

## Advanced Coastal Mapping to Support Hydrodynamic Modelling: Final Report







Prepared by

Submitted to

Dr. Tim Webster & AGRG Team Applied Geomatics Research Group NSCC, Middleton Tel. 902 825 5475 email: <u>tim.webster@nscc.ca</u> CAPP OERA ECRC-SIMEC

April 31, 2017





How to cite this work and report:

Webster, T. 2017. "Advanced Coastal Mapping to Support Hydrodynamic Modelling: Final Report" Technical report, Applied Geomatics Research Group, NSCC Middleton, NS.

#### **Copyright and Acknowledgement**

The Applied Geomatics Research Group of the Nova Scotia Community College maintains full ownership of all data collected by equipment owned by NSCC and agrees to provide the end user who commissions the data collection a license to use the data for the purpose they were collected for upon written consent by AGRG-NSCC. The end user may make unlimited copies of the data for internal use; derive products from the data, release graphics and hardcopy with the copyright acknowledgement of **"Data acquired and processed by the Applied Geomatics Research Group, NSCC"**. Data acquired using this technology and the intellectual property (IP) associated with processing these data are owned by AGRG/NSCC and data will not be shared without permission of AGRG/NSCC.

### Table of Contents

Та	ble of	Con	tents	. iii			
Та	ble of	Figu	res	v			
Ex	Executive Summary1						
1	Intro	oduc	tion	. 2			
	1.1	Stud	dy Area	. 3			
2	Met	hods	· · · · · · · · · · · · · · · · · · ·	. 3			
	2.1	Sen	sor Specifications	. 3			
2	2.2	Lida	r Survey Details	. 5			
2	2.3	Gro	und Truth Data Collection	. 6			
2	2.4	Tim	e of Flight Conditions	13			
2	2.5	Aco	ustic Doppler Current Profiler (ADCP)	14			
2	2.6	Elev	vation Data Processing	19			
	2.6.	1	Lidar processing	19			
	2.6.	2	Ellipsoidal to Orthometric Height Conversion	22			
:	2.7	Bott	om Type Classification	22			
	2.8	Sho	reline Classification	25			
	2.9	Hyd	rodynamics and Particle Tracking	27			
	2.9.	1	Model Bathymetry Preparation	28			
3	Res	ults.	· · · ·	35			
	3.1	Lida	r Validation	35			
	3.1.	1	Topographic Validation	35			
	3.1.	2	Bathymetric Validation	36			
;	3.2	Surf	ace Models	36			
	3.2.	1	Digital Elevation Model	36			
	3.2.	2	Colour Shaded Relief	37			
	3.2.	3	Depth Normalized Intensity	40			
	3.2.	4	Air Photos	42			
	3.3	Gro	und Truth Maps	43			
	3.4	SA\	/ and Bottom Type Maps	45			
3.5 Shoreline Classification Maps		reline Classification Maps	50				
4	3.6	Hyd	rodynamic Model Results	56			
	3.7	Part	icle Tracking Model Results	58			
4	Disc	cussi	on and Conclusions	68			

5	References	70
7	Acknowledgements	70

### **Table of Figures**

Figure 1: The topographic-bathymetric lidar study area west of Halifax Harbour. (Basemap source: GeoNova Topographic Database and NRCan NTS map)	
në RCD30 camera system. The detail is sunicient to actually see the RiverRay instrument (inset image).	۱
Figure 8: Ground truth collection at Cow Bay in July 2016. (a) and (d) Ground truth imagery results from juadrat, (b) Submerged quadrat collecting ground truth imagery, (c) RiverRay field log sheet to show an example of field collection, (e) AGRG researchers establishing a base station over benchmark, (f) AGRG esearchers deploying RiverRay, (g) AGRG and ECRC field teams collaborating	
Figure 16: Observed surface elevation and depth averaged currents between July 13 and July 19 during a	3
nixed semidiurnal tidal phase	3
Figure 18: Example of the 20cm QA orthophoto mosaic used in the bottom classification	5
Figure 21 Example of input bands for shoreline classification (Note: the NDVI is not included in the figure).	
Figure 22 Model domain of the Cow Bay study area showing data sources and varying resolutions 29 Figure 23 Nested model domains at within the Cow Bay hydrodynamic model study area at 1:3 resolution Steps, D4: 243 m; D3: 81 m; D2: 27 m	) )

Figure 24 Nested model domains at within the Cow Bay hydrodynamic model study area at 1:3 resolution
Sieps, D2. 27 III, D1. 9 III, D0. 5 III.
Figure 25 Cow Bay high-resolution model domains to support particle tracking scenarios
rigure 20 Contaminant source location (red circle) used to simulate the fate of particles that reach the
Serve 27. The server big validation for Courd Day
Figure 27: Topographic validation for Cow Bay
Figure 28: Bathymetric validation for Cow Bay
Figure 29: Digital Elevation Model for Cow Bay, scaled to show bathymetry relief for the entire study area
with insets showing smaller features. Insets are matched to the larger figure by border colour
Figure 30: Colour Shaded Relief for the DSM at Cow Bay. The map is scaled to show bathymetry relief for
the entire study area with insets showing smaller features. Insets are matched to the larger figure by
border colour
Figure 31 Colour Shaded Relief for the DEM at Cow Bay. The map is scaled to show bathymetry relief for
the entire study area with insets showing smaller features. Insets are matched to the larger figure by
border colour
Figure 32 Cow Bay DSM of combined lidar and bathymetry from CHS
Figure 33 Top map is the direct amplitude-intensity image. The bottom map is the Depth Normalized
Intensity (DNI) image from the lidar
Figure 34: Depth Normalized Intensity model for Cow Bay. Typically, darker areas represent submerged
vegetation, while brighter areas represent sand. Insets are matched to the larger figure by the red border.
The top inset is the elevation model and the lower inset is the DNI
Figure 35: RCD30 Orthophoto Mosaic for Cow Bay with insets showing smaller features. Insets are
matched to the larger figure by border colour
Figure 36: Cow Bay underwater photo ground truth for the AGRG boat survey on July 6. Map is
symbolized to show cover type. Background image is RCD30 orthophoto RGB mosaic
Figure 37: Cow Bay underwater photo ground truth for the AGRG (ECRC boat) survey on July 6. Map is
symbolized to show cover type. Background image is RCD30 orthophoto RGB mosaic
Figure 38: Map showing submerged aquatic vegetation in Cow Bay where green represents presence.
Shown underneath the SAV data is the depth normalized intensity
Figure 39: Map showing submerged aquatic vegetation in Cow Bay where green represents presence.
Shown underneath the SAV data is the orthophoto RGB mosaic
Figure 40 Map showing submerged aquatic vegetation in Cow Bay with ground truth points. Where the
classification matched the ground truth presence and absence the points are circled. An agreement of
82.5% was achieved
Figure 41: Map showing bottom classification in Cow Bay. Shown underneath the SAV data is the depth
normalized intensity image
Figure 42: Map showing bottom classification in Cow Bay. Shown underneath the SAV data is the RGB
orthophoto mosaic
Figure 43: Map showing bottom classification in Cow Bay. Shown underneath the SAV data is the RGB
orthophoto mosaic
Figure 44 The map on the left is an example of the Environment Canada map depicting the shoreline. The
map on the right has been simplified to match the classes and colours of the Environment Canada map
and derived from the RCD30 and lidar data
Figure 45 A close up of the EC map and that derived in this study shows that EC only uses a line whereas
we have derived polygons covering the area. Also of note is the change in the tidal inlet position from the
EC map ca. 1997
Figure 46: Map showing shoreline classification in Cow Bay. Shown underneath the data is the RGB
orthophoto mosaic
Figure 47: Map showing shoreline classification near the tidal inlet in Cow Bay. Shown underneath the
data is the RGB orthophoto mosaic
Figure 48: Map showing shoreline classification in the tidal inlet at Cow Bay. Shown underneath the data

