Avon River Aboiteau and Causeway Upgrades: Pre-Construction Monitoring of the Avon River Estuary

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Executive Summary

The monitoring of a range of physical and biological components of the Avon River mudflat and salt marsh system has been underway since 2002 (van Proosdij, 2005). In 2016 CBWES was commissioned to develop and implement a monitoring program to complement previous research efforts and further document habitat conditions downstream of the Avon River Aboiteau and Causeway in advance of potential upgrades as part of the Highway 101 Twinning Project. Pre- and post-construction monitoring including unmanned aerial vehicle (UAV or drone) surveys will be undertaken in order to quantify environmental impact predictions of the Environmental Assessment (EA) report and to support efforts to adequately offset any unavoidable negative impacts to salt marsh and fish habitat.

Main objectives of the monitoring program are:

1. *Measure changes in surface elevation*
2. *Measure changes in the location, stability and capacity of tidal channel networks*
3. *Measure changes in the amount of vegetated marsh and mudflat habitat conditions (habitat mapping)*
4. *Measure changes in vegetation community structure*

The purpose of the pre-construction monitoring program was to update and expand upon the existing information on the physical and biological indicators of habitat condition. This ‘baseline’ will be used to detect changes in habitat conditions, as well as, determine the nature, extent and direction of change, as a result of the aboiteau/causeway upgrades. The results for the pre-restoration monitoring are detailed in the following report and summarized below.

Surface Elevation

An elevation survey was carried out on the Windsor salt marsh within 250 m of the existing causeway. Surveyed elevations, the UAV-derived digital surface model (DSM), and the 2011 LiDAR digital elevation model (DEM) were compared to understand current conditions and recent changes at the site. Elevation transects showed a general pattern of accretion on the marsh platform and a narrowing of tidal channels. The patterns observed fit with a maturing marsh platform. As the marsh grows in height the tidal prism decreases, resulting in a reduction in cross-sectional area of the channel network. When positive change was considered in isolation to understand accretion, the mean increase was 0.26 ±0.17 from 2011 to present.

Accretion and erosion for intertidal channels within the DSM footprint (Newport Bar, Windsor Salt Marsh, Elderkin Marsh) was calculated for the period 2007-2017. Overall the net sediment budget for the un-vegetated portions of the study area indicated a gain of 1.3 million m^3 of sediment over the approximately the ten year period. The total (absolute) change in sediment volume, was much greater (2.7M m^3) reflecting differences in erosion and infilling between and within sub-sections of the study area.

Hydrology and Tidal Channel Networks

In 2017, the highest recorded tide downstream of the causeway was 8.22 m (CGVD28), while the highest predicted tide was 7.97 m. The hypsometric curve showed a marsh that does not yet fit the pattern typically observed at a mature marsh. The minimum high tide (5.58 m) floods just over 45% of the marsh surface and the mean observed high tide (6.58 m) floods over 90% of the marsh. At low water (-1.23 m)

only the primary channel (Tide Gate Channel) flooded, while all channels within the salt marsh remained dry. The average recorded water level (1.64 m), which in meso- or micro-tidal systems may correspond to the low marsh boundary, still fail to fill the tidal channels of the main marsh. The minimum observed tide level required to fill the tidal channels within the marsh and flood the edges of the vegetated marsh surface as well as some of the lower vegetated edge areas was 5.58 m. The mean water depth of 5.36 m resulted in 50% of the marsh surface flooded, while the recorded 8.22 m flooded the entire marsh area (95 ha) with a mean depth of ~2.55 m. The main river channels (St. Croix and Avon), particularly in the area of confluence, were found to be very dynamic, experience large fluctuations in sediment volume, location, and morphology. The leading edge of the main marsh and mudflat at the confluence of the Avon and St. Croix Rivers experienced the greatest net change in sediment volume within the area studied (841,300 m^3 of infilling and 167,400 m^3 of export.

Habitat Mapping

Surface cover and other habitat features were delineated from the UAV orthomosaic to determine change in vegetation location and extent. Within the boundaries of the current study area, the greatest percent change in vegetated salt marsh habitat occurred between 1992 and 2003 (62% increase), followed by the 2003 to 2007 period (29% increase). The rates of increase in vegetated area have since levelled off to approximately 2.0 to 2.1 $ha \cdot yr^{-1}$; this is expected because as the marsh platform rises within the tidal frame it becomes less and less inundated. The growth in vegetated salt marsh area was found to be highly variable across the site, with much of the marsh experiencing varying rates of continued expansion. Despite this expansion, there was evidence in certain locations of scour, erosion and loss of foreshore. Overall, although the rate of change resulting from the original causeway construction appears to have slowed, the Avon River estuary continues to be a very dynamic and evolving tidal system which is likely to be impacted by any alterations to the existing causeway and tide gate structure.

Vegetation

Non-metric multidimensional scaling reveals that the Windsor vegetation plots mostly contain a low marsh community dominated by *Spartina alterniflora.* Reference condition plots had a greater range of salt marsh vegetation including high marsh communities. The Windsor plots could be viewed as early successional vegetation that has not yet had a chance to develop the zonation typical of reference marshes in the region. Vegetation cover was close to 100% across all plots in both reference and study sites. Several species of *Suaeda* have been observed in the Windsor area, one of which is a species at risk regionally (*Suaeda rolandii*). Samples were taken from the marsh edge at the base of the causeway, the marsh platform, and from two locations on the Avonport side of the Avon River to confirm the absence/presence of *Suaeda rolandii*. Three of the four samples were identified in the lab as *Suaeda maritima ssp. maritima* (S5 – secure - exotic), while a fourth (located on the Avondale side in the high marsh) was identified as *Suaeda calceoliformis* (S3/S4 – vulnerable/apparently secure – limited range).

Summary

Baseline monitoring indicates that the extensive mudflat and salt marsh habitat that has formed immediately downstream, and as a result of, the Avon River Causeway is a young marsh that is still in the process of developing the elevation and vegetation patterns of a mature marsh. The system is highly dynamic and continues to evolve and adjust in response to changes in human activities in the area. The twinning of Highway 101 and the associated expansion of the causeway and aboiteau (tide gate) structure will likely result in changes, particularly in the near-field physical and biological conditions. The exact nature of the change, or the extent, is beyond the scope of this report. This report provides a baseline against which such changes maybe compared.

Acknowledgements

This work would not have been able to be completed without the assistance of the Saint Mary's University's In_CoaST and MP_SpARC research team (Greg Baker, Logan Horrocks, Graeme Matheson, Julia Purcell, Reyhan Akyol, Chris Ross and Sam Cunningham); Dr. Ian Spooner, Baille Holmes, Kirklyn Davidson and Ashton Baich (Acadia University); and especially to Darren and Erica Porter for the use of their time, boat and extensive knowledge of the Avon River system for the bathymetric survey.

We would also like to acknowledge and thank Tim Webster from the Advanced Geomatics Research group at the Center for Geographic Sciences for flying and processing the original 2007 LIDAR aerial survey. Funding for the previous research (i.e., historical analysis) that was used for this project and referenced in this report was funded by the NS Department of Transportation and Infrastructure Renewal (NSTIR), Nova Scotia Department of Agriculture, Land Protection Section (NSDA), and Natural Resources Canada. In addition, we acknowledge the Canadian Foundation for Innovation for Infrastructure funding of equipment essential for this analysis.

This baseline monitoring project was funded by NSTIR.

1.0 Introduction

It is well known that the construction of causeways and tide gates across tidal estuaries causes significant, often negative, impacts to the physical and biological conditions of the system. Salt marshes and mudflat complexes often experience the most dramatic and observable effects caused by the change in the movement of water and sediment. The Avon estuary is a dynamic, coastal system that has a long history of morphodynamic change in response to natural and anthropogenic driving forces. Morphodynamics refers to the change in morphology (form) of coastal features such as salt marshes, tidal creeks and mudflats over time as sediment is re-distributed. The change in morphology then alters the hydrodynamics and sediment transport processes within the coastal system.

This study follows several previous studies carried out by Saint Mary's University (SMU) (van Proosdij, 2005; van Proosdij et al., 2006; van Proosdij and Baker, 2007; van Proosdij et al 2009) and SMU-CBWES (van Proosdij and Bowron, 2017). These studies showed that the construction of the Avon River causeway and tide gate between 1968 and 1970 significantly affected the hydrodynamics and sediment transport processes at play in the system, resulting in the rapid accumulation of fine sediments in the 1970s and '80s downstream of the causeway. The initial colonization of the mudflat by salt marsh vegetation (*Spartina alterniflora*) began in 1992 and has progressed and expanded since that time. As the elevation of the Windsor Salt Marsh platform rose within the tidal frame, the rate of sediment deposition slowed and shifted downstream to form a second intertidal bar (Newport Bar), which has also started to vegetate in recent years (Figure 1).

The current study seeks to document habitat conditions downstream of the Avon River Causeway in advance of potential upgrades to the causeway and aboiteau as part of the Highway 101 Twinning Project. Baseline monitoring was completed in 2017, and post-construction monitoring will be undertaken during and following construction in order to quantify environmental impact predictions of the EA report (https://novascotia.ca/nse/ea/highway-101-twinning-three-mile-plains-to-falmouth.asp), inform the Ramsar Administrative Authority of any changes to the ecological character of this globally-significant wetland (https://rsis.ramsar.org/ris/379), and to support efforts to adequately offset any unavoidable negative impacts to salt marsh and fish habitat. The monitoring study will focus primarily on the Windsor Salt Marsh, but will include the Elderkin Marsh, Newport Bar, and the broader Avon River and St Croix Rivers in analysis involving ecomorphodynamics, bathymetry, and vegetation. Figure 1 shows the layout site and the primary areas of focus, which include the expected highway footprint and adjacent area, the tide gate channel and the Elderkin Marsh/Newport Bar area.

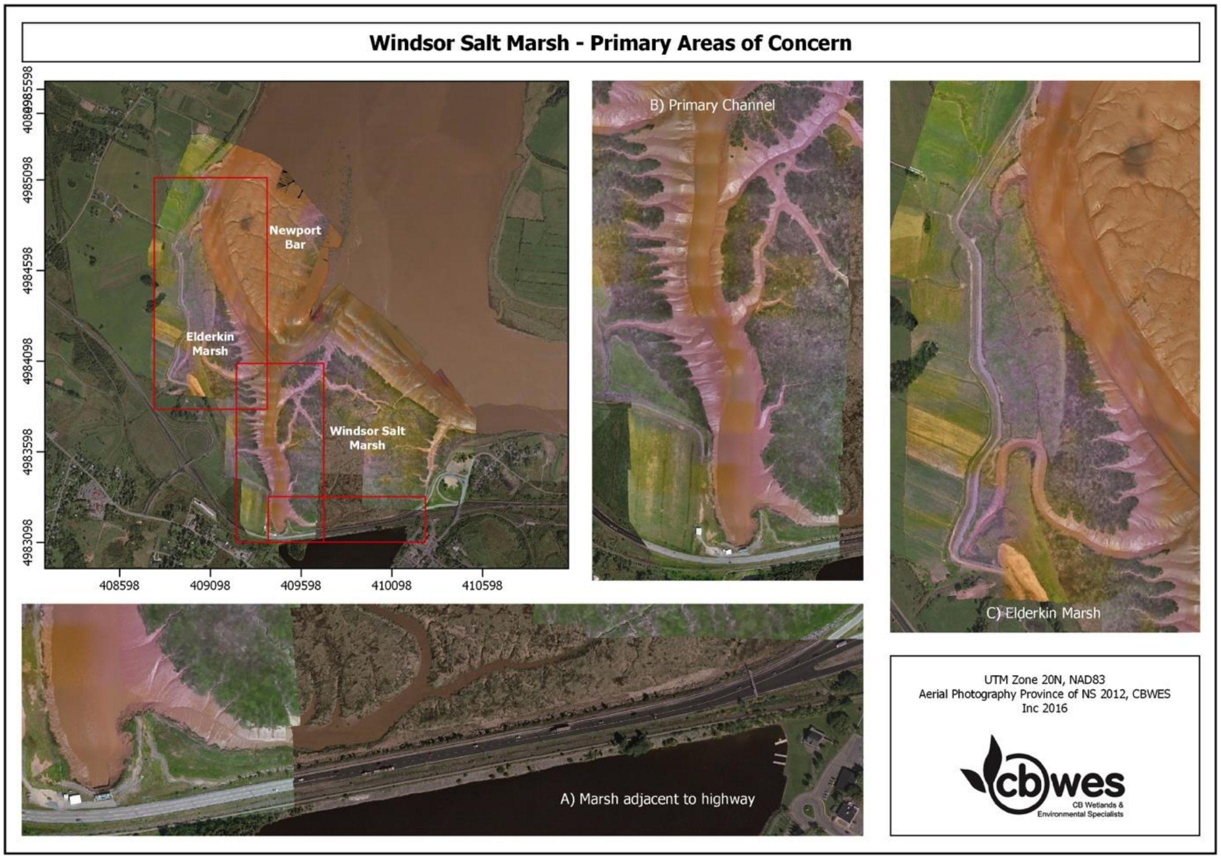


Figure 1: Windsor Salt Marsh system and areas of potential impact.

