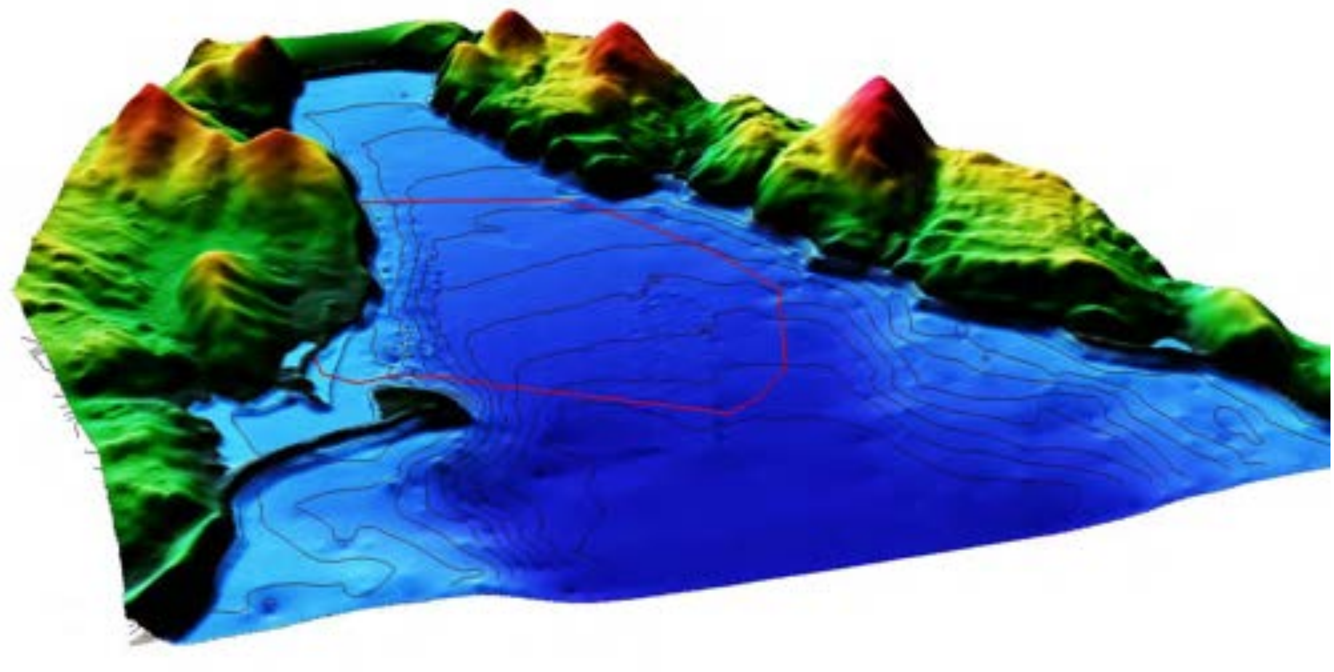

Physical Oceanographic Study of the Proposed Whale Sanctuary Site, Port Hilford, NS

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Executive summary

The first site in North America for the whale sanctuary was chosen along the Eastern Shore of Nova Scotia near Port Hilford. The Applied Geomatics Research Group (AGRG), Nova Scotia Community College were commissioned to collect physical oceanographic data for the site and develop a hydrodynamic model for the area to derive various metrics. Information on the benthic zone was acquired through a series of grab and photo sampling of the seabed. Substrate samples were acquired using an Ekman grab sampler and two GoPro cameras installed on a quadrat with a 50 cm X 50 cm base to capture the seabed conditions. Most of the study site appeared to be covered in sand with rocky reefs extending from the western shore seaward. A down-looking ADCP was towed along orthogonal transects through the study area at variable tidal states to get an understanding of the variability of current speeds throughout the study site. A hydrodynamic model was constructed using the DHI Mike-21 suite of tools-based bathymetry represented as a variable mesh with a high level of detail in the shallower water zone. Hydrodynamic model results accurately simulated current velocities, water levels and were used to derive a flushing rate for Indian Harbour. The model relied on accurate bathymetry which was obtained through a combination of a multibeam echo-sounding survey carried out by AGRG and supplemented by soundings from nautical charts. The model was driven with a set of boundary conditions consisting of the predicted tide from WebTide, although these data were found to be slightly out of phase with water level observations obtained from an ADCP deployed in the study area. As a result, the predicted tide was modified for the boundary conditions to adjust for this phase shift. The Sentinel-V ADCP was deployed on the seabed for 43 days and collected information on waves, water levels and currents in 50 cm bins throughout the water column. When the modelled water levels were compared to those observed with the ADCP, a mean difference of 0.00 m with a standard deviation of 3 cm was calculated as a residual. The current speeds agreed well between the model and ADCP observations, with very good agreement for the U (east-west) component and to a lesser degree the V (north-south) component. The modelled currents deviated from those observed by the ADCP significantly during Hurricane Teddy on Sept. 22-23, 2020. No significant storm surge was observed in the ADCP water level data, however the current speeds increased dramatically during this event. The ADCP also measured waves during the deployment with the most significant wave heights being measured during Hurricane Teddy reaching 3.2 m.

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1. Introduction

The Whale Sanctuary Project mission is to establish a seaside sanctuary for whales and dolphins from marine parks so they can be rehabilitated. It is the first organization focused exclusively on creating seaside sanctuaries in North America for orcas and beluga whales who are being retired from entertainment facilities or have been rescued from the ocean and need rehabilitation or permanent care (Whale Sanctuary Website, https://whalesanctuaryproject.org/). The goal of the proposed sanctuary is to offer captive orcas and beluga whales a natural environment that maximizes their opportunities for autonomy, exploration, play, rest, and socializing. The first site in North America was chosen along the Eastern Shore of Nova Scotia. The site is located near Port Hilford and Sherbrooke on the Eastern Shore. The Applied Geomatics Research Group (AGRG), Nova Scotia Community College were commissioned to collect physical oceanographic data for the site and develop a hydrodynamic model for the area to derive various metrics. AGRG worked with the Whale Sanctuary to supply moorings to attach pressure and temperature sensors, collect substrate samples and photographs, collect tidal current information through variable tidal cycles, deploy an Acoustic Doppler Current Profiler (ADCP) device on the seabed to collect waves, water level, and currents for a month, and conduct a multibeam bathymetric survey of the proposed site. The results of the multibeam survey were integrated with spot soundings to build a mesh for the seabed covering Indian Harbour and the surrounding bays and coastal areas. This mesh was used to develop a depth averaged hydrodynamic model to calculate current speeds and flushing time within the harbour. The ADCP was used to validate the hydrodynamic model and to capture wave events during the deployment such as Hurricane Teddy which made landfall very near the site.

2. Study Area Description

The study area for this project was located in Indian Harbour Bay, near the community of Port Hilford in Guysborough County, on the Eastern Shore of Nova Scotia (Figure 1). The tidal range for this area was approximately 1.4 m during a spring tide, and 1 m during a neap tide. The Ice charts from the Canadian Ice Service indicated that the bay was mostly ice-free during winter seasons. The study site was located between Sherbrooke and Port Bickerton communities approximately 250 km (2.5 hours) from Halifax, Nova Scotia. The main source of employment for these communities was determined to be fishing and the region was sparsely populated with no significant heavy industry. For this reason, it was determined that the area had a very clean and pollution free marine environment.

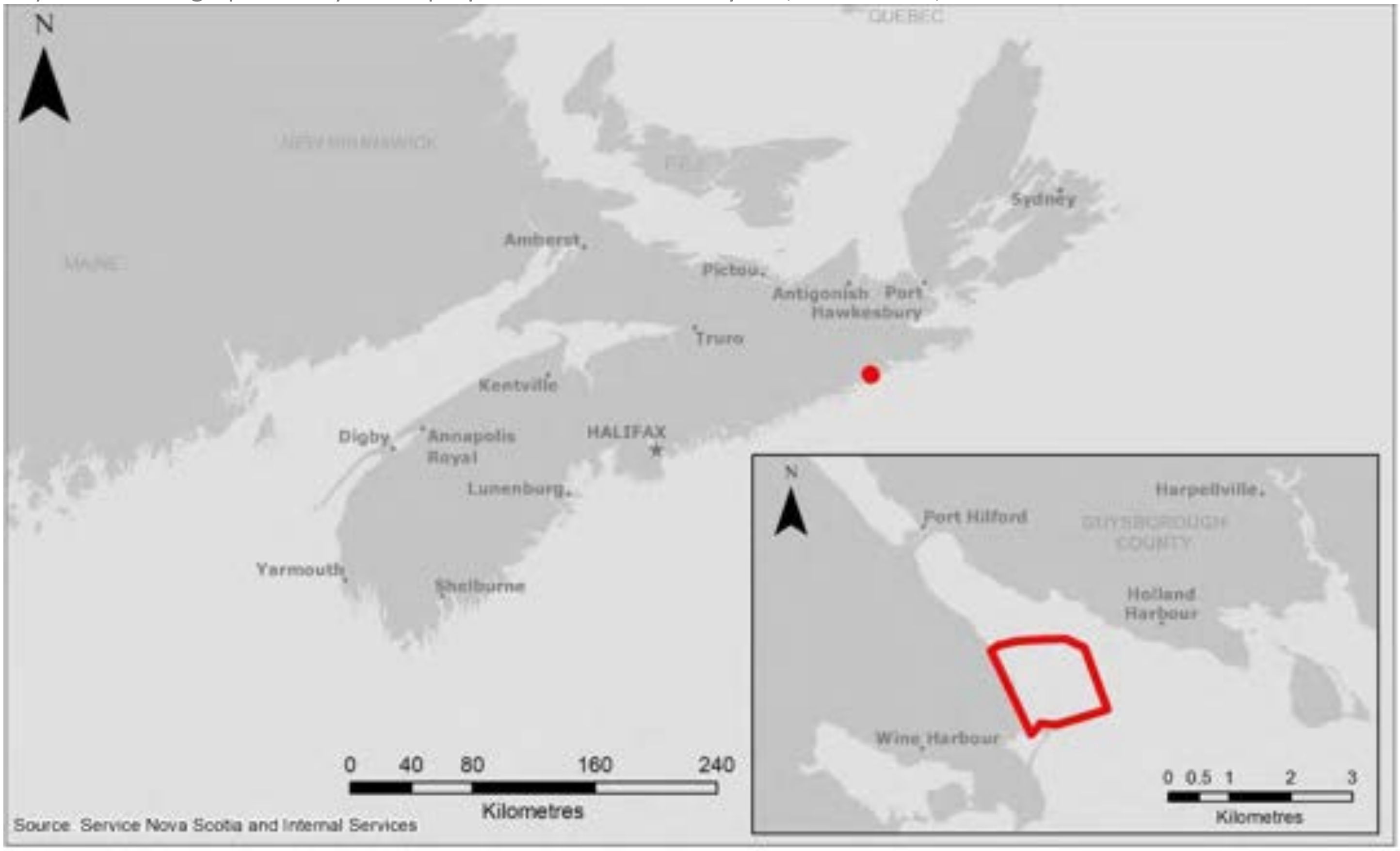


Figure 1 Map showing the location of the whale sanctuary site on Eastern Shore of Nova Scotia, with an inset of the study area in Indian Harbour, near Port Hilford, NS.

3. Field work

Over the late summer and fall of 2020 AGRG conducted field work in the Port Hilford study site. A 17' Boston Whaler Montauk was launched from a publicly accessible boat ramp at the nearby Coast Guard station in Port Bickerton, NS, located approximately 45 to 60 minutes from the study site. Weather conditions were monitored from the Environment Canada website prior to field activities. Travel time from the AGRG lab in Middleton to the study site was approximately 5 hours hence the first day of field work consisted mostly of mobilization. A summary of the field work conducted in Port Hilford is given in Table 1.

Date (mm/dd/yyyy)	Field work activities	Crew	Comments
09/02/2020	Acoustic Doppler Current Profiler (ADCP) deployment, River Ray ADCP transects, and ground truthing.	AGRG researchers, Dr. Babin from Whale Sanctuary Project	Weather conditions made it impossible to reach study site from Port Bickerton. ADCP deployment aborted.
09/09/2020	ADCP deployment, River Ray ADCP transects, and ground truthing.	AGRG researchers, Dr. Babin from Whale Sanctuary Project	Successful deployment of ADCP and River Ray surveys and substrate sampling
10/03/2020	Global Positioning System (GPS) points collection near shore for multibeam validation.	AGRG researchers, Dr. Babin from Whale Sanctuary Project	Reson T20 multibeam and Novatel SPAN- CPT setup. Base station and collected some GPS points
10/04/2020	Multibeam survey	AGRG researchers	Collected data for few survey lines near shore. Trouble shooting and equipment issues.
10/05/2020	Continue Multibeam Survey	AGRG researchers	Trouble shooting and equipment issues. Mission aborted as a result of faulty equipment.
10/22/2020	New Multibeam survey and ADCP retrieval	AGRG researchers, Dr. Babin from Whale Sanctuary Project	Successful retrieval of ADCP. R2Sonic setup and completion of 20 survey lines with multibeam
10/23/2020	Continue Multibeam Survey	AGRG researchers	Survey the rest of lines to complete the multibeam survey and demobilization

Table 1 Summary of the field work conducted in Port Hilford.

4. Methods

4.1 River Ray Down-Looking ADCP

A Teledyne RDI River Ray was used to measure current flow and direction in several sets of transects in the study area. The River Ray consists of three components. The first is the pontoon boat (Figure 2a), which was rigged with a line to be towed with the work boat. The hull of the pontoon boat contained a 12V battery to power the River Ray and Global Navigation Satellite System (GNSS) unit. The core of the River Ray was a 600 kHz Acoustic Doppler Current Profiler (ADCP) (Figure 2b), which has 4 directional beams for current velocity and direction measurements, a vertical beam for depth measurements and bottom tracking, a temperature sensor, a compass, and sensors to measure roll, pitch, and yaw during operation. The compass heading was adjusted for the magnetic declination at the study site. A Hemisphere

A101 GNSS antenna (Figure 2c) was attached to the top of the transducer that was used to provide position data in World Geodetic System (WGS) 84 format for each recorded ensemble in a transect.

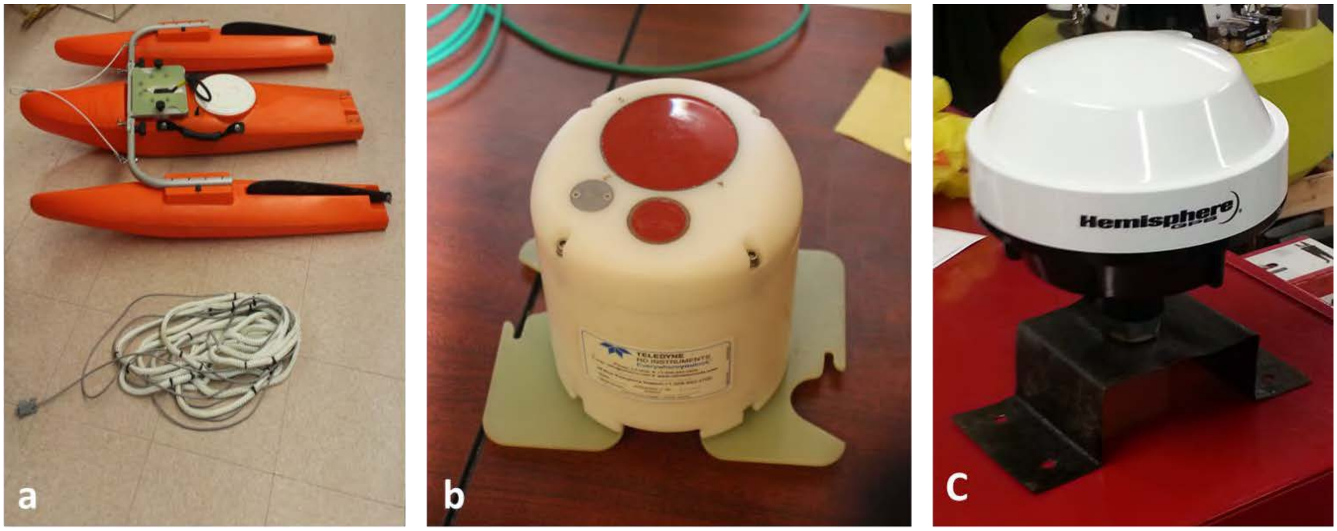


Figure 2 River Ray down-looking ADCP. A- River Ray pontoon body. B- 600 kHz ADCP. C- Hemisphere A101 GNSS Antenna.

4.1.1 River Ray Set up

Data for the River Ray was collected and processed using the WinRiver II v2.18 application. This software ran on a laptop which was connected to the River Ray ADCP via Bluetooth. Before the start of the survey, the Bluetooth was turned on and at the wharf in Port Bickerton a measurement (.mmt) file was created to store the magnetic compass calibration and setting related to GPS unit, and the start position of each transect. Magnetic compass calibration was generally performed at Mean Sea Level (MSL), this process involved rotating the pontoon 360°. A magnetic variation of 17.2° W as calculated using the Government of Canada Magnetic Declination Calculator and added to the file to reference true north.

4.1.2 Data collection

A total of eight transects were completed using the River Ray on September 9th, 2020 on rising, high, falling, and mid tides (Figure 3). The transects were plotted with the predicted tide generated by the XTide program (David Flater, Biological Sciences Department, University of South Carolina) that was extracted at the Port Bickerton station from Tbone tide website (Figure 3). The first transect of each pair (transect 000 and transect 001) began in deep water off the Barachois Island and ended in shallow water near an unnamed rocky feature on the mainland and took about five minutes to complete. The second transect (transect 001) of the pair spanned the width of the harbour from the end point of the previous transect toward Triford Head on the eastern side of Indian Harbour and took 15 min to complete (Table 2, Figure 4).

Transect #	Start Time (UTC)	End Time (UTC)	Tidal State
000	14:10	14:15	Rising
001	14:18	14:34	
002	15:55	16:00	High
003	16:01	16:16	
004	17:30	17:35	Falling
005	17:36	17:49	
006	19:13	19:17	Mid-tide
007	19:19	19:34	

Table 2 River Ray transects start and end time along with the tidal state of each transect collected on September 9th, 2020.

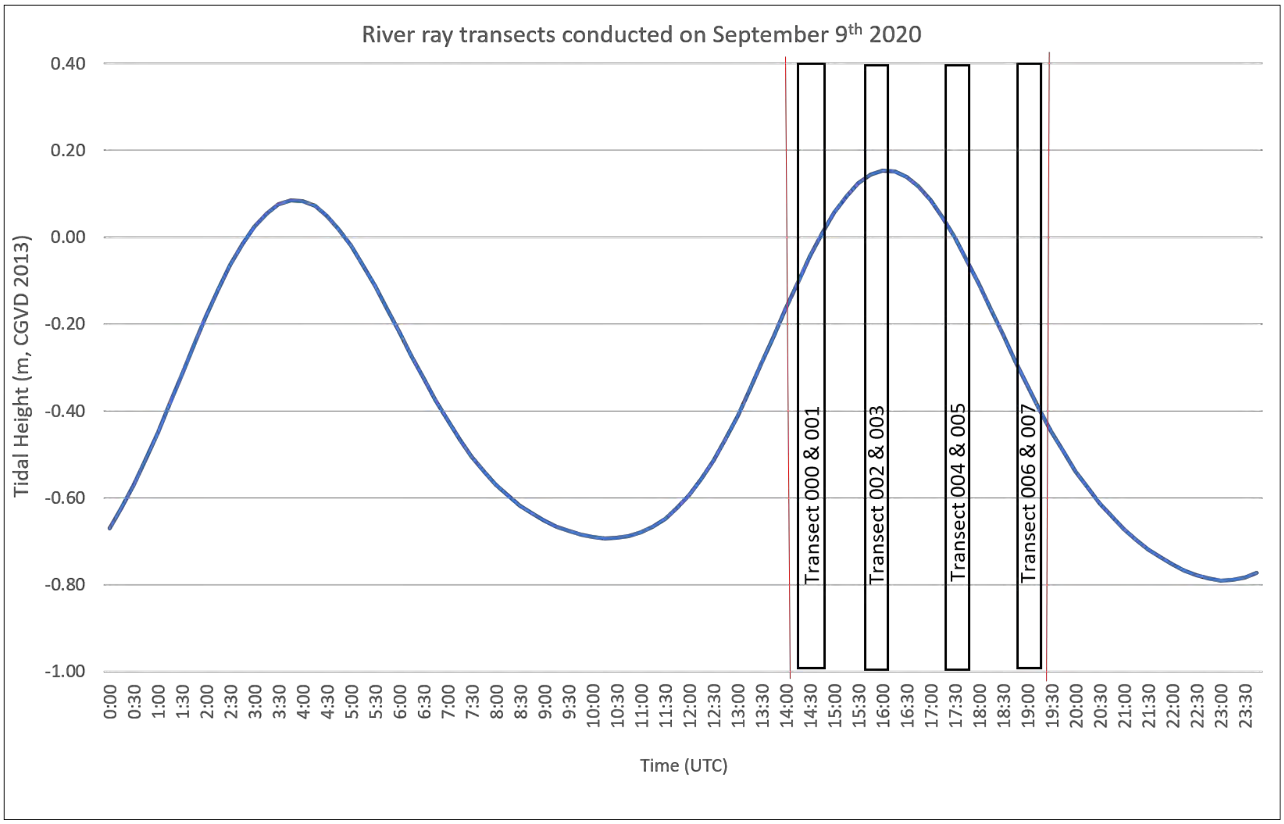


Figure 3 Tidal level in Port Hilford, NS during the River Ray transects.

The River Ray was towed beside the Boston Whaler attached to a boat hook with a safety line (Figure 4). The transect path and direction along with the location of the ADCP and the study area are shown in Figure 4.

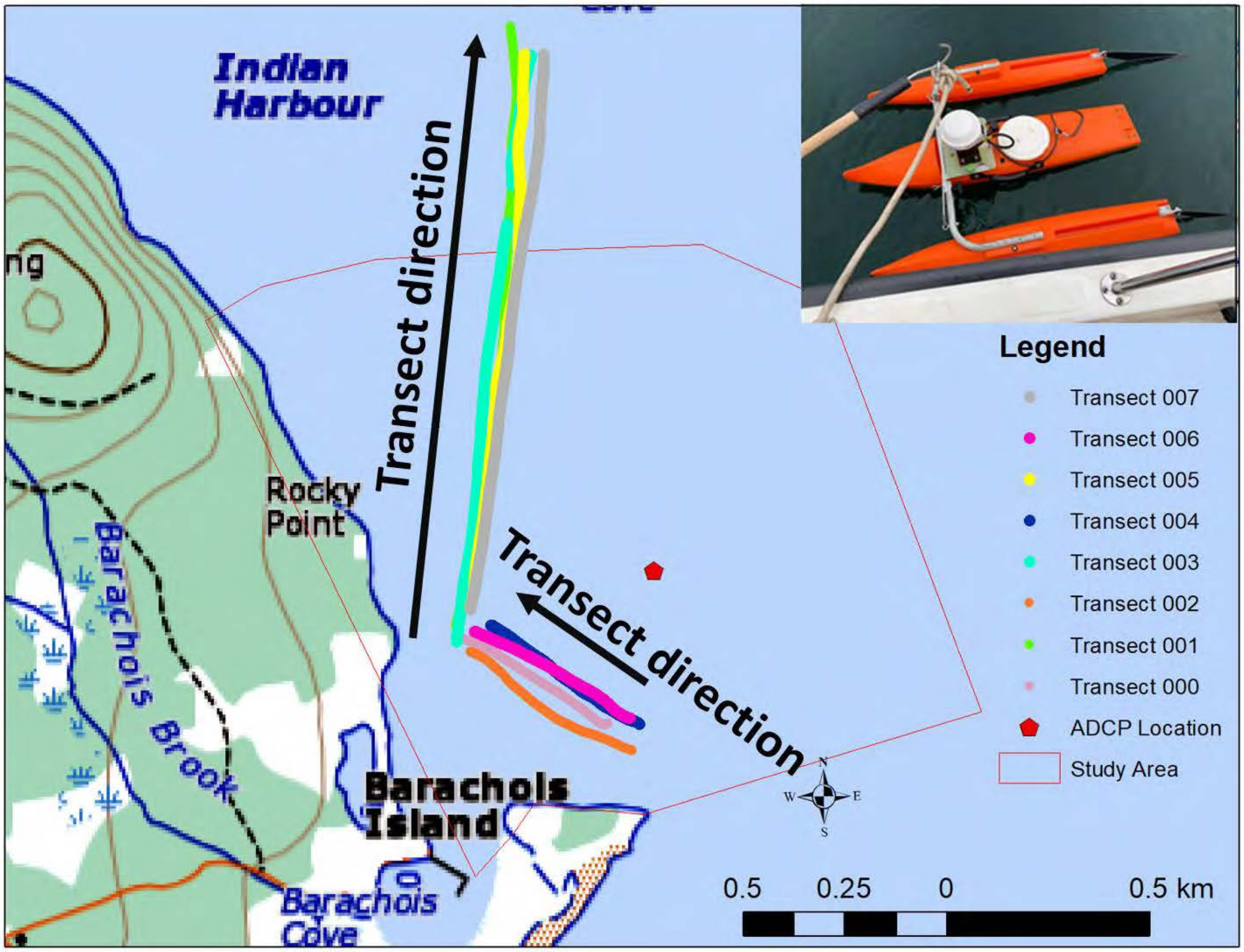


Figure 4 River Ray transects and direction overlaid on a National Topographic System map, along with study area boundary (thin red line) and ADCP location (red pentagon). Inset showing River Ray being towed along side the boat to collect data.