is the RGB orthophoto mosaic	
Figure 49: Map showing shoreline classification in Cow Bay. Shown underneath th	he data is the RGB
orthophoto mosaic	
Figure 50: Map showing shoreline classification adjacent to the tidal inlet in Cow E	Bay. Shown underneath
the data is the RGB orthophoto mosaic.	
Figure 51: Map showing shoreline classification within the saltmarsh at Cow Bay.	Shown underneath the
data is the RGB orthophoto mosaic.	
Figure 52: Comparison between modelled water depth and observed ADCP water	r depth over the July
Simulation period.	
rigule 55. Comparison between modelled depth-averaged current velocity and or	
Figure 54: Comparison between modelled denth-averaged current velocity and of	served ADCP current
velocity in the V vector	57
Figure 55: ADCP measured current magnitude and directions binned by depth sh	ow the complex
stratification of the bay over different moments of the tidal cycle noted by the red	circle above each of the
plots. The depth averaged magnitude and direction are noted by the red vector at	the bottom of each plot.
Figure 56: Heavy, medium and light oil dispersion from a simulated tanker approa	ch trail 17.5 hours after
release. Light oil dispersion (8 m <sup>2</sup> /s), class medium oil dispersion (4 m <sup>2</sup> /s), and cla	ass heavy oil dispersion
(2 m²/s)	
Figure 57: Heavy, medium and light oil dispersion from a simulated tanker approa	ich trail 46.75 hours after
release. Light oil dispersion (8 m <sup>2</sup> /s), class medium oil dispersion (4 m <sup>2</sup> /s), and cla	ass heavy oil dispersion
(2 M <sup>2</sup> /S)	
right 50. Light on dispersion from a simulated tarket approach train 7 hours after aradient represents the concentration of light oil (dispersion 8 $m^2/s$ )	felease. Coloui
Figure 59: Light oil dispersion from a simulated tanker approach trail 46 hours after	er release Colour
aradient represents the concentration of light oil (dispersion 8 $m^2/s$ ).	
Figure 60: Hydrodynamics within the Cow Bay area under the no wind condition.	A current magnitude of
0.2 m/s is represented by the legend vector on the right	
Figure 61: Hydrodynamics and particle distribution within the Cow Bay area after 2	2 hours under the no
wind condition. The orange to green color range represents the concentration of s	suspended particles, and
the purple gradient denotes the concentration of sedimented particles	
Figure 62: Hydrodynamics and particle distribution within the Cow Bay area after	71 hours under the no
wind condition. The orange to green color range represents the concentration of s	suspended particles, and
the purple gradient denotes the concentration of sedimented particles. Particles m	hade landfall after 14
Nours.	
magnitude of 1 m/s is represented by the legend vector on the right	condition. A current
Figure 64. Hydrodynamics within the isolated Cow Bay estuary under a 15 m/s on	shore wind condition A
current magnitude of 1 m/s is represented by the legend vector on the right.	
Figure 65: Hydrodynamics and particle distribution within the Cow Bay area after	71.25 hours under a 15
m/s onshore wind condition. The orange to green color range represents the cond	centration of suspended
particles, and the purple gradient denotes the concentration of sedimented particle	es. Particles made
landfall after 3 hours	
Figure 66: Hydrodynamics and particle distribution within the Cow Bay area after	1 hours under a 25 m/s
onshore wind condition. The orange to green color range represents the concentr	ation of suspended
particles. Particles made landfall after 0.25 hours	

#### **Executive Summary**

The objectives of this initial phase of the project were to utilize the NSCC's Chiroptera II topo-bathymetric lidar to capture detailed topography and imagery along the coastal zone and use it to better inform emergency preparedness officials of the conditions. The data acquired with this instrument allows for the construction of a high resolution seamless elevation model that transitions from the land into the sea. In addition to this seamless DEM that was derived from the lidar survey, high quality image data were acquired from two cameras: a 60 MPIX RCD30 capable of visible RGB and NIR and a 5 MPIX quality assurance camera. Staff from ECRC, who where instrumental in identifying the limitations and the lack of nearshore current information and accurate up to date maps on tidal inlets and other sensitive areas for oil spill preparedness, assisted in deploying an ADCP to collect water level and current data for one month to compare to model results. In addition ECRC's vessle and an AGRG vessel were deployed to collect ground truth data during the July 6 aerial campaign. These data consisted of bottom photographs, water clarity measures using a secchi disk, survey grade GPS bottom elevations and tidal inlet geometry and currents using a RiverRay ADCP. The seamless DEM was integrated with other bathymetry data to establish multiple domains and a hydrodynamic model was constructed that used the predicted tidal elevation as its boundary condition. The model used a nested grid and was scaled to a resolution of 3 m within the Cow Bay domain. The hydrodynamic model was validated against the bottom ACDP data for water levels and currents. Once satisfied with the hydrodynamics of the model, several particle tracking runs were simulated to estimate the trajectory of contaminants if a spill where to occur offshore. Characteristics of heavy, medium and light oil were initially used in the model. Only light oil was simulated for the local domain near Cow Bay where it was released approximately 2 km offshore and under normal tidal conditions took 14 hours to make landfall and impact the tidal inlet. This time was significantly reduced to only 3 hours when the model had a 30 knot landward wind imposed on it in order to visualize the effects of surface winds on the nearshore currents and the fate of the contaminants. The high resolution elevation data provided by the topo-bathymetric lidar survey allowed detailed currents to be generated nearshore to allow such simulations. In addition to the elevation and hydrodynamic models, the imagery and lidar were used to construct bottom and shoreline classified maps. The exposed shoreline materials where classified based on texture and spectral characteristics which allowed boulders and cobble to be separated from sand, which impacts the ability to clean such material if contaminated, as well as sensitive vegetated habitat. A full bottom classification of multiple submerged aquatic vegetation (SAV) and substrate types as well as a simplified SAV presence-absence map was derived with an 83% accuracy compared to ground truth data. This project has demonstrated the wide breadth of information products that can be derived from a single topo-bathymetric survey and demonstrated how these nearshore data can enhance our ability to model currents and predict the fate of contaminants and map the exposed and submerged materials to aid the spill preparedness community.

#### 1 Introduction

The Atlantic coast exhibits a variety of shorelines that may be vulnerable to contamination in event of an offshore spill. From an oil spill response perspective, protecting highly dynamic and biologically rich tidal inlets poses a particular challenge for responders compared to more accessible linear sections of the coast. Variable currents, changing water levels, shoals, and exposed seaside conditions together make effective response difficult for tidal inlets. Protecting tidal inlets is important, as the associated sheltered back bays often feature highly productive salt marsh and tidal-flat environments that are very sensitive to oil spills. Information related to tidal inlet morphology is limited or out-of-date, and no information regarding water current speeds and bathymetry is available to aid response organizations in planning to respond to a spill in this environment. This lack of information also presents risks to the health and safety of first responders with respect to secure access and safe navigation in light of shifting channels and shoals, unpredictable currents, etc. This project was designed to utilize new mapping technology to address these limitations and was funded by the Canadian Association of Petroleum Producers (CAPP) with contributions from Shell Canada, BP and the Offshore Energy Research Association (OERA) with in-kind support from Eastern Canada Response Corporation (ECRC), a marine oil spill response organization.

The ECRC provides marine oil spill response strategies and cleanup for most navigable waters east of the Rocky Mountains. They deliver planning, equipment, resources, and management for spill cleanups during both emergency response events and longer term remediation and rehabilitation projects. The ECRC had suggested that a more detailed understanding of nearshore bathymetry and current patterns would significantly aid in emergency spill planning and response. The primary outcome of this project was a more comprehensive knowledge of nearshore tidal inlet hydrodynamics. This will allow ECRC to more effectively contain and recover oil in the marine environment, before it makes landfall. This in turn results in cost savings while reducing health and safety risks. In order to generate detailed maps of the shallow nearshore zone where the use of traditional bathymetric methods is limited, Nova Scotia Community College (NSCC) has conducted a survey using an innovative airborne lidar system to collect surface and shallow submarine topographic data. We then used these bathymetric data in a hydrodynamic model to predict water movement (and by extension nearshore oil dispersion) adjacent to a complex marine tidal inlet system. A ground truthing campaign was conducted which involved the deployment of an Acoustic Doppler Current Profiler (ADCP) in Cow Bay for one month. In addition, two boats were employed to collect water clarity samples, seabed cover photos, and survey grade GPS seabed measurements, as well as to measure the current in the inlet using a RiverRay ADCP. Other areas along the south shore of Nova Scotia will be surveyed in future project phases, and these techniques applied.