2.0 Monitoring Program

The monitoring methodology was developed in order to allow for the documentation of habitat conditions and the evaluation of whether a change has occurred to the Windsor salt marsh, mudflat and associated tidal channel system as a result of the proposed NSTIR-NSDA highway expansion project. The monitoring program replicates and builds upon the research and monitoring activities conducted by SMU between 2002 and 2007 (van Proosdij, 2005; van Proosdij et al., 2006; van Proosdij and Baker 2007).

The monitoring program focused on four main objectives:

1. ***Measure changes in surface elevation*** using digital elevation models (DEM) derived from LiDAR, digital surface models (DSM) derived from georeferenced UAV low-altitude aerial photography, and differential RTK elevation surveys along reproducible transection.

2. ***Measure changes in the location, stability and capacity of tidal channel networks***, particularly the primary tide gate channel and the secondary causeway/east channel, which runs roughly parallel to the causeway and is the proposed location of an expanded causeway structure.

3. ***Measure changes in the amount of vegetated marsh and mudflat habitat conditions*** using habitat and surface cover maps developed from low-altitude aerial photography.

4. ***Measure changes in vegetation community structure and productivity*** using plot based vegetation survey (species composition, abundance, height) and low-altitude aerial photography.

The aerial photography and associated habitat and channel mapping activities encompassed the entire Windsor Salt Marsh-mudflat system including the Elderkin Marsh and Newport Bar. The more detailed monitoring activities (elevation and vegetation surveys) focus on those parts of the system where the change is anticipated to be greatest and most critical (i.e., channels and marsh area bordering the tide gate-causeway structure itself and tide gate channel) (Figure 1). Attention is also given to the geomorphic stability of the western portion of the site (Elderkin Marsh) and the integrity of the existing foreshore marsh which is providing protection for the dyke infrastructure.

The pre-construction phase of the monitoring program (Table 1) was carried out during the summer and fall of 2017 and the winter of 2018, and is presented in this report. Construction is tentatively scheduled to begin in 2019 and be completed in 2020. Post-construction would be initiated in Summer 2020 and continue for at least seven years to verify EA predictions and ensure adequate salt marsh and fish habitat compensation for this Ramsar wetland.

The DEM, DSM, habitat, and surface cover maps were used to document habitat conditions prior to causeway expansion activities. They will serve as a baseline against which changes in habitat conditions post-construction can be compared. Compilation and comparison of contemporary and historical conditions aided in the establishment of a more detailed picture of the sites geomorphic condition in advance of causeway expansion.

Table 1 Avon River Estuary monitoring program.

Category	Parameters	Sampling Method	Annual Sampling Frequency	Monitoring Year						
				Pre	Construction	Post-Restoration				
				2017 2018	2019 & 2020	Year 1	Year 2	Year 3	Year 5	Year 7
Hydrology	Tidal signal; hydroperiod; tidal flow patterns	Tide level data from the Windsor tide gate station; UAV &/or fixed camera stations	Minimum 29 day period during sampling year; minimum 1 spring and neap tide event	X		X	X	X	X	X
Geomorphology	Marsh surface elevation	Digital Elevation Model (DEM/DSM); G8 GNSS RTK surveying unit (or equivalent); transect based elevation profiling	Once per required sampling year.	X		X	X	X	X	X
	Tidal Creek Network	DGPS/GIS; Geo-referenced	Annually, once per sampling	X	X	X	X	X	X	X

		low-altitude aerial photography	year							
	Sediment Dynamics	DGPS/GIS; Geo-referenced low-altitude aerial photography; volumetric calculations	Once per required sampling year	X	X	X	X	X	X	X
	Bathymetry	Ship-based bathymetric survey (replication of 2005 survey)	Once per required sampling year			X				X
	Geo-referenced low-altitude aerial photography	UAV based camera system	Twice per sampling year (spring, mid-late summer)	X		X	X	X	X	X
Vegetation	Composition Abundance Height	Transect based, Point Intercept Method (1 m^2 plots)	Once per sampling year (August)	X		X		X		X
	Habitat map	DGPS/GIS; Geo-referenced low-altitude aerial photography	Once per sampling year	X		X		X		X
Evaluation of Habitat Response to causeway expansion	Visual Assessment of habitat condition, geomorphic change, wildlife usage, etc.	Structured summer walks & photo-documentation	Once per sampling year (August)	X	X	X	X	X	X	X
Winter Conditions	Visual assessment of ice/snow, habitat conditions	Structured winter walk; photo-documentation	Minimum once per sampling year (Jan-Mar)	X		X	X	X	X	X

3.0 Methods

3.1 Geospatial Data

Geospatial data serve as the backbone for much of the baseline monitoring activities described in this report. Elevation, hydrology, ecomorphodynamic and vegetation analysis used several common datasets at different scales to understand ecosystem dynamics immediately adjacent to the highway, for the Windsor Salt Marsh at large, and in the Avon River Estuary from the causeway downstream to the mouth of the estuary/river (historic bathymetric survey).

UAV Orthomosaic and DSM

An orthomosaic and DSM were derived from a series of aerial flights using a DJI Phantom 3 Professional lightweight UAV and post-processed using industry approved software Pix4D (Figure 2). The first set of flights were conducted on September 25, 26, and 28, 2017, but poor weather conditions and errors in the grid layout resulted in unsatisfactory results for the 3rd day of flights. These were re-flown on October 20 and were processed separately, and the resulting datasets merged. Over 3600 vertical and oblique photos were taken covering ~400 hectares, as well as video in four predefined locations and oblique imagery at multiple locations. An example of oblique image is provided in Figure 3. Orthomosaics had a 4 cm horizontal pixel resolution and 30 ground control points (GCP) were used. The surface generated using the UAV imagery and Structure from Motion algorithms (Westoby et al., 2012) are DSMs not bare earth elevation models; therefore, they cannot be used to determine marsh surface (bare ground) elevation in vegetated areas due to the height of the vegetation (canopy). However, the DSM is excellent in areas where vegetation was not present (i.e., mudflat, channels, exposed river bottom).

LiDAR DEM

Two LiDAR DEMs were used in this analysis. The first, which was used in the ecomorphodynamics analysis, was produced from a survey conducted at low tide in May 2007. The 2007 LiDAR data were collected by the Advanced Geomatics Research Group (AGRG) at the College of Geographical Sciences, as a collaborative initiative with SMU, NSTIR and NSDA. LiDAR data were processed by AGRG (Webster et al., 2011). A 2011 LiDAR dataset, whose extent matched well with the Windsor Salt Marsh area but did not extend to the entire DSM footprint, was used for analysis of the salt marsh and areas immediately downstream of the Windsor Causeway. The 2011 LiDAR DEM was acquired from the GeoNova Digital Elevation Data archive (Project Name = Avon_Hydro_System, Product Creator = Internal Service Department).

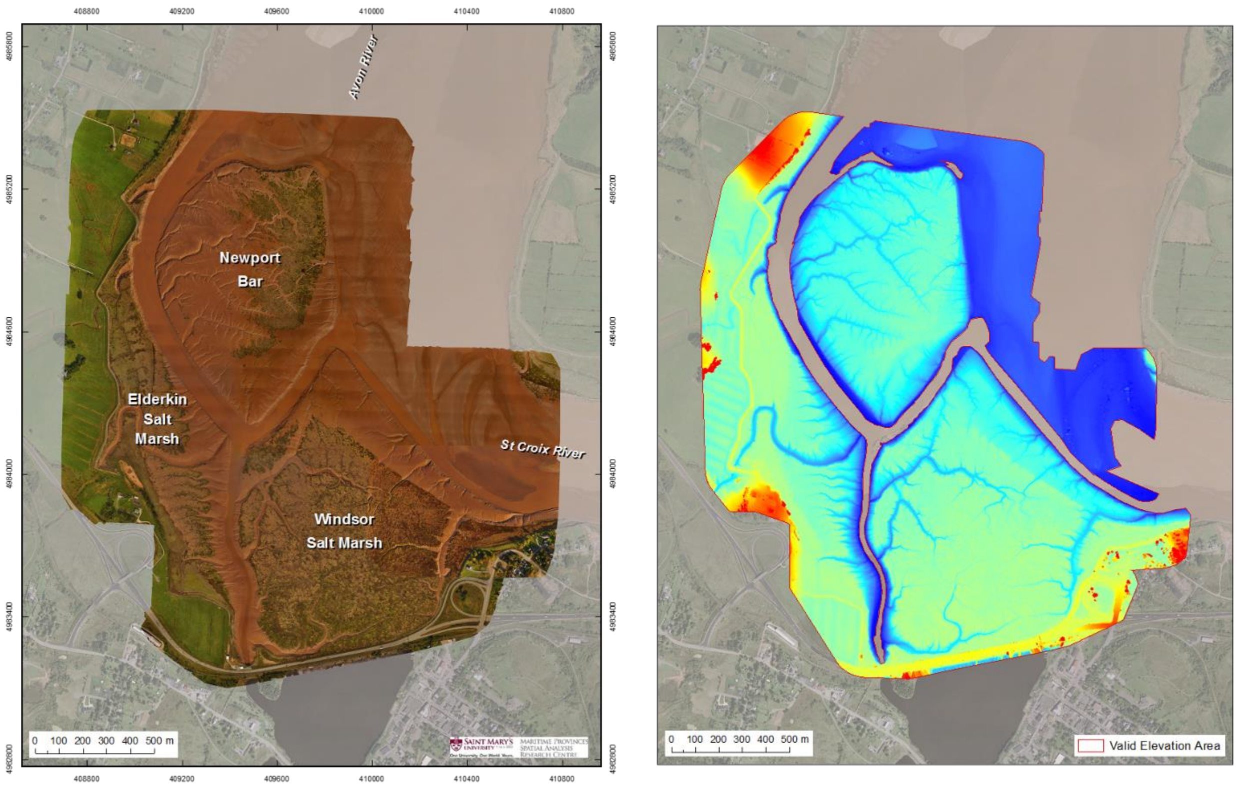


Figure 2 A) Orthomosaic generated from calibrated October 2017 imagery in valid capture area based on GCP distribution, water levels, and pix4d processing shown on 2012 imagery. B) Valid DSM generated from Oct 2017 georeferenced imagery with pix4d, water filled channels excluded from analysis.