4.1.3 Data processing

Data collected by the River Ray down-looking ADCP was stored on a Bluetooth-connected laptop as a <measurement name>.mmt file, with each transect as a separate .pd0 file with the naming convention of <measurement name>_<transect_number>.pd0. The WinRiverII software automatically numbered transect files from 000. The ADCP recorded binned flow direction and velocity data. Bin size was automatically determined by the software based on the depth measurements provided by the ADCP transducers and a dedicated vertical beam. These transects were replayed in the software to extract information such as the water flow data in tabular and graphic representation. A typical screenshot of the WinRiver II dashboard during collection and processing is shown in Figure 5. A combination of vertical beam depth, and a composite depth value returned by the four ADCP beams (“Bottom Track” or BT) were used to calculate the depth from the River Ray ADCP. The gaps in measurements can be seen in the vertical profile graph in the lower left/bottom section as an empty area between the stored values in the coloured profile, and the measured bottom shown with a heavy black line (Figure 5).

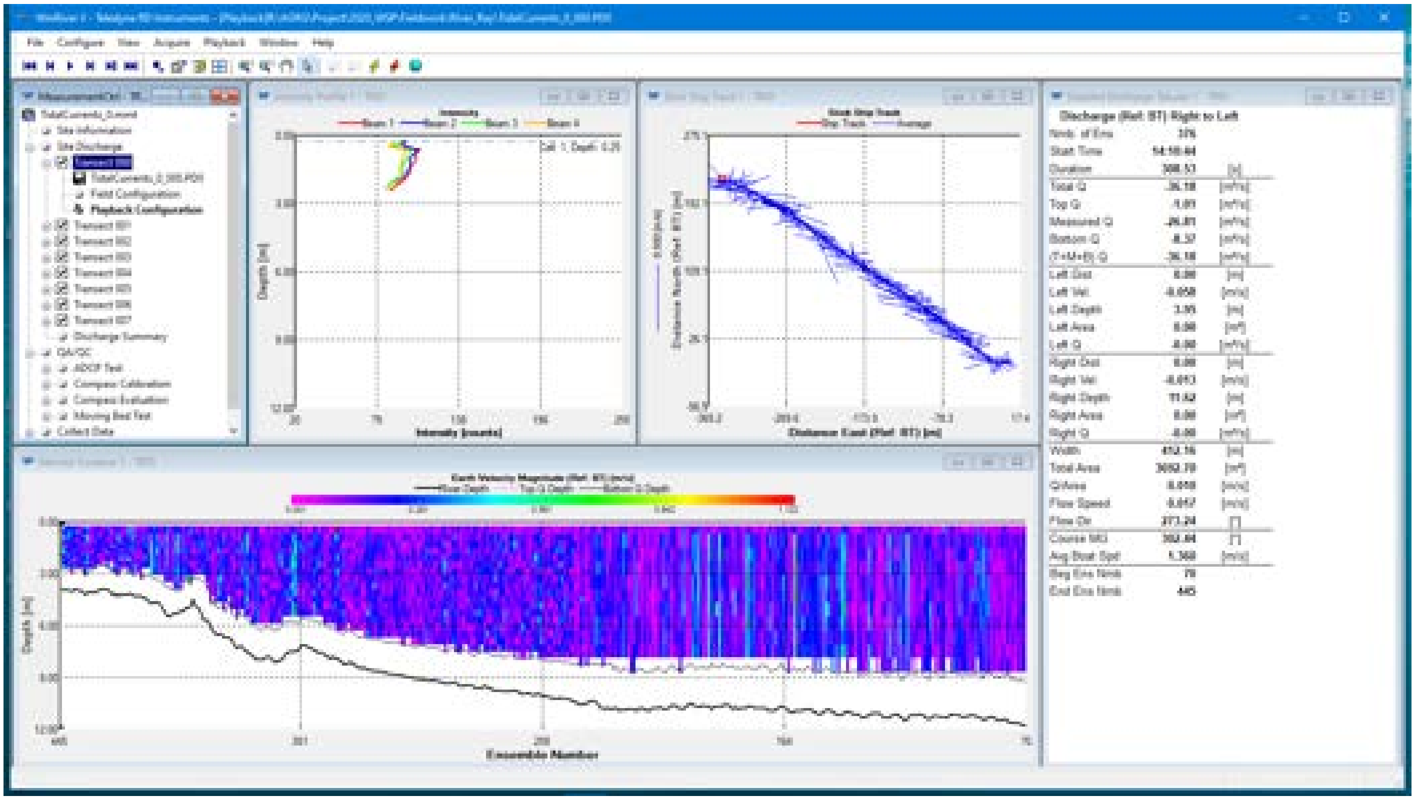


Figure 5 WinRiverII main screen showing each transect in the Measurement Ctrl on the left side, intensity of each beam and the ship track, binned velocity in the lower central region, and discharge statistics for the selected transect on the right side of the window.

The values for magnetic declination and start/stop bank designation were selected at the time the transect was stored under “Field Configuration” in the Measurement Control window. These values could be changed under “Playback Configuration” if required. Note that changing the start bank designation would result in the sign of discharge totals (Q) changing from positive to negative, or vice versa, but the Q magnitude would remain the same. Changing the start bank designation would not change the values of flow speed and direction as shown in the Detailed Discharge Tabular window. A positive discharge (Q) value indicated net flow of water down stream, while negative flow indicated movement of water upriver during a high tide. In this case, the starting point of the even numbered transects (000, 002, 004, 006) was designated as the right bank, and the beginning of the odd numbered transects (001, 003, 005, 007) as the left bank (Figure 6). This was used as a standard so each group of four transects could be compared.

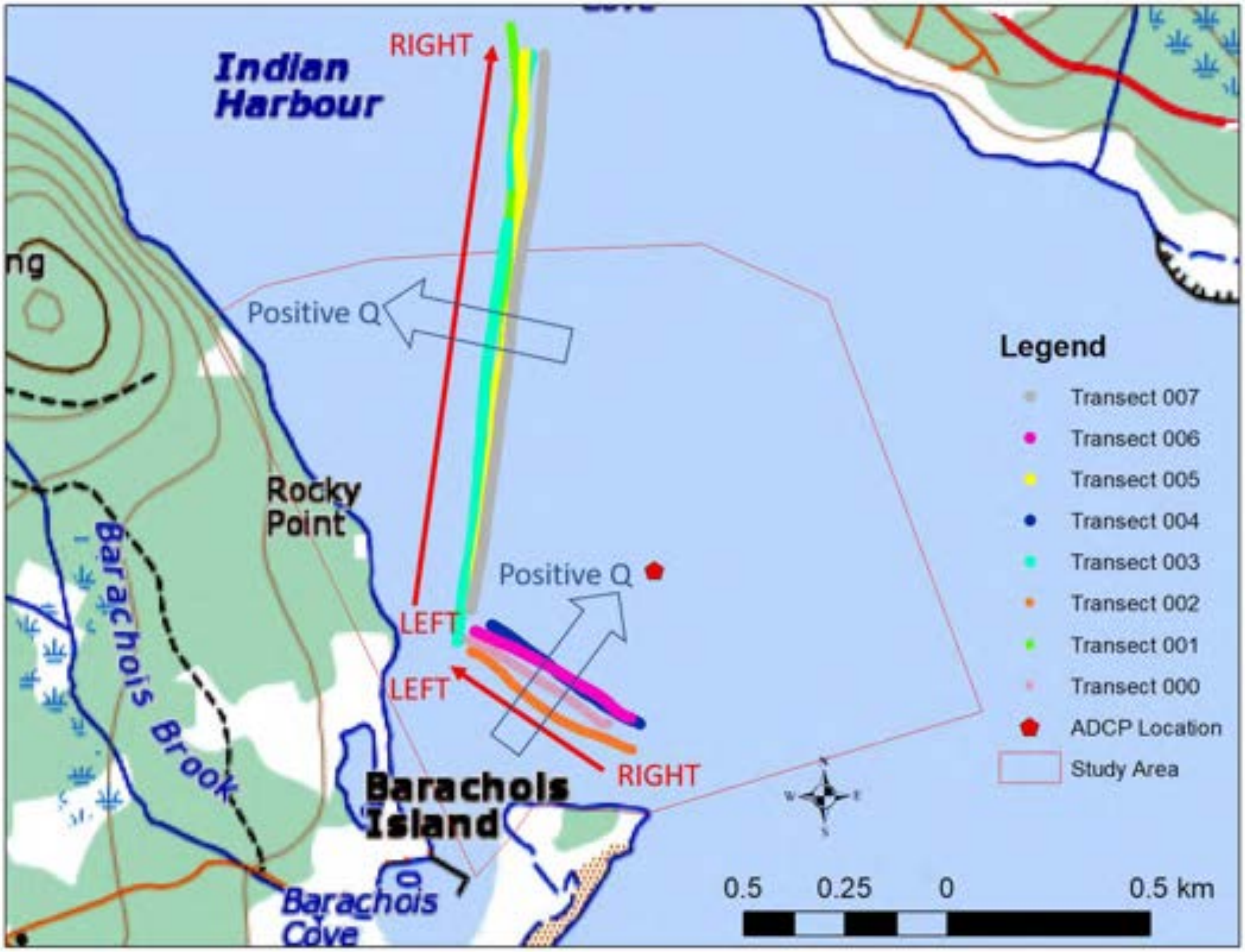


Figure 6 Diagram showing the defined RIGHT and LEGT bank setting for the Rive Ray transects which effect the sign and direction of flow Q.

There were 603 data points stored for each ensemble in a transect. Position information from the Hemisphere GPS antenna was stored as Global Positioning System Fix Data ($GPGGA) National Marine Electronics Association (NMEA 0183) sentences. For every transect GGA latitude, GGA longitude from the Hemisphere GPS, depth, river direction and mean river velocity were extracted from the data points measured by the ADCP.

The total discharge for each of the transects is summarized in Table 3. Note the sign of the discharge is related to the transect left and right bank setting and tidal state (Figure 3, Figure 6).

Transect #	Start Time (UTC)	End Time (UTC)	Tidal State	Total Discharge (m^3/sec)	Net Flow Direction (°)	Transect Length (m)
000	1410	1415	Rising, above MSL	-36.18	273	412.6
001	1418	1434		118.08	0	1474.44
002	1555	1600	High, slack water	-6.72	100	465.08
003	1601	1616		-10.99	342	1462.63
004	1730	1735	Falling, above MSL	0.64	63	435.93
005	1736	1749		-46.97	37	1355.62
006	1913	1917	Mid-tide, approx. MSL	-35.29	54	437.66
007	1919	1934		-57.21	46	1372.04

Table 3 Summary of River Ray ADCP transects discharge and flow direction.

4.2 Ground Truth Data Collection

Over the duration of the project, several ground truthing data were collected to understand the water quality and seabed substrate type in the study area. GPS points of the seabed were also collected in the near shore to validate the multibeam data. These samples were collected by deploying equipment from the Boston Whaler.

4.2.1 Grab Samples and Quadrat Drops

Sample locations were provided by Dr. Amanda Babin, Whale sanctuary, to obtain substrate samples and seabed photos in the study area. Camera drops were executed at each sample location using a quadrat with two mounted GoPro cameras. The GoPro cameras were set up to take images every 5 seconds. One camera was mounted at the top of the quadrat pointed downward to the seabed, while a second camera was mounted on one of the legs of the quadrat pointed across to reference marks on the opposite leg (Figure 7 A). The bottom of the quadrat was 50 cm X 50 cm and the white markings up the legs were graduated at 5 cm increments. Bottom samples were taken using the Ekman grab sampler attached to a rope (Figure 7 B). The collected substrate samples were stored in bags.

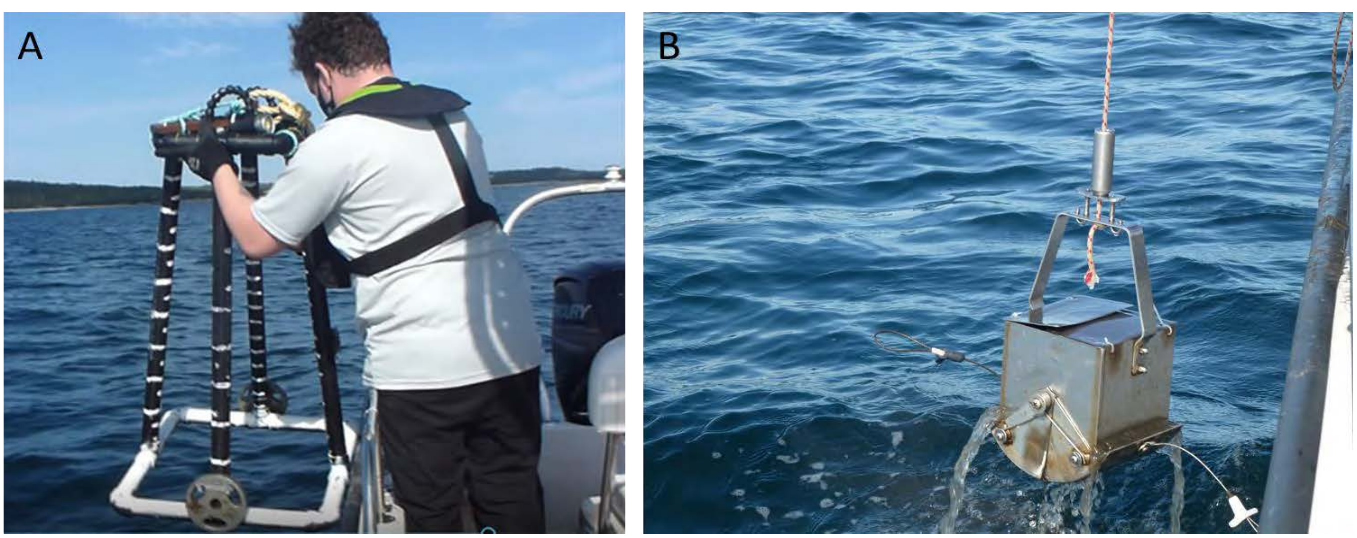
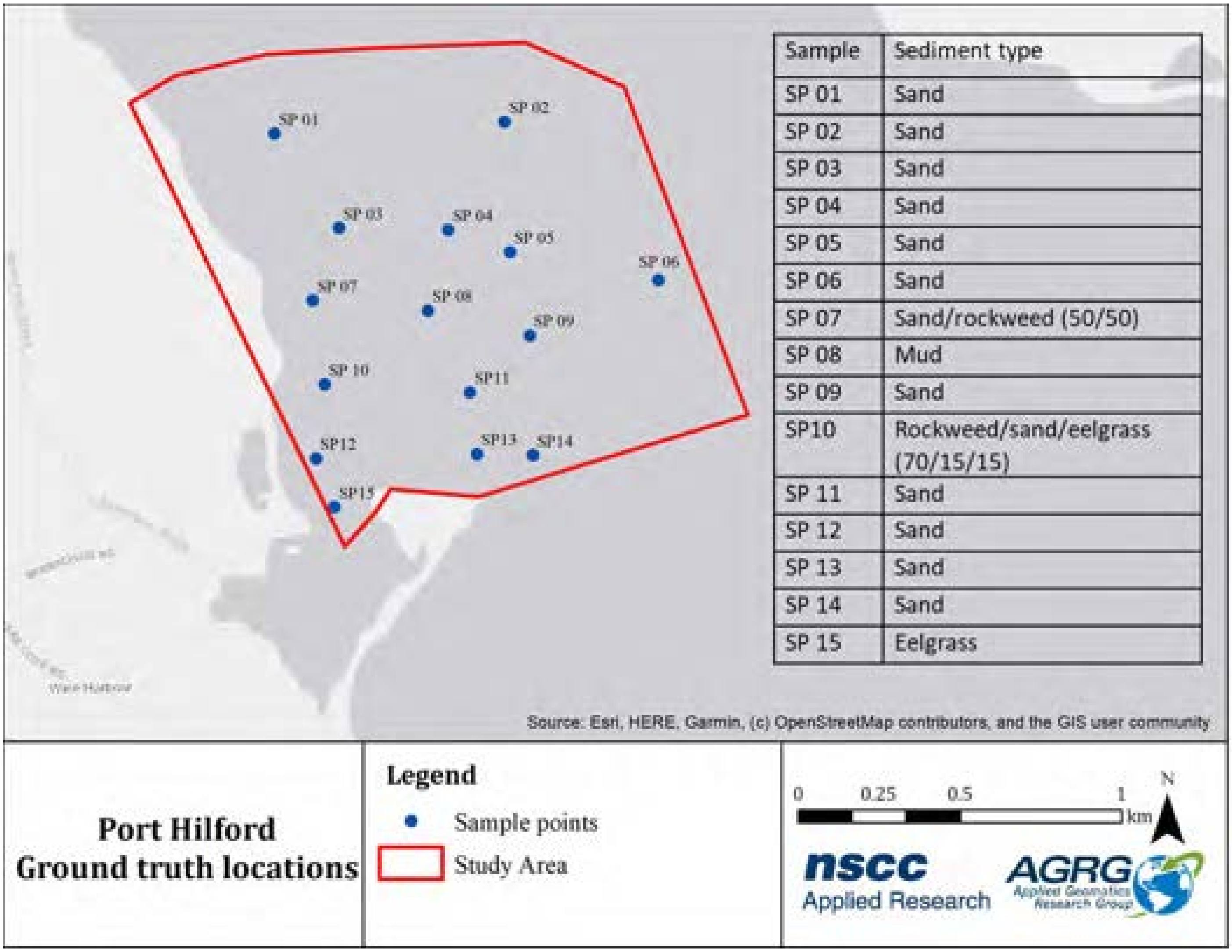


Figure 7 AGRG researcher deploying a quadrat with two GoPro cameras on left side (A) and an Ekman grab sampler on the right (B).

Sampled sediment type, along with the location for each sample point, is as shown in Figure 8. Sand was the most dominant sediment type in the study area. Thick eelgrass was detected areas near the Barachois Cove (SP 15), and fucus seaweed along the coast (SP 07 and 10) (Figure 8).



Sample	Sediment type
SP 01	Sand
SP 02	Sand
SP 03	Sand
SP 04	Sand
SP 05	Sand
SP 06	Sand
SP 07	Sand/rockweed (50/50)
SP 08	Mud
SP 09	Sand
SP10	Rockweed/sand/eelgrass (70/15/15)
SP 11	Sand
SP 12	Sand
SP 13	Sand
SP 14	Sand
SP 15	Eelgrass

Figure 8 Location of grab and photo samples in Port Hilford, NS along with a table showing the type of sediment found at each sample location.

Photo and grab samples showed consistent results. Example photos obtained from the down-looking and side cameras in shallow and deep water are presented Figure 9 and Figure 10. In deep water (>10 m) the light penetration was sufficient such that no additional lighting was required while taking photos.

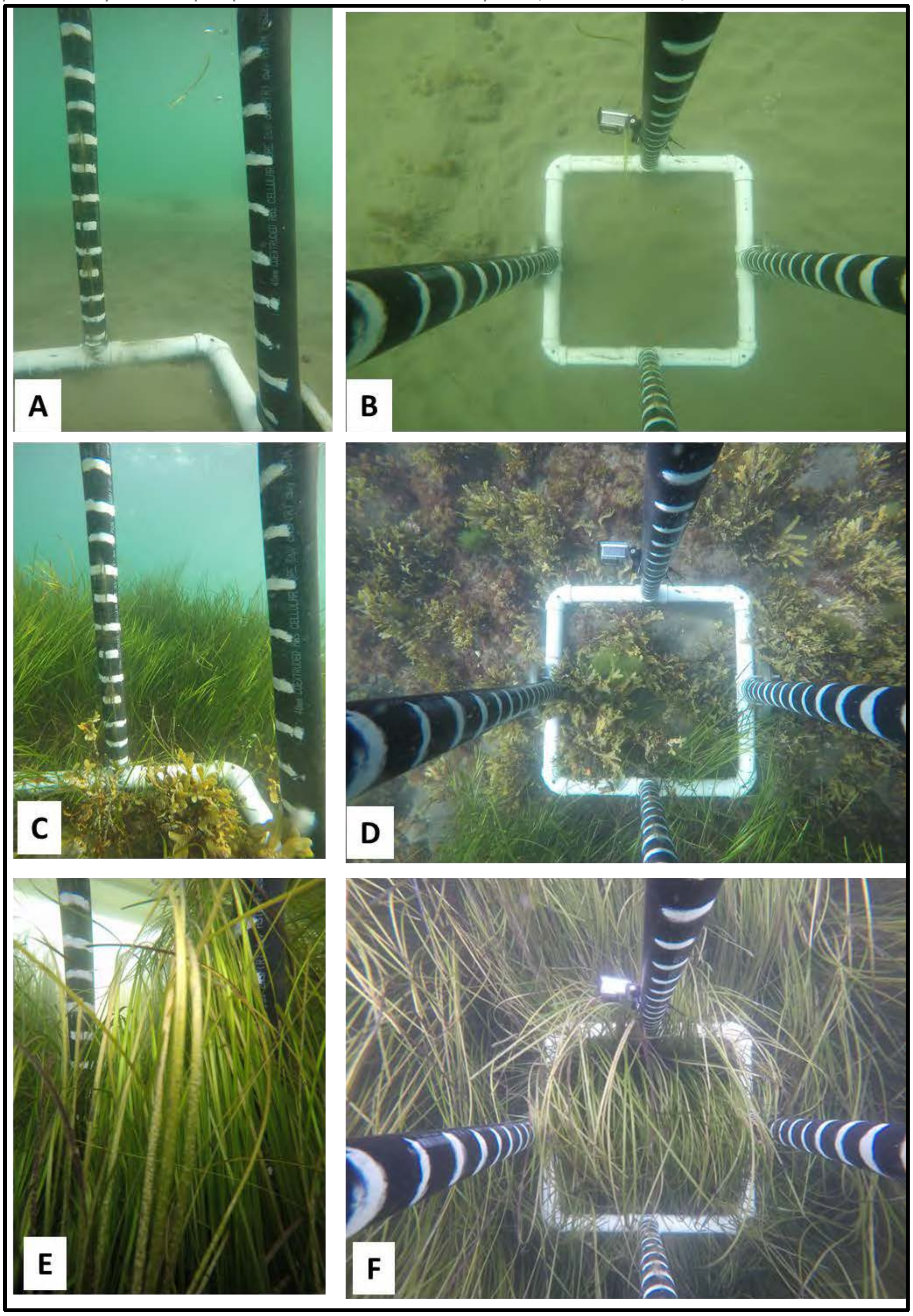


Figure 9 Example of photos taken in shallow water. On the left side of the image is the photo taken by a camera mounted on the quadrat leg and right side is the photo captured by the camera facing down. A and B photos showing the sediment type as sand at the location of sample point 12. C and D photos showing fucus and eelgrass at the location of sample point 10. D and E photos showing thick eelgrass at location of sample point 15.