#### 1.1 Study Area

The study area of Cow Bay was selected for the initial phase of this project for two main reasons: 1) it is a typical bay with a tidal inlet that connects the ocean to a sensitive salt marsh, and 2) its close proximity to Halifax to facilitate the involvement of ECRC staff and equipment for field work. AGRG researchers worked with ECRC staff and a vessel to deploy and retrieve the Acoustic Doppler Current profiler (ADCP) on the bottom and also conducted in-situ data collection during the lidar flight. The lidar and photo survey covered a larger area than depicted in Figure 1. The total area of the survey was 11.36 sqkm.



Figure 1: The topographic-bathymetric lidar study area west of Halifax Harbour. (Basemap source: GeoNova Topographic Database and NRCan NTS map)

#### 2 Methods

2.1 Sensor Specifications

The lidar sensor used in this study is a Chiroptera II integrated topographic-bathymetric lidar sensor equipped with a 60-megapixel multispectral camera. The system incorporates a 1064 nm near-infrared laser for ground returns and sea surface and a green 515 nm laser for bathymetric returns (Figure 2, Figure 3d). The lasers scan in an elliptical pattern, which enables coverage from many different angles on vertical faces, causes less shadow effects in the data, and is less sensitive to wave interaction. The bathymetric laser is limited by depth and clarity, and has a depth penetration rating of roughly 1.5 x the Secchi depth (a measure of turbidity or water clarity using a black and white disk). The Leica RCD30 60 mpix camera (Figure 3d) collects co-aligned RGB+NIR motion compensated photographs which can be mosaicked into a single image in post-processing, or analyzed frame by frame for maximum information extraction.



Figure 2: (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 Geosystems).



Figure 3: (a) Aircraft used for 2016 lidar survey; (b) display seen by lidar operator in-flight; (c) main body of sensor (right) and the data rack (left); (d) large red circles are the lasers; the RCD30 lens (right) and low resolution camera quality control (left).

#### 2.2 Lidar Survey Details

AGRG partnered with Leading Edge Geomatics to assist in the survey operations and arranging the aircraft (AGRG-NSCC does not own an aircraft, only the sensor). The lidar sensor was installed in the twin engine aircraft in Fredericton, NB and calibration flights were conducted over Fredericton at altitudes of 400m and 1000m. The lidar survey was conducted using the Chiroptera II sensor on July 6 2016. The survey was planned using Mission Pro software and was flown at an altitude of 400 m above ground. The aircraft required ground-based high precision GPS data to be collected during the lidar survey in order to provide accurate positional data for the aircraft trajectory. The Nova Scotia Active Control Stations (NSACS) network was used to provide geodetic control and a GNSS base station during the survey was used to process the trajectory of the survey aircraft (Figure 4). An additional Leica GS14 RTK GPS system was used to establish a local base station for real-time kinematic collection of ground truth data within the study area.

# 2016 OERA Flight Lines Cow Bay, NS





#### 2.3 Ground Truth Data Collection

Ground truth data collection is a crucial aspect of topo-bathymetric lidar surveys. In July 2016, AGRG researchers conducted traditional ground truth data collection including hard surface validation and depth measurements to validate the lidar, Secchi depth measurements for information on water clarity, and underwater photographs to

obtain information on bottom type and vegetation (Figure 5). Additional hard surface GPS points were collected for validation in September 2016 using the cellular active control network for precise GPS accuracy (Figure 5). During the July ground truth collection, the seabed elevation was measured directly using a large pole onto which the RTK GPS was threaded, in addition to manual measurements using a depth mate and a lead ball on a graduated rope, in addition to a commercial-grade single beam echo sounder. By threading the RTK GPS antenna on the pole and measuring the elevation of the seabed directly we eliminated errors introduced into depth measurements obtained from a boat such as those caused by wave action, tidal variation, and angle of rope for lead ball drop measurements. Table 1 summarizes the ground truth measurements undertaken for Cow Bay in 2016 and Figure 5 shows a map of the distribution of ground truth measurements.



Figure 5: Location of hard surface GPS validation points (green), and boat-based ground truth points from AGRG (red) and ECRC (blue), and ADCP deployment location at Cow Bay.

Date	Base Station (id) or *	GPS System (GS14 or 530/1200)	Secchi (Y or -)	Depth (see caption for options)	ADCP (Deployed, -, or Retrieved)	Underwater Photos (see caption for options)	Hard Surface GPS (Y or - )	RiverRay (Y or -)
Jun 29	204599	530	-	Ρ	-	-	-	Y
Jun 30	204599	GS14	-	-	Deployed	-	Y	-
Jul 06	204599	GS14,1200	Y	P,DM,M		Q <sub>50</sub>	-	Y
Sep 15	*	GS14	-	-	-	-	Y	-

Table 1: Ground truth data summary. Base Station Column: \* Indicates the Nova Scotia Active Control Stations (NSACS) cellular network was used. GPS Column: The Leica GPS systems used were the GS14, 530 and the 1200. Depth Column: P=GPS antenna threaded onto the large pole for direct bottom elevation measurement; M=manual depth measurement using lead ball or weighted Secchi disk; DM=handheld single beam DepthMate echo sounder. Underwater Photos: Q<sub>50</sub>=0.25 m<sup>2</sup> quadrat with downward-looking GoPro camera.

As mentioned in the ground truth summary above, on July 6 2016, AGRG researchers conducted ground truth data collection to coincide with the lidar survey. One field team deployed the RiverRay ADCP to capture the inlet cross-section and measure the flow (Error! Reference source not found.). The RiverRay ADCP is mounted in a small boat that is towed across the inlet channel to measure the cross-section and flow within the channel.



Figure 6: Quality Assurance (QA) camera mosaic in background of the tidal inlet at Cow Bay. Inset photos show the RiverRay (orange boat) being deployed across the channel.

Multiple transects were collected with the RiverRay and different locations along the tidal inlet channel. The system is equipped with a GPS receiver and measures the cross-sectional depth and flow for the channel (Figure 7).



Figure 7: RiverRay transect locations collected on July 6. Background image is the 5 cm orthophoto from the RCD30 camera system. The detail is sufficient to actually see the RiverRay instrument (inset image).

The ground truth collection by AGRG and ECRC boats on July 6 were successful in retrieving depth measurements, as well as gathering information on water clarity, bottom type and vegetation. Underwater photos were captured using a 0.25 m<sup>2</sup> quadrat with a downward-looking GoPro camera (Figure 8). The inset images show a presence of kelp and cobble, though these results will be highlighted further in Section 3.3. As mentioned above, RiverRay was deployed across the channel; Figure 8c illustrates the log sheet used by AGRG researchers during the RiverRay transect collections. It is important to document the transect number and start time as well as left and right banks, although the GPS can be used for positioning as well.



Figure 8: Ground truth collection at Cow Bay in July 2016. (a) and (d) Ground truth imagery results from quadrat, (b) Submerged quadrat collecting ground truth imagery, (c) RiverRay field log sheet to show an example of field collection, (e) AGRG researchers establishing a base station over benchmark, (f) AGRG researchers deploying RiverRay, (g) AGRG and ECRC field teams collaborating.

The variety of ground truth data collected in Cow Bay provides valuable data for the validating the lidar, as well as data to support other analyses such as bottom type and classification maps. Figure 9 illustrates the hard surface GPS points collected for validation in September 2016. The GNSS active control network was used for correction of the precise GPS survey data. These data were used to validate the vertical accuracy of the lidar DEM and can be found in the results section.



Figure 9: Additional hard surface validation points were collected in Cow Bay in September 2016.