Figure 3 Oblique aerial image taken October 20, 2017. UAV hovering over Tide Gate Channel looking south towards causeway.

3.2 Elevation and Hydrology of the Windsor Salt Marsh

This analysis focused primarily on the area immediately adjacent to the causeway and the main body of the Windsor Salt Marsh. Three types of elevation data were employed. The 2011 LiDAR was used as a foundation to understand recent changes at the. The bare mud areas from the DSM previously described were used in the marsh elevation analysis and hydrology sections, while the vegetated areas were used for habitat interpretation and hydrology analysis. A series of transects matching the location of the 2005 study transects, running perpendicular to the causeway and extending ~250 m into the marsh were used as the basis for the detailed elevation and vegetation surveys (Figure 4) (van Proosdij 2005). A Differential RTK GPS was used to map the beginning and end of each transect, vegetation sampling plots, and marsh surface elevations along each transect.

To create a surface for use in hypsometric curve generation and flood mapping the 2011 LiDAR DEM was updated by adding the mean observed change in elevation to the LiDAR and then masking and merging bare channels from the DSM with the LiDAR. Flood mapping was carried out using the above DEM and flood levels obtained from the causeway tide gate automatic water level recorders (tide gauge). In addition to flood mapping, hypsometric curves and hydroperiod for sample stations were calculated. Hypsometric curves describe the way in which a marsh floods (area under water at given tide height). Hydroperiod was calculated for the sample stations as both hydroperiod (percent of time during the recording period the station was flooded) and inundation frequency (percent of high tides which inundate station regardless of duration of flooding). These metrics are important for both vulnerability assessment and vegetation community structure.

Channel networks and drainage basins also play an important role in how the site floods. These were delineated for the Windsor and Elderkin Marshes, as well as the Newport Bar using the hydrology toolbox in QGIS. The tool was run on the DSM, and the network validated using the elevation survey data, DEM, and orthomosaics.

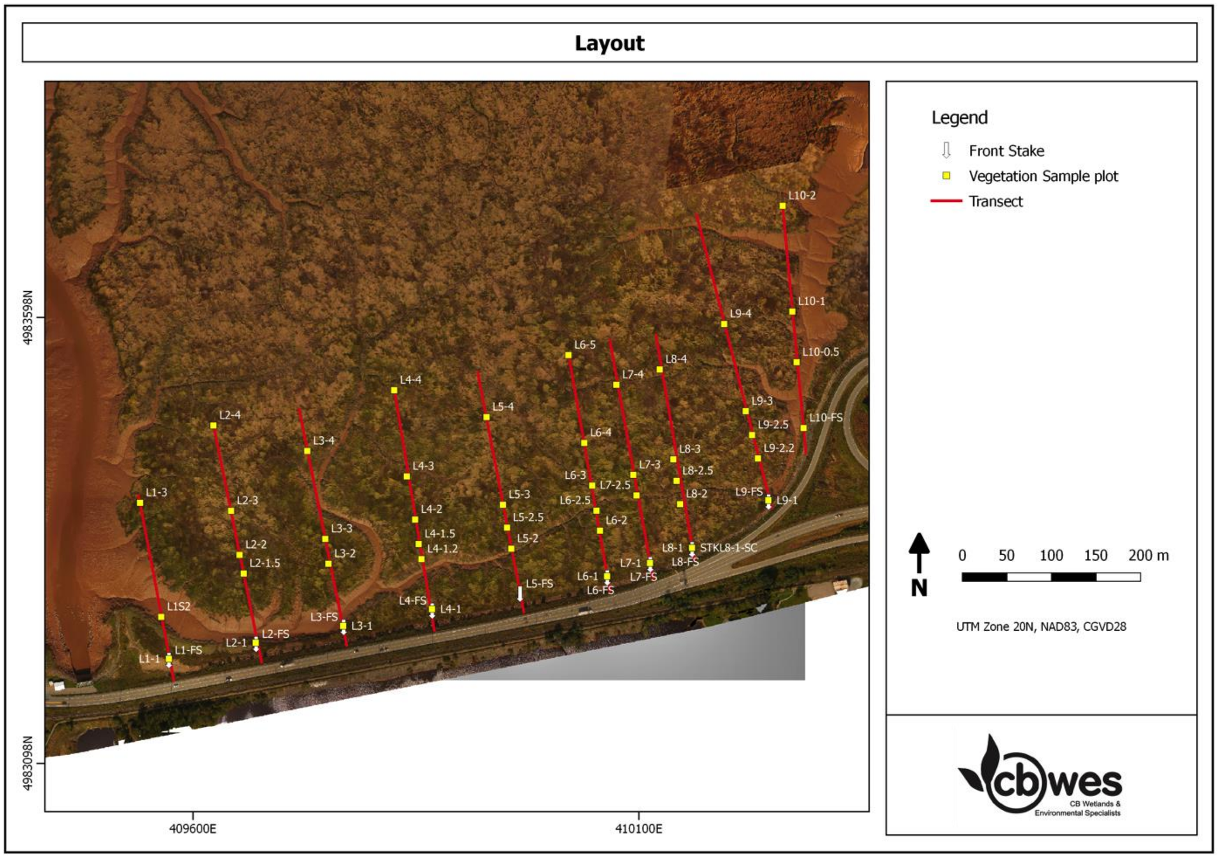


Figure 4 Location of survey transects and vegetation sampling stations, based on 2005 study (van Proosdij, 2005) overlain on 2017 imagery.

3.3 Ecomorphodynamic Analysis

'Ecomorphodynamics' refers to the study of the interactions and feedbacks that occur between topography, biota (e.g., vegetation and invertebrates), hydrodynamic (e.g., waves and currents) and sedimentary (e.g., suspended sediment concentration, deposition, erosion) processes, and the resultant adjustments of morphology. This section will focus on the larger footprint of the full orthomosaic (Windsor Salt Marsh, Elderkin Marsh, and Newport Bar). For this part of the analysis, a basic subtraction surface was calculated within ArcGIS 10.5.1 to delineate areas of vertical erosion and accretion based on the 2017 DSM and the 2007 LIDAR DEM which had a 1 m resolution. The resultant difference surface had a vertical accuracy of approximately 15 cm, therefore differences less than 0.15 m were considered 'no change' and excluded from the analysis.

Changes in tidal channel morphology were examined by extracting cross-sectional profiles along 17 transects from the 2007 and 2017 elevation models in ArcGIS (Figure 5) (Appendix B). Five of the profiles were identical to those surveyed immediately after construction of the current causeway and in

2005 (van Proosdij and Baker 2007). The remainder were added as part of this study in order to provide greater detail in areas of potential relevance for highway twinning.

Vegetated areas of salt marsh were digitized from the 2017 orthomosaic and used to mask vegetated areas in the 2017 DSM. This permitted the most accurate direct comparison of changes in volume in tidal channels or cross-sectional profiles between 2007 and 2017. Historical marsh polygons were obtained from previous studies (van Proosdij and Baker, 2007; van Proosdij et al., 2009) and used to explore changes in marsh area over time. For the purposes of this study, marsh change was only examined for time periods after the causeway was constructed (post 1969-71). These were digitized based on available air photography or satellite images at low tide. Detailed analyses of changes in marsh habitat pre and post causeway construction are reported in van Proosdij and Baker, 2007.

Current patterns and tidal flow interactions, particularly during the shift from flood to ebb tides, at the confluence of main channels (i.e., western Avon River channel and St. Croix River channel), within the Tide Gate Channel and at the tide gate structure itself, were monitored using video footage obtained by UAV.

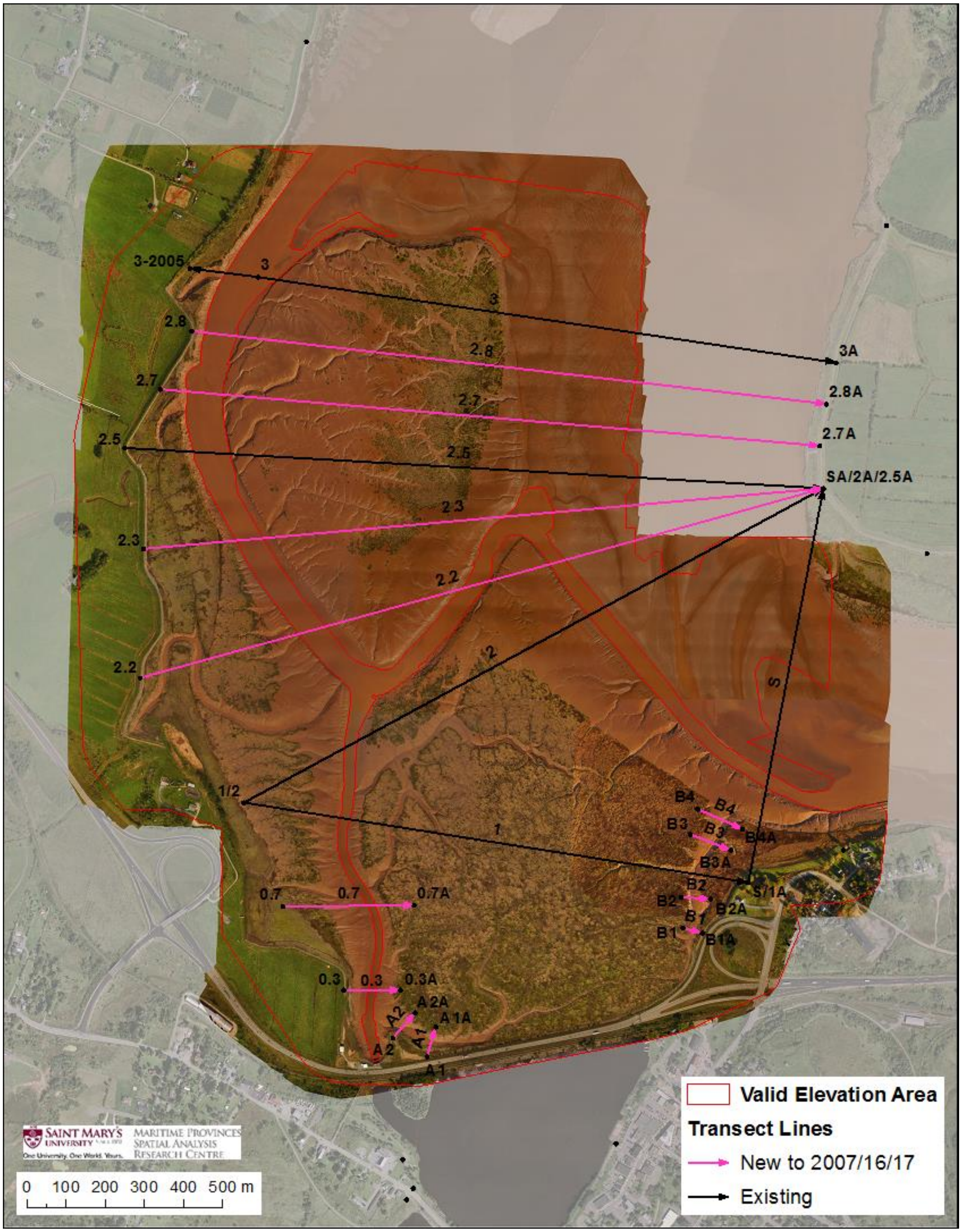


Figure 5 Location of the 17 elevation transects used to derive cross-sectional profile comparisons. Transects overlain on the 2017 orthomosaic.