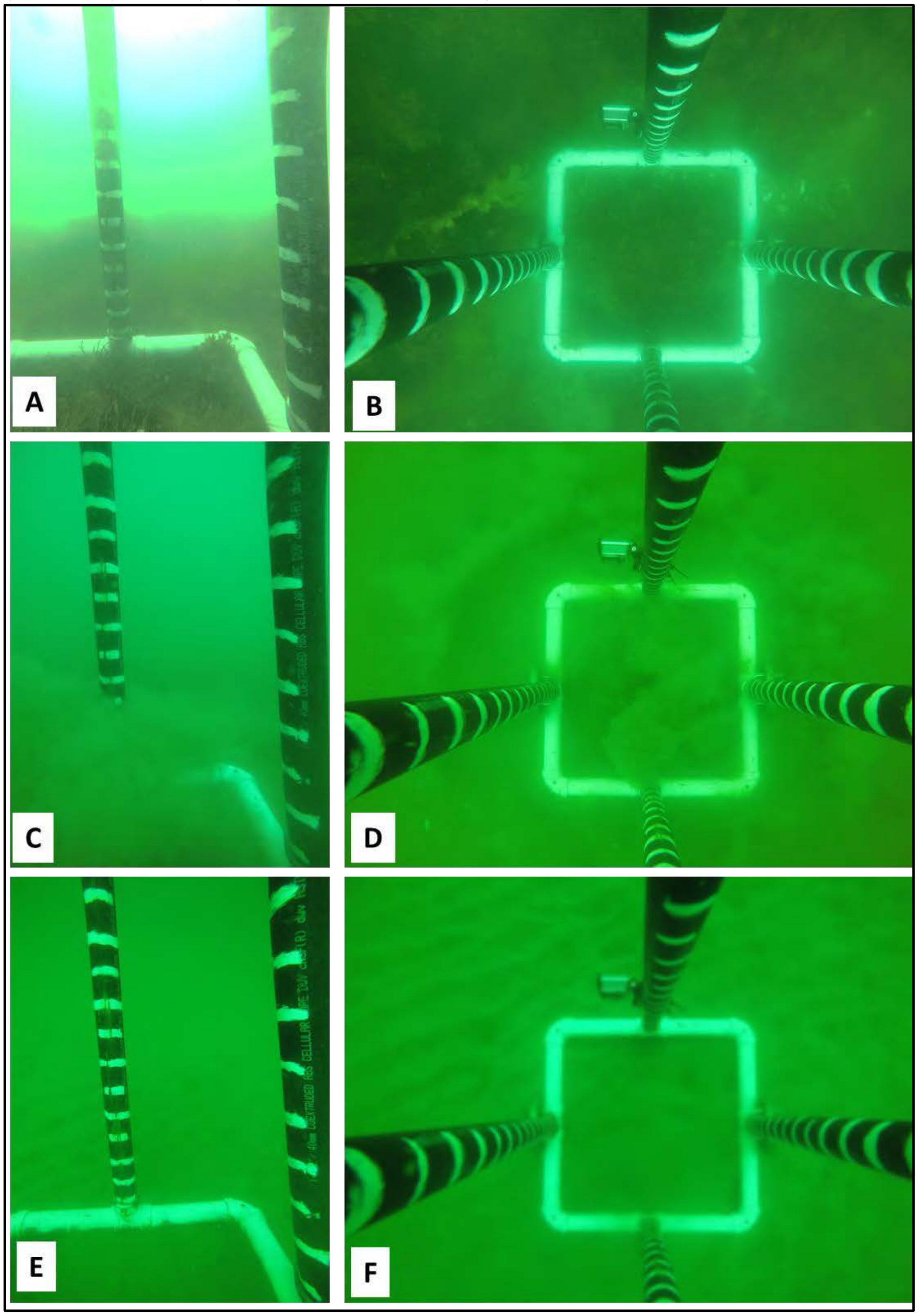


Figure 10 Example of photos taken in deep water. On the left side of the image is the photo taken by a camera mounted on the quadrat leg and right side is the photo captured by the camera looking down. A and B photos showing the sediment type as fucus at the location of sample point 07. C and D photos showing the sediment types as sand at the location of sample point 03. D and E photos showing the sediment type sand at the location of sample point 09.

4.3 **GPS validation points**

A total of 16 survey grade GPS points were collected on October 3rd, 2020. These points were collected along the coastline in shallow waters during high tide using a GPS receiver threaded on an extendable painter's pole (Figure 11). A base station was setup at a High Precision Network monument (station number 210968) on Sonora road to broadcast Real Time Kinematic (RTK) corrections (accuracy of less than 2cm in horizontal and 5cm in vertical for positions) for the GPS points (Figure 12). These corrections were received by the radio antenna that was attached to the GPS receiver which was threaded on the painter's pole.

Figure 11 Global Positioning System (GPS) points for multibeam validation collected on Oct 3rd, 2020 in Port Hilford, NS.

Figure 12 Base station set up on High Precision Network (HPN) station 210968 on Sonora road, to broadcast corrections using Pacific Crest ADL radio.

4.4 **Sentinel-V Acoustic Doppler Current Profiler (ADCP)**

The Sentinel-V ADCP was mounted in a frame and placed on the seabed facing up to measure water current velocities, within the water column, water depth and waves. The Teledyne Sentinel V20 ADCP deployed in Port Hilford consisted of 5 transducers and a pressure and temperature sensor.

The system was set up to collect current velocity data in 3 bursts lasting 3 minutes every hour with 15 minutes between the start of each burst, and the first burst of each ensemble occurred 20 minutes past the hour as shown in Table 4 and Figure 13. The currents were measured at the 20 min, 35 min and 50 min time periods per hour. The waves profile collected one burst for 17.5 minutes on the hour every hour. Prior to the ADCP deployment a compass calibration was performed on the Port Bickerton wharf.

Figure 13 Setup of the Sentinel-V ADCP for waves and current measurement.

Waves Setup (Profile 1)	
Ensemble interval	3600 sec (1 hr)
Ping interval	0.5 sec
Number of pings per ensemble	2100
Burst count	1
Sampling duration	17.5 minutes
Cell size	0.5 m
Currents Setup (Profile 2)	
Ensemble interval	900 sec (15 min)
Ping interval	1 sec
Number of pings per ensemble	180
Sampling duration	3 minutes
Cell size	0.5 m
Depth of deployment	14.35 m
Sequential offset	1200 sec
Burst interval	900 sec
Burst count	3

Table 4 Wave and Currents Setup for the Sentinel V20 ADCP for the Port Hilford deployment.

4.4.1 Deployment

The Sentinel V20 was deployed in Indian Harbour near Port Hilford on September 9th, 2020 from a Vessel of Opportunity called the "True Sprit". The unit sat on the bottom of the harbour at an average depth of approximately 13m, recording data over the course of 43 days, from 1500 UTC on the day it was deployed until 1645 UTC on the day it was recovered. The geographic location of the deployment site can be seen in Figure 14 .

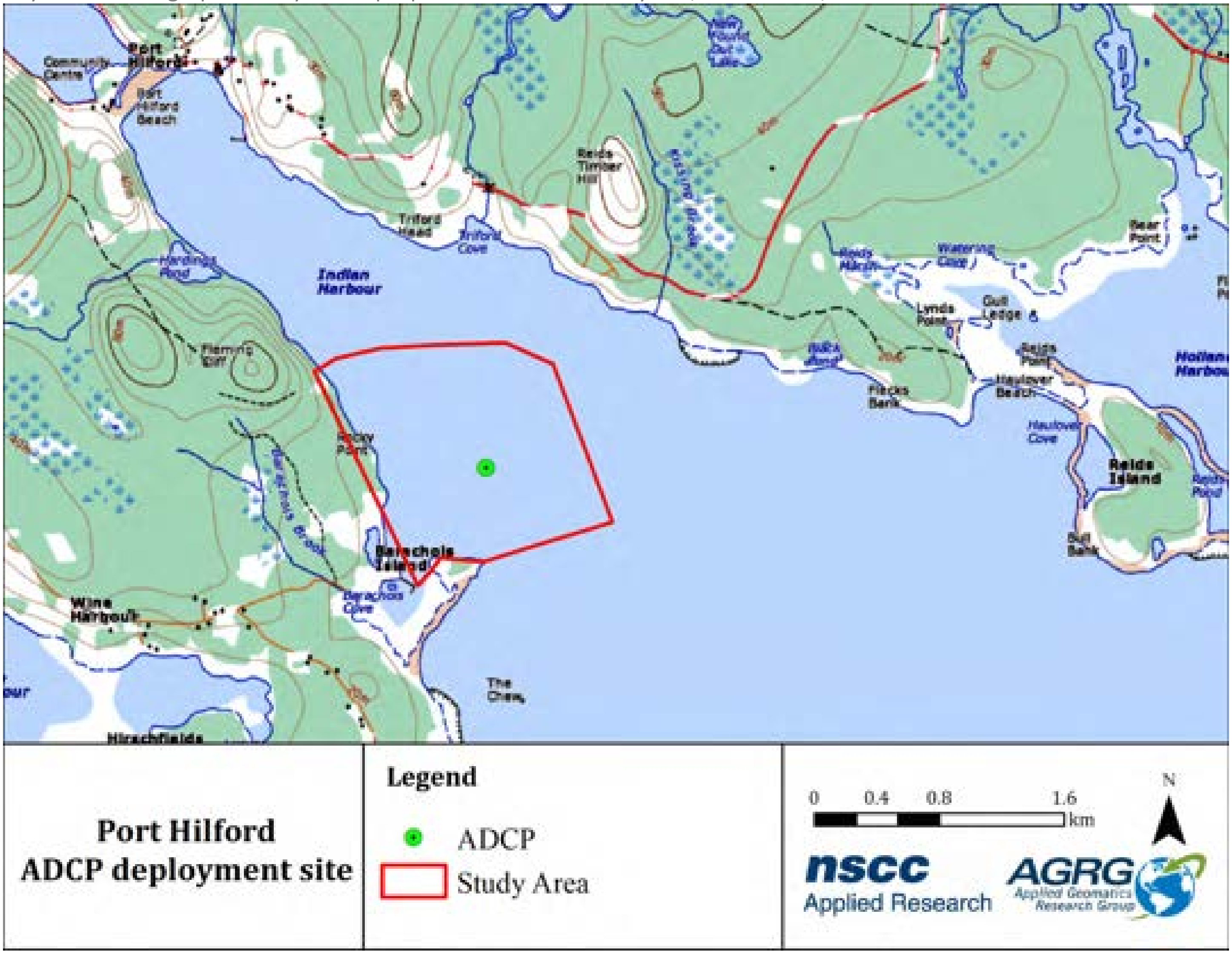


Figure 14 ADCP deployment location in Indian Harbour, Port Hilford, NS

The ADCP was mounted in a metal frame with additional weights added to the frame which was connected to 70 lb. pyramid anchor with a line to a marker buoy to assist in recovering the instrument at the end of its deployment (Figure 15). Two zinc anodes were attached to the frame to reduce galvanic corrosion.

Data were retrieved at end of the deployment time to be processed in the Velocity software, developed by Teledyne, the manufacturers of the Sentinel V series of ADCP.

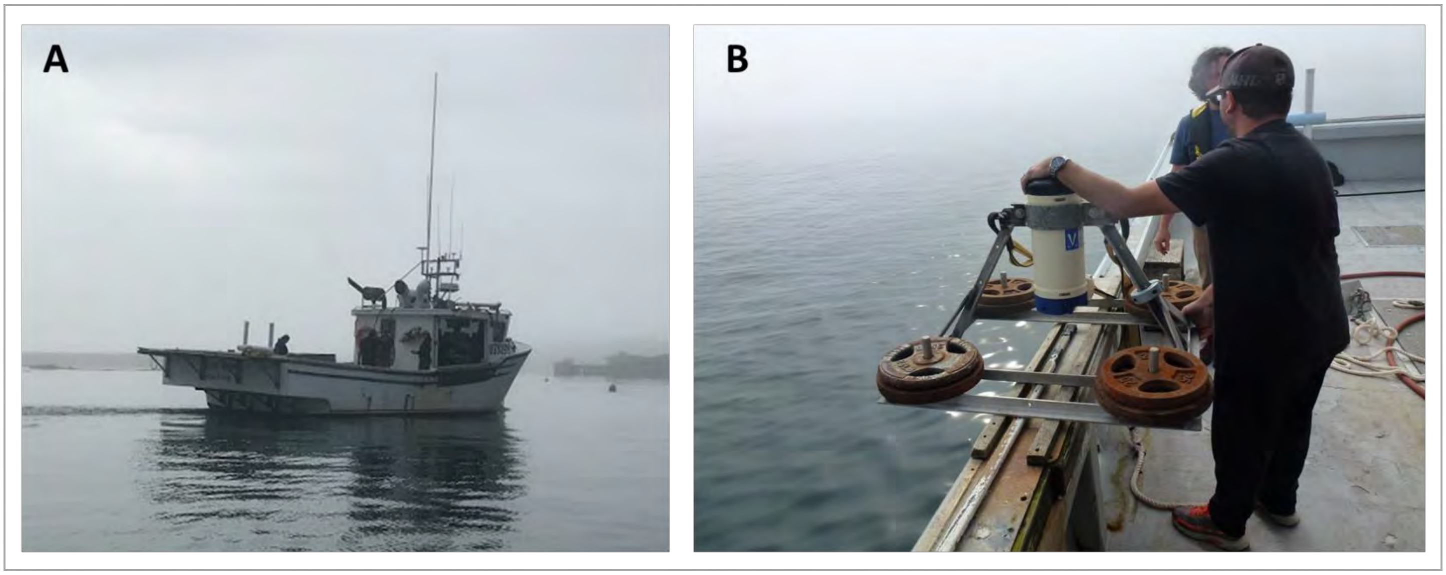


Figure 15 Deployment of the ADCP. A - fishing vessel "Ture Spirit" used to deployment the ADCP using a crane system. B - Teledyne Sentinel V20 ADCP in a metal frame with weights attached. Crew of the fishing vessel along with AGRG Research Specialist can also be seen in the picture.

The ADCP was retrieved on Oct 22nd, 2020 after collecting currents and waves data for a span of 43 days. The system was retrieved using a winch system on the vessel of opportunity called the “Atlantic Crabber 2006” (Figure 16).

Figure 16 Retrieval of the ADCP from Indian Harbour. A- Fishing vessel Atlantic Crabber. B- ADCP being retrieved from the seabed along with the weights.

4.4.2 ADCP Data Processing

Currents

Processing for currents was done in Teledyne's Velocity software. The most basic processing settings that need to be taken into consideration before conducting any kind of analysis are displayed in Figure 17.

Figure 17 Sample "Basic" post-processing setting window for current processing.

Much of the post-processing involved cleaning up the data, reducing interference, and ensuring that the information extracted was as accurate as possible. An averaging interval of 1 hour for the currents data was used as it best filled out the data without losing too much detail to be useful. The next step of currents processing was to remove side lobe interference, which removed the interference caused by currents near the measurement cells. Range to boundary typically remained set to Range (pressure), meaning the pressure transducer on the unit was used to determine the range to the water column boundary. Next, the magnetic variation offset was entered as -17.20. This step was necessary to correct the data to get the most correct representations of the vector components of the measured currents. As most compasses do, the one on board the Sentinel V20 detected its orientation by finding magnetic north. True north and magnetic north vary by latitude, longitude, and over time. Using the Magnetic declination calculator web tool found on Natural Resources Canada's website, we determined this offset to input into Velocity.

Waves

Data were processed using Velocity 1.7.22 WavesMon 4.05 (a package within the Velocity software). A profile averaging interval was set to 15 minutes to match the average current profile. As the ADCP sat in a frame above the seabed, the measurement in metres from the bottom to the sensor (60 cm) was added in the initial stages of the processing. The measurement was useful for applying the correct gain in the lower bins. In the more advanced options, a magnetic variation of -17.20 degrees was applied to calculate the direction information with respect to true north as shown in Figure 18. As the waves data were set up to be collected every hour for 17.5 minutes on the hour, the samples/bursts processed along with the frequency were adjusted to process all the data. Only the top three cells, which were 1.5 m from the water surface, were considered for the height of the waves and direction spectrum.

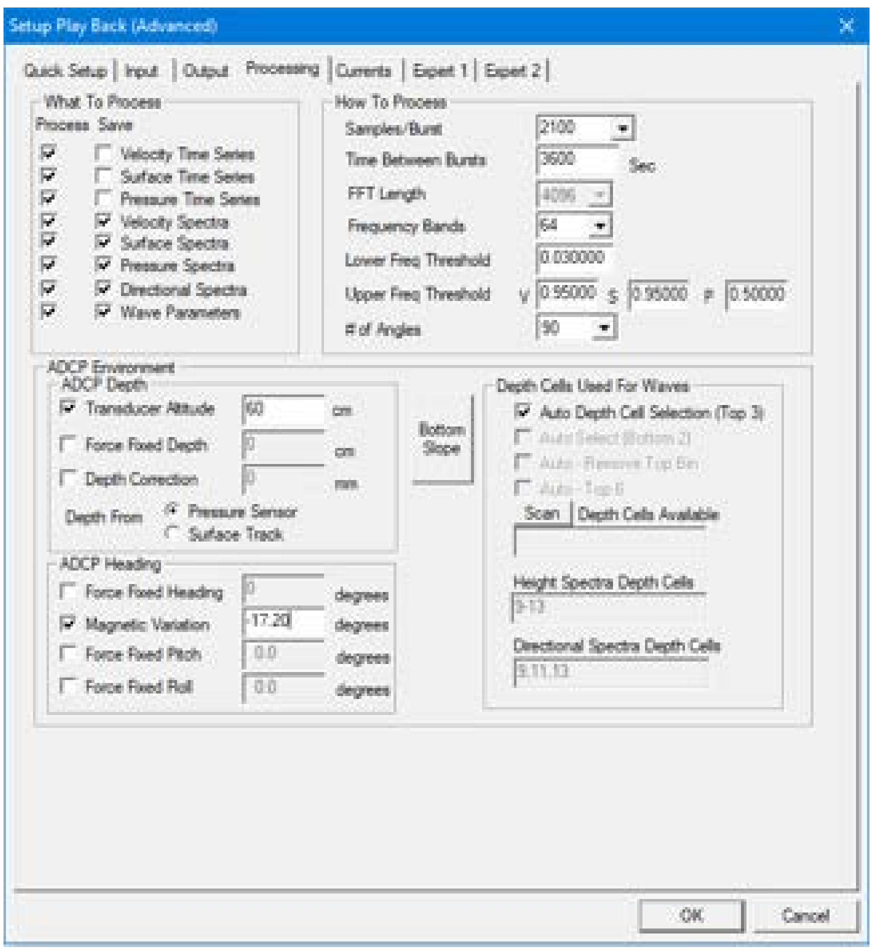


Figure 18 Parameters set up in the processing tab of WavesMon.

In the more advanced settings for the WavesMon package, expert 1 and 2 tabs were set such that data were processed with a sample rate at 2 Hz between ensembles. It was also set up so that all the time series for the duration were processed and flagged for bad data that exceeded four times the standard deviation. Only bursts with good data, more than a threshold of 90%, were processed along with auto bias removal, and the negative values in the spectra were set up to be clipped.

4.4.3 Data visualization

To relate the observations from the ADCP with atmospheric drivers, wind data were obtained from the nearby Environment and Climate Change Canada station (ECCC) at Beaver Island. The wind data for this site was available at 1-hour intervals (Figure 19).

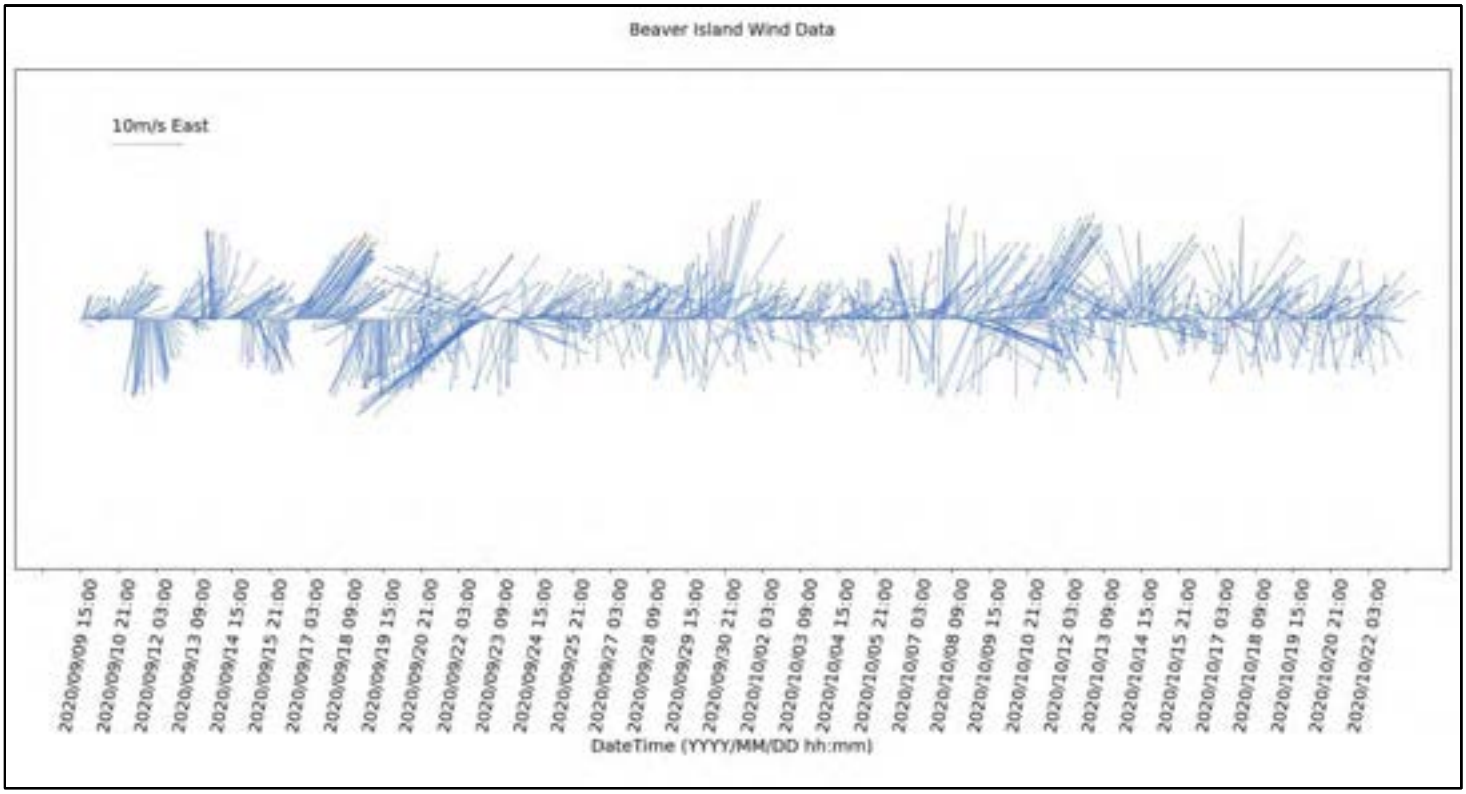


Figure 19 Wind direction and magnitude from ECC Beaver Island weather station. Note strong winds Sept 22-23 associated with Hurricane Teddy. Time is in UTC.

Currents

The ADCP data were processed and graphed to reveal trends in currents in the water above the deployment site for the duration of the deployment. At first glance, there is one event that can be seen clearly in Figure 20. Taking place on September 22nd and 23rd, 2020, this is the result of Hurricane Teddy passing over and across Nova Scotia. Current throughout the water column reached ~0.13 metres/second for the duration of the event, with dominant current direction flowing in the direction of ~130 degrees, to the Southeast. Interestingly, more water flowed down in the direction of the ocean floor during this event as well, as seen in Figure 20 D.

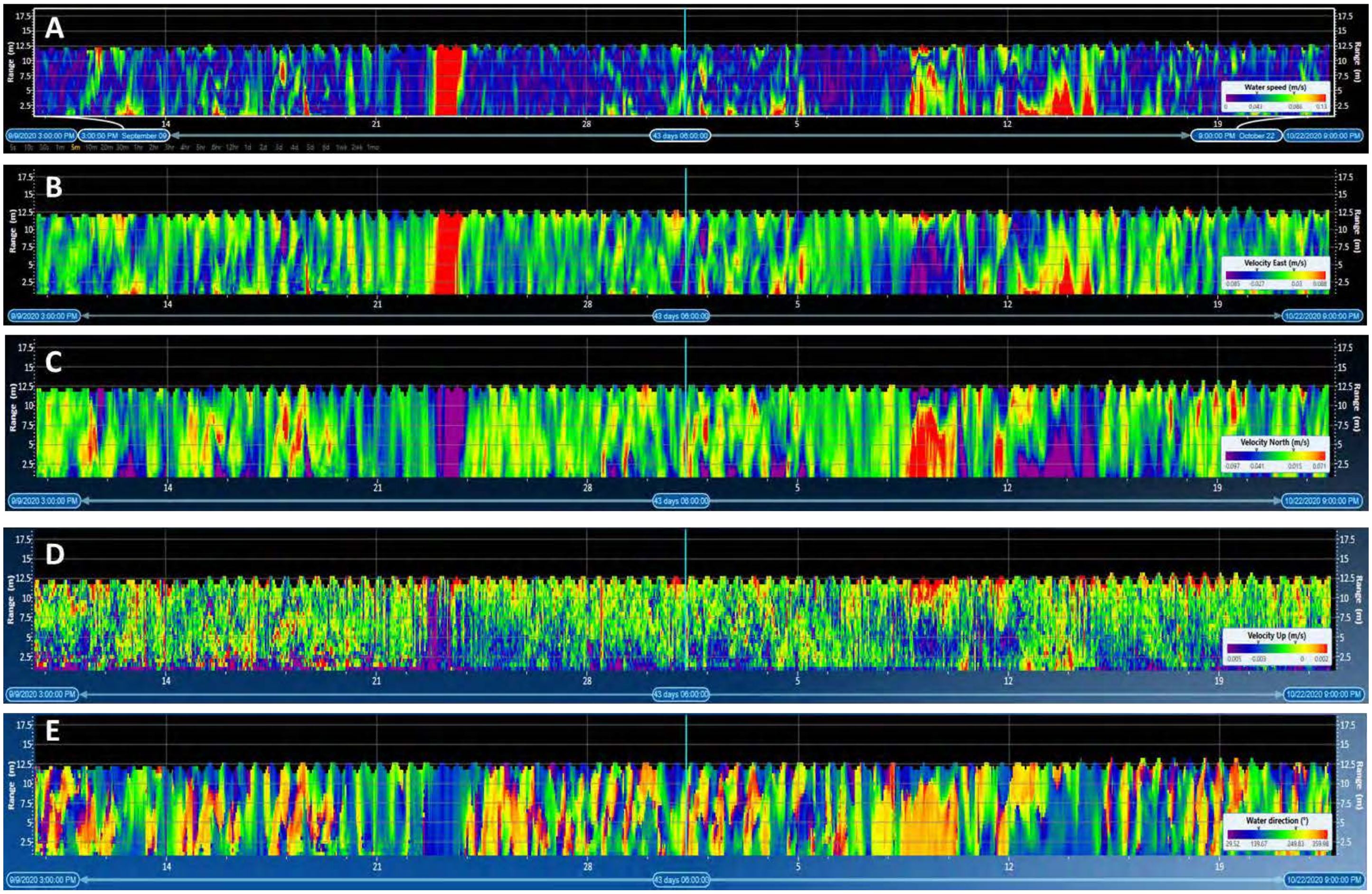


Figure 20 Screenshots from Velocity software showing the ADCP data during the deployment period. The X-axis represents time and consists of approximately 43 days. A: Water binned current speed (m/s). B: Binned Water Velocity, Eastern Component. C: Binned Water Velocity, Northern Component. D: Binned Water Velocity, 'Up' Component. E: Binned Water Direction, corrected for true north. The repeating pattern represents the daily tidal cycles.