Figure 10 illustrates the different types of ground-truth data that were collected including precise GPS measurements of the seabed, Secchi depth locations, quadrat photos of the seabed cover material as well as some inset photos showing examples of the quadrat photos and the ADCP location. The background map is a colour shaded relief image derived from the lidar survey (Figure 10). The inset photos of the pole and quadrat are shown from the GoPro's perspective, as well as the deployed Secchi disk. Additional maps and ground truth results are highlighted in Section 3.3.



Figure 10: An overview example of ground truth data collected. Results are further discussed in the section below.

#### 2.4 Time of Flight Conditions

Meteorological conditions during and prior to topo-bathy lidar data collection are an important factor in successful data collection. As the lidar sensor is limited by water clarity, windy conditions have the potential to stir up any fine sediment in the water and prevent laser penetration. Rain or fog are not suitable for lidar collection, and the reflection from the water (sun glint) must also be factored in for the collection of aerial photography. Before each lidar survey, we primarily monitored weather forecasts using four tools: the Environment Canada (EC) public forecast (<u>http://weather.gc.ca/</u>) (Figure 11); EC's Marine Forecast (<u>http://weather.gc.ca/marine/index\_e.html</u>); SpotWx (<u>www.spotwx.com</u>), which allows the user to enter a precise location and choose from several forecasting models of varying model resolution and forecast length; and the predicted fog for the lidar survey provided to AGRG every eight hours. Each of these tools had strengths and weaknesses and it was through monitoring all four that a successful lidar mission was achieved. For example, the customized EC forecast was the only tool that provided a fog prediction, on an hourly basis. However, the SpotWx graphical interface proved superior for wind monitoring. Only the EC public forecast alerted us to Weather

Warnings that were broadcast in real-time, such as thunderstorms, and the marine forecast provided the only information for offshore conditions. EC Canadian Marine Warning Program has 4 different threshold categories of wind warnings; strong wind warnings, issued when wind speeds of 20-30 knots are occurring or are expected, gale warnings, issued when wind speeds of 34-47 knots are occurring or are expected, storm warnings, issued when wind speeds of 48-63 knots are occurring or are expected, and hurricane force winds, issued when winds of 64 knots or greater are occurring or are expected. (Environment Canada, 2014) Weather leading up to the survey was fairly steady with winds blowing to the North. Weather during the survey was overcast with 9-12 knot winds.



Figure 11: Weather preceding and during the Cow Bay lidar survey. (a) Wind speed and (b) direction collected at the EC weather station at Halifax between June 30 and July 8, 2016 at 1-hr intervals. Panel (c) shows a vector plot of the wind, where the arrows point in the direction the wind is blowing, and the red box indicates the lidar survey duration. Panel (d) shows predicted tide at Cow Bay. The pink solid line represents the time of the survey that occurred on July 06.

#### 2.5 Acoustic Doppler Current Profiler (ADCP)

A Teledyne RDI Sentinel V20 1000 kHz Acoustic Doppler Current Profiler (ADCP) was deployed at Cow Bay by AGRG and ECRC field teams on June 29th to measure current speed and direction for a minimum of one month (Figure

12). On the day of the deployment, the weather was quite foggy, as can be seen in the inset photos in Figure 13. The ADCP was retrieved on July 29, 2016. The current data were obtained for hydrodynamic model validation. Water level data from the ADCP were also compared to the CHS predicted tide and the surface elevation of the ADCP agreed fairly well to the predicted tide. The tidal range was about 2m (Figure 14). The ADCP current was influenced by tidal circulation, as can be seen in Figure 15 and Figure 16. Currents ranged from 0.05 to -0.05 m/s in both the north-south and east-west directions (Figure 16). The vertical structure and magnitude of the currents varied throughout the tidal cycle, though the ADCP currents in the north-south direction were more consistent with the tidal cycle, rather than the currents in the east-west direction. Currents were generally stronger during the higher tide and lower in the lower tide, however in the east-west direction, currents varied from the tide much more. As an example, during the high tide on July 14, currents were weak in the east-west direction, inconsistent with the high tide, while the north-south currents were stronger, consistent with the high tide. The range in directions at that point in the tidal cycle was about 1m (Figure 16).



Figure 12: Location of ADCP in Cow Bay and the route taken to deploy the ADCP. The white polygon represents the Cow Bay study area, Google Earth background image.

# ECRC Assisted in ADCP deployment

June 29 retrieved July 29, 2016

Establish GPS base station for survey grade RTK positioning



Figure 13: ECRC boat deploying ADCP in Cow Bay on June 29, 2016. Note foggy weather conditions pictured in upper left inset photo taken from the road looking towards the bay.



Figure 14: Example of water level measured by the ADCP (red line) compared with the CHS predicted tide (blue line) throughout the ADCP deployment in July 2016.



Figure 15: Current speeds over time (x-axis) and depth (y-axis, measured as range from ADCP) for East-West currents (top panel) and North-South currents (bottom panel). Colours indicate magnitude and direction.



Figure 16: Observed surface elevation and depth averaged currents between July 13 and July 19 during a mixed semidiurnal tidal phase

#### 2.6 Elevation Data Processing

#### 2.6.1 Lidar processing

#### 2.6.1.1 Point Cloud Processing

Once the GPS trajectory was processed for the aircraft using the Nova Scotia Active Control Stations (NSACS) network as a base station, where the aircraft GPS observations were combined with the inertial measurement unit to determine the trajectory in Inertial Explorer. Once determined the navigation data was linked to the laser returns and they were georeferenced. Lidar Survey Studio (LSS) software accompanies the Chiroptera II sensor and was used to process the lidar waveforms into discrete points. These data were then inspected to ensure sufficient overlap between flight lines (30%) and that no gaps existed in the lidar coverage.

Integral to the processing of bathymetric lidar is the ability to map the water surface. The defined water surface is critical for two components of georeferencing the final target or targets that the reflected laser pulse recorded: the refraction of the light when it passes from the medium of air to water and the change in the speed of light from air to water. The LSS software computes the water surface from the lidar returns of both the topo (NIR) and bathy (green) lasers. In addition to classifying points as land, water surface or bathymetry, the system also computes a water surface that ensures the entire area of water surface is covered regardless of the original lidar point density. As previously mentioned, part of the processing involves converting the raw waveform lidar return time series into discrete classified points using LSS signal processing. Waveform processing may include algorithms specific to classifying the seabed. The points were examined in LSS both in planimetric and cross-section views. The waveforms for each point can be queried so that the location of the waveform peak can be identified and the type of point defined, for example water surface and bathymetry.

The LAS files, the file type output from LSS, were then read into TerraScan<sup>™</sup> with the laser returns grouped by laser type so they could be easily separated, analyzed and further refined. Because of the differences in the lidar footprint between the topo and bathy lasers, the bathy points are derived from the bathy green laser and the topo points that represent targets on the land were derived from the topo NIR laser. See Table 2 and the attached Data Dictionary report for the classification codes for the delivered LAS 1.2 files. The refined classified LAS files were read into ArcGIS<sup>™</sup> and a variety of raster surfaces at a 1 m spatial resolution were produced.

Class number	Description
0	Water model
1	Bathymetry (Bathy)
2	Bathy Vegetation
3	N/A
4	Topo laser Ground
5	Topo laser non-ground (vegetation & buildings)
6	Hydro laser Ground
7	Bathy laser non-ground
8	Water
9	Noise
10	Overlap Water Model
11	Overlap Bathy
12	Overlap Bathy Veg
13	N/A
14	Overlap Topo Laser Ground
15	Overlap Topo Laser Veg
16	Overlap Bathy Laser Ground
17	Overlap Bathy Laser Veg
18	Overlap Water
19	Overlap Noise

Table 2. Lidar point classification Codes and descriptions. Note that 'overlap' is determined for points which are within a desired footprint of points from a separate flight line.