3.4 Bathymetric Analysis

The Avon River estuary is a dynamic intertidal system that has and will continue to respond to anthropogenic activities (e.g., dyking, dredging, causeway construction, armouring, damming) and natural drivers of change (e.g., storms, seasonal fluvial discharge, ice conditions and sea level rise). This response is seen in patterns of erosion and deposition as the estuary channel seeks an equilibrium form with the tidal prism moving through it. Although previous studies (van Proosdij and Baker, 2007; van Proosdij et al., 2009) have demonstrated that the ecomorphodynamic response of the Avon system to the construction of the causeway was limited to the first 2 km downstream of the structure, recent observations in the field and other changes in the estuary warrant further study. This is particularly relevant given the public interest and continued comparison to the Petitcodiac causeway and its removal. van Proosdij et al., 2009 demonstrated that due to a range of factors, the Avon system is not directly comparable to the Petitcodiac and did not see the same level of decrease in tidal prism the length of the estuary. The comprehensive 2007 report examined changes in estuarine morphology over time using all available bathymetric survey data, details of which are outlined in detail in van Proosdij and Baker, 2007 and will not be repeated here. In that study, 20 cross channel transects were delineated for comparison of cross-sectional area and various measures of hydraulic geometry were determined including channel depth, width and cross-sectional area for each profile line (Figure 6). Both intertidal cross-sectional area (A) and tidal prism (V) upstream of each section were calculated for HHWLT and HHWMT based on Canadian Hydrographic Service (CHS) tide stations at Hantsport. Intertidal cross-sectional areas (between HHW and LLW) were calculated using a modified Trapezoid rule with a mean distance between points of 2 m and tidal prism calculated using an average end-area method. Since it has been over 10 years since the last bathymetric survey of the estuary has been performed and recent large-scale physical activities have been undertaken within the system (i.e., closure of Fundy Gypsum and dredging at Hantsport wharf; relocation and construction of sewage treatment facility on the St. Croix River), a new baseline was required for comparison with any construction activities at the causeway and repeat monitoring of these transects post-construction is recommended.

The 2017 bathymetric survey was conducted during large spring tides December 3-5 using a single frequency echosounder deployed on a fishing boat. The survey had an estimated mean vertical position accuracy (NRTK GNSS) of 0.010 m (excluding lines 5.5 and K1) with a standard deviation of 0.002 m and maximum error of 0.033 m.

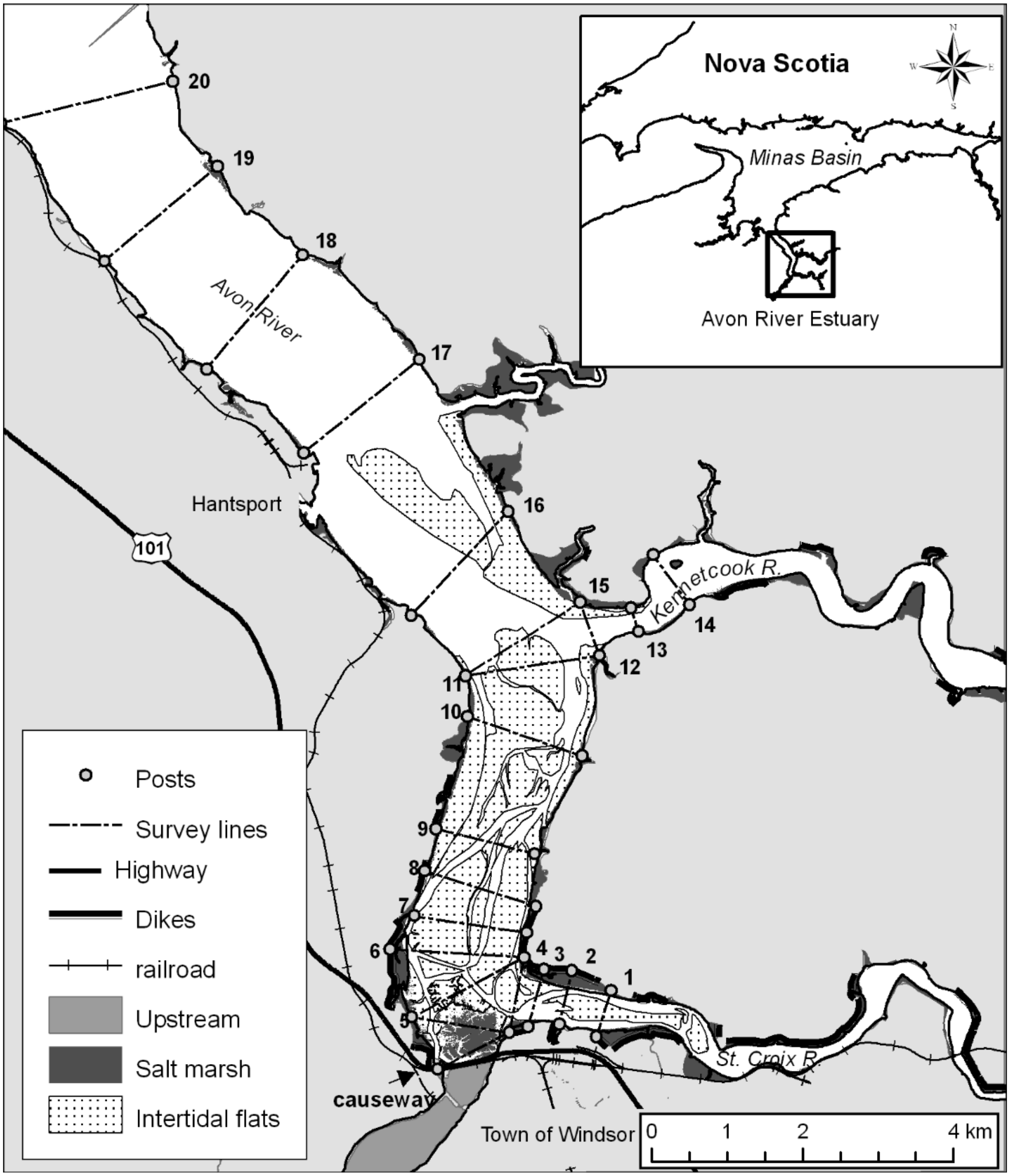


Figure 6 Location of historical bathymetric transect lines from van Proosdij and Baker, 2007 used to compare changes in channel cross-sectional area over time.

3.5 Habitat and Vegetation

The current extent and recent changes in salt marsh habitat (vegetation) were quantified using a combination of low-altitude aerial photography and a targeted ground-based vegetation survey.

Vegetated areas of salt marsh were digitized from the 2017 orthomosaic with vegetation community identification informed by the vegetation survey and site visits. Historical marsh polygons were obtained from previous studies (van Proosdij and Baker, 2007; van Proosdij et al., 2009) and used to explore changes in marsh area over time. For the purposes of this study, marsh change was only examined for time periods after the causeway was constructed (post 1969-71). These were digitized based on available air photographs or satellite images at low tide. Detailed analyses of changes in marsh habitat pre and post causeway construction are reported in van Proosdij and Baker, 2007.

Vegetation sampling was conducted using a modified version of the point intercept method at 1 m^2 plots located along the ten causeway transects (Roman et al. 2001; Roman et al. 2002) (Figure 4). For each plot species composition, abundance, and height (of dominant species) was recorded. Additionally, a qualitative vegetation survey was conducted as part of all on-site activities, with emphasis on the identification of invasive, non-tidal wetland, and rare plant species. The presence, identity and location of any species of significance (i.e., salt marsh species representing high marsh development) were also noted and mapped.

The CBWES-SMU tidal wetland monitoring database was used to identify a reference condition for comparison of the vegetation survey data. Reference plots with a similar range of each variable (i.e., geography, elevation, inundation frequency, hydroperiod) to those of the Windsor Salt Marsh vegetation plots were chosen from the database for the analysis (Table 2). A total of 92 reference plots that overlapped the range of environmental variables at the study site were chosen. For the purpose of reference site selection hydroperiod and inundation frequency were calculated using predicted tide signal for Hantsport for the year 2012, converted to geodetic datum based on conversion factors calculated at the nearby Cogmagun site (Bowron et al, 2010).

Reference plots were compared with study site plots for average species richness, halophyte richness and abundance. Non-metric multidimensional scaling was used as an ordination technique to show differences between plot-level vegetation communities. Species identification verification and vegetation data analysis was conducted by Dr. Jeremy Lundholm (SMU).

Table 2 Characteristics of Study and Reference plots.

	Windsor Study Site Plots	**Selected Reference Plots**
Elevation (m)	3.66 – 6.82	4.22 – 6.98 (upper Minas Basin only)
Inundation frequency	17.31 - 100	10.21 – 99.01
Hydroperiod	1.65 – 29.02	1.14 – 24.53

3.4 Structured Winter Walk (Winter Conditions)

A structured winter walk (mid-winter) was conducted February 7, 2018, in order to document and evaluate winter conditions at the site. The structured walk included traversing the perimeter of the site with landscape photographs being taken along transects, tide channels and of key features such as the tide gate structure, causeway edge, dykes, significant ice formations, areas of erosion or deposition and other features of note.

4.0 Results and Discussion

4.1 Elevation and Hydrology of the Windsor Salt Marsh

Elevation

All elevation data (surveyed elevations, UAV-derived DSM, and the 2011 LiDAR DEM), were compared to understand current conditions and recent changes at the site. The 2011 DEM has a reported vertical accuracy (NVA RMSEz) of 0.22 m ± 0.44 m at a 95% C.I. The DSM had a reported RMS error of 0.009 m, while the RTK survey had a mean 3d error of 0.011 ± 0.001 m. Elevations extracted from the DSM at the locations of RTK points which were captured on bare mud were compared to see how well the two surfaces matched. On average DSM points were 0.04 m below the surveyed elevation, with a standard deviation of 0.15 m. Part of this error can be attributed to seasonal changes in the system as the survey data were not collected concurrently (RTK on Aug 12 & Nov 27; aerial photography September 25 & 26 and Oct 20). Despite the differences in sampling period, both the DSM and RTK survey had low reported and observed errors and the surfaces compare well. Due to the reported error of the LiDAR DEM and based on the approach used in previous reports, changes below 0.15 m are considered “no change”.

Elevation transects, shown in Figure 7 and profiles shown in Figure 8, show a general pattern of accretion on the marsh platform and narrowing of channels. Exceptions to this were observed on transect 1, where the mouth of the large channel running perpendicular to the highway has deepened and shifted northward, eroding the northern bank and accreting on the southern bank. The patterns observed fit with a maturing marsh platform, as the marsh grows in height the tidal prism decreases, resulting in a reduction in cross-sectional area of the channel network. Mean elevation for all surfaces, changes in elevation and canopy height (DSM-RTK) are shown by transect in Table 3. The mean change in platform elevation was 0.20 ± 0.22 m, narrowly above the margin of error identified previously. Given the spatial patterns described above (erosion in areas of channel migration, accretion on platform), positive change was considered in isolation to understand accretion. The mean increase was 0.26 ±0.17 m, slightly higher and with less deviation than when total change was considered. The canopy height was an average of 0.69 m, however field measurements put the average *S. alterniflora* (dominant species) height at 1.43 m. The difference can largely be attributed to the fact that the grass was not likely upright and the Structure from Motion algorithm was therefore matching points lower on the stem. Another contributing factor could be that the vegetation survey was carried out in August while the DSM was captured in October, when the growing season is past and vegetation is often dying and flattened by weather.

