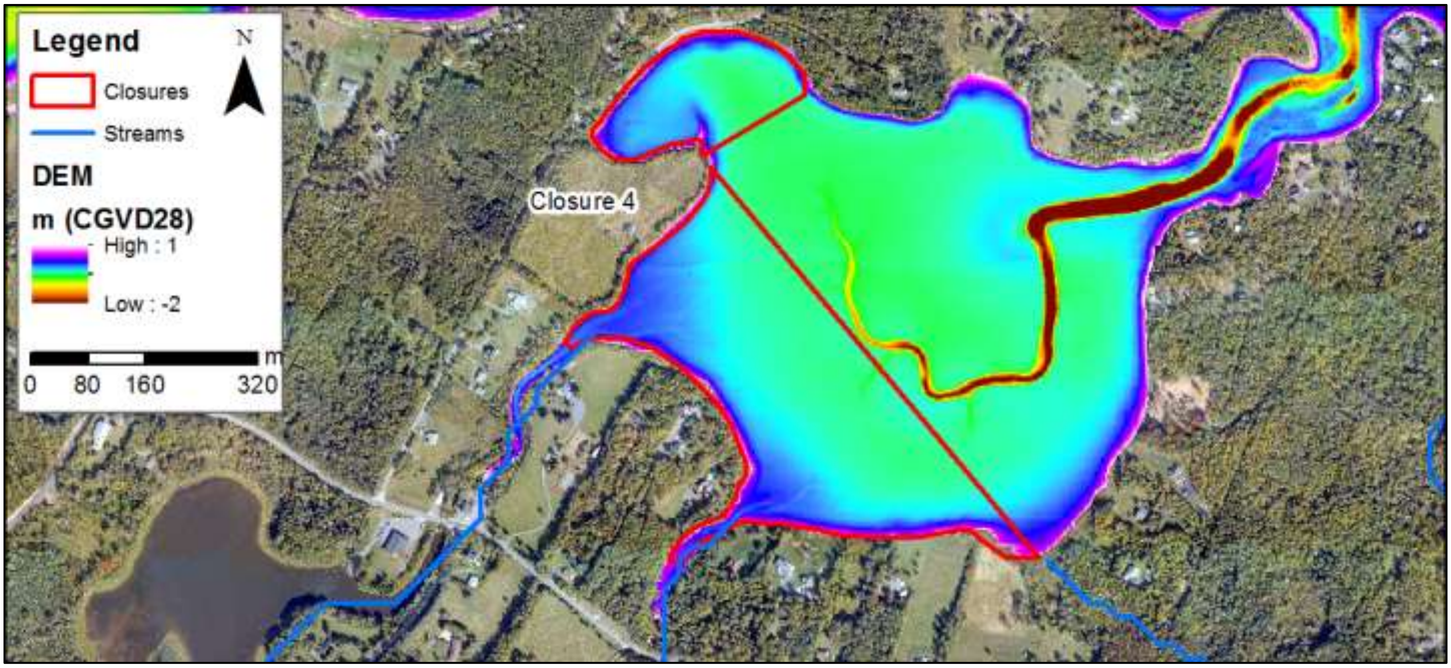

Figure 4.5: Shellfish closure area 4 on lidar DEM bathymetry and true colour orthophoto on land.

Closure 5 is very small, located at the mouth of a small stream that drains approximately 0.7 km^2 of agricultural and residential land. The dwellings in this watershed are typically 500 m away from the shoreline and include some older buildings. The eastern arm of Little Harbour is also shallow, but has much better circulation via the large channel coming in from outside the harbour.