#### 2.6.1.2 Gridded Surface Models

There were three main data products derived from the lidar point cloud. The first two were based on the elevation and include the Digital Surface Model (DSM), which incorporates valid lidar returns from vegetation, buildings, ground and bathymetry returns, and the Digital Elevation Model (DEM) which incorporates ground returns above and below the water line. The third data product was the intensity of the lidar returns, or the reflectance of the bathy laser. The lidar reflectance, or the amplitude of the returning signal from the bathy laser, is influenced by several factors including water depth, the local angle of incidence with the target, the natural reflectivity of the target material, the transmission power of the laser and the sensitivity of the receiver.

#### 2.6.1.3 Depth Normalization of the Green Laser Amplitude

The energy that is transmitted into the water column by the green laser is exponentially lost with depth. The amplitude of the returning signal from the bathy laser provides a means of visualizing the seabed cover. However, the raw amplitude data are difficult to interpret because of variances as a result of signal loss due to the attenuation of the laser pulse through the water column at different scan angles and depths. Gridding the amplitude value from the bathy laser results in an image with a wide range of values that are not compensated for depth and have significant differences for the same target depending on depth and the local angle of incidence from flight line to

flight line. As a result, these data are not suitable for quantitative analysis and are difficult to interpret for qualitative analysis. A process has been developed to normalize the amplitude data for signal loss and is reported in a recent publication (Webster et al., 2016). The process involved sampling the amplitude data from a location with homogeneous seabed cover (e.g., sand or eelgrass) over a range of depths. These data were used to establish a relationship between depth and the amplitude value (Figure 17). The inverse of this relationship was used with the depth map to adjust the amplitude data so that they could be interpreted without the bias of depth. This map is referred to as a depth normalized intensity (DNI) image, is more consistent in tone, and can be interpreted for the seabed cover material. Note that this analysis considers only bathymetric lidar values and ignores any topographic lidar returns.



## Figure 17 Distribution of amplitude or lidar intensity values of the green laser with respect to depth for Cow Bay.

#### 2.6.1.4 Aerial Photo Processing

The RCD30 60 MPIX imagery were processed using the aircraft trajectory and direct georeferencing. The low altitude and high resolution of the imagery required that the lidar data be processed first to produce bare-earth

digital elevation models (DEMs) that was used in the orthorectification process. The aircraft trajectory, which combines the GPS position and the IMU attitude information into a best estimate of the overall position and orientation of the aircraft during the survey is required for this process. This trajectory, which is linked to the laser shots and photo events by GPS based time tags, is used to define the Exterior Orientation (EO) for each of the RCD30 aerial photos acquired. The EO, which has traditionally been calculated by selecting ground control points (x, y, and z) locations relative to the air photo frame and calculating a bundle adjustment; however, in this case it was calculated using direct georeferencing and exploiting the high precision of the navigation system. The EO file defines the camera position (x, y, z) for every exposure as well as the various rotation angles about the x, y and z axis known as omega, phi and kappa. The EO file along with a DEM was used with the aerial photo to produce a digital orthophoto. After the lidar data were processed and classified into ground points, the lidar-derived DEM (above and below the water line) was used in the orthorectification process in Erdas Imagine software and satisfactory results were produced.

The 5 MPIX Quality Assurance (QA) camera were also processed and georeferenced in a similar fashion as with the RCD30 photos. Although the resolution of the orthophotos of the QA camera is less than the RCD30, 20 cm as compared to 5 cm, the QA photos provide excellent information over water for the water column and seabed.

#### 2.6.2 Ellipsoidal to Orthometric Height Conversion

The original elevation of any lidar product are referenced to the same elevation model as the GPS they were collected with. This model is a theoretical Earth surface known as the ellipsoid, and elevations referenced to this surface are in ellipsoidal height (GRS80). To convert them to orthometric height (OHt), which is height orthogonal to the geoid we utilize a geoid-ellipsoid separation model. In this case the elevations were corrected to the Canadian Geodetic Vertical Datum of 1928 (CGVD28) based on the geoid-ellipsoid separation model, HT2, from Natural Resources Canada.

#### 2.7 Bottom Type Classification

The full cover types and the submerged aquatic vegetation (SAV) maps were derived from the lidar and QA orthophotos. The layers used included the water depth derived from the DEM and water surface at the time of flight, depth normalized intensity, and arithmetic combinations of the true-color QA camera orthophoto mosaic. As mentioned, the 20 cm QA photos provide a more consistent level of detail in the water than the RCD30 photos, so the QA photos were used in the seabed mapping (Figure 18). Ratios of the different RGB band differences and their sums were utilized in similar fashion as a traditional Normalized Difference Vegetation Index (NDVI) using red and NIR imagery. The bottom cover map represents an index of vegetation presence that is then further

interpreted for bottom vegetation type and substrate type. This complex map was then simplified to produce a simpler Submerged Aquatic Vegetation (SAV) as well. This method was used to classify the material that were submerged during the survey.





Another classification method focused on the exposed shoreline material that may be vulnerable to contamination in the event of a spill. Here, texture and spectral details of the RCD30 imagery were used to classify the beach materials, which included true colour (Figure 19), and NIR false colour (Figure 20) and the details are discussed below.



Figure 19: Example of the RCD30 orthophoto mosaic in true colour RGB.





#### 2.8 Shoreline Classification

Shoreline substrates, such as cobble and sand, are defined by their grain sizes rather than their chemical compositions. This is due to the fact that they are typically derived from the same parent materials. As such, their spectral characteristics are quite similar and cannot be used as the sole basis for a robust classification. In order to achieve the latter, it is necessary to take image texture into account as well. In this analysis, image texture was quantified by means of a line density filter. In natural imagery, lines appear at the boundaries of objects (ex. boulders) and as such are analogous to edges. Theoretically, larger and brighter materials (ex. cobble) will produce stronger edges than finer ones (ex. sand), allowing them to be differentiated. This edge density raster was produced in the following way. Firstly, a series of line detectors were convolved over the image, detecting all lines oriented at 0, 45, 90, and 125 degree angles in the RCD30 imagery. This produced 4 different rasters per image frame, each representing the intensity of the edges in the image that shared that specific orientation.

These four rasters were averaged on a cell-by-cell basis and smoothed using a 9x9 mean filter to produce the final edge density raster. Iterating the line detector over different angles was necessary in order to ensure that the edge density metric was rotation-invariant, and as such sufficiently robust for use in the subsequent classification. A Normalized Difference Vegetation Index (NDVI) layer was also derived from the RCD30 imagery and included in the classification, which is calculated from the NIR and red bands. Firstly, it was used as a mask to narrow down the spatial extent of the region to be classified. Any image region with an NDVI above 0.40 was assumed to be vegetation and was therefore removed from further analysis. This greatly reduced the amount of data that needed to be processed, speeding up the analysis significantly. Once the image had been classified statistically, these high NDVI regions were defined as vegetation and appended to the classified image.

The NDVI was also included in the classification. The rationale for this was as follows. Firstly, rocky materials have low NDVIs whereas vegetation tends to have very high NDVI values. As such, NDVI provides a concise descriptor of the amount of rocky material that is exposed in regions with vegetation cover (ex. swash zone). Rocky materials with vegetation on them tend to appear darker, and as such have weaker edges than they would without it. As such, based on the texture alone cobble with vegetation on it could statistically be closer to dry pebbles than it would be to dry cobble. Adding the NDVI takes this phenomenon into account, increasing the reliability of the classified results.

The NDVI and edge density rasters were then used in conjunction with multispectral RCD30 imagery bands in the context of a supervised Maximum Likelihood classification (**Figure 21**). In order to account for illumination changes over the course of the aerial survey, this classification was done on a per-flightline basis. This assumes that light and water conditions were unlikely to change significantly over the period of time needed to fly a single flightline. As such, the frames collected during a flightline are more similar in those respects to one another than they are to the frames of other flightlines. This greatly reduced the number of artifacts in the final classification, particularly if the imagery was acquired in variably cloudy conditions. One of the limitations of this approach was that it was difficult to reliably differentiate bedrock from similar classes. For example, very smooth bedrock was commonly confused for sand whereas rough bedrock was often mistaken for boulders. As such, the bedrock class was removed from the classification and outcrops of that nature were digitized manually.