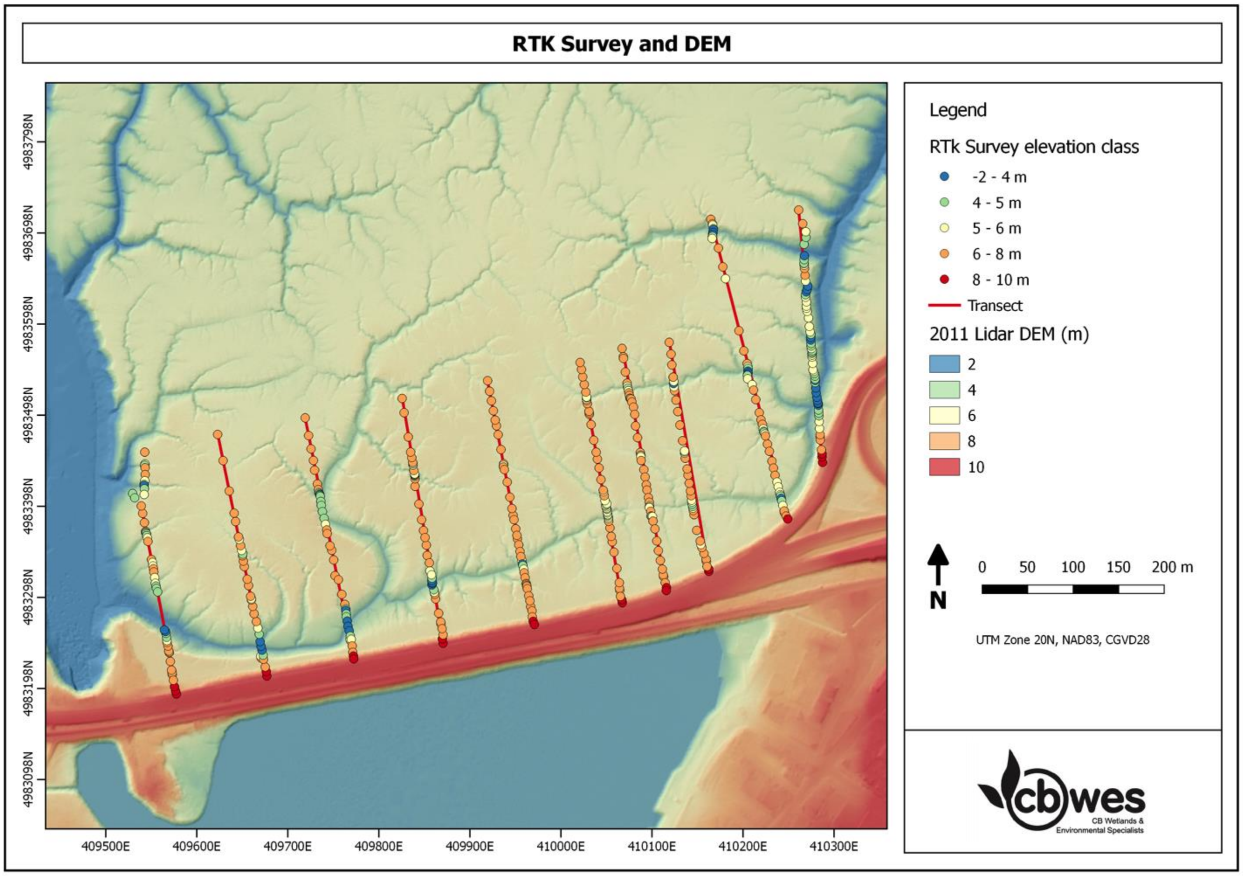
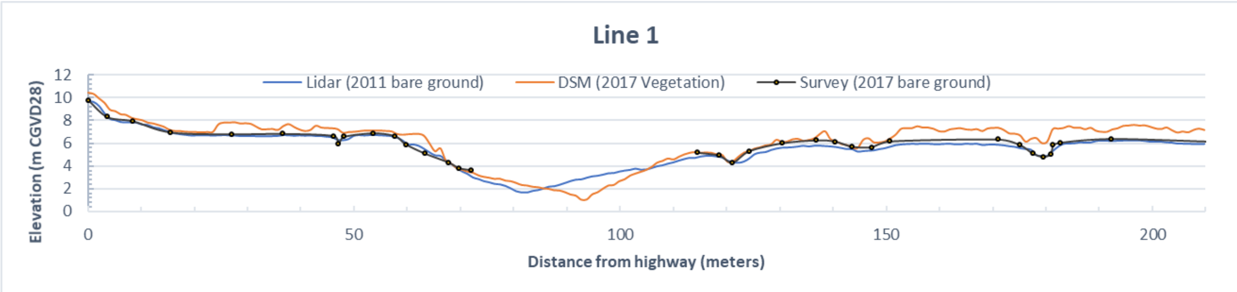
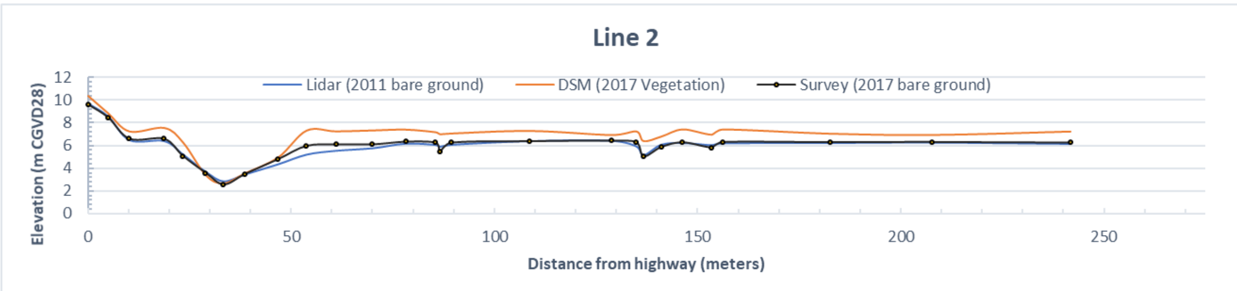


Figure 7 Surveyed transects overlaying 2011 LiDAR DEM.


Line 1
Lidar (2011 bare ground)
DSM (2017 Vegetation)
Survey (2017 bare ground)
Elevation (m CGVD28)
0
2
4
6
8
10
12
0
50
100
150
200
Distance from highway (meters)


Line 2
Lidar (2011 bare ground)
DSM (2017 Vegetation)
Survey (2017 bare ground)
Elevation (m CGVD28)
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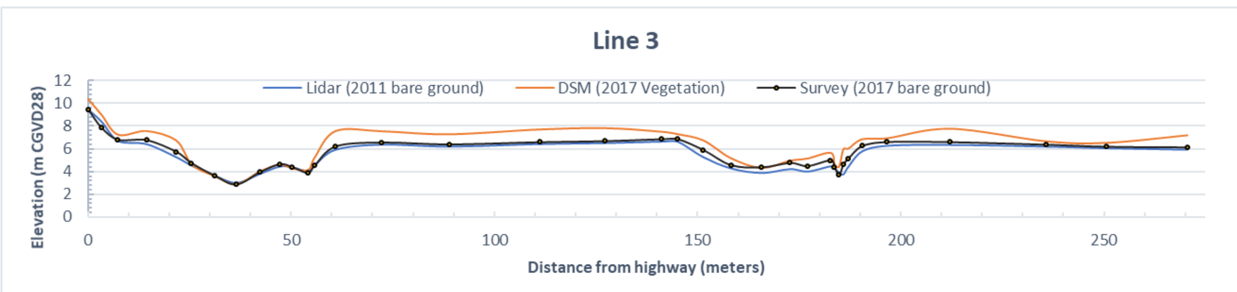
2
4
6
8
10
12
0
50
100
150
200
250
Distance from highway (meters)


Line 3
Lidar (2011 bare ground)
DSM (2017 Vegetation)
Survey (2017 bare ground)
Elevation (m CGVD28)
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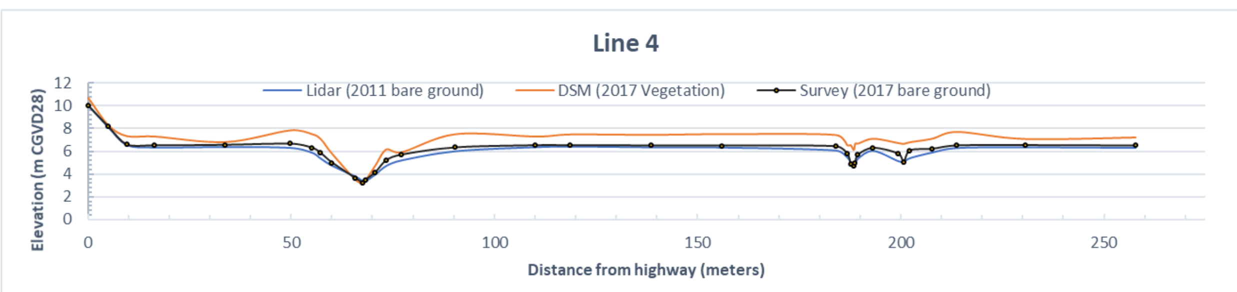
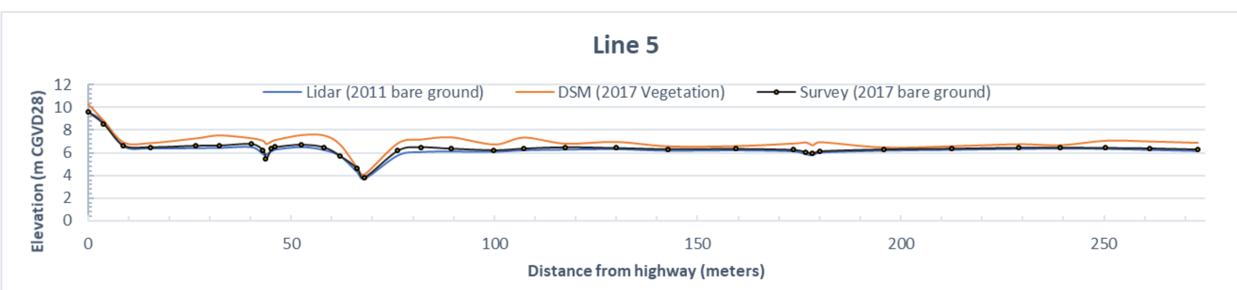
2
4
6
8
10
12
0
50
100
150
200
250
Distance from highway (meters)


Line 4
Lidar (2011 bare ground)
DSM (2017 Vegetation)
Survey (2017 bare ground)
Elevation (m CGVD28)
0
2
4
6
8
10
12
0
50
100
150
200
250
Distance from highway (meters)


Line 5
Lidar (2011 bare ground)
DSM (2017 Vegetation)
Survey (2017 bare ground)
Elevation (m CGVD28)
0
2
4
6
8
10
12
0
50
100
150
200
250
Distance from highway (meters)