Other anomalies in the data occurred on the 9th and 14th of October 2020. Here, the large portions of the water column flow Northwest and Southeast, respectively. These events last well beyond the typical duration of cyclic, tidal related events we can see for the rest of the deployment. These events also line up with high wind speed events seen in Figure 21.

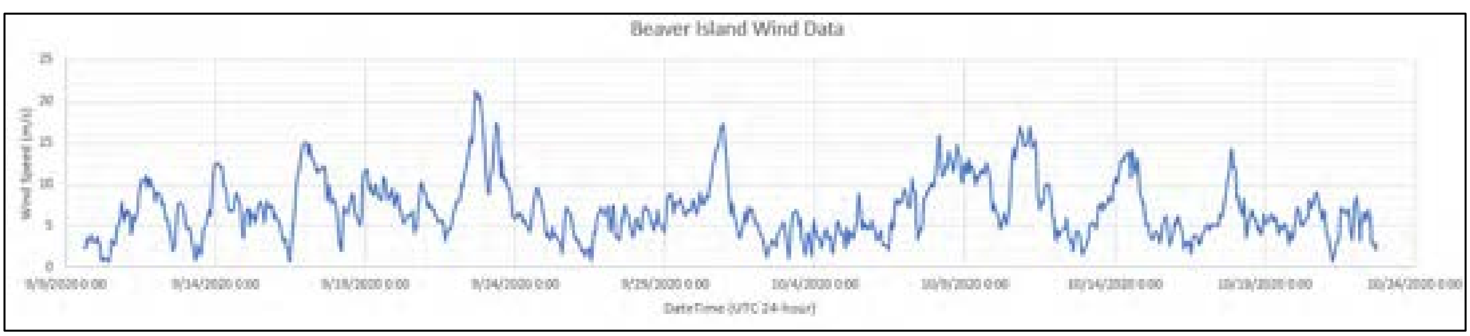


Figure 21 Wind speed data from nearby ECCC weather station at Beaver Island.

In addition to measuring the current speed and direction for these vertical bins (50 cm increments), the ADCP also measured water level from a pressure sensor. To investigate the relationship of the currents, water level, and wind velocity (ECCC Beaver island weather station) the data were integrated into an animation. This animation allowed all three parameters, ADCP current and water level results and wind speed and direction, to be visualizing simultaneously. Frames from the animation showed the water level and current speeds during normal tidal events with variable wind conditions (Figure 22). The wind is denoted with a quiver plot showing the direction of wind and the length of arrow defines the speed. The current speed was denoted by the x and y-axis in m/s, and the direction by the four cardinal points (N, E, S, W red lines and text) and the water level above the sensor was denoted on the z-axis (m). The average current velocity is denoted with the green line and green circle at the bottom on the graph (Figure 22).

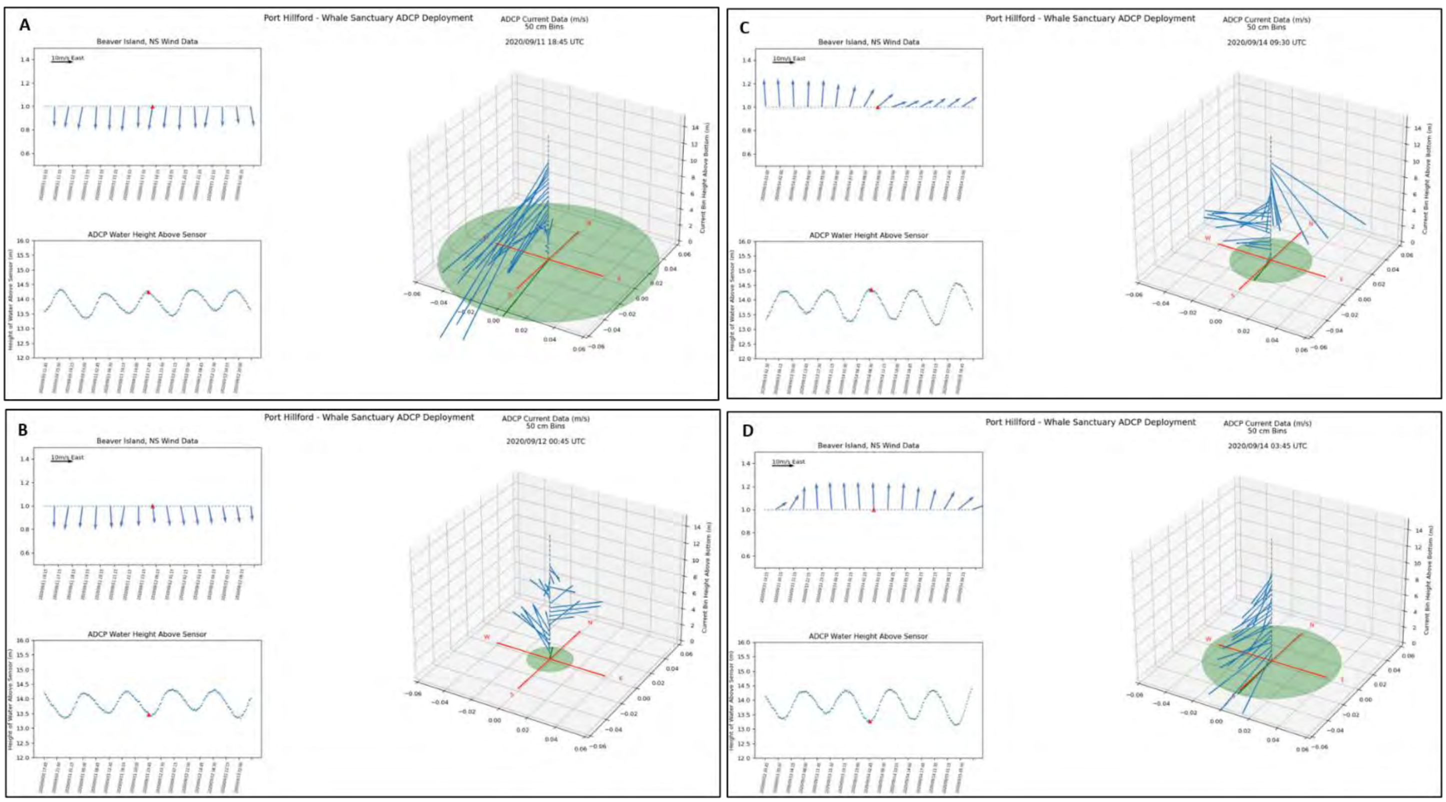


Figure 22 Example of visualizing the wind, ADCP currents and water levels. A – High tide with a northerly wind. B - Low tide with a northerly wind. C - High tide with a southerly wind. D- Low tide with a southerly wind.

Waves

Data from WavesMon were exported in two formats: A Waves Log file containing the summary of the wave parameters, and a Waves record file to visualize the data in WaveView. A time series plot with Significant Wave Height (Hs), Peak Period (Tp) along with the Water Level (WL) is shown in Figure 23.

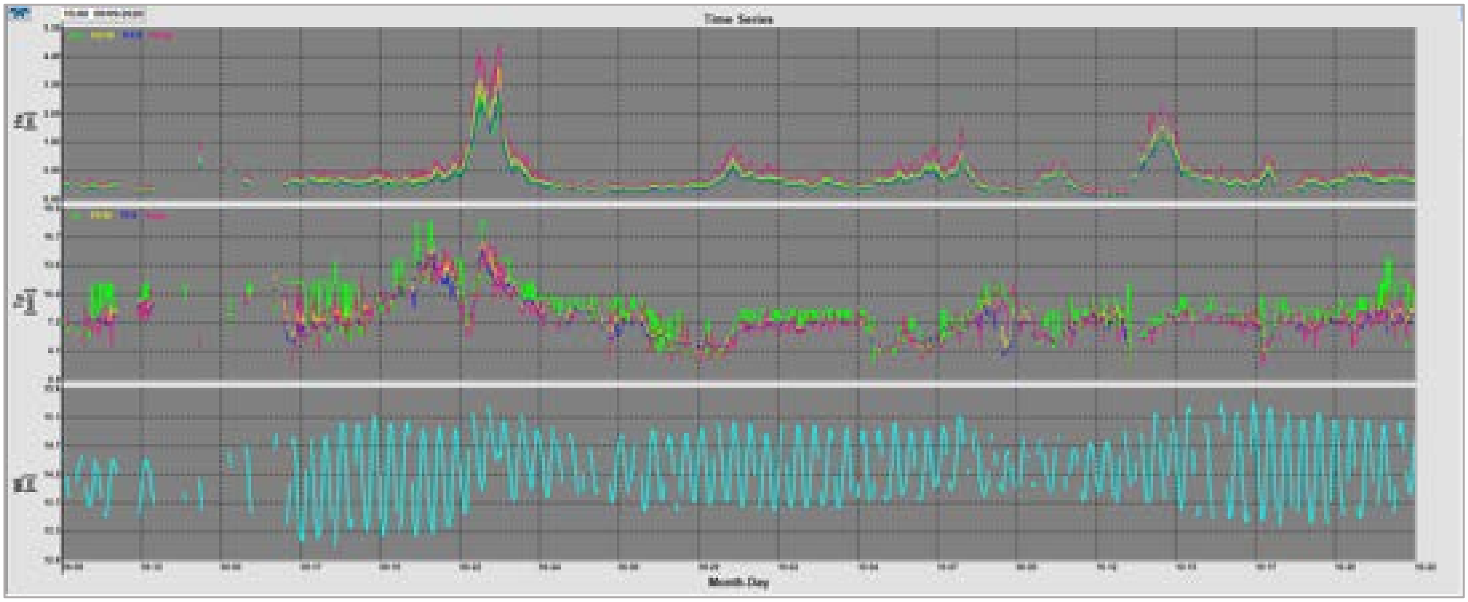


Figure 23 A plot showing the significant wave height (Hs) (top graph), wave period (Tp) (middle graph) and water level (WL) (bottom graph) during the ADCP deployment time frame.

The significant wave height, Hs in the harbour was close to 90 cm with an average peak period of 9 seconds for most of the deployment with the exception of Hurricane Teddy which made landfall near the site on September 22nd and 23rd, 2020. The wave height spectra and directional spectrum plots exhibit the wave frequency and direction during the Hurricane Teddy event with Hs and Tp as 3.19m and 18.29s respectively on September 22nd, 2020 (Figure 24).

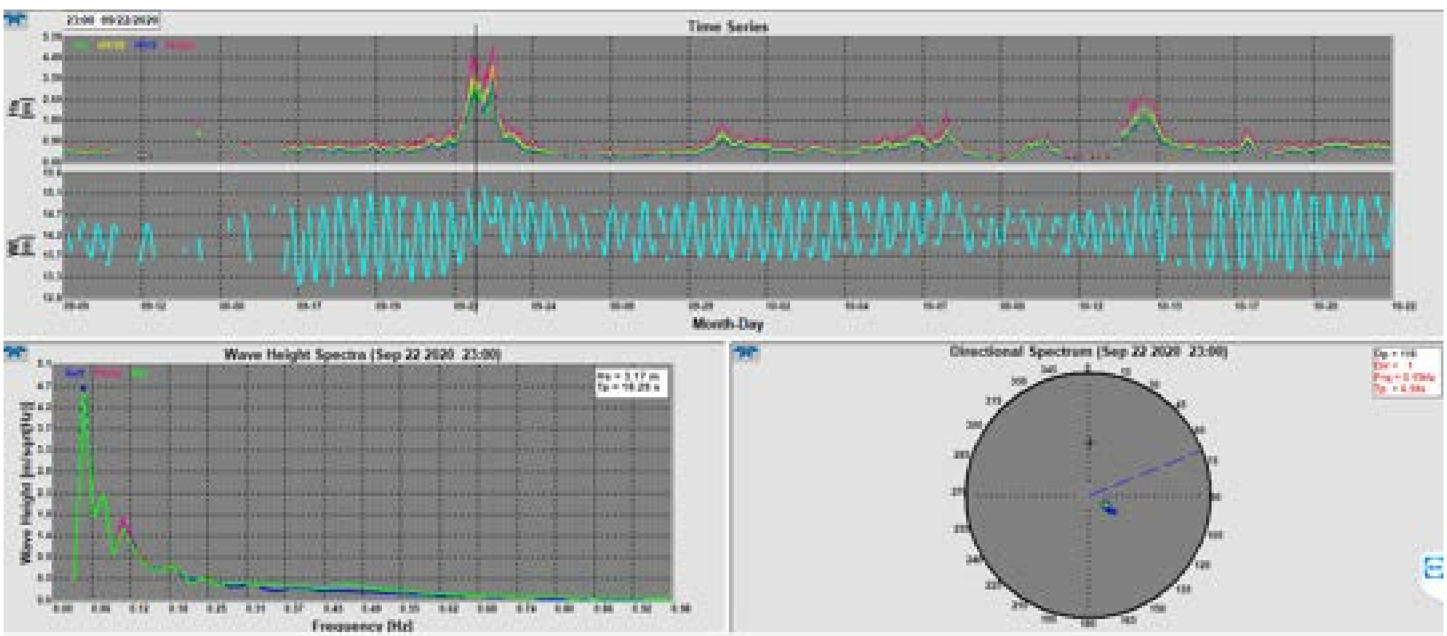


Figure 24 Wave Height Spectra and Directional Spectrum on Sep 22nd, 2020 during Hurricane Teddy. Top graph shows the Significant Wave Height (Hs) and Water level (WL). Bottom graph left shows a close up of Hs and bottom right shows a rose diagram showing which direction the waves are coming from and the Peak Period.

The first peak of Hurricane Teddy (Sep 22nd), there were very high frequency waves. The peak direction (Dp) during the event was 123 degrees (waves are from the southeast travelling to the northwest).

4.5 Multibeam survey

A multibeam survey was conducted using a multibeam sonar and an Inertial Navigation System (INS) which consisted of a Motion Reference Unit (MRU) and two antennas used to calculate the position and heading of the vessel. A typical multibeam sonar consists of a transducer, receiver, a processing unit, and a controller unit. The transducer transmits a beam that is narrow in the along track direction and wide in the across direction. After this beam is reflected or backscattered off the ocean floor, it is sensed by the array of the receiver which is separated into multiple discrete beams. The captured returns are processed for bottom detection by the processing unit. The bottom detection is then associated with ancillary data from the positioning and orientation system and stored as a depth positioned in three dimensions and time.

4.5.1 Sensor specifications and installation

Initially the Reason T-20 multibeam and NovAtel navigation system were deployed on the Boston Whaler to conduct a multibeam survey. After some initial surveying, the system experienced various technical issues related to computer communications and eventually the survey was aborted. A revised set of equipment, multibeam and navigation system, were acquired and deployed on the Boston Whaler to complete the multibeam survey. An R2Sonic 2026 multibeam system along with an integrated Applanix Wavemaster Navigation unit were used to complete the survey in Port Hilford. The Multibeam Echo Sounder (MBES) consisted of a wide frequency range from 170 kHz to 450 kHz which made it adaptable to a wide range of survey depths and conditions. In the study area a frequency of 400 kHz was used. The system consists of 256 beams with across and along track beam width of 0.5° at nadir. A 20% overlap was considered while planning survey lines in QINSy survey manager. These survey lines were planned considering the depth and beam width, as the swath width is narrower in shallow areas.

The system was mounted on a fabricated stainless-steel pole attached with an adaptor plate, on the port side of the Boston Whaler. The Motion Reference Unit sat above the system on the adaptor plate. Two metal poles with 5/8-inch threaded rods were also fabricated and attached on the port side for the GPS antennas (Figure 25).

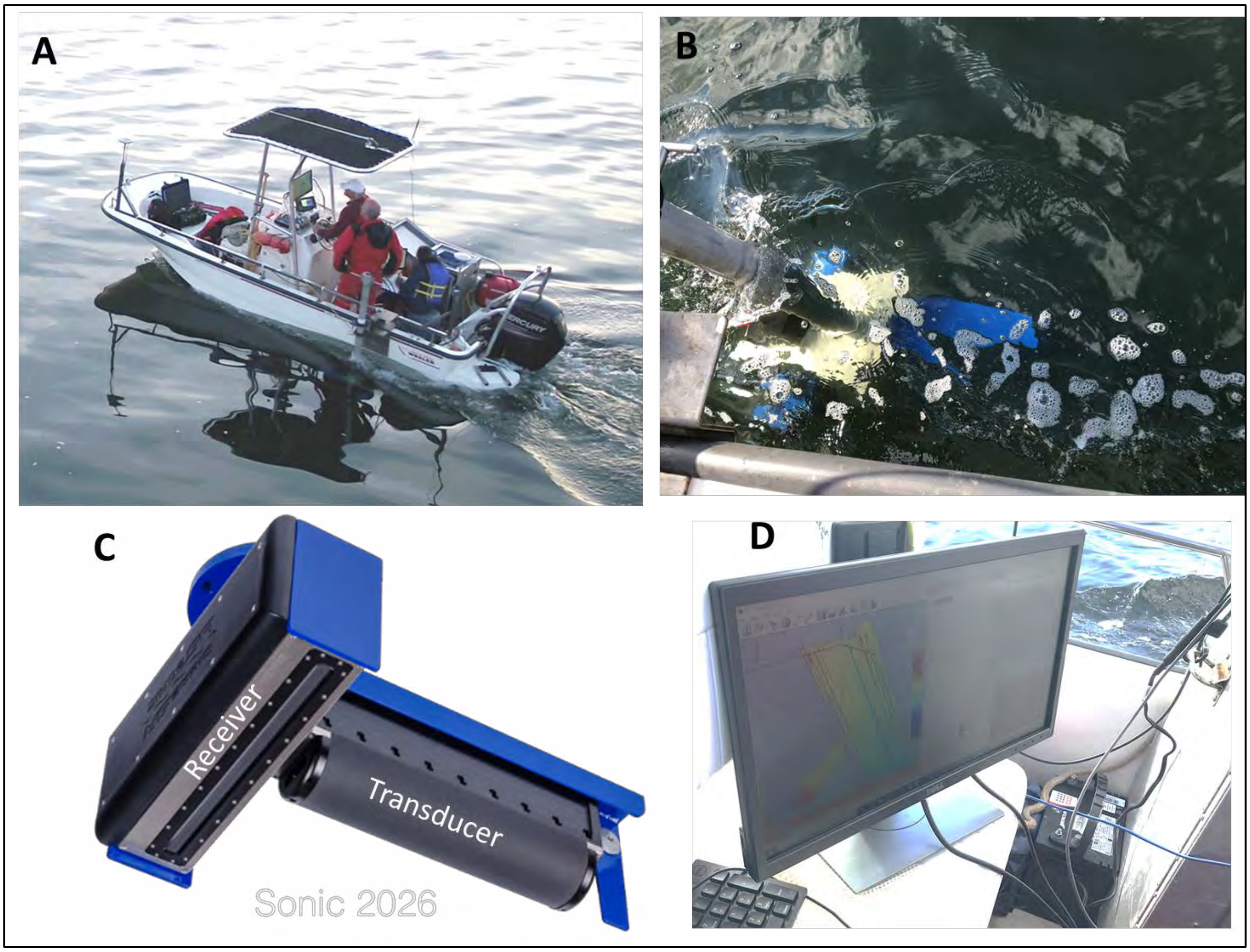


Figure 25 Multibeam survey components. A- Shows the two GPS antennas on the threaded poles and the arm (stainless steel pole) in water along with crew performing the multibeam survey. B- Pole was down in the water showing the MRU (Black box) on the adapter plate and blue frame holding the multibeam system. C- R2Sonic 2026 multibeam system with transducer and receiver. D- Computer setup on the Boston Whaler.

4.5.2 Data collection

A total of 35 survey lines were conducted over the course of two days Oct 22nd and 23rd, 2020 (Figure 26). An additional five lines were collected on Oct 22nd, 2020 before the start of the survey for a patch test. As the multibeam swath depends on depth more survey lines were needed in shallow waters. A patch test is a calibration process performed to determine the angular misalignment between the R2Sonic 2026 and the motion sensor. Several Sound Velocity Profiler (SVP) drops were also collected using the AML Oceanographic Base X 25131 system (Figure 26) with an SV Xchange probe. The SVP measures the speed of sound in the water and was required to correct the sound pings from the multibeam system. The speed of sound in water is influenced by temperature and salinity. For high accuracy positions, Real Time Corrections (accuracy of less than 2cm horizontal and 5cm in vertical) were transmitted from the base station which was set up over a known point (this point was established by collecting rapid statics for six hours and post processing with the near by Canada Active Control Station (CACS) Sherbrooke (250013), in Leica Geo Office) at the Barachois Island wharf which is located near the study area, to be received by the radio antenna setup on the boat.

These corrections were fed into the navigation system. QINSy software was used for navigation and data collection. Unfortunately, the GPS validation points were collected during the first multibeam mission using the Reason-T-20 system that had significant technical issues and was aborted. The second multibeam mission did not allow us to get near the shore to overlap with the GPS points for validation.

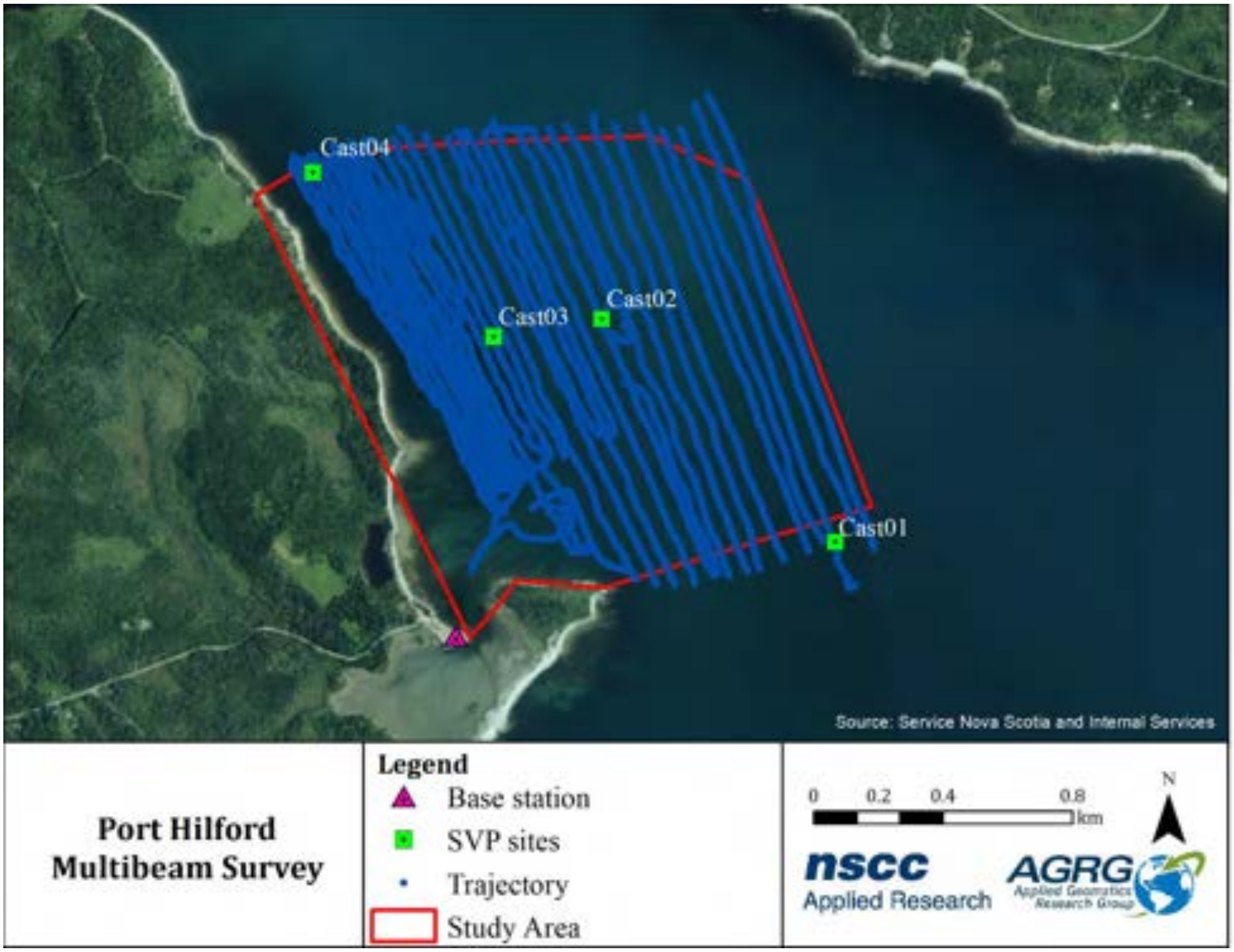


Figure 26 Multibeam survey lines collected on Oct. 22nd and 23rd, 2020 along with the Sound Velocity Profile (SVP) drop sites and GPS base station location which was set up on the Barachois wharf.