Figure 21: Example of input bands for shoreline classification (Note: the NDVI is not included in the figure).

#### 2.9 Hydrodynamics and Particle Tracking

Hydrodynamic (HD) models have been developed to predict the dispersion of contaminants within marine systems. These models are often not applicable in nearshore areas with complex hydrology due to a lack of suitable input data within the shallow coastal zone. However, it is precisely these areas where it is necessary to predict the dispersion of nearshore contaminants since they may enter bays and inlets that contain sensitive habitat that would be negatively impacted if the contaminants were to make landfall.

A high-resolution 2-D hydrodynamic (HD) model was developed using the DHI Mike-21<sup>™</sup> software module to simulate current flow and water level variations within the Cow Bay area. The Mike software includes the capability to simulate the transport and fate of dissolved and suspended substances discharged or accidentally spilled within the model domain. The required model inputs included a bathymetric surface and tidal predictions at the model boundaries that are described in detail in sections below. The domain of the bathymetric surface was designed to be large enough to simulate circulation within a large region around the area of interest. This regional approach helped to reduce errors inherent in the coarse tidal predictions.

#### 2.9.1 Model Bathymetry Preparation

A bathymetric surface model was developed to be used as an input to constrain 2D free-surface flow calculations. The surface was interpolated from the highest resolution bathymetric data available within the model domain. These data were from various sources and were collected at several resolutions (Table 3, Figure 22).

Provider	Data Source	Resolution
AGRG/CHS	LIDAR	3 m
NSDNR	Rasterized 1:10 000 Contour Data	20 m
CHS	Echo soundings, digitized paper charts	Various resolutions
GSC	Compiled satellite-derived gravity & soundings	750 m

Table 3 HD model bathymetric data sources and resolutions. NSDNR: Nova Scotia Department of Natural Resources; CHS: Canadian Hydrographic Service; GSC: Geological Survey of Canada; GSC: Geological Survey of Canada.



Figure 22: Model domain of the Cow Bay study area showing data sources and varying resolutions.

Point data were interpolated into a surface using the topographic data to raster toolset within the ESRI ArcGIS<sup>™</sup> software package. The interpolation procedure used an iterative finite difference interpolation technique. It was designed to have the computational efficiency of local interpolation methods without losing the surface continuity of global interpolation methods. It is described as a discretized thin plate spline technique (Wahba, 1990) for which the roughness penalty has been modified to allow the fitted DEM to follow abrupt changes in terrain. A surface was interpolated at the highest required resolution, 3 m, for the entire model domain. A nested grid approach was adopted to reduce the complexity and number of required calculations to run the simulation. This technique effectively reduced the resolution of model input data in regions distant from the main areas of interest (AOI) by nesting high-resolution AOI grids within low resolution 'background' grids at 3:1 resolution steps resulting in a more efficient and stable model (Table 4, Figure 23, Figure 24, Figure 25).
Model Domain	Cell Resolution (m)		
D0	3		
D1	9		
D2	27		
D3	81		
D4	243		

Table 4. Nested model bathymetry domains and cell resolutions.



Figure 23: Nested model domains at within the Cow Bay hydrodynamic model study area at 1:3 resolution steps, D4: 243 m; D3: 81 m; D2: 27 m.



Figure 24: Nested model domains at within the Cow Bay hydrodynamic model study area at 1:3 resolution steps, D2: 27 m; D1: 9 m; D0: 3 m.



Figure 25: Cow Bay high-resolution model domains to support particle tracking scenarios.

The hydrodynamic simulation was driven by tidal predictions along the open water boundaries in the largest model domain. These predictions were obtained using the built in tidal prediction model within Mike21<sup>™</sup> and were driven by 16 global tidal constituents. The HD model was run at a 2-second simulation time-step and surface elevations, water depth, current magnitude, and current directions were recorded at 5-minute simulation intervals.

A preliminary particle tracking (PT) model was developed to simulate the distribution of potential oil contamination for different dispersion scenarios using the hydrodynamic model results. Oil spills were simulated with varying wind and dispersion rate variables to determine how changes in these factors affected the critical distances at which coastal contamination, the magnitude of impact, and the timing of contamination to make landfall. The rate of contaminant dispersion, decay, and erosion (resuspension) were estimated based three oil classes: heavy, medium,

Class	Description	Decay	Horizontal	Erosion
		(p/s)	Dispersion (m <sup>2</sup> /s)	(N/m²)
Type 2	Light Oils (Diesel, No. 2 Fuel Oil, Light Crudes)	1e-005	8	0.01
Туре 3	Medium Oils (Most Crude Oils)	1e-006	4	0.01
Type 4	Heavy Oils (Heavy Crude Oils, No. 6 Fuel Oil, Bunker C)	1e-007	2	0.01

 Table 5. Simplified oil dispersion and decay characteristics for preliminary PT simulations.

Two sources of contamination were modelled. The first sources followed the track of a tanker entering the Halifax Harbour at a course resolution. This scenario was developed to determine if contaminants from the defined traffic path would eventually reach the Cow Bay study area. The second modelled source point was located at easting, 466500 and northing, 4938500. This source was used to determine the fate of particles that reach the outer extent of the mouth of Cow Bay (Figure 26). For each scenario, 10 000 particles were released to simulate dispersion.



Figure 26: Contaminant source location (red circle) used to simulate the fate of particles that reach the outer extent of the Cow Bay study area.

Wind was used as a variable to affect the distribution of contamination. Three conditions were used to examine the effect of wind on particle distribution: a no wind scenario, 15 m/s onshore gale wind, and a 25 m/s onshore storm wind. In each scenario, the wind originated from 135 degrees and has a surface wind acceleration kinematic viscosity of 1.14e-6 m<sup>2</sup>/s.

Each model was run from 2016/07/17 1800h to 2016/07/21 1800h at a 1-minute computational time-step where particles were released between 2016/07/17 1800h and 2016/07/17 2350h. Suspended and sedimented particle positions were recorded for each 5-minute model time-step. The simulated dispersion extents were examined over several tides to determine the extent and magnitude of contamination.

## **3** Results

### 3.1 Lidar Validation

Ground elevation measurements obtained using the RTK GPS system were used to validate the topographic lidar returns on areas of hard, flat surfaces. The GPS survey was collected along roads, trail and the beach within the study area (Figure 5).

Boat-based ground truth data were used to validate the bathymetric lidar returns (blue and red dots on Figure 5). Although various methods were used to measure depth during fieldwork, for this report only points measured using the large pole fitted with the RTK GPS antenna to directly measure the seabed elevation were used for the accuracy assessment; points that measured depth using sonar or a weighted rope were not considered at this time.

For both hard surface and boat-based GPS points, the differences in the GPS elevation and the lidar elevation ( $\Delta Z$ ) were calculated by extracting the lidar elevation from the DEM at the checkpoint and subtracting the lidar elevation from the GPS elevation. GPS points were subject to a quality control assessment such that the standard deviation of the elevation was required to be < 0.05 m.

## 3.1.1 Topographic Validation

There were 171 points collected in the study area and were compared against the 1 m lidar derived DEM. The difference in elevation between the GPS and DEM was used to calculate the  $\Delta Z$ . The results indicate the mean  $\Delta Z$  of -0.12 m ± 0.07 m (1 standard deviation) (Figure 27).



Figure 27: Topographic validation for Cow Bay.

## 3.1.2 Bathymetric Validation

There were 38 points collected from vessels in the study area during the survey flight. These validation points were taken with a pole that had the GPS antenna mounted on the top of it and measured the seabed elevation directly. The orthometric height of the GPS was then subtracted from the DEM and the  $\Delta Z$  calculated. The results indicate the mean  $\Delta Z$  of -0.08m ± 0.16 m (1 standard deviation) (Figure 28).