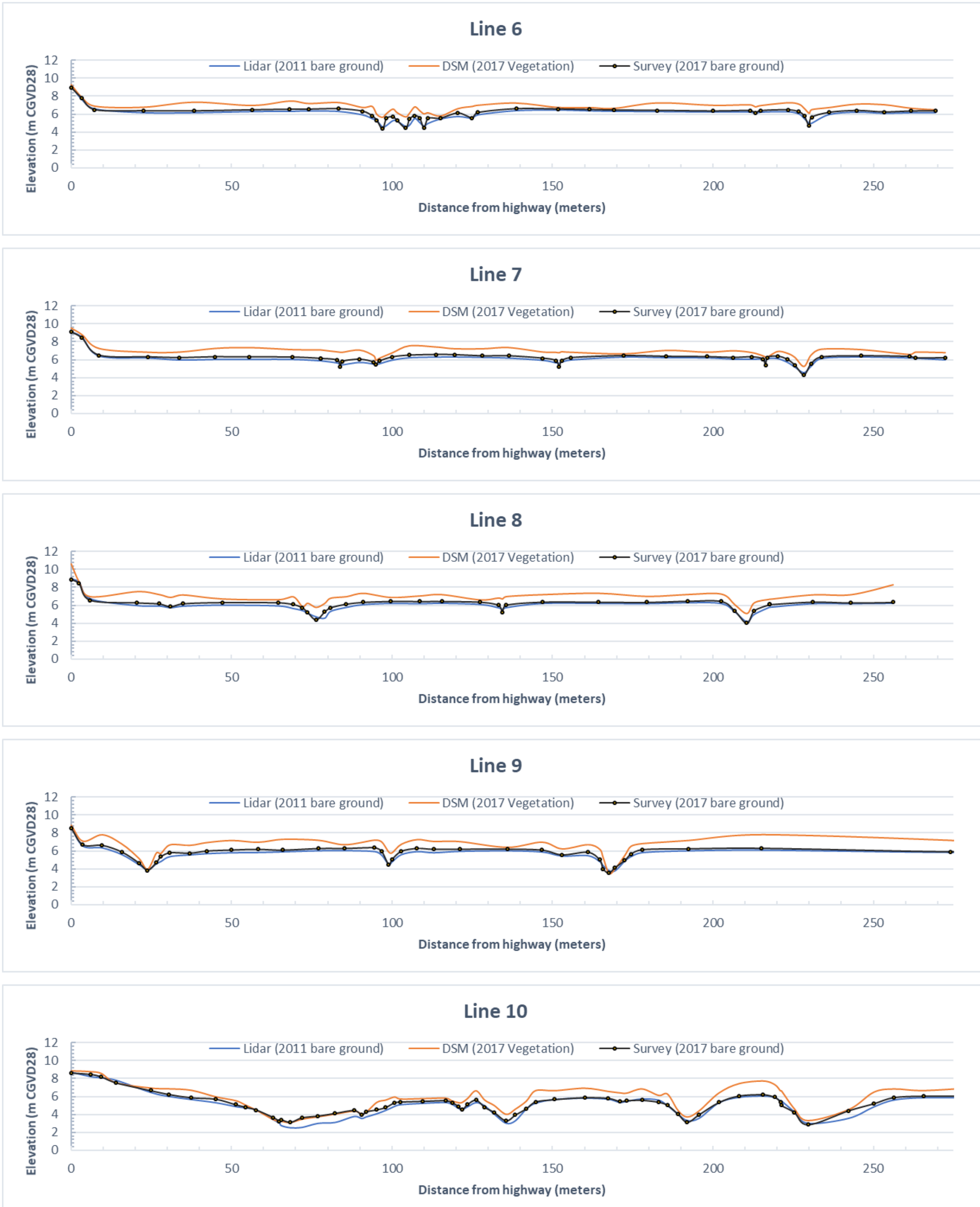


Figure 8 Transects 1- 10 comparing surveyed elevation, DSM and DEM surfaces. VE=2.96.

Table 3 Mean changes in elevation by transect.

	Mean Elevation (m CGVD28)						
Transect	2011 Lidar	2017 RTK	2017 DSM	Change (2011-2017)	Canopy 2017 (DSM)	Accretion (+ Change)	Erosion (- Change)
1	5.76	6.00	6.58	0.24	0.58	0.28	-0.10
2	5.84	5.95	6.75	0.12	0.79	0.25	-0.14
3	5.35	5.58	6.15	0.23	0.57	0.31	-0.17
4	5.70	5.92	6.74	0.23	0.82	0.28	-0.09
5	6.22	6.38	6.97	0.16	0.59	0.19	-0.26
6	5.89	6.08	6.79	0.19	0.71	0.25	-0.20
7	6.03	6.19	6.93	0.16	0.74	0.22	-0.22
8	5.94	6.14	6.98	0.20	0.85	0.27	-0.19
9	5.41	5.61	6.36	0.20	0.75	0.26	-0.15
10	4.89	5.11	5.68	0.23	0.57	0.31	-0.16
Average	5.65	5.85	6.54	0.20	0.69	0.26	-0.16
Standard Deviation	1.15	1.13	1.26	0.22	0.42	0.17	0.13

Hydrology

Drainage channels and basins were delineated from the DSM in QGIS. First marshes were isolated (Windsor, Newport Bar, and Elderkin), the DSM up-sampled to 1 m and filled. Than the Saga Channel network and drainage basin tool (threshold=6) was run. The channel network will be used as a basis to track future changes at the site (Figure 9). Channel statistics are shown in Table 4. Total channel length was 40,323 m, and drainage density across the DEM at the selected threshold was 0.0224 m/m^2. The largest marsh (Windsor), had the shortest channel segments and the fewest basins due to the complex dendritic network at the site. Elderkin, which fringes the Avon and is dyked on the backshore, had the shortest total channel length and the smallest drainage area. Newport Bar, a still evolving mudflat and sparsely vegetated, had the lowest drainage density.

Tide level data was provided by NSDA from the gauging station at the Windsor Causeway. For this analysis all available data for the year 2017 was used, with tide levels for 56 days between January 1 and July 10. In addition, predicted tides for Hantsport (CHS station 282) were obtained for the same period. The upstream and downstream of the Windsor tide gate tidal signals, as well as precipitation are shown in Figure 10. A comparison of tidal signals upstream and downstream of the tide gate showed a large difference in water levels. The 2017 data shows the upstream tidal range was 4.69 m (CGVD28) while the downstream tidal range was 9.45 m (CGVD28), for a difference in water level of 4.76 m. This is expected since the tide gates are used to control upstream water levels. Lower upstream water levels correspond with the tide gates being fully open for alternating 6-hour periods during low tide. Higher upstream water levels are observed when the gate is open for 15-minute periods during low tides. While precipitation would have a larger influence on upstream water levels (particularly in higher reaches of the Avon) high water levels immediately upstream of the causeway did not correlate well with precipitation, indicating that upstream water levels are controlled primarily by gate operation.

During the study period the highest recorded tide downstream was 8.22 m (CGVD28), while the highest predicted tide was 7.97 m. Utilizing the recorded tide signals and DEM, a hypsometric curve was produced for the area shown in Figure 11. The hypsometric curve (Figure 12) shows a marsh that does not yet fit the pattern typically observed at a mature marsh, where the marsh floods rapidly near the mean high tide elevation and flood extents reach their maximum near the highest high tide (Figure 13). Critical tide heights from both observed and predicted tides, such as the highest and mean high tides were calculated and used to determine area flooded (Table 5). At this site the minimum high tide (5.58 m) floods just over 45% of the marsh surface and the mean observed high tide (6.58 m) floods over 90% of the marsh. Even when predicted tides were used, which were lower than observed tides, 75% of marsh was flooded by the mean high tide (6.17 m).

Flood extents and inundation frequency are shown in Figure 14. At low water (-1.23 m) only the primary river channel (Tide Gate Channel) downstream of the tide gate is flooded, while all channels within the Windsor Salt Marsh remain dry. The average recorded water level (1.64 m), which in meso- or micro-tidal systems may correspond to the low marsh boundary, still failed to fill the tidal channels of the Windsor Salt Marsh. The minimum observed tide level required to fill the tidal channels within the marsh and flood the edges of the vegetated marsh surface was 5.58 m. The only part of the marsh that was not flooded by the mean observed high tide (6.58 m), because of its elevation, was the portion of the marsh bordering the edge of the causeway. The observed high tide of 8.22 m would have flooded the entire marsh area (95 hectares) with a mean water depth of ~2.55 m (50% marsh flooded at 5.36 m). Hydroperiod was calculated using both observed and predicted tides and is shown in **Error! Reference source not found.** and Figure 14. Hydroperiod ranged from 2% (minimum predicted tides) to 32% (maximum observed tides). Inundation frequency ranged from 19% (minimum predicted tides) to 100% (maximum observed and predicted) tides. As previously noted, observed tides were higher than predicted resulting in higher observed hydroperiod and inundation frequency than predicted. The mean recorded inundation frequency of 56% is 21% higher than the predicted hydroperiod of 36% (used for vegetation analysis).

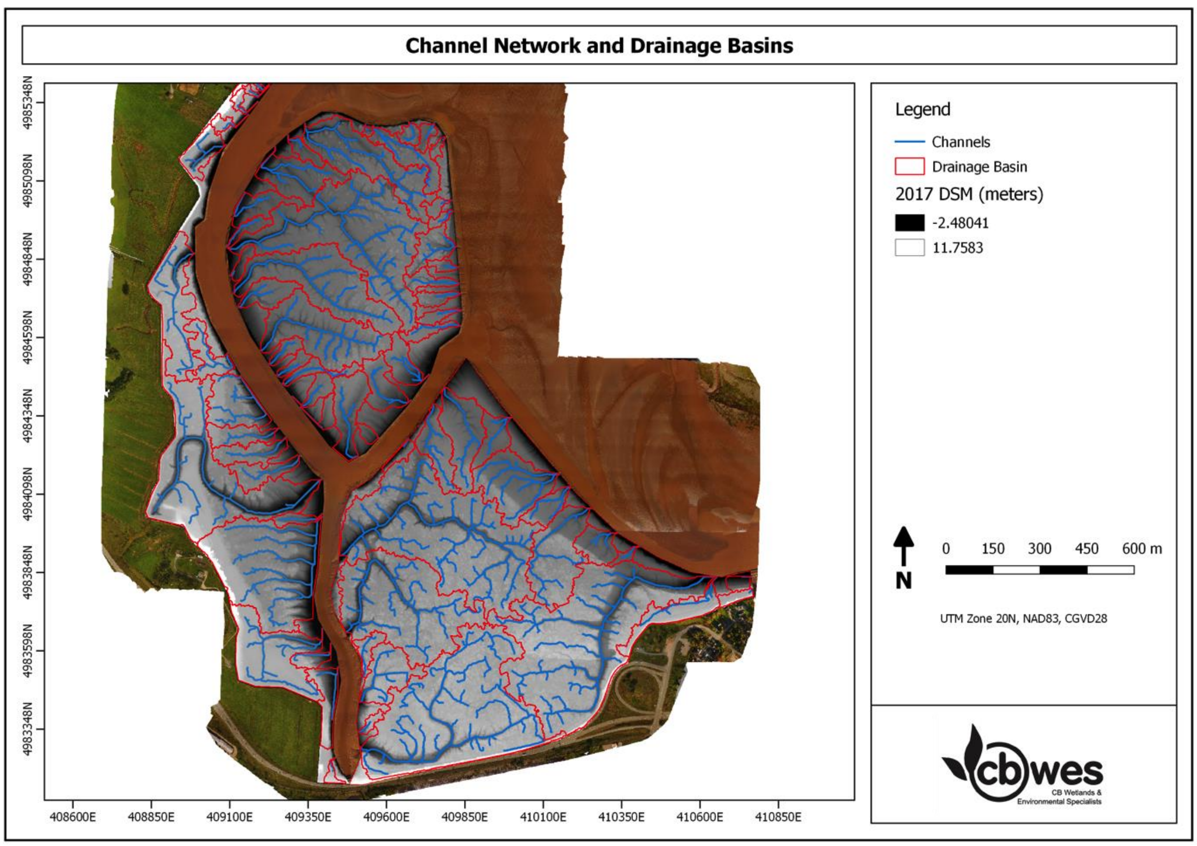


Figure 9 Drainage Basins and channel thalwegs for marsh and mudflat delineated from DSM.