The sound velocity (m/s) was found to change with depth (m) at each cast location (Figure 27). The Down Cast (blue line) shows the sound velocity values from the surface to the bottom of the cast, and Up Cast (orange line) shows the values from the bottom of the cast to the surface while retrieving the probe. Cast 04 was conducted on Oct 23rd, 2020 and shows a pronounced thermocline or halocline at a 1 m depth as compared to the rest of the casts conducted on Oct 22nd (Figure 27 D).

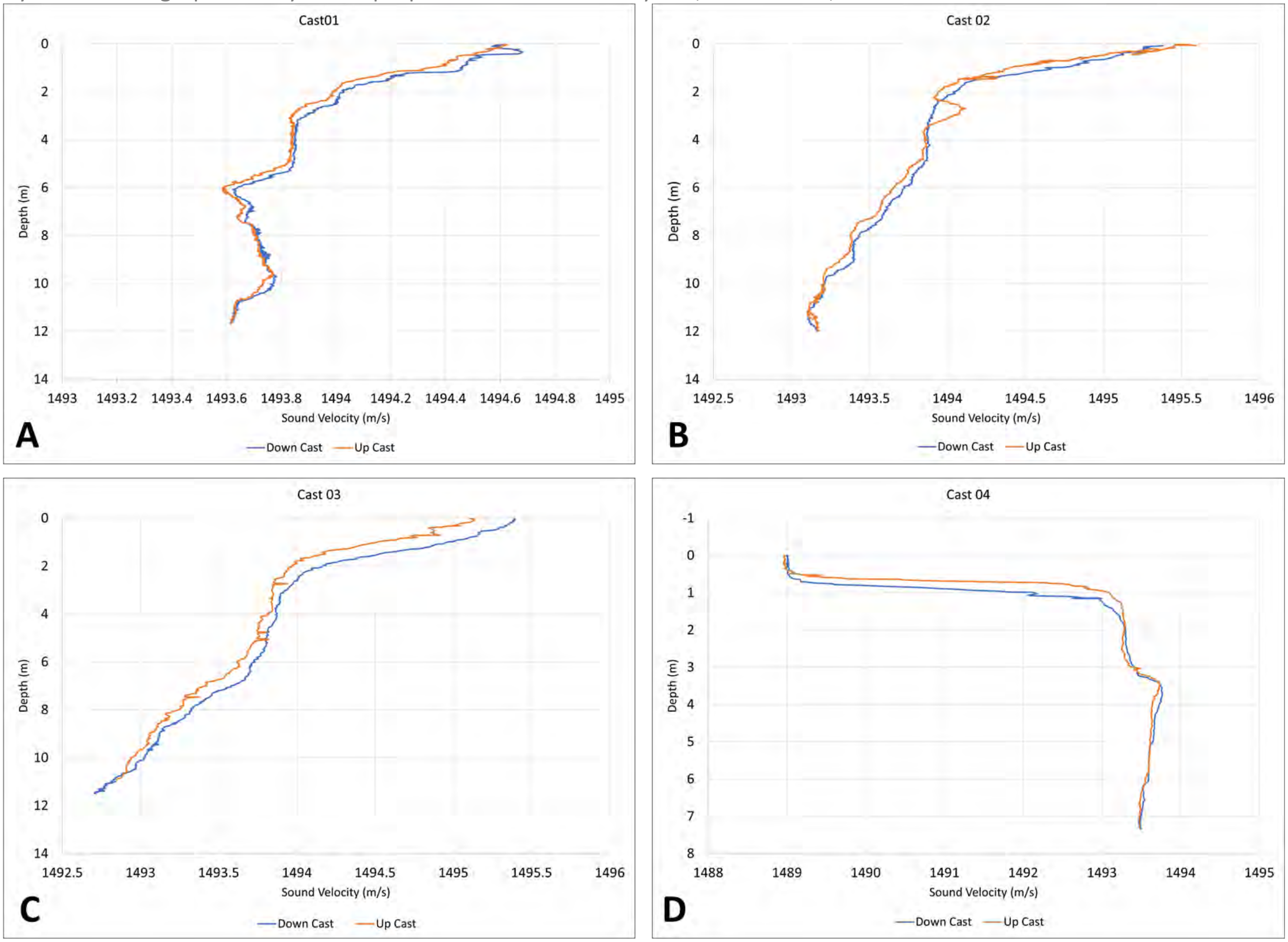


Figure 27 Sound Velocity Profiles (SVP) casts in Port Hilford, NS. Cast 01, 02 and 03 were conducted on Oct. 22nd, 2020 and Cast 04 on Oct. 23rd, 2020.

4.5.3 Data processing

Patch test data were first processed using Qimera 2.1.1 software to calculate roll, pitch and heading offsets, these offsets were used in the data collection. SVP data exported from the Base X were used to correct the sonar pings. Trajectory data from the GPS and motion unit were post-processed in POSPac *MMS* using the active control station in Sherbrooke and known point on the Barachois wharf as the base stations, and the resultant Smoothed Best Estimate of Trajectory (SBET) was applied to the sonar points. Post processing the trajectory was a mandatory step for this survey as during the data collection the corrections were not received by the radio antenna on the boat at all times (Figure 28). Sonar files were cleaned using various filters in the software for noise removal after the SBET and SVP files were applied.

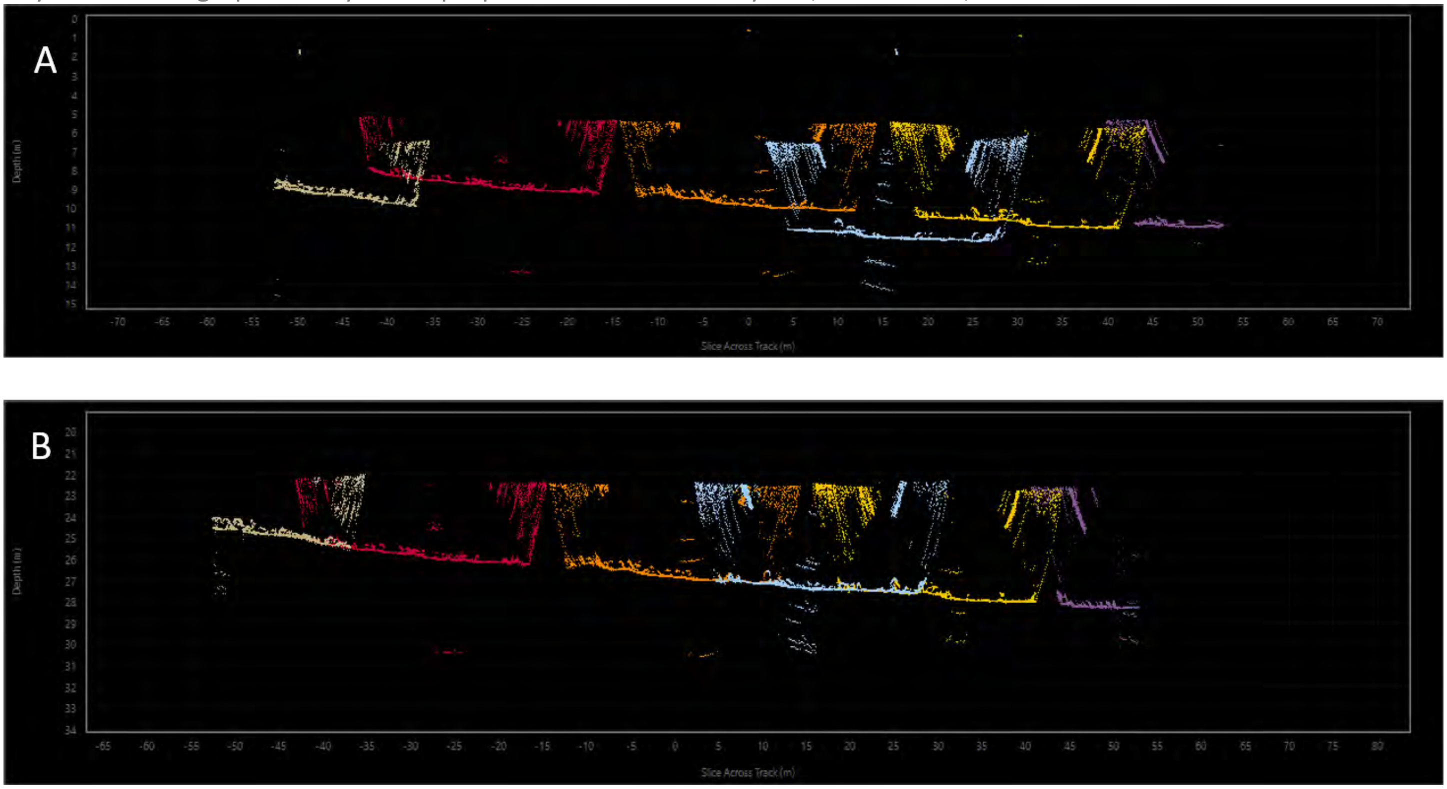


Figure 28 Survey lines trajectory before applying the corrected SBET file in A and after applying SBET file in B. The data shown here was not cleaned yet to remove the noise on the sides of the swaths.

The post-processed sonar points were exported as .LAS files containing position, depth, and backscatter. The .LAS files were further cleaned using TerraScan™ software to remove the noise in the water column. The cleaned .LAS files were gridded in ArcMap using the las dataset tools.

5. Hydrodynamic modelling

A hydrodynamic model (HD) was developed using DHI Mike 21 Flow Model Flex Mesh application. A variety of modules within the Flex Mesh were used to obtain the project outputs. Flushing time was determined using the transport module of Flex Mesh. Mean and maximum monthly current magnitudes were calculated directly using Mike 21 from the hydrodynamic model.

5.1 Mesh Generation

The hydrodynamic model was driven by two major inputs: a surface created with bathymetric points and a driving boundary condition. As the Flex Mesh module works with meshes instead of a grid, a mesh was created using the Mesh Generator tool in Mike Zero. A variety of sources of topography and bathymetry were used to complete the model mesh. Raw data for generating the mesh was the land boundary (3m contour) and bathymetry (resolution of 3m) in XYZ form. Bathymetry was obtained from the multibeam survey for the study area and Canadian Hydrographic Service (CHS) Non- Navigational (NONNA) data converted to Canadian Geodetic Vertical Datum of 2013 (CGVD2013) which were utilized for rest of the domain. Topographic data as a Digital Elevation Model (DEM) was downloaded from GeoNova (GeoNova DataLocator – Elevation Explorer, https://nsgi.novascotia.ca/datalocator/elevation/). Values relative to CGVD 2013 for Higher High Water Large Tide (HHWLT), Mean Sea Level (MSL) and Lower Low Water Large Tide (LLWLT) were obtained from CHS and are shown in Table 5.

	CGVD 2013
HHWLT	0.598 m
MSL	-0.356 m
LLWLT	-1.356 m

Table 5 Tidal range values obtained from CHS relative to CGVD2013.

A mesh was generated with lower mesh resolution in the deep water and fine mesh resolution in the Indian Harbour (Figure 29). The heavy grey line represents the boundary condition where the predicted tide levels were defined at locations A, B, C, and D (Figure 29). The mesh was interpolated using the Natural Neighbour interpolation method. The output mesh file contained geographical position information along with water depth relative to CGVD 2013 at each node point in the hydrodynamic model.

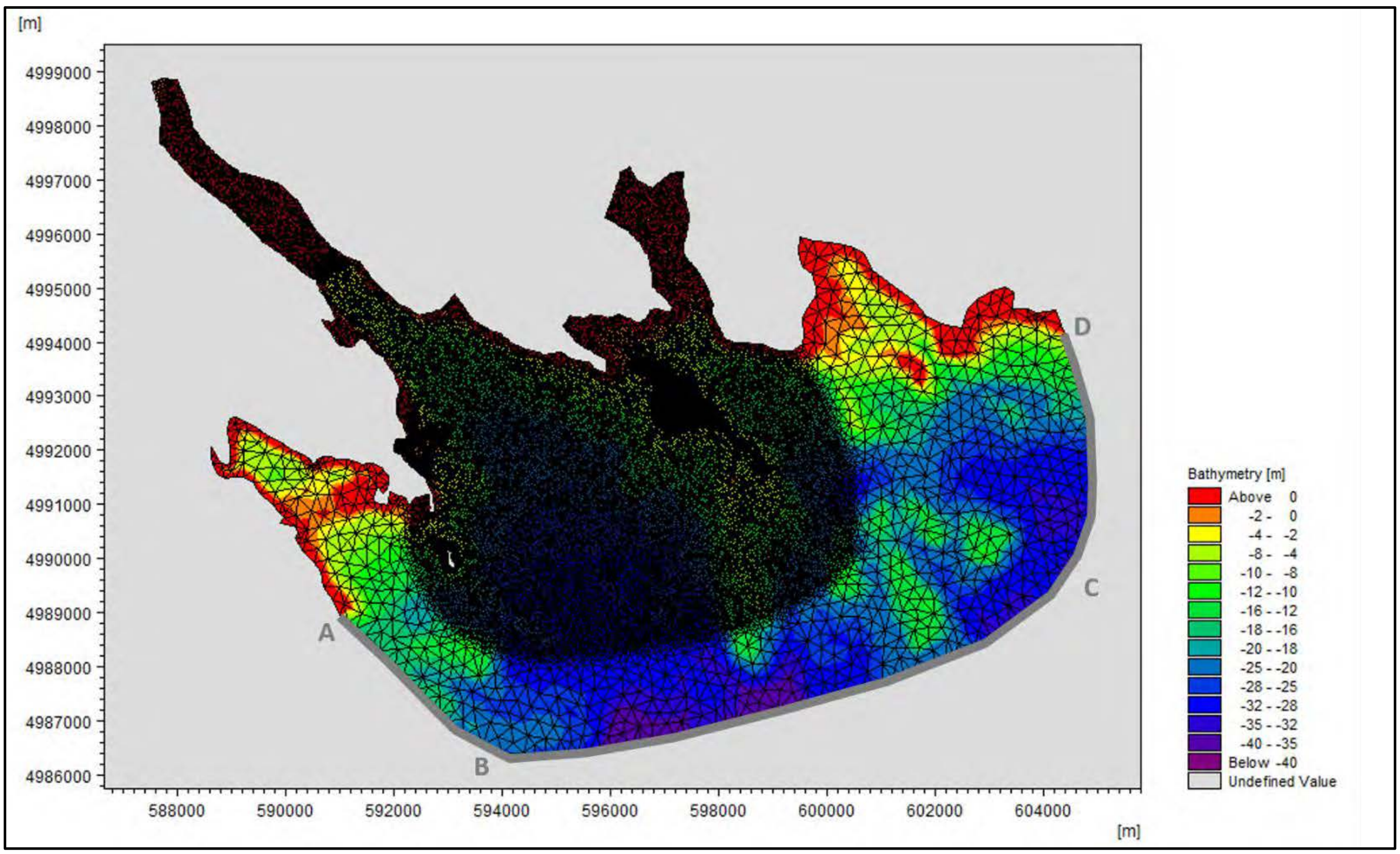


Figure 29 Computational mesh used for studying hydrodynamics in the study area generated using Mike Mesh Generator tool, also showing the model boundary in grey color line with the four points (A, B, C and D) where the WebTide predictions were extracted.

A large extent (domain) was selected and used to run the model to provide accurate results by understanding the water movement from the North Atlantic Ocean into the harbour.

5.2 **Boundary Conditions**

The other major inputs for the models were the boundary conditions as shown in Figure 29. Predicted tide generated from the WebTide Tidal Prediction Model (Dupont et al., 2002) was extracted at four points along the open boundary and at the ADCP location. The WedTide files were referenced to Mean Seal Level (MSL) and were converted to CGVD2013 and used to drive the model. A comparison of the predicted water levels (Webtide) with the observed water levels from the ADCP showed that the predictions had a significant phase offset and high residuals (Figure 30).

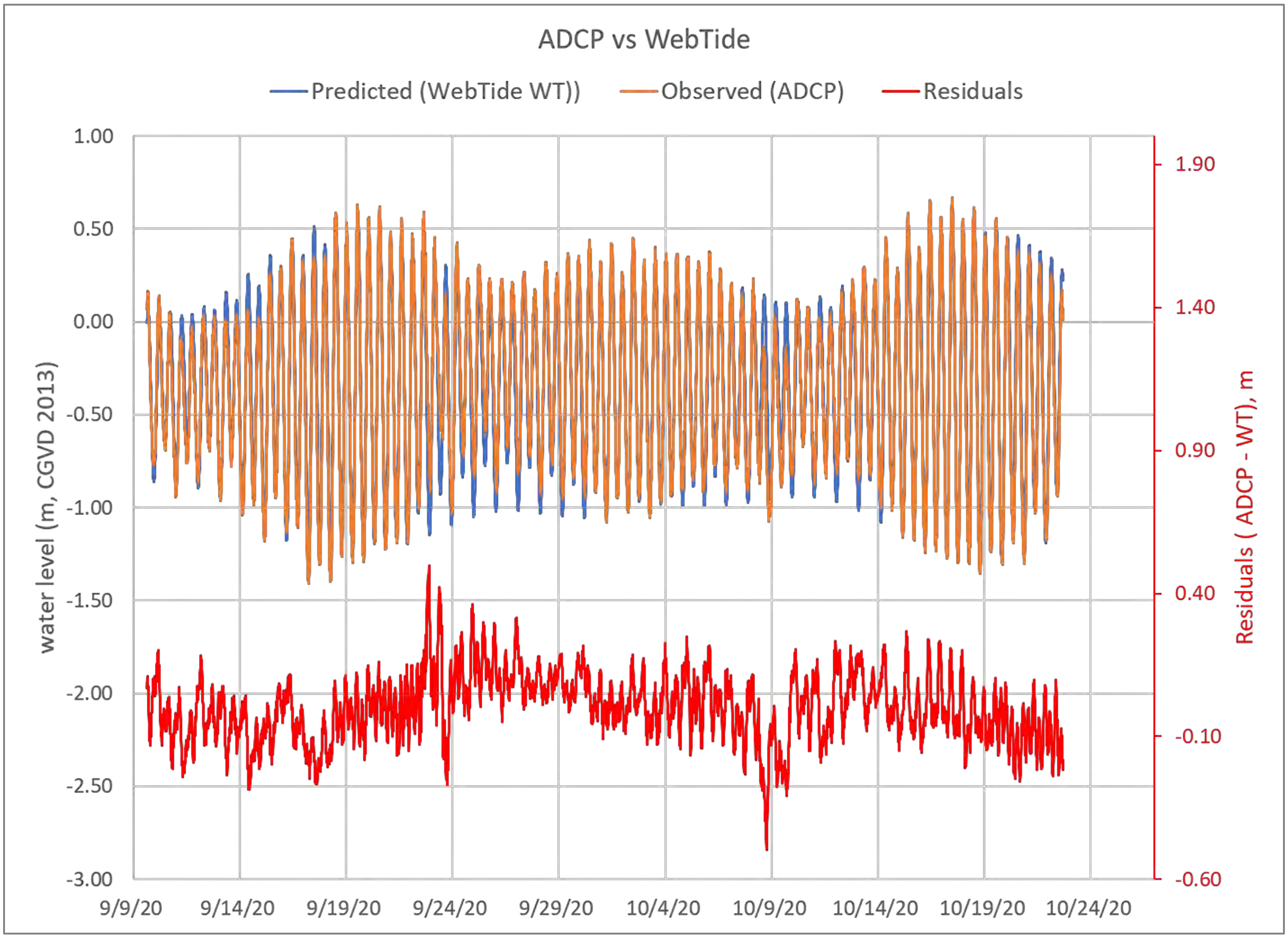


Figure 30 Water levels in CGVD 2013 as observed by the ADCP (orange, top graph) compared to the water levels obtained from the WebTide (blue), and residuals which is ADCP water levels subtracted with the WebTide water levels (red, bottom graph).

The mathematical prediction model (WebTide) gave high residuals when compared to the observed water levels. This is expected for anomalies generated by atmospheric effects like changes in atmospheric pressure and strong wind events. However, when examining the residuals (difference between ADCP water level and WebTide water level), there appeared to be a consistent phase shift in the WebTide data. To fine tune the boundary condition to better match the observed conditions, these residuals were added to the predicted tide at the four boundary points. A comparison of the predicted (predicted + residuals) and observed water levels at point B is as shown in Figure 31. The hydrodynamic model was validated by comparing the observed water levels and currents from the ADCP to that of the model. In the calibration process of the hydrodynamic model, values of bed resistance and eddy viscosity were adjusted to produce results that best match the ADCP.

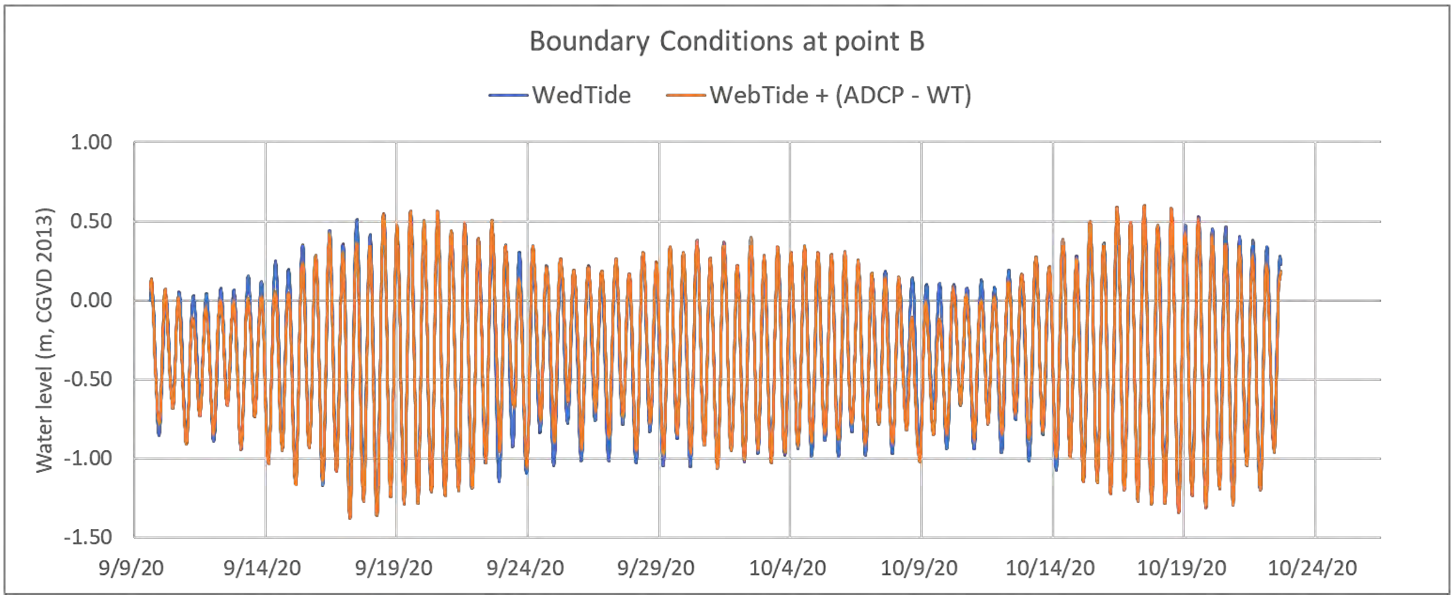


Figure 31 Boundary condition at point B. Comparing the predicted tide in blue (Webtide) with the predicted modified water level in orange (Webtide plus residual).