Figure 28: Bathymetric validation for Cow Bay

## 3.2 Surface Models

#### 3.2.1 Digital Elevation Model

Lidar penetration at Cow Bay was successful in the nearshore and inner bay areas of the study area, penetrating to a maximum of -10 m CGVD28, located outside the central area of Cow Bay (Figure 29). The water in the center of the bay was darker and murkier (as indicated in the ground truth maps in Figure 36 and Figure 37). Additionally, the water was deeper in the center of the bay, contributing to the lack of lidar penetration in that area.



Figure 29: Digital Elevation Model for Cow Bay, scaled to show bathymetry relief for the entire study area with insets showing smaller features. Insets are matched to the larger figure by border colour.

## 3.2.2 Colour Shaded Relief

The Colour Shaded Relief (CSR) models show the topographic relief in shades of green-red-yellow, and the bathymetry relief in shades of blue where darker blue represents deeper water. CSRs provide an exaggeration of the DSMs (Figure 30) and DEM's (Figure 31) (5x actual height) and include artificial shading to accentuate topographic and bathymetric features.



Figure 30: Colour Shaded Relief for the DSM at Cow Bay. The map is scaled to show bathymetry relief for the entire study area with insets showing smaller features. Insets are matched to the larger figure by border colour.



Figure 31: Colour Shaded Relief for the DEM at Cow Bay. The map is scaled to show bathymetry relief for the entire study area with insets showing smaller features. Insets are matched to the larger figure by border colour.

The lidar did not penetrate beyond 13 m water depth. As a result the lidar data were merged with bathymetry from the Canadian Hydrographic Service to provide as much detail as possible for Cow Bay (Figure 32).



Figure 32: Cow Bay DSM of combined lidar and bathymetry from CHS.

#### 3.2.3 Depth Normalized Intensity

As mentioned previously, the energy of light exponentially decays with water depth. As a result the amplitudeintensity of the reflected green laser pulse is influenced by this loss of energy and the grey scale image that may be dark because of dark features of the seabed such as vegetation or dark because of depth (Figure 33). Thus, this image is difficult to interpret qualitatively and not useable quantitatively. The effects of depth have been reversed to produce a Depth Normalized Intensity (DNI) image (Figure 33). This DNI image can now be used to interpret the seafloor cover material and detect information that is challenging to see in the air photos. The intensity data show the contrast between brightly reflected seabed cover in the green spectrum, such as sand and the dark colour of submerged vegetation. The DNI maps suggest the presence of sand in the center of the bay with bands of vegetation in the nearshore (Figure 33).



Figure 33: Top map is the direct amplitude-intensity image. The bottom map is the Depth Normalized Intensity (DNI) image from the lidar.



Figure 34: Depth Normalized Intensity model for Cow Bay. Typically, darker areas represent submerged vegetation, while brighter areas represent sand. Insets are matched to the larger figure by the red border. The top inset is the elevation model and the lower inset is the DNI.

## 3.2.4 Air Photos

Both the quality assurance camera and the RCD30 camera data were processed to produce orthophotos. The aerial orthophoto mosaics provide insight into land use, water clarity, bottom type, wave action, and shoreline morphology. The orthophoto panels show the different levels of water clarity throughout the study area. At Cow Bay, submerged features such as sand ripples and vegetation can be seen in the red panel. (Figure 35).



Figure 35: RCD30 Orthophoto Mosaic for Cow Bay with insets showing smaller features. Insets are matched to the larger figure by border colour.

# 3.3 Ground Truth Maps

The underwater photographs taken using a GoPro camera mounted to a quadrat are useful indicators of bottom type throughout the study area (Figure 36, Figure 37). The following sections present some of the images obtained during the field season displayed on the RCD30 5 cm resolution orthophoto mosaics.



Figure 36: Cow Bay underwater photo ground truth for the AGRG boat survey on July 6. Map is symbolized to show cover type. Background image is RCD30 orthophoto RGB mosaic.



Figure 37: Cow Bay underwater photo ground truth for the AGRG (ECRC boat) survey on July 6. Map is symbolized to show cover type. Background image is RCD30 orthophoto RGB mosaic.

## 3.4 SAV and Bottom Type Maps

Figures 38 to 45 depict the submerged aquatic vegetation (SAV) distribution and the complete bottom type classification produced by the methodology described in the Methods section. The SAV map is a simplified version of the full bottom cover map and depicts vegetation cover of multiple types.



Figure 38: Map showing submerged aquatic vegetation in Cow Bay where green represents presence. Shown underneath the SAV data is the depth normalized intensity.



Figure 39: Map showing submerged aquatic vegetation in Cow Bay where green represents presence. Shown underneath the SAV data is the orthophoto RGB mosaic.

The ground truth bottom photos data were classified into SAV presence and absence and used to validate the SAV map derived from the QA photos and lidar metrics. An 82.5% accuracy was achieved when compared between the ground truth data and the SAV map (Figure 40).



Figure 40: Map showing submerged aquatic vegetation in Cow Bay with ground truth points. Where the classification matched the ground truth presence and absence the points are circled. An agreement of 82.5% was achieved.

The full bottom classification is a much more complicated map which involved interpreting what type of SAV occurs at different subtidal water levels and the substrate type was interpreted from the bottom reflectance and roughness (Figure 41, Figure 42, Figure 43).



Figure 41: Map showing bottom classification in Cow Bay. Shown underneath the SAV data is the depth normalized intensity image.



Figure 42: Map showing bottom classification in Cow Bay. Shown underneath the SAV data is the RGB orthophoto mosaic.



Figure 43: Map showing bottom classification in Cow Bay. Shown underneath the SAV data is the RGB orthophoto mosaic.

## 3.5 Shoreline Classification Maps

Environment Canada is responsible for mapping the shoreline with respect to identifying areas that could be vulnerable to contamination from a spill. They utilize an oblique video camera system and then manually interpret the shoreline material with follow up ground truth. In this study we examined how we could automate the process making use the of the RCD30 imagery and lidar metrics (Figure 44, Figure 45).



Figure 44: The map on the left is an example of the Environment Canada map depicting the shoreline. The map on the right has been simplified to match the classes and colours of the Environment Canada map and derived from the RCD30 and lidar data.



Figure 45: A close up of the EC map and that derived in this study shows that EC only uses a line whereas we have derived polygons covering the area. Also of note is the change in the tidal inlet position from the EC map ca. 1997.

The following figures (46 - 51) show detailed examples of the shoreline classification using the RCD30 and lidar metric data from this study.



Figure 46: Map showing shoreline classification in Cow Bay. Shown underneath the data is the RGB orthophoto mosaic.



Figure 47: Map showing shoreline classification near the tidal inlet in Cow Bay. Shown underneath the data is the RGB orthophoto mosaic.



Figure 48: Map showing shoreline classification in the tidal inlet at Cow Bay. Shown underneath the data is the RGB orthophoto mosaic.



Figure 49: Map showing shoreline classification in Cow Bay. Shown underneath the data is the RGB orthophoto mosaic.



Figure 50: Map showing shoreline classification adjacent to the tidal inlet in Cow Bay. Shown underneath the data is the RGB orthophoto mosaic.



Figure 51: Map showing shoreline classification within the saltmarsh at Cow Bay. Shown underneath the data is the RGB orthophoto mosaic.

## 3.6 Hydrodynamic Model Results

HD models were found to produce realistic simulations of water flow and the results of these models were validated using ADCP data collected during the simulated period from 2016/07/17 to 2016/07/29. Simulated water depth was in nearly perfect agreement with observed water depth measured by the ADCP with a calculated Pearson Correlation Coefficient (PCC) of 0.99 (Figure 52).



Figure 52: Comparison between modelled water depth and observed ADCP water depth over the July simulation period.

Depth averaged current magnitudes in both the U (east - west) and V (north - south) vectors agreed poorly with the observed ADCP data. Current magnitude in the U vector was found to have a PCC of 0.21 when compared to the ADCP data (Figure 53).



Figure 53: Comparison between modelled depth-averaged current velocity and observed ADCP current velocity in the U vector.

Similarly, the current magnitude in the V vector was found to have a PCC of 0.28 when compared to the ADCP data (Figure 54).