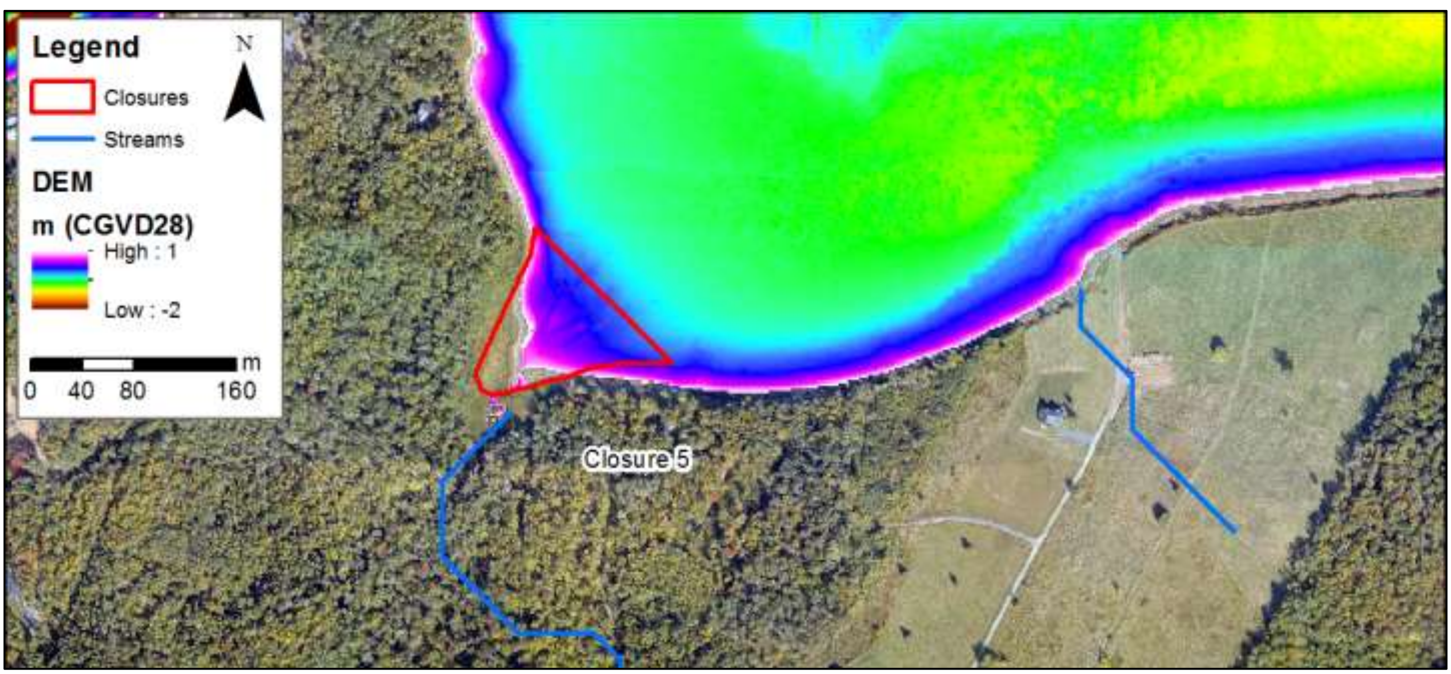

Figure 4.6: Shellfish closure area 5 on lidar DEM bathymetry and true colour orthophoto on land.

4.2 Future

Climate change research is pointing towards changing precipitation patterns in the future. Richards and Daigle (2011) projected a variety of climate variables into the future based on an ensemble of several climate models. For the Pictou area, they predicted an annual increase in precipitation; most of that increase is predicted to occur in the winter and spring, with minimal increase in summer and fall precipitation. Extreme rainfalls that happened only once every 50 years in the last century could occur once every 10 years in this century (Nova Scotia Department of Environment, 2009), and precipitation is expected to vary more from season to season and from year to year. Natural Resources Canada (Government of Canada, 2010) predicts that Atlantic Canada will have hotter and drier summers, warmer winters, and more precipitation to fall as rain rather than snow. In studies of precipitation in Atlantic Canada during the last half of the 20th century, Bruce *et al.* (2000) report an increasing trend in the number of daily precipitation events >20 mm, and Mekis and Hogg (1999) note an increase in the fraction of total precipitation falling in heavy events. A study on global warming and precipitation in the United States reports that snowstorms and rainstorms have already become 30% more frequent and more severe than in 1948, producing 10% more precipitation, on average (Madsen and Willcox, 2012). Of particular note to Atlantic Canada is the reported 85% increase in frequency of extreme rainfall and snowfall events in New England, meaning that a storm that used to occur every 12 months now occurs on average every 6.5 months.

The effect of rainfall on water quality in Little Harbour is to flush land-based contaminants into the water, and heavier rainfall events are indicative of higher levels of contamination, whether the source is an overflowing or malfunctioning septic system, or a source upstream. In areas with denser development, such as Southern California, most beaches are closed for 72 hours following a rainfall event as a precautionary measure (County of San Diego, 2016; LA County Department of Public Health, 2016) but no such policy exists in NS. Although Melmerby beach is monitored for contamination, the back harbours and other areas used recreationally in Little Harbour are not tested for recreational safety. The water sampling done by EC is for shellfish safety, and although the data would be invaluable to recreational users of Little Harbour, it is not possible for the public to access the data in order to determine the safety of the water for swimming and boating. The climate change research pointing to increased extreme rainfall events suggests increased incidences of high fecal coliform levels in Little Harbour if nothing is done to eliminate the sources of contamination, and therefore a continued threat to the safety of recreational users.