Table 4 Drainage basin and channel statistics for the Elderkin Marsh, Newport Bar, and Windsor Salt Marsh.

	Elderkin	Newport Bar	Windsor	Total
Total Channel Length (m)	9783	11135	19405	40323
Total Drainage Area (m^2)	433699	507199	855609	1796507
Drainage Density (m/m^2)	0.0226	0.0220	0.0227	0.0224
# Channel Segments	132	160	321	613
# Drainage Basins	20	32	19	71
Average Channel Length (m)	74.1	69.6	60.5	--

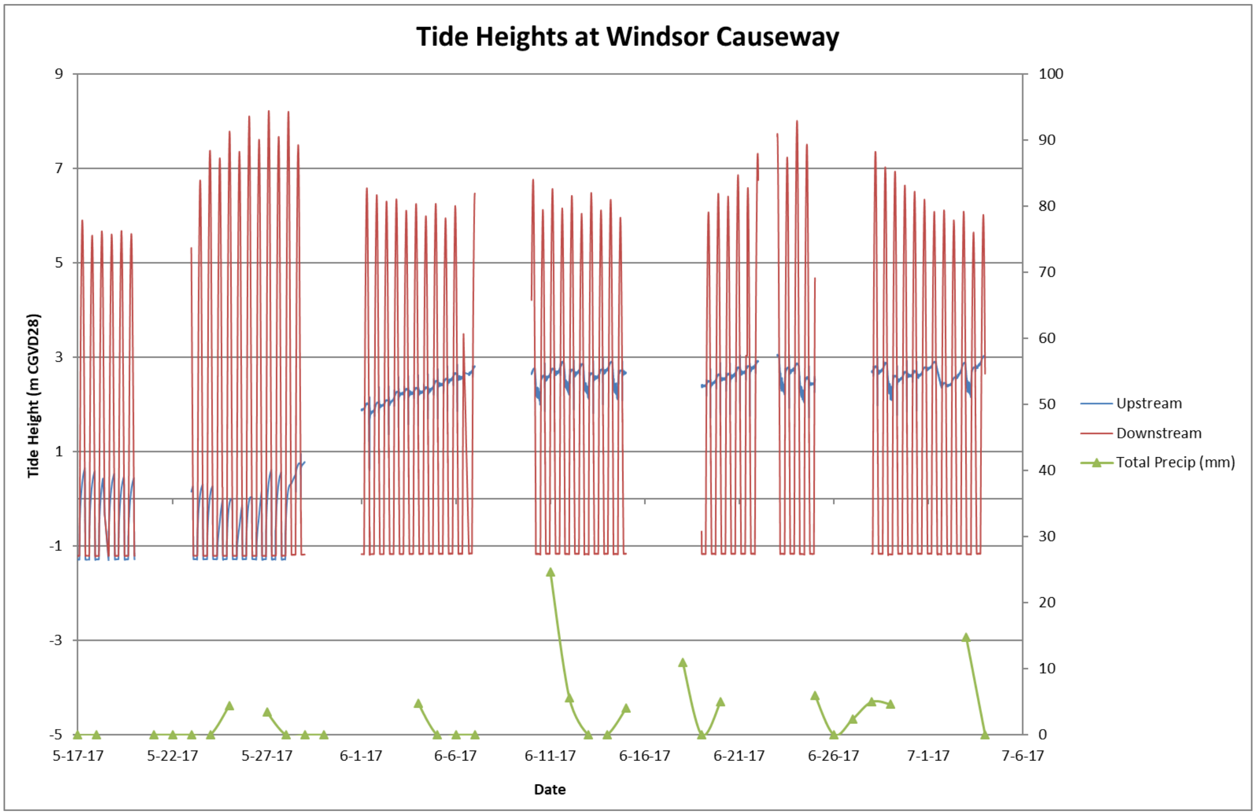


Figure 10 Tide signal at Windsor Causeway with upstream water level (Lake Pisiquid) and rainfall amounts (White Rock, NS).

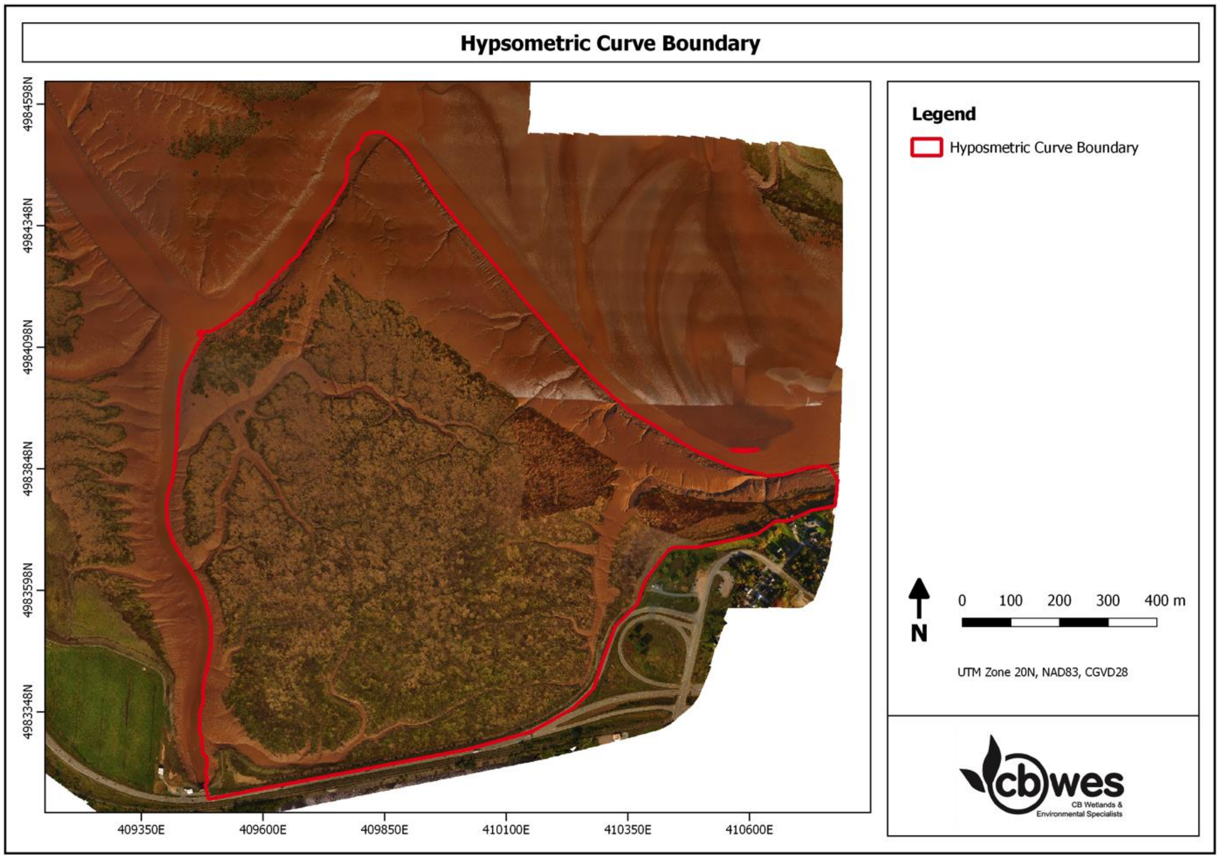


Figure 11 Boundary for hypsometric curve generation - main tidal marsh bounded by river thalweg and highway.

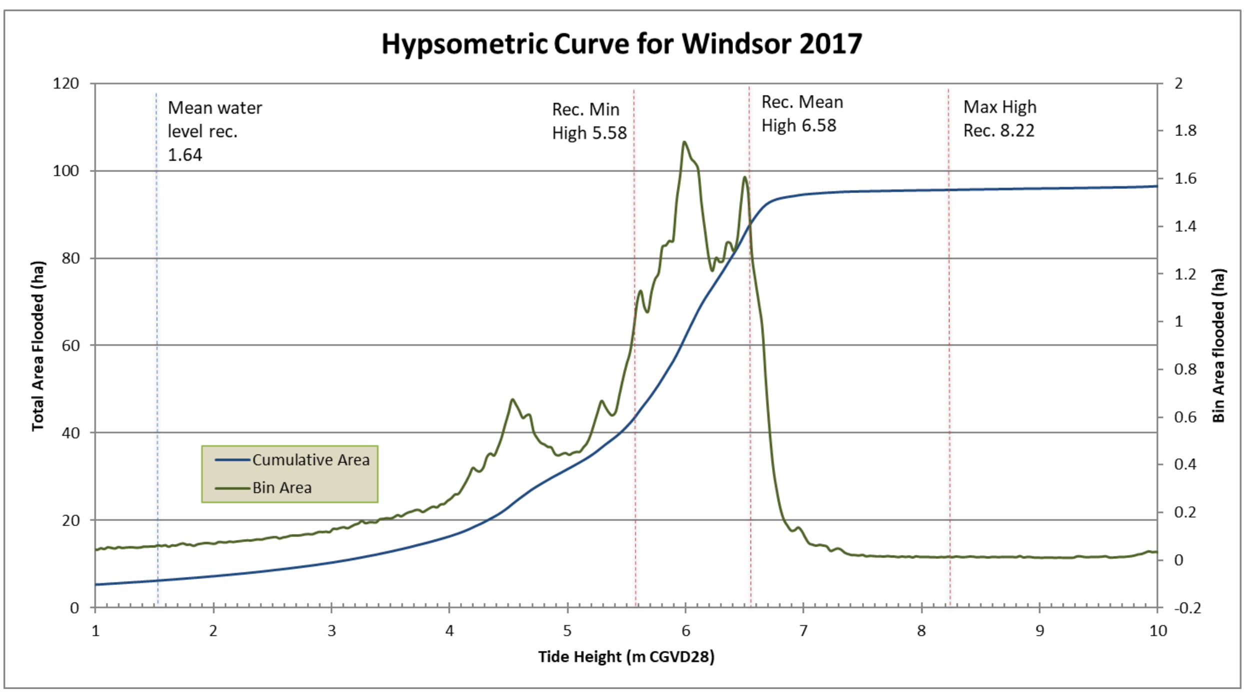


Figure 12 Hypsometric curve for Windsor Salt Marsh.