5.3 **Hydrodynamic Simulation**

The hydrodynamic model simulation ran for September 9th to Oct 22nd, 2020, a span of 43 days covering the one-month timeframe when the ADCP was deployed. Wind data obtained from the nearby Environment and Climate Change Canada station (ECCC) Beaver Island weather station was also included in the model (Figure 32).

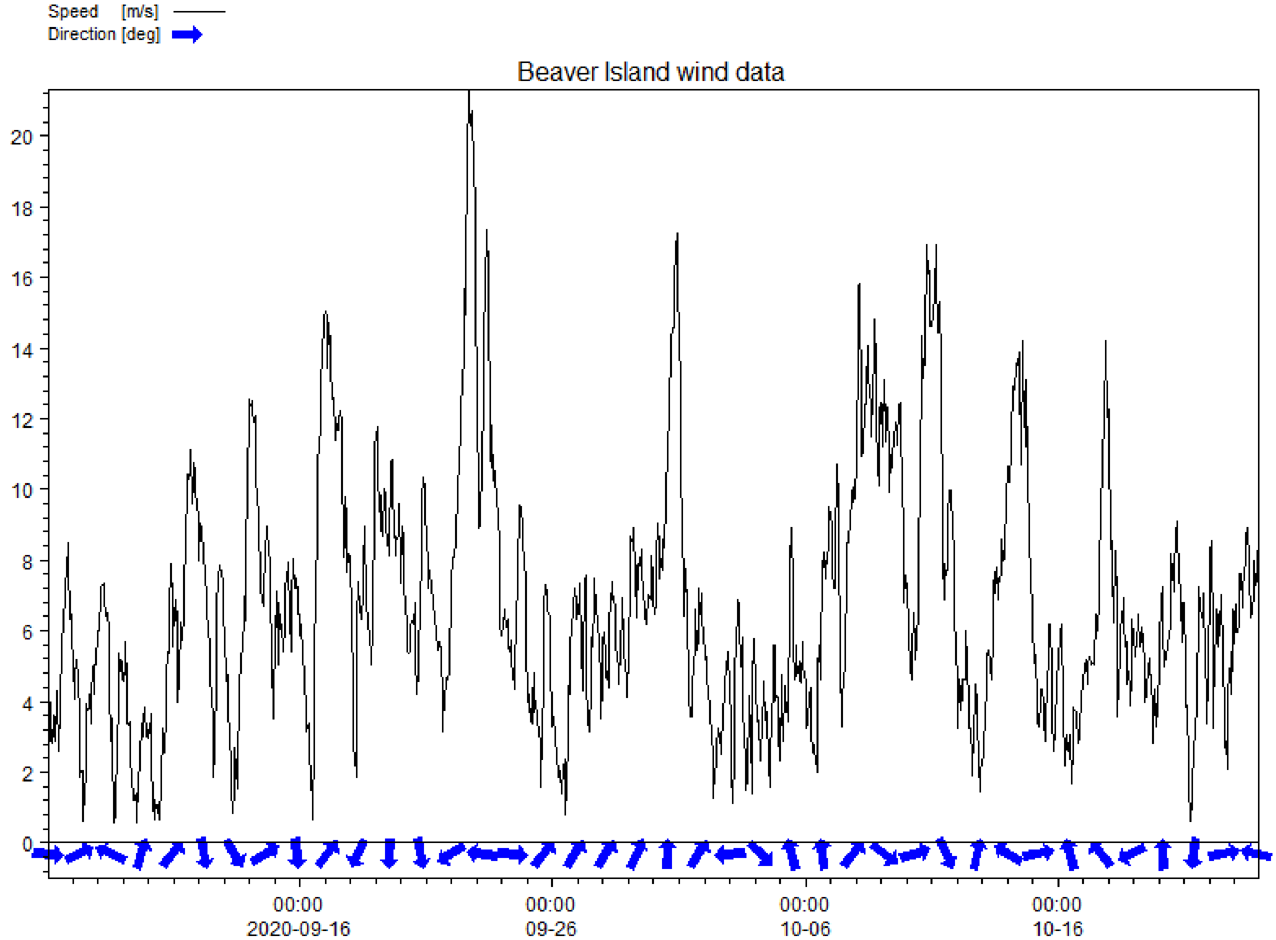


Figure 32 Wind data from the Beaver Island ECCC station. Plotted using Mike Plot Composer.

Several parameters in the model were changed while validating and stabilizing. In the hydrodynamic model a Bed Resistance of 32 m^ (1/3)/s constant was applied over the domain along with an initial surface elevation of 0.07m and an eddy viscosity constant of 0.28.

The boundary conditions as described in section 5.2 were used to calibrate the model. Once the hydrodynamic model parameters like bed resistance, initial surface elevation, Coriolis effect, eddy viscosity and bathymetry were found to be reliable for running the simulation to produce the best results through the calibration process, these parameter values were used along with the predicted tide (WebTide + residual) boundary conditions to produce the metrics of interest (Flushing rate, mean and maximum currents).

5.4 **Transport Module Simulation (Flushing time)**

The Transport module in the Flex Mesh was used to calculate the minimum concentration that remained in the harbour based on the flow conditions. A proportional concentration of 1.0 was added to the harbour on the first model timestep, the model ran for a period of 30 days. No decay factor was added, and the model was run with a WebTide predicted boundary and no wind conditions. As the model ran, the proportional concentration was lowered by the influx of new water and model results showed the time it took for the concentration to reach zero (fully replaced by new water). The results were interpreted for flushing time estimates.

6. Results

6.1 Multibeam survey

The las files exported from Qimera and TerraScan were gridded in ArcMap 10.8.1 at 1m (Figure 33). The horizontal coordinate system for the raster datasets is North American Datum of 1983 (NAD 83) Canadian Spatial Referencing System (CSRS) with projection set as Universal Transverse Mercator (UTM) Zone 20 North (N). The vertical datum used for the elevations is the Canadian geodetic vertical datum of 2013 (CGVD2013).

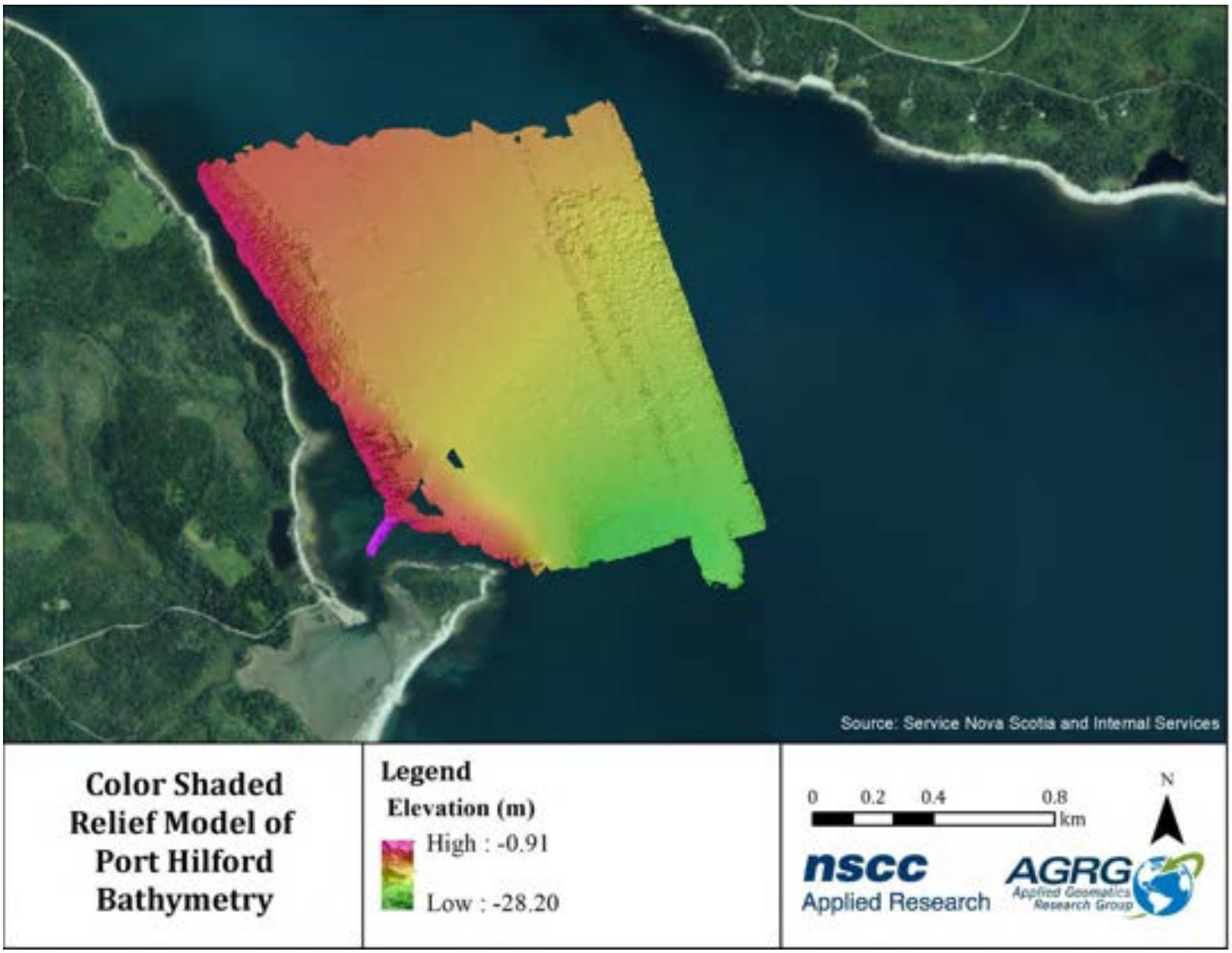


Figure 33 Bathymetry collected by R2Sonic multibeam system, gridded at 1 m for the study site. Elevations referenced to CGVD2013.

A continuous raster shows the various features picked up by the sonar unit. The seaward portion of most of the study area was dominated by sand. A series of hummocks can be observed near the east end of the study area. Gaps between the survey lines were void filled using the Elevation Void fill function in ArcMap. Indian Harbour gets deeper towards the ocean with a deep pool at the south edge of the study area. The multibeam survey was conducted from the 2 m contour to avoid the areas near shore which are shallow and rocky.

The multibeam data collected by AGRG, single beam soundings from CHS and topographic data from GeoNova were combined and interpolated in ArcMap to produce a 3 m seamless raster for the Indian Harbour (Figure 34). This raster was converted to xyz format was used to drive the detailed hydrodynamic model. A Digital Elevation Model (DEM) represents bare earth surface and has been colour shaded to enhance the relief (Figure 34).

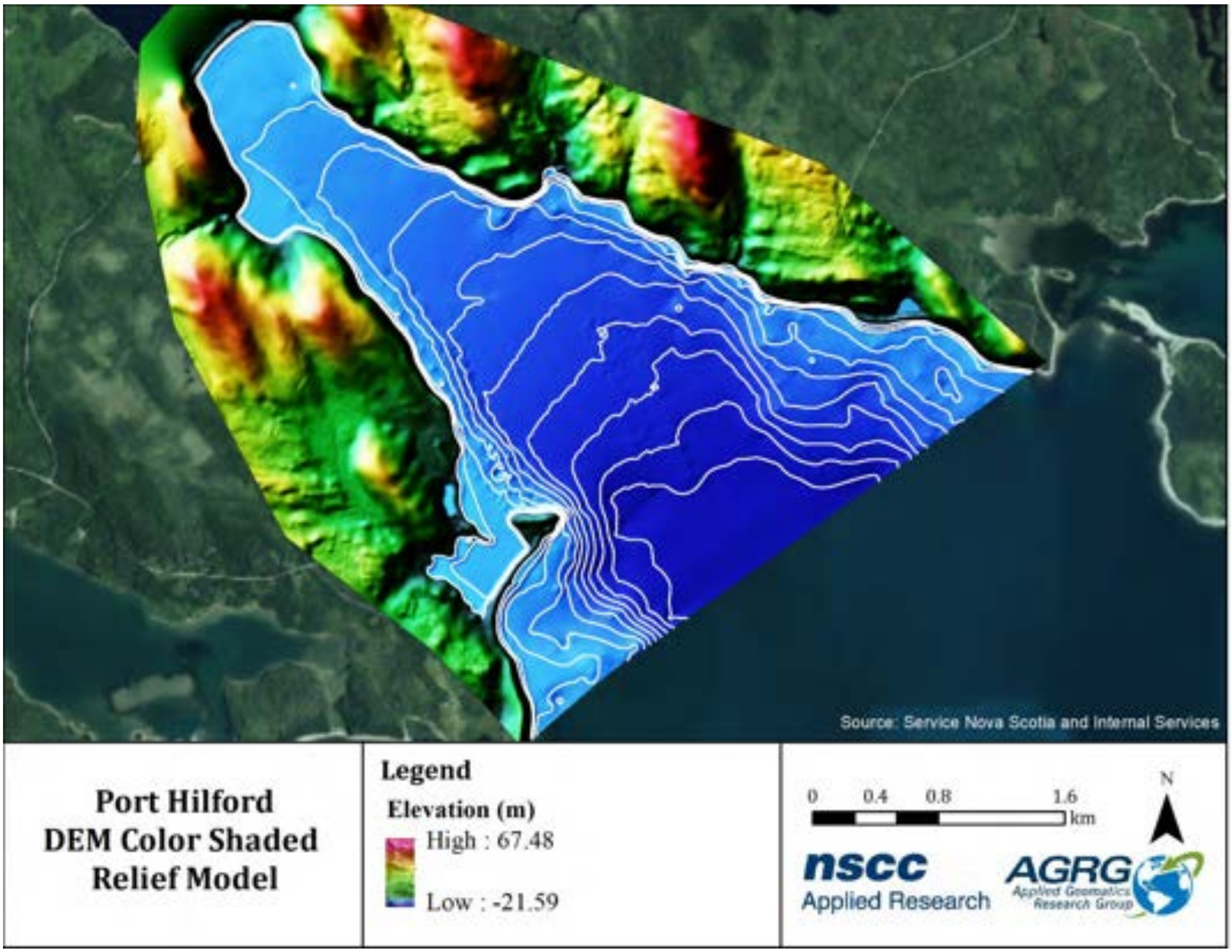


Figure 34 Colour shaded relief model generated from the DEM with 2 m contours (white lines).

6.2 **Acoustic Doppler Current Profiler (ADCP)**

Once the ADCP was retrieved the water levels were analyzed, a systematic trend was observed that we have interpreted to represent the ACDP sinking into the mud approximately 40 cm during the deployment. The water levels were adjusted linearly from the start of the deployment to adjust for this 40 cm effect.

6.2.1 Currents

The ADCP measured waves on the hour and currents every 50 cm from the sensor to the sea surface every 15 minutes. In addition to measuring the current speed and direction for these vertical bins (50 cm increments), the ADCP also measured water level from a pressure sensor. As mentioned previously, the wind data from Beaver Island were also downloaded and compared to the ADCP measurements. The relationship between wind and surface currents and deeper net water movement is shown in Figure 35.

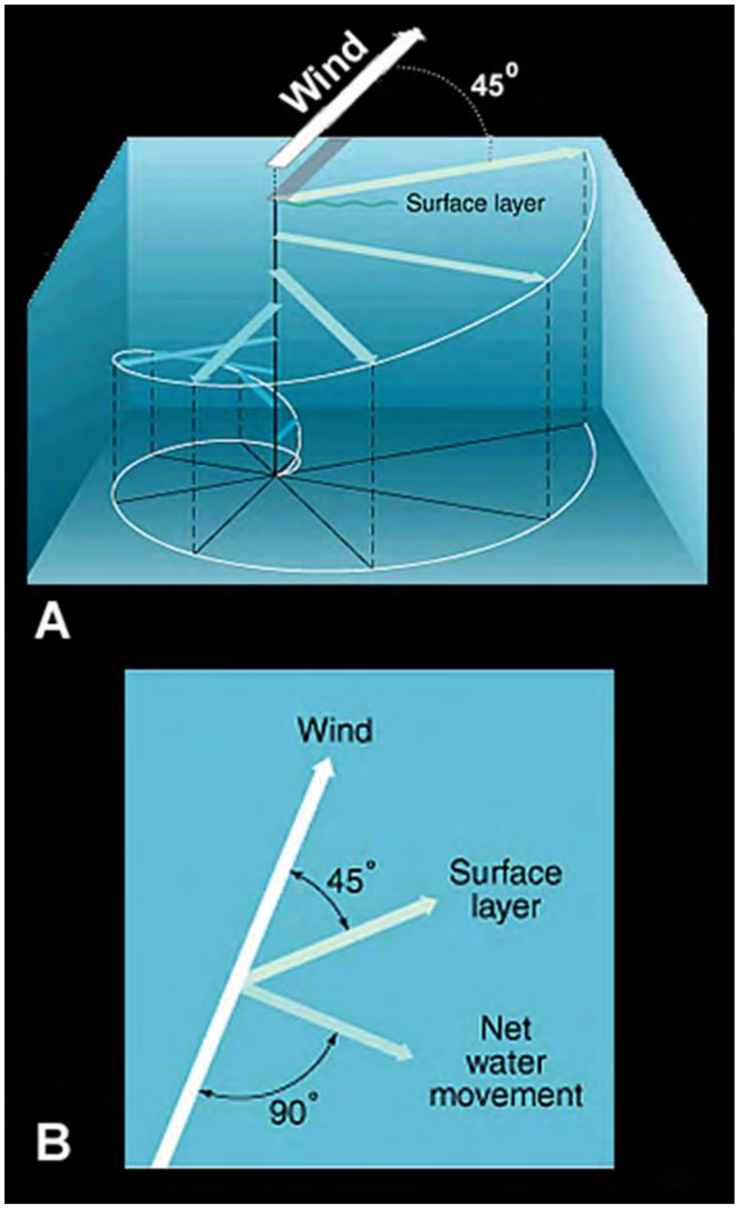


Figure 35 Relationship between surface winds, surface current direction and net water movement. Source (http://oceanmotion.org/html/background/ocean-in-motion.htm).

The average currents observed by the ADCP were plotted with the wind data from Beaver Island (Figure 36) and the water level observed by the ADCP were plotted with the wind data from Beaver Island (Figure 37).

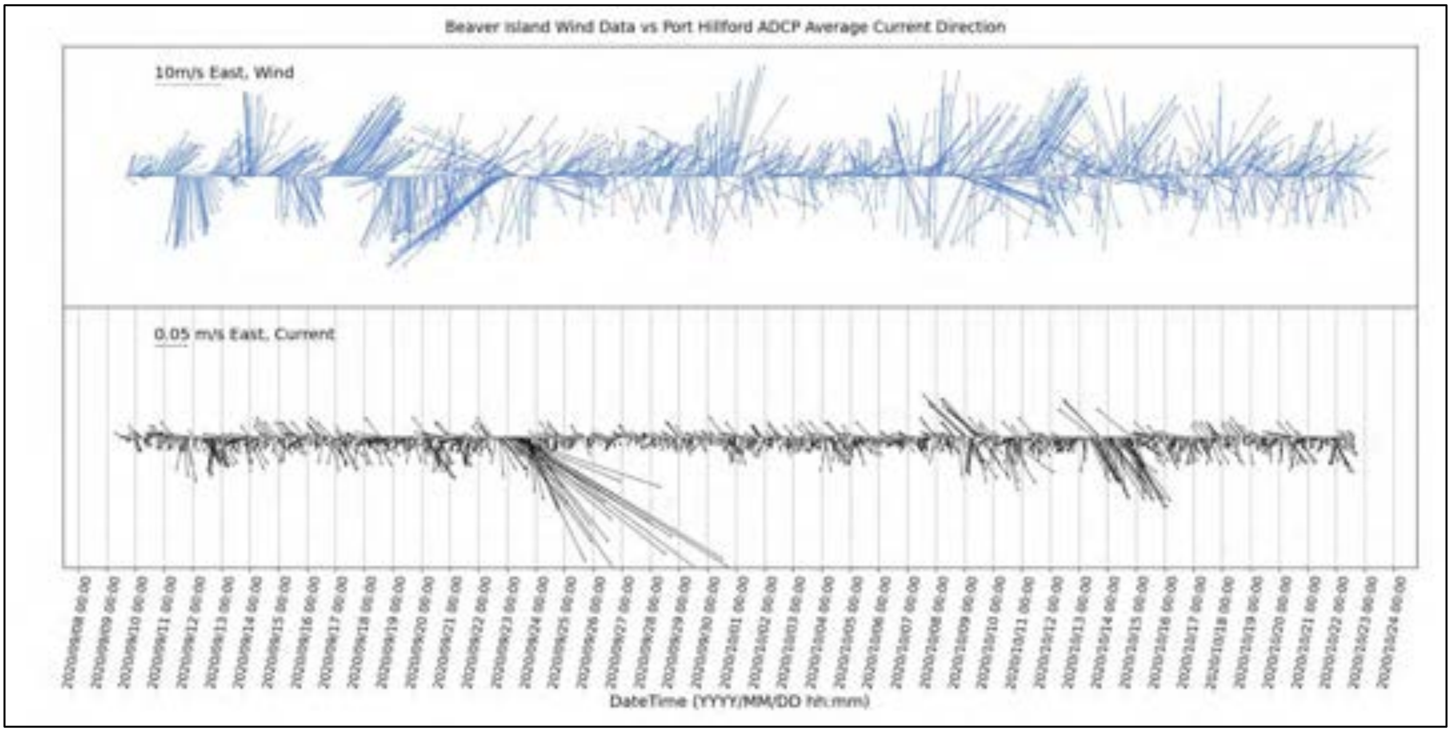


Figure 36 Wind and average ADCP current velocities. Top graph is the wind from ECCC Beaver Island weather station. Bottom graph is the depth averaged currents observed by the ADCP.

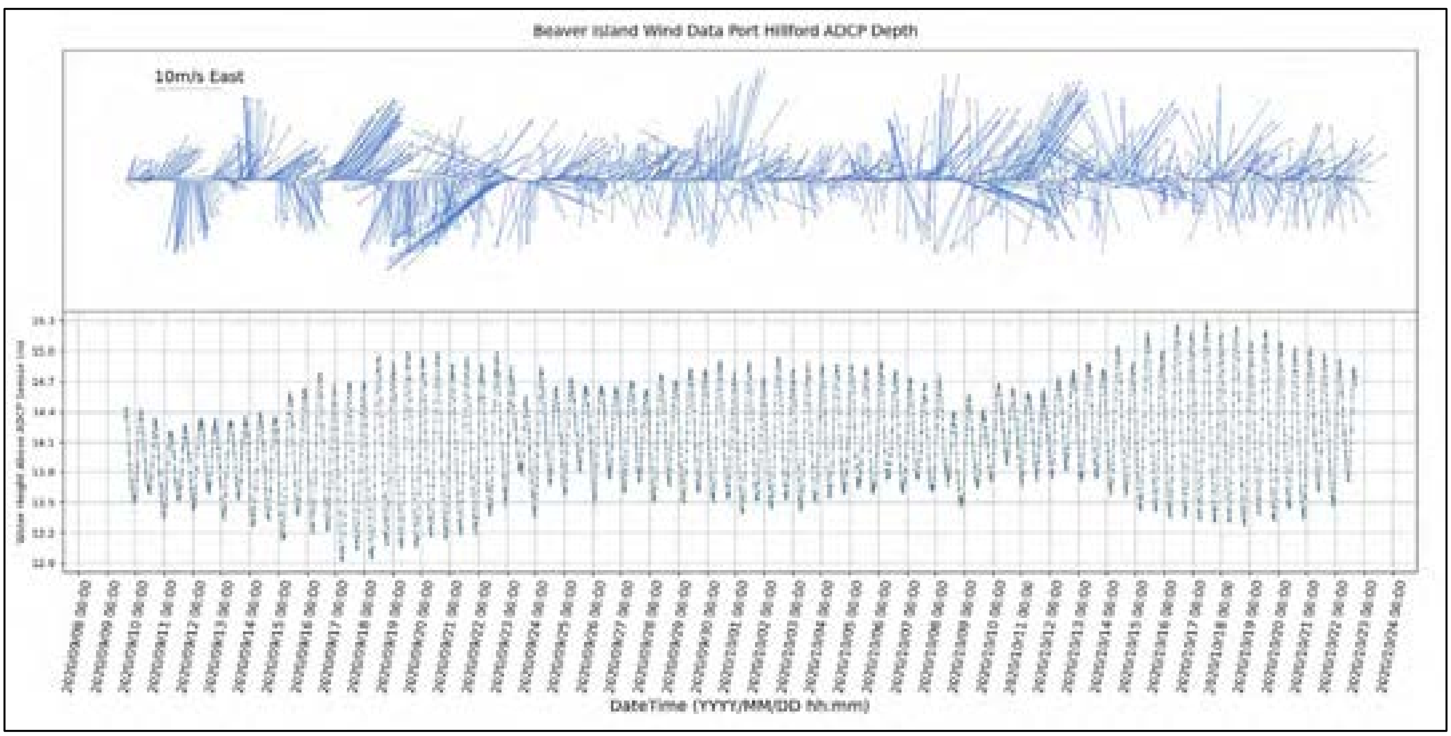


Figure 37 Wind and ADCP water levels. Top graph is the wind from ECCC Beaver Island weather station. Bottom graph is water level observed by the ADCP.