In addition to concerns related to climate change, future water quality in Little Harbour could decrease if aging septic systems are not maintained. Care must be taken with future development to ensure proper septic systems, especially if the pattern of dense, shoreline hugging housing is to be continued.

4.3 Community Meeting

A public meeting was held in Little Harbour on September 1, 2016, to share the results of this project with the community. The meeting was hosted and organized by the Aquaculture Association of NS, and was well-attended. There was a great deal of interest in the research and in identifying and remediating sources of contamination in Little Harbour, and there was discussion of creating a Community Watershed Management Group in order to investigate the contamination sources, and local politicians promised to bring the issue to municipal and provincial levels of government.

The community is now aware of the contamination that is occurring in Little Harbour and motivated to make changes. If action is taken, the water quality can be improved, as has been observed in other locations. It has been shown that community watershed management and pollution reduction can improve water quality in shellfish growing areas (Pinho, 2000; Pinkerton, 1991). Pinkerton (1991) describes the efforts of community members in Puget Sound, Washington to work together, with the help of a coordinator, to address the issue of deteriorating water quality which was affecting aquaculture. The program was successful in reducing fecal coliform contamination and stressed the importance of voluntary compliance versus enforced. Government officials, shellfish harvesters, and local residents in a community on Vancouver Island, BC, used educational septic system kits for homeowners, and worked with farmers to develop and implement best practices to reduce agricultural runoff.

A report on pollution and coastal zone management in St. Margaret's Bay, NS, following a dramatic increase in shellfish closure areas between 2001 and 2003, documented land and water activities related to the increased fecal coliform in the bay (Barrington et al., 2003). The report suggested a community group take the lead on addressing the water quality issue. The St. Margaret's Bay Stewardship Association was formed in 2003 and has coastal development and environmental best practices as part of their mandate; in 2014 the group's Water Resources Committee conducted water quality studies of three sub-watersheds in the St. Margaret's Bay area. This group is an excellent example of a nearby community working together to protect and enhance their community (The St. Margaret's Bay Stewardship Association, 2016).

5 Conclusions

The analysis of 25 years of water quality data at Little Harbour revealed many instances of contamination levels exceeding both the shellfish threshold (43 MPN/100 ml) and the swimming threshold (200 MPN/100 ml) at several locations in Little Harbour. The frequency of contamination is increasing with time and the amount by which the threshold is exceeded is also increasing with time.

The water quality in Little Harbour was found to be consistently poor in some areas (Chapel Cove and Powells Cove) with high bacterial contamination occurring frequently in the past decade, while other areas were consistently clean (eastern Little Harbour, behind Melmerby Beach). The shellfish threshold of 43 MPN/100 ml was exceeded 94 times between 1990 and 2015, and the swimming threshold of 200 MPN/100 ml was exceeded 30 times. During the 2016 summer sampling program conducted by AGRG the shellfish threshold was exceeded four times and the swimming threshold was exceeded twice.

The GIS analysis provided insight on potential sources of contamination. The delineation of the Little Harbour watershed and basins, the examination of the land use within the basins, and the analysis of housing development and density revealed that sources of contamination to Little Harbour do not appear to be typical or of especially high source concentration, such as cattle farms or sewage treatment plans.

The hydrodynamic model showed that particles representing fecal coliform stayed near the shore, close to their modelled point of origin, and did not get flushed out of Little Harbour with the tide. At Black Point modelled particles were circulated from the western arm to the eastern arm, but still did not exit Little Harbour during the model simulation.

These results were presented at a community meeting to heighten awareness of the water quality problem occurring in Little Harbour. The safety threat posed to recreational users was highlighted, as well as the economic threat to aquaculture operators. Attendees were engaged in the presentation and receptive to forming a community group to address the sources of contamination in Little Harbour to restore it to its former, cleaner, state for all to enjoy.

6 Acknowledgements

The authors would like to thank Paul Budreski of AquaDelights Seafood Limited for being an active, motivated and engaged participant in this project; David MacArthur of Environment Canada for supplying the 25 years of fecal coliform data; Jessica Fiendel of NS Dept. of Fisheries and Aquaculture and her colleagues for deploying and recovering their current meters in Little Harbour; and Peter Sykes and all of the Aquaculture Association of Nova Scotia for connecting AGRG with Mr. Budreski, and for organizing and hosting the Community Meeting. The authors would also like to thank the Applied Geomatics Research Group for data collection, data processing, and administrative support.

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