Figure 54: Comparison between modelled depth-averaged current velocity and observed ADCP current velocity in the V vector.

The poor agreement between modelled and observed current direction was determined to be due to strong stratification in the tidal signal (Figure 55). A rip tide forms in the area where the ADCP was deployed. The water is constantly moving in opposite directions over the same point on both flood and ebb tides. This is a problem for 2-dimensional depth averaged model where the opposing magnitudes nullify each other to produce a very weak vector that makes comparison to ADCP observations difficult. The similarities in current magnitude are promising, but it is understandable that phase and direction are not well aligned. These models are preliminary and the conversion to a 3-dimensional HD model should be examined. Despite the shortcoming on direction and phase, HD results on a larger scale were determined to be acceptable for preliminary particle tracking scenarios.



Figure 55: ADCP measured current magnitude and directions binned by depth show the complex stratification of the bay over different moments of the tidal cycle noted by the red circle above each of the plots. The depth averaged magnitude and direction are noted by the red vector at the bottom of each plot.

## 3.7 Particle Tracking Model Results

Particle tracking models were run successfully for several potential spill scenarios. Contamination extents were simulated by varying horizontal dispersion and decay rates for three classes of oil: heavy, medium, and light (Figure 56). The majority of coastline within the model domain was impacted by contamination after several hours of

dispersion (Figure 57).



Figure 56: Heavy, medium and light oil dispersion from a simulated tanker approach trail 17.5 hours after release. Light oil dispersion (8 m<sup>2</sup>/s), class medium oil dispersion (4 m<sup>2</sup>/s), and class heavy oil dispersion (2 m<sup>2</sup>/s).



Figure 57: Heavy, medium and light oil dispersion from a simulated tanker approach trail 46.75 hours after release. Light oil dispersion (8 m<sup>2</sup>/s), class medium oil dispersion (4 m<sup>2</sup>/s), and class heavy oil dispersion (2 m<sup>2</sup>/s).

The extent and concentration of the light oil dispersion parameter was examined in more detail. The Cow Bay study area was found to be heavily impacted by a potential spill along the tanker approach path after fewer than 48 hours (Figure 58, Figure 59).



Figure 58: Light oil dispersion from a simulated tanker approach trail 7 hours after release. Colour gradient represents the concentration of light oil (dispersion 8 m<sup>2</sup>/s).



Figure 59: Light oil dispersion from a simulated tanker approach trail 48 hours after release. Colour gradient represents the concentration of light oil (dispersion 8 m<sup>2</sup>/s).

Once it was determined that the Cow Bay study was potentially impacted by a spill, local particle tracking results were examined to determine the timing and extent of contamination over the three wind conditions. In the no wind condition, the hydrodynamics were in a natural state and particles made landfall after 14 hours. The distribution and concentration of particles were evenly distributed along the intertidal zone (Figure 60, Figure 61, Figure 62).



Figure 60: Hydrodynamics within the Cow Bay area under the no wind condition. A current magnitude of 0.2 m/s is represented by the legend vector on the right.



Figure 61: Hydrodynamics and particle distribution within the Cow Bay area after 2 hours under the no wind condition. The orange to green color range represents the concentration of suspended particles, and the purple gradient denotes the concentration of sedimented particles.



Figure 62: Hydrodynamics and particle distribution within the Cow Bay area after 71 hours under the no wind condition. The orange to green color range represents the concentration of suspended particles, and the purple gradient denotes the concentration of sedimented particles. Particles made landfall after 14 hours.

In the 15 m/s wind condition, the impacted and formed a counterclockwise eddy in the middle of the bay (Figure 63, Figure 64, Figure 65). The wind forcing was strong enough to propel the oil particles against this current and the contamination made landfall after only 3 hours. The contamination was uniform and was limited to a 1.5 km section along the Cow Bay intertidal zone (Figure 65). Finally, the 25 m/s wind condition forced the contaminants onshore after only 1 hour along a 600 swath of coastline (Figure 66).



Figure 63: Hydrodynamics within the Cow Bay area under a 15 m/s onshore wind condition. A current magnitude of 1 m/s is represented by the legend vector on the right.


Figure 64: Hydrodynamics within the isolated Cow Bay estuary under a 15 m/s onshore wind condition. A current magnitude of 1 m/s is represented by the legend vector on the right.



Figure 65: Hydrodynamics and particle distribution within the Cow Bay area after 71.25 hours under a 15 m/s onshore wind condition. The orange to green color range represents the concentration of suspended particles, and the purple gradient denotes the concentration of sedimented particles. Particles made landfall after 3 hours.





## 4 Discussion and Conclusions

The field campaign to collect airborne topo-bathymetric lidar and photography of Cow Bay was extremely successful. The relatively clear water conditions along the Atlantic Coast were ideal for this type of lidar technology and greater than 13 m of water depth were achieved. In addition to the aerial campaign, an ACDP was deployed for 1 month and ground truth information regarding the water clarity, seabed cover, and elevation were acquired. Additionally, the morphology and flow of the water from the tidal inlet was analyzed using a RiverRay ADCP. Analyses of the lidar and air photo data have produced mosaic datasets that reside in a GIS that were used for further classification of the submerged area and exposed shoreline material and the construction of a hydrodynamic model to simulate oil spills.

Data regarding the critical distance, magnitude, and timing of impacts from potential oil spills will provide better information to responders to help guide restoration efforts, reduce costs and mitigate health and safety risks. The hydrodynamic model nearshore was possible because of the high resolution of the seamless elevation model derived from the lidar survey. The ability of the lidar sensor and camera to map near shore topography and bathymetry and sensitive habitats was evaluated and the SAV map produced an 83% accuracy when compared to ground truth data. Finally, hydrodynamic modeling under different wind and tidal conditions was evaluated to

determine the effects of the movement of oil floating on the surface. Under normal tidal conditions oil that was simulated to occur approximately 2 km offshore took 14 hours to make landfall and effect the tidal inlet. With the addition of a 30 knot landward wind added to the model changed the time from 14 hours to 3 hours for the oil to make landfall and effect the inlet. This demonstrates how wind can play a significant role on the behavior of material floating on the surface. Overall this project will help spill responders plan for different oil spill scenarios and have better maps of the sensitive habitats, shoreline material, and submerged bottom cover material. Future phases of the project based on results from this project, may further refine the model and test these methods in other larger and more complex areas of sensitive tidal inlets.

## **5** References

DHI Water & Environment (2008). Mike 21 Flow Model Hints and Recommendations in Applications with Significant Flooding and Drying.

Dupont, F., Hannah, C.G., and Greenberg, D. (2005). Modelling the Sea Level in the Upper Bay of Fundy. Atmos-Ocean *43*, 33–47.

Varma, H., Hannah, C., MacNab, R., Costello, G., Spears, T., Woodford, W., and Delbridge, C. (2008). The Complexities in the Design and Definitions of the North West Atlantic Data Set; Searching for Rational Architecture to Implement Diverse Bathymetric Data. Proc. Can. Hydrogr. Conf. Natl. Surv. Conf.

Webster, T.L., McGuigan, K., Crowell, N., Collins, K., and MacDonald, C. (2016). Optimization of data collection and refinement of post-processing techniques for Maritime Canada's first shallow water topographic-bathymetric lidar survey. J. Coast. Res.

Wahba, G. 1990. Spline models for Observational data. Paper presented at CBMS-NSF Regional Conference Series in Applied Mathematics. Philadelphia: Soc. Ind. Appl. Maths.

Environment Canada. (2014). Canadian Marine Warning Program: Wind Warnings. Government of Canada.

## 7 Acknowledgements

We would like to thank the Offshore Energy Research Association of Nova Scotia (OERA) for providing funding for this project. Thank you to CHS for providing CHS charts and multibeam data and ECRC for the assistance in deploying the ADCP and collecting ground truth data for Cow Bay. Thanks to staff from Leica Geosystems, Leading Edge Geomatics staff for operations and AGRG staff for administrative support, the pilots from Leading Edge Geomatics.