As mentioned earlier Hurricane Teddy approached the study site with strong winds Sept. 22-23, 2020 and made landfall early in the morning of Sept. 23, 2020 near Port Hilford with wind gusts over 100 km/hour. The hourly wind data available from ECCC for the Beaver Island weather station only reports winds reaching 76 km/hour on the night of the 22nd.

Figure 38 Track of Hurricane Teddy making land fall near Port Hilford and beaver Island. (Source CBC News).

Examination the ADCP water level and current velocities showed that there was not a significant storm surge associated with Hurricane Teddy making landfall, however the current speeds did increase significantly as the system approached Sept. 22-23, 2020 (Figure 39). Figure 39 represents frames that were extracted from the animation constructed by AGRG researchers to aid in visualizing the ADCP current and water level results in relation to wind speed and direction. The current speed was denoted by the x and y-axis in m/s, and the direction by the four cardinal points (N, E, S, W red lines and text) for each of the 50 cm bins within the water column and the average current velocity denoted by the green line and circle and the water level above the sensor denoted on the z-axis (m).

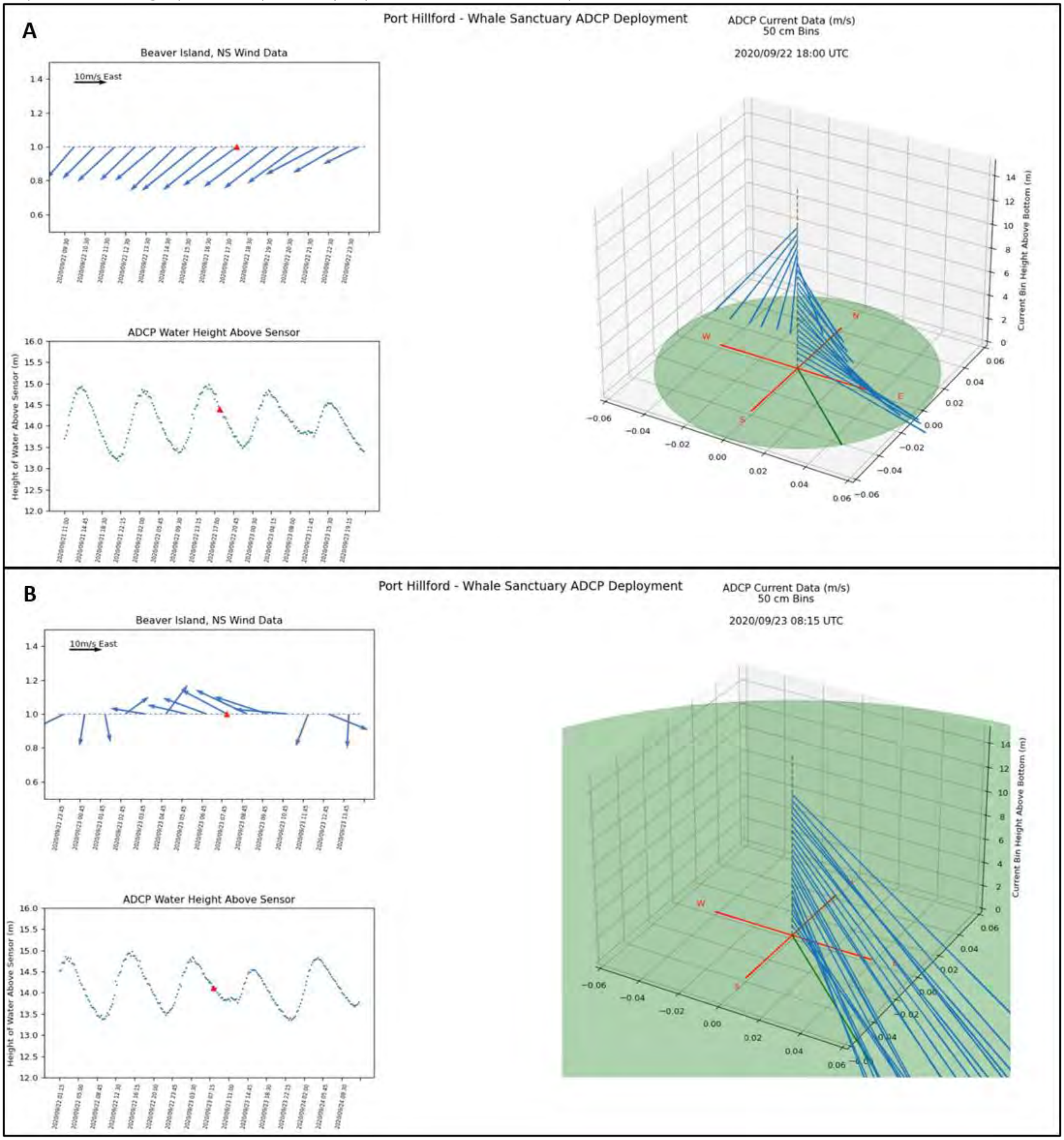


Figure 39 Example of wind, water level and current velocities during Hurricane Teddy. A- Sept. 22 strong northeast winds and currents on a falling tide. B- Sept. 23 winds have shifted to the southeast producing very strong currents on the falling tide.

6.2.2 Waves

Wind and the significant wave height were plotted together showing how strong winds can generate waves in Indian Harbour (Figure 40). Significant Wave Heights during Hurricane Teddy were in the order of 3.2 m as recorded by the

ADCP, with strong northeast winds recorded at the Beaver Island ECCC weather station. Another small event on Oct 14th where waves reached above 1.6 m in the harbour (Figure 40).

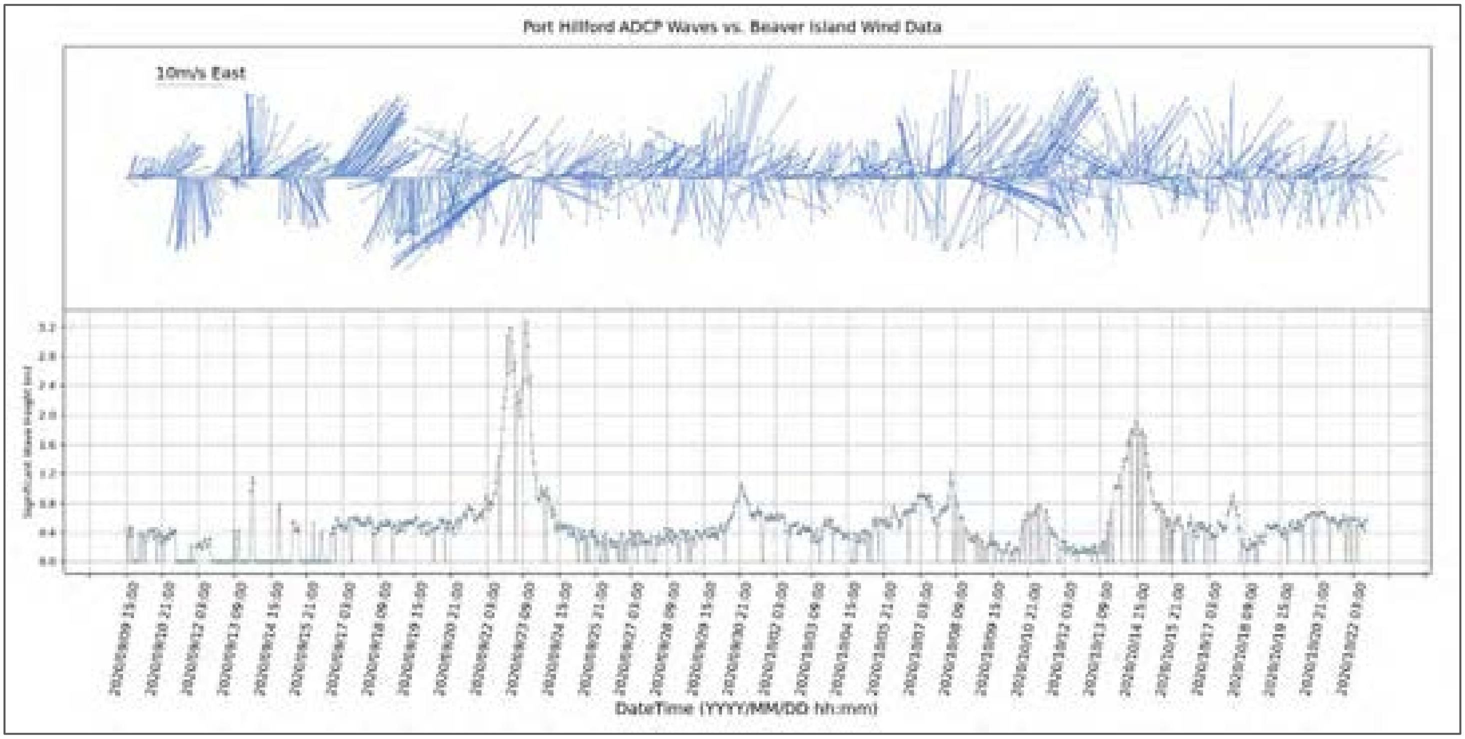


Figure 40 Wind plotted from Beaver Island weather station (top) and significant wave height from the ADCP (bottom) for September - October 2020.

Waves coming a shore of Port Hilford during Hurricane Teddy shown in Figure 41. These photos were taken by Dr. Amanda Babin.

Figure 41 Photos taken by Dr. Amanda Babin during hurricane Teddy (Sep 22, 2020).

6.3 **Hydrodynamic modelling**

Several map products were derived from the results of the hydrodynamic modelling including the flushing rate and the mean and maximum monthly currents.

Mike result plotted with U and V vectors shows the water movement during a high tide (Figure 42). Currents have a low magnitude in the Indian Harbour with comparatively high magnitudes closer to the land.

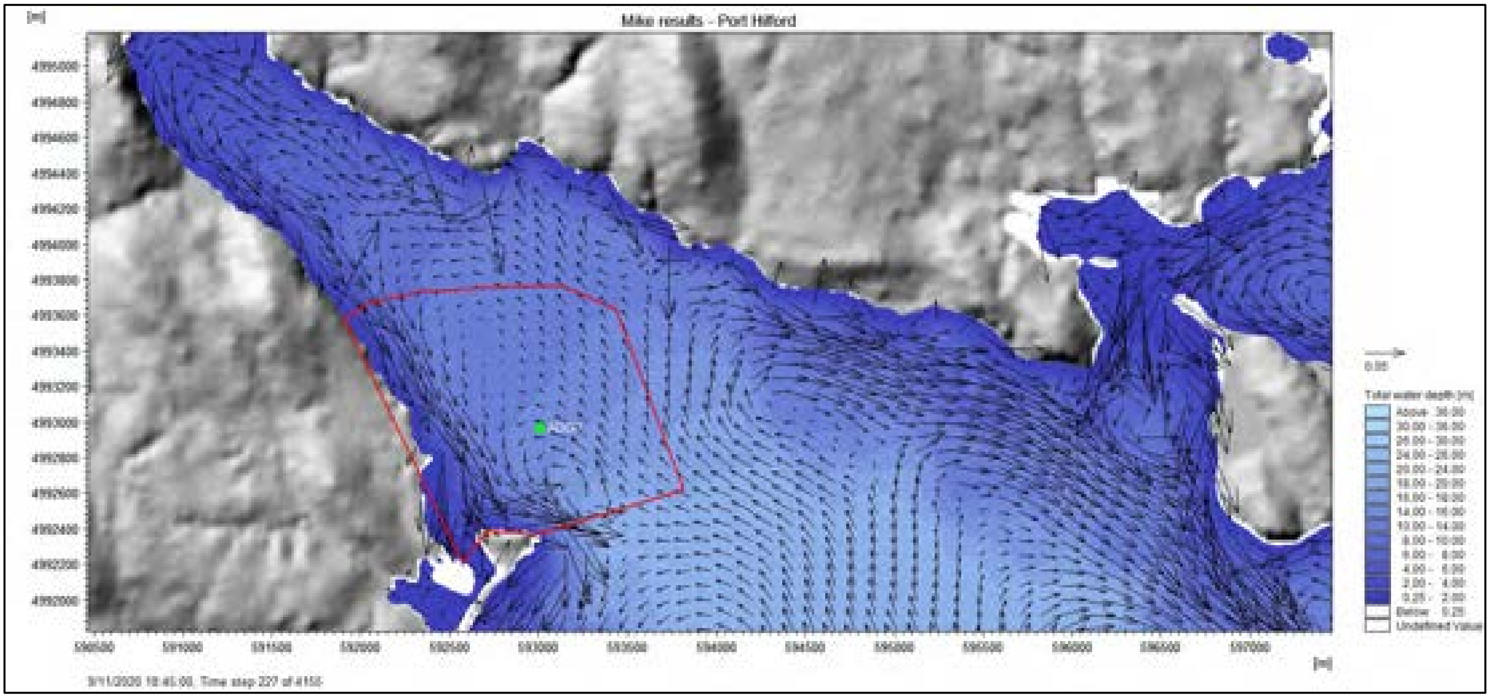


Figure 42 Mike result extraction at a high tide with U and V vectors plotted. Vectors are enlarged for visualization.

Mike result plotted with U and V vectors shows water circulation in the harbour during a low tide (Figure 43). Currents seem to move near the mouth of the water in a semi-circular form.

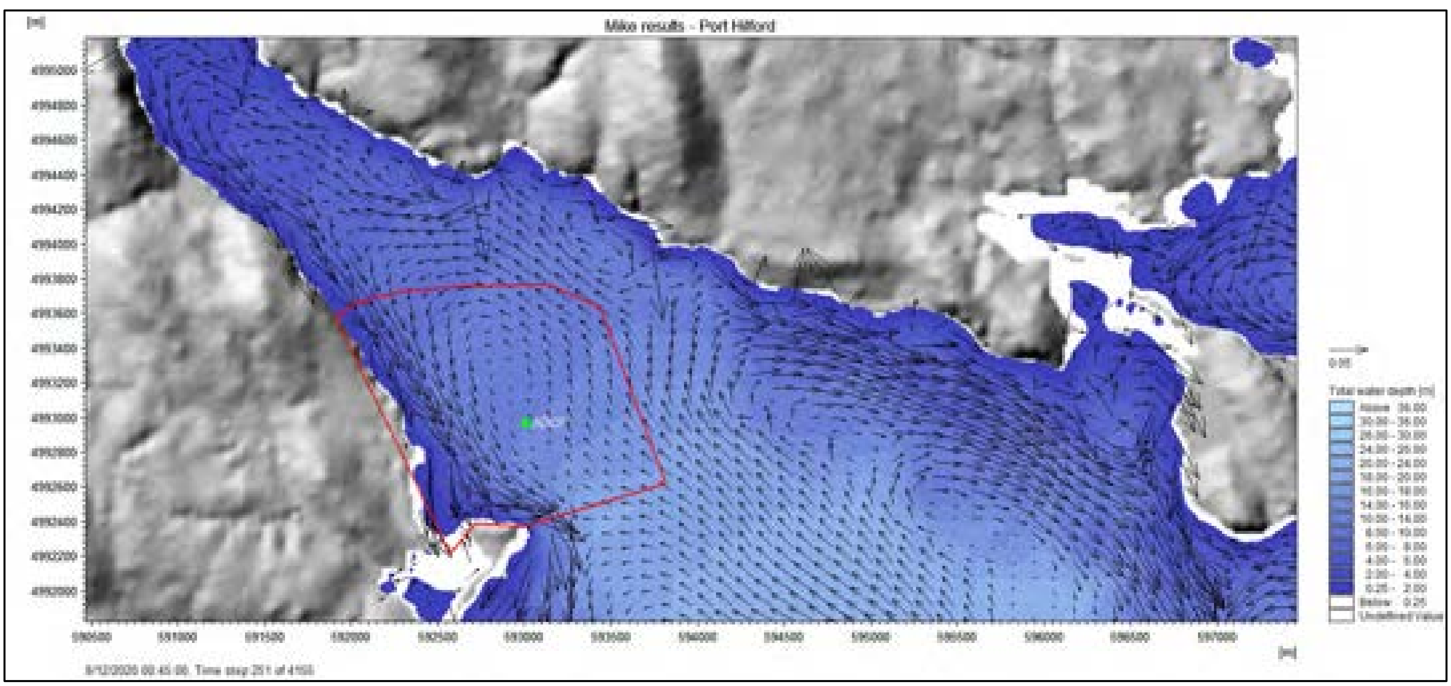


Figure 43 Mike result extraction at a low tide with U and V vectors plotted. Vectors are enlarged for visualization.

6.3.1 Flushing Rate

An initial proportional starting concentration of 1 was applied uniformly to the transport model which then ran for 1 month. The minimum concentration left in the harbour at the end of the model run indicated that the northern areas of Indian Harbour are flushed more slowly compared to the rest of the harbour (Figure 44).

The flushing rate shows that the mouth of the harbour (seaward) gets flushed faster than rest of the harbour. The classification of the flushing rate values represents five classes from very well flushed (0 - 20% concentration after one month), well flushed (20 - 40% concentration), 50% flushed (40 – 60% concentration), poorly flushed (60 – 80% concentration), and not flushed after one month (80 – 100% concentration) (Figure 45).

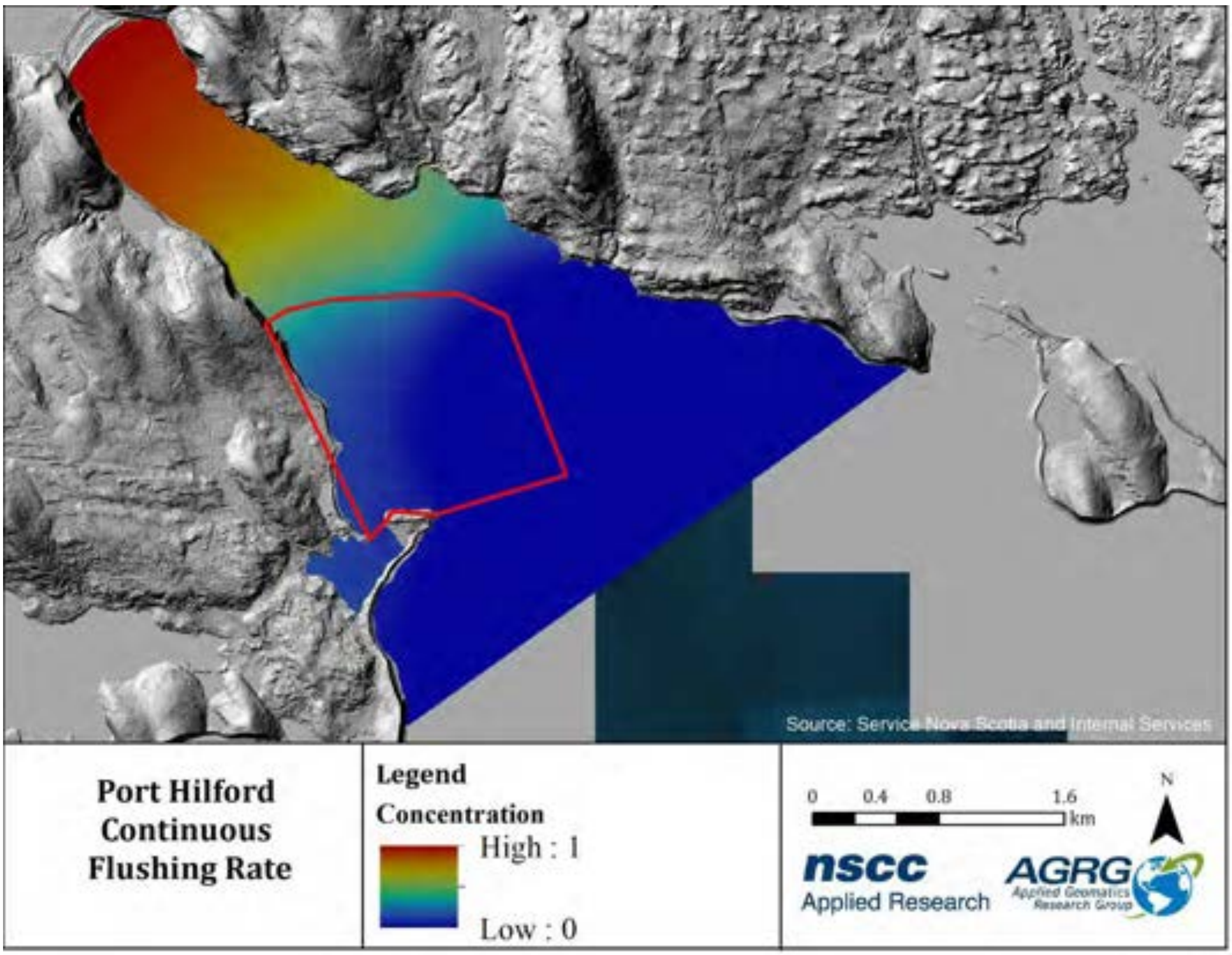


Figure 44 The continuous flush layer was generated from the minimum concentration left in the harbour after a 30-day simulation of the hydrodynamic model. The blue indicates faster flushing rates than the red areas. Red polygon is the study area.

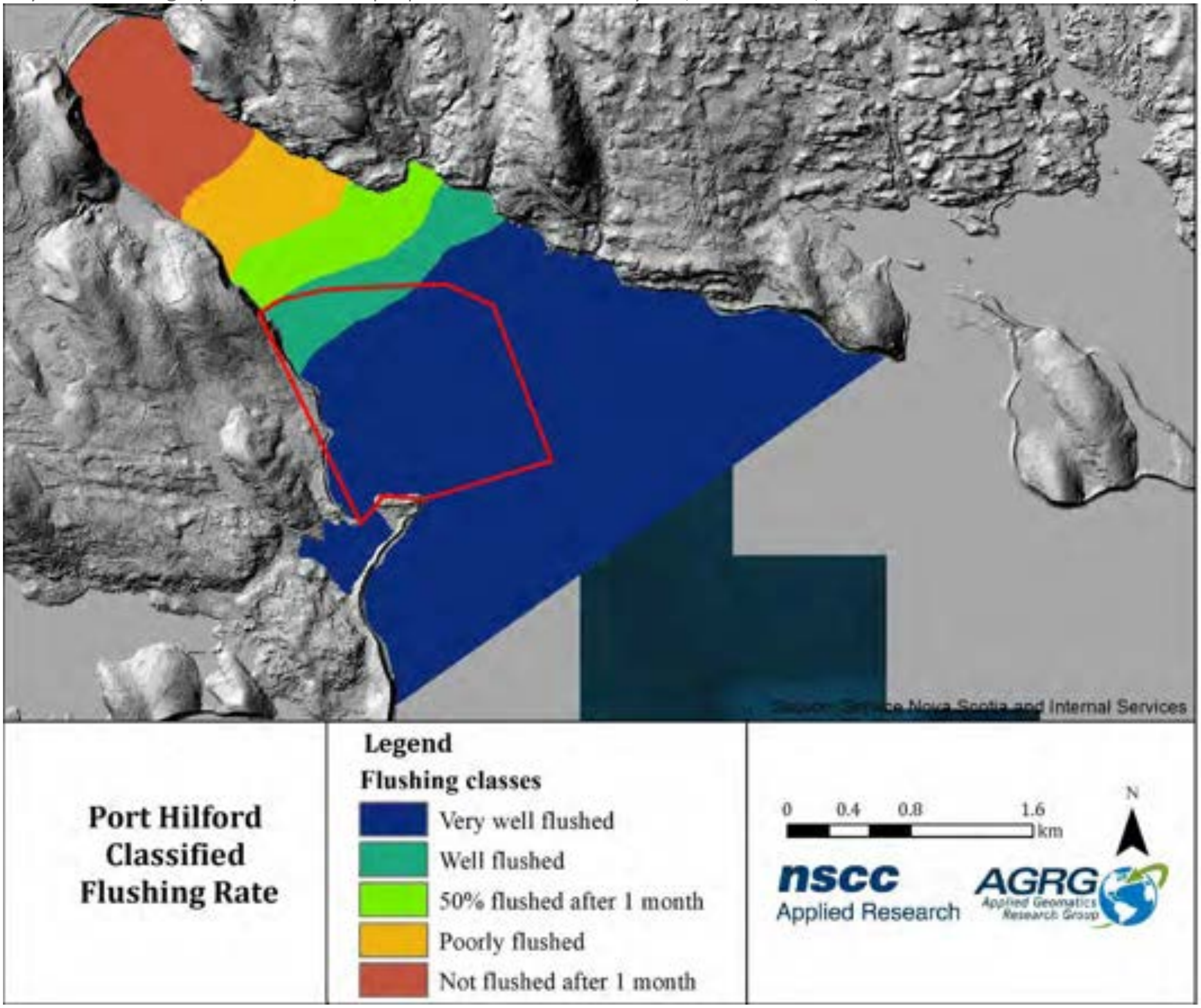


Figure 45 The minimum concentration left in the harbour after the hydrodynamic model simulation was classified into five flushing classes. Red polygon is the study area.

The concentration obtained from the transport simulation was multiplied by a value of 100 to represent the percentage of flushed water. A MATLAB script was developed to get the number of days such that only 1/e of particles present at day 1 of the simulation remained, where e is Euler's number, ~2.718. The flushing time associated with a concentration of 36.79 % of initial concentration is given in Figure 46. The mouth of the harbour (seaward) was flushed within the first day, while most of the study area was flushed within 15 days.

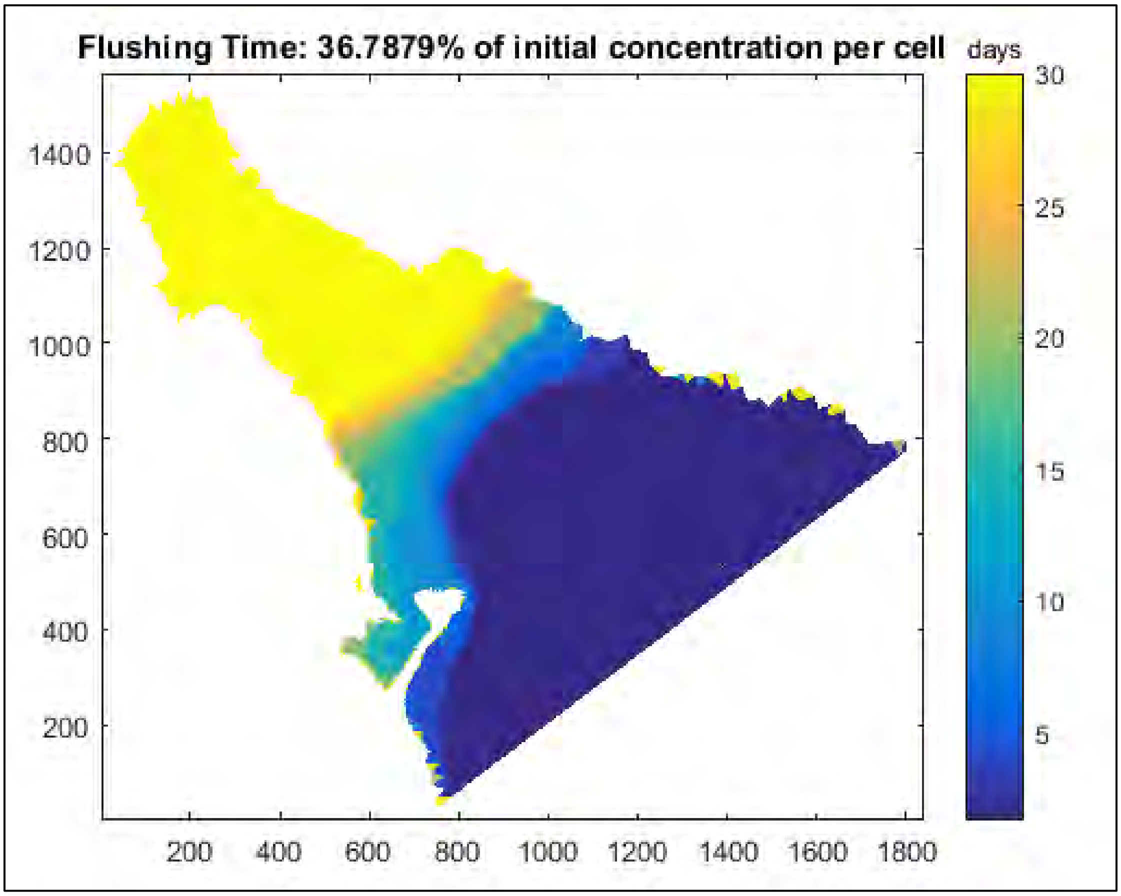


Figure 46 The number of days it takes for the harbour to be reach a concentration of ~37%.

6.3.2 Mean and Maximum currents

The mean current speed recorded at the ADCP location was 0.033 m/s and the hydrodynamic model simulation mean current speed was 0.030 m/s at this location, indicating good agreement between the model and ADCP. The mean current speed was high at the mouth of the Barachois Cove compared to rest of the study area (Figure 47). Current magnitudes were greatest near the coast and least in the deepest parts of the harbour.

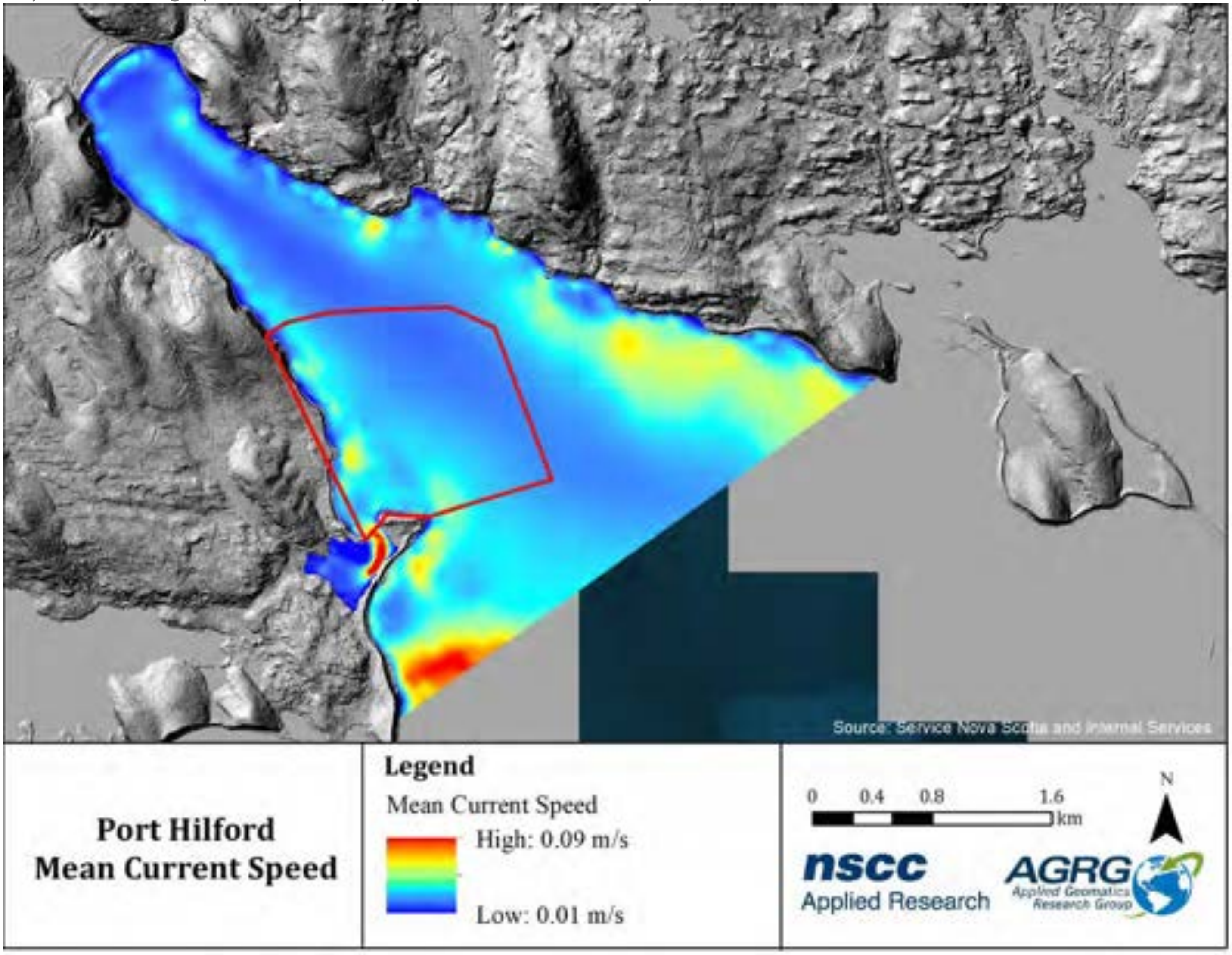


Figure 47 Mean of current magnitudes (m/s) during a 43-day simulation of the hydrodynamic model.

The maximum current speed occurred near the mouth of the Barachois Cove and reached 0.36 m/s during the simulation (Figure 48). Maximum current speed in the study area was about 0.16 m/s and exhibited a pattern similar to the average current speed with the fastest currents occurring near the shore compared to middle of the harbour.

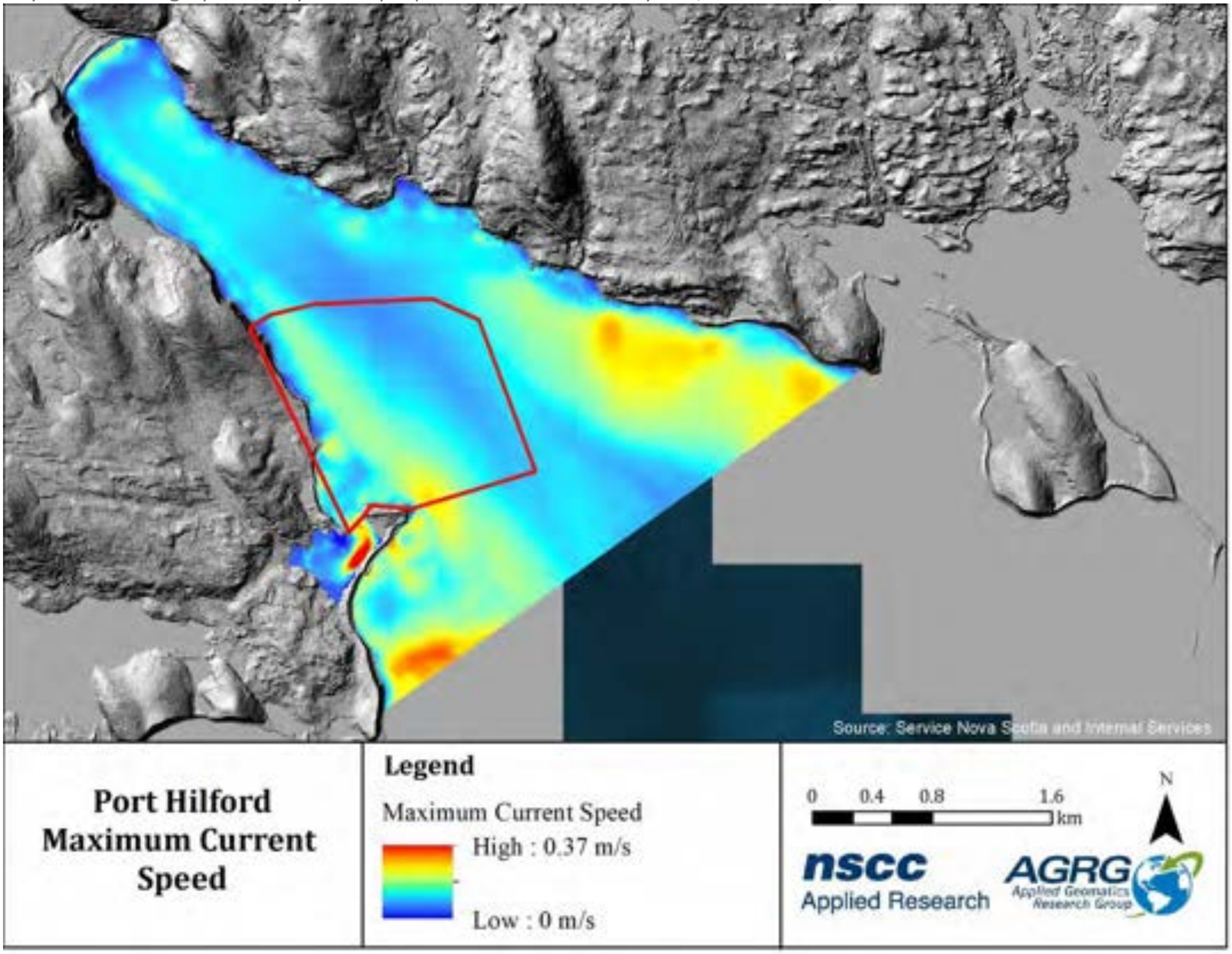


Figure 48 Maximum of current magnitudes (m/s) during a 43-day simulation of the hydrodynamic model.

7. Hydrodynamic model validation

Simulated water levels and depth averaged current velocities were extracted from the hydrodynamic model at the location of the ADCP for the duration of the deployment. These data were compared against the ADCP observations to validate the accuracy of the model. Simulated water levels matched ADCP observations for the majority of the deployment with a mean difference (residual) of 0.00 m and a standard deviation in the differences of 0.03 m (Figure 49).

The model slightly under predicted water level at high tide and over predicted water level at low tide. The residuals (ADCP – Mike simulated results) at high and low tide were less than 10 cm for majority of the deployment period except during Hurricane Teddy.

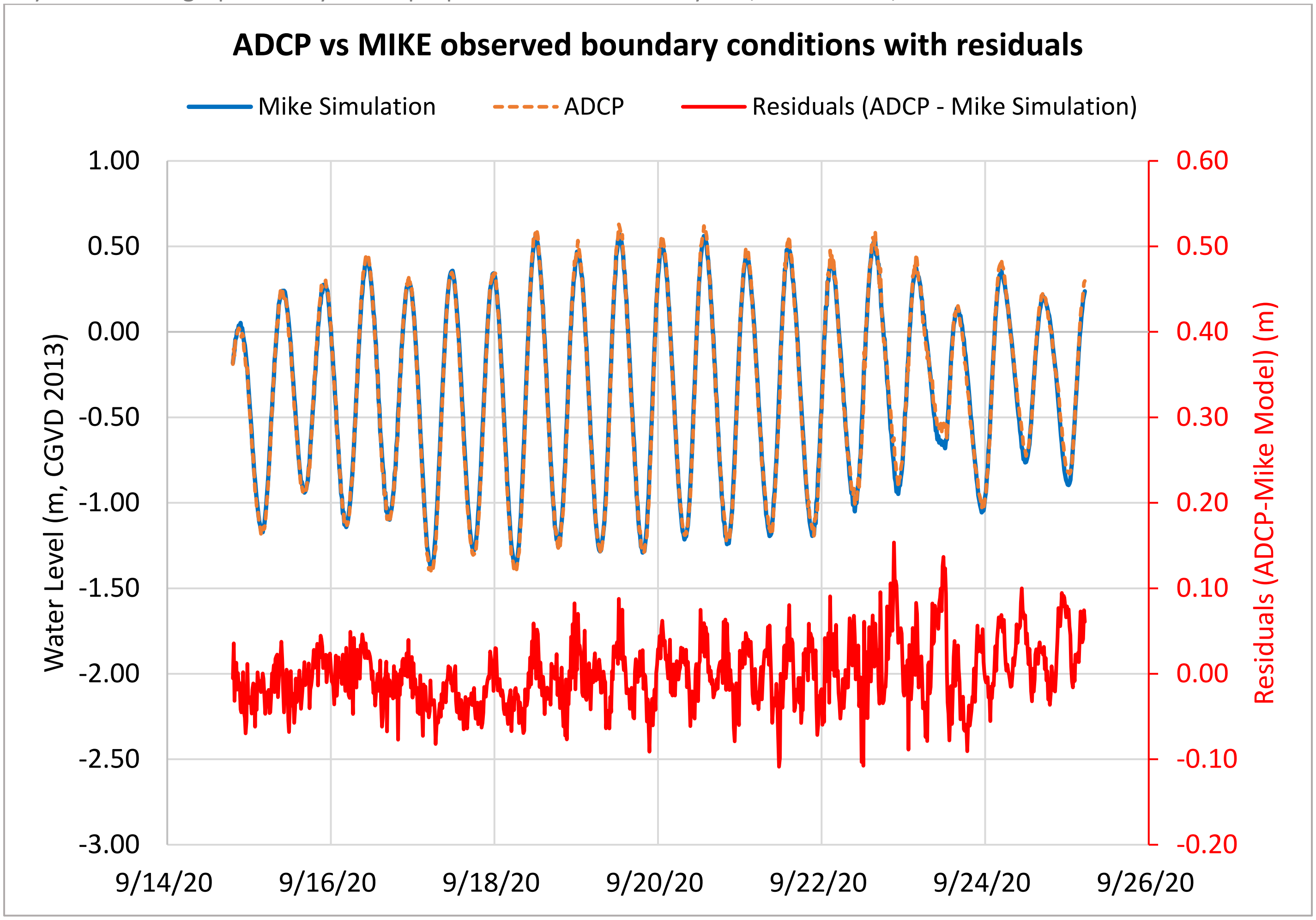
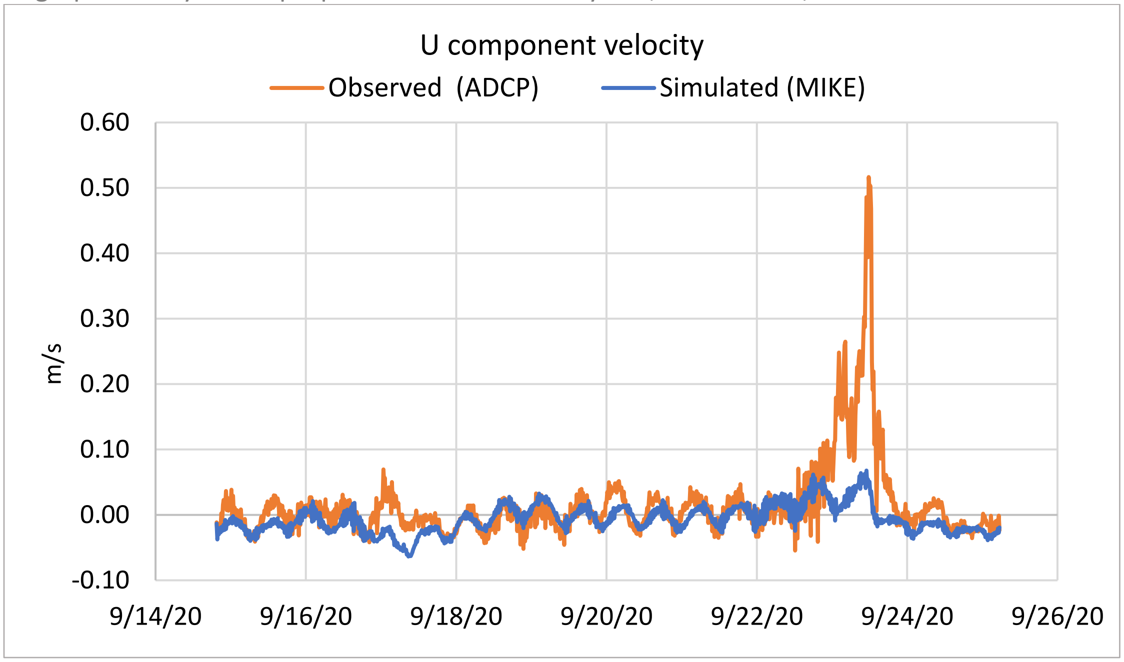


Figure 49 Mike simulated results compared to the ADCP observations.

The convention for representing vector data (magnitude and direction) is to break with vector unit up into their orthogonal x-y components. These have been defined as U and V respectively for X (east-west) and y (north-south) axis. A positive U indicates current speeds moving east while a negative U indicates a westerly direction. Similarly, a positive V indicates current speeds moving north while a negative V indicates a southerly direction. Comparing the current magnitudes and direction of the ADCP observations and the model results showed that the magnitudes matched well for the east-west directional component (U) better than the north-south component (V) (Figure 50). The model did not accurately capture the currents during Hurricane Teddy as shown on Figure 50. In general, the currents matched the observations from the ADCP enough to provide us confidence in our mean and maximum current speed calculations.



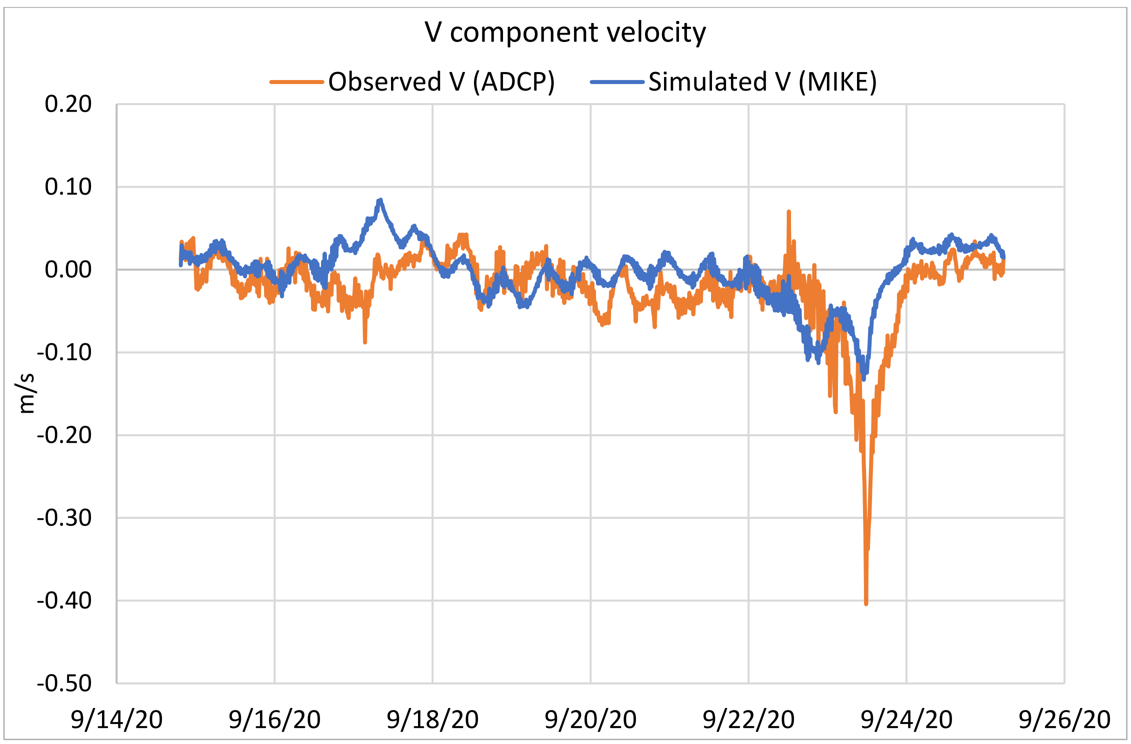


Figure 50 Observed versus simulated current speed in the east-west direction (U component) in the top graph. Observed versus simulated current speed in the north-south direction (V component) in the bottom graph.

8. Conclusion

This project has demonstrated the ability of a hydrodynamic model to accurately simulate current velocities, water levels and to derive a flushing rate for Indian Harbour. The model relied on accurate bathymetry which was obtained through a combination of a multibeam echo-sounding survey results for the proposed whale sanctuary site and supplemental sounding from CHS for the rest of the harbour and approaches. The model was driven with a set of boundary conditions consisting of the predicted tide from WebTide. These data were found to be slightly out of phase with water level observations obtained from an ADCP deployed in the study area, as a result, the predicted tide was modified for the boundary condition to account for this phase shift. The Sentinel-V ADCP was deployed for 43 days and collected information on waves, water levels and currents in 50 cm bins throughout the water column. When the modelled water levels were compared to those observed with the ADCP, a mean difference of 0.00 m with a standard deviation of 3 cm was calculated as a residual. The current speeds agreed well between the model and ADCP observations, with very good agreement for the U component and to a lesser degree the V component. The modelled currents deviated from those observed by the ADCP significantly during Hurricane Teddy on Sept. 22-23, 2020. No significant storm surge was observed in the ADCP water level data, however the current speeds increased dramatically during this event. The ADCP also measured waves during the deployment and the most significant wave heights of the deployment were measured during Hurricane Teddy with waves reaching 3.2 m in height. Additional information on the benthic zone was acquired through a series of grab and photo sampling. Substrate samples were acquired using an Eckman grab sampler and two GoPro cameras were installed on a quadrat with a 50 cm X 50 cm base to capture the seabed conditions. Most of the study site appears to be covered in sand with rocky reefs extending from the western shore seaward. A down-looking ADCP was towed along orthogonal transects through the study area at variable states of the tide to get an understanding of the variability of current speeds throughout the study site.

9. Acknowledgements

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