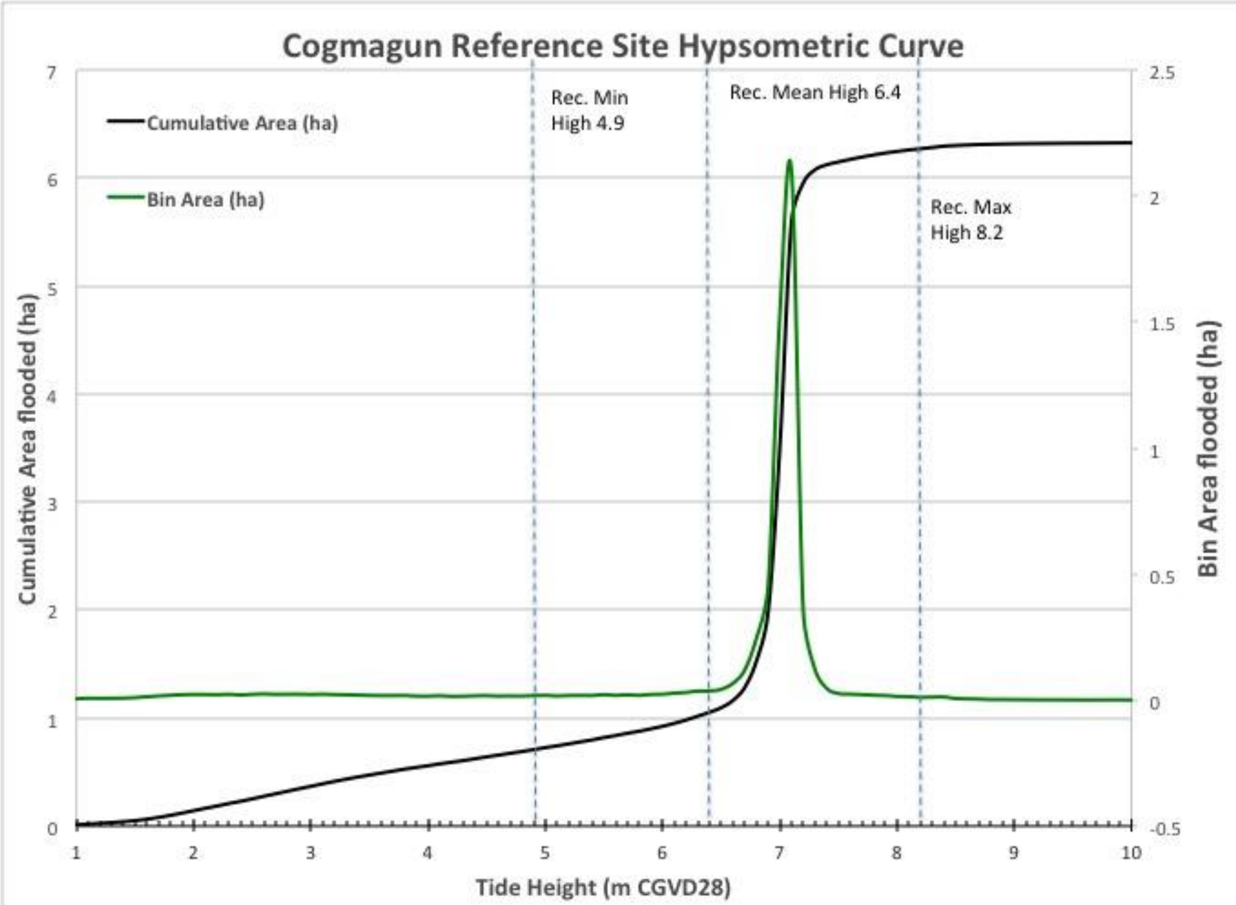


Figure 13 Example of typical hypsometric curve for a salt marsh in the upper Bay of Fundy, in this case the reference site for the Cogmagun River salt marsh restoration project (Bowron et al. 2015).

Table 5 Critical tide heights and area flooded.

Tide Height Metric	Tide Elevation (m CGVD28)	Area Flooded (ha)	% area to HHWLT
HHWLT Sourthern Bight	8.15	95.7	100
Recorded Water Level			
Max	8.22	95.7	100
Mean	1.64	6.4	7
Min	-1.23	2.7	3
Recorded High Tides			
Max	8.22	95.7	100
Q3 (75th percentile)	6.92	94.2	98
Mean	6.58	88.4	92
Q2 (Median)	6.41	81.1	85
Q1 (25th percentile)	6.08	66.4	69
Min	5.58	43.3	45
Predicted High Tides (Hantsport)			
Max	7.97	95.6	100
Q3 (75th percentile)	6.77	93.3	97
Mean	6.17	70.9	74
Q2 (Median)	6.17	70.9	74
Q1 (25th percentile)	5.67	46.6	49
Min	4.17	18.0	19

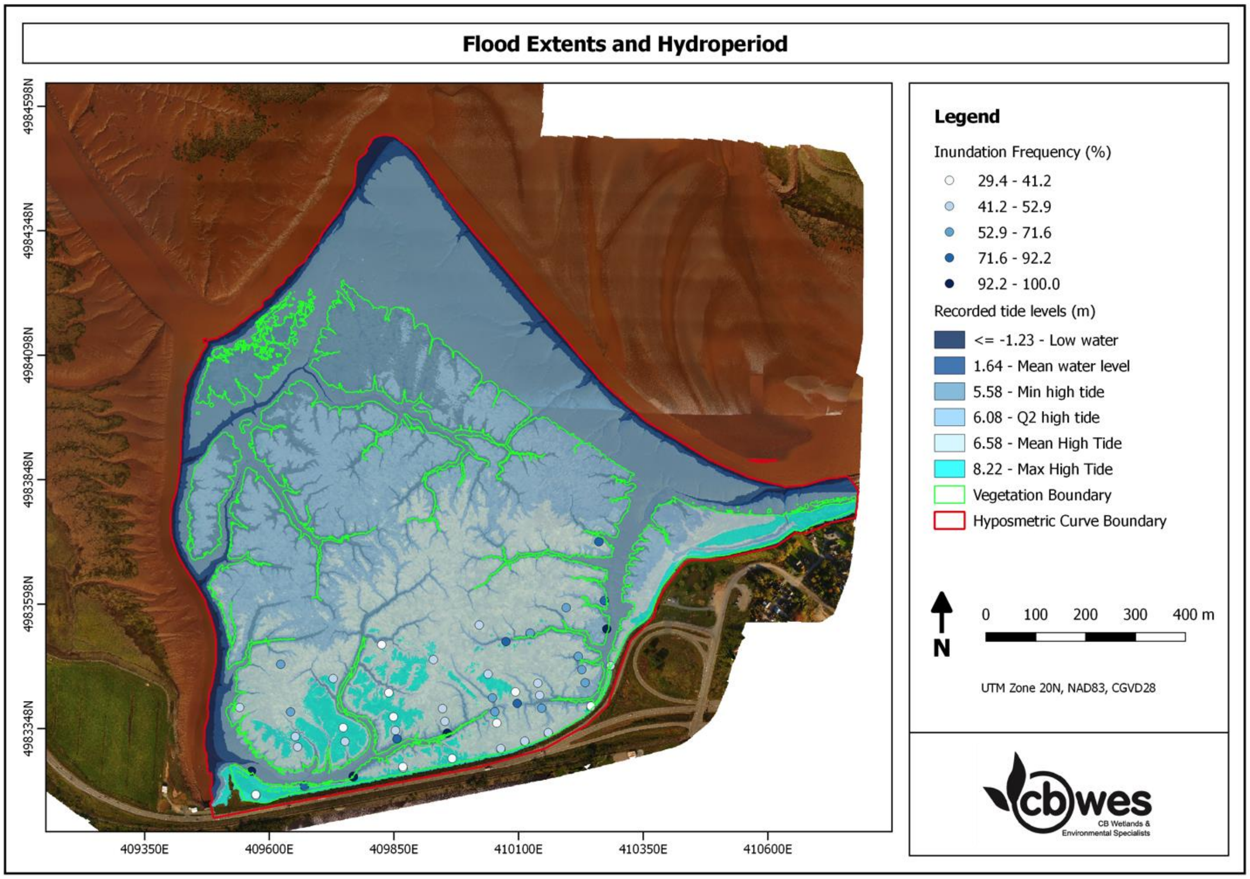


Figure 14 Flood extents for observed tides and inundation at vegetation stations.

Table 6 Hydroperiod and Inundation Frequency for vegetation stations.

PtID	Line	Elevation (m CGVD28)	Distance from causeway (m)	Hydroperiod (%) Recorded	Hydroperiod (%) Predicted	Inundation Frequency (%) Recorded	Inundation Frequency (%) Predicted
WIN_L1-FS_17	1	6.783	0	4.0	1.8	24.1	19.2
WIN_L1-1SC_17	1	6.768	2	4.0	1.9	27.2	19.2
WIN_L1S2-V_17	1	3.662	50	32.1	29.0	100.0	100.0
WIN_L1-3SC_17	1	6.372	180	6.7	4.0	39.5	29.8
WIN_L2-FS_17	2	6.502	0	5.6	3.3	35.7	28.8
WIN_L2-1SC_17	2	6.002	2	11.2	6.9	57.4	48.1
WIN_L2-1.5_17	2	6.429	81	6.2	3.7	39.5	29.8
WIN_L2-2SC_17	2	6.35	102	6.9	4.1	43.8	30.8
WIN_L2-3_17	2	6.273	152	7.7	4.7	43.8	34.6
WIN_L2-4_17	2	6.289	250	7.5	4.6	43.8	34.6
WIN_L3-FS_17	3	5.801	0	13.9	8.5	66.0	57.7
WIN_L3-1SC_17	3	5.383	2	18.7	12.8	81.6	69.2
WIN_L3-2_17	3	6.5	73	5.6	3.3	35.7	28.8
WIN_L3-3SC_17	3	6.647	102	4.6	2.4	31.9	21.2
WIN_L3-4_17	3	6.487	202	5.7	3.4	35.7	28.8
WIN_L4-FS_17	4	6.55	0	5.2	3.0	35.7	27.9
WIN_L4-1C_17	4	6.556	2	5.2	3.0	35.7	27.9
WIN_L4-1.2_17	4	5.839	59	13.4	8.2	66.0	51.9
WIN_L4-1.5_17	4	6.489	77	5.7	3.4	35.7	28.8
WIN_L4-2_17	4	6.552	104	5.2	3.0	35.7	27.9
WIN_L4-3_17	4	6.529	154	5.4	3.2	35.7	27.9
WIN_L4-4_17	4	6.636	251	4.7	2.5	31.9	21.2
WIN_L5-FS_17	5	6.601	0	4.8	2.6	31.9	22.1
WIN_L5-2C_17	5	5.471	52	17.8	11.8	79.6	67.3
WIN_L5-2.5_17	5	6.384	76	6.6	3.9	39.5	29.8
WIN_L5-3SC_17	5	6.48	102	5.8	3.4	35.7	28.8
WIN_L5-4_17	5	6.407	202	6.4	3.8	39.5	29.8
WIN_L6-FS_17	6	6.433	0	6.2	3.7	39.5	29.8
WIN_L6-1SC_17	6	6.419	2	6.3	3.8	39.5	29.8
WIN_L6-2C_17	6	6.544	54	5.3	3.0	35.7	27.9
WIN_L6-2.5_17	6	6.332	77	7.1	4.2	43.8	30.8
WIN_L6-3SC_17	6	6.131	105	9.3	5.8	53.1	41.3
WIN_L6-4_17	6	6.463	154	5.9	3.5	39.5	28.8
WIN_L6-5_17	6	6.383	254	6.7	3.9	39.5	29.8
WIN_L7-FS_17	7	6.405	0	6.4	3.8	39.5	29.8
WIN_L7-1SC_17	7	6.425	2	6.2	3.7	39.5	29.8
WIN_L7-2.5_17	7	5.855	79	13.2	8.1	66.0	50.0
WIN_L7-3SC_17	7	6.564	103	5.1	2.9	35.7	27.9
WIN_L7-4C_17	7	6.068	205	10.2	6.3	57.4	46.2
WIN_L8-FS_17	8	6.412	0	6.4	3.8	39.5	29.8
WIN_L8-1SC_17	8	6.348	2	6.9	4.2	43.8	30.8
WIN_L8-2SC_17	8	6.305	53	7.4	4.4	43.8	33.7
WIN_L8-2.5_17	8	6.347	79	7.0	4.2	43.8	30.8
WIN_L8-3SC_17	8	6.447	104	6.1	3.6	39.5	29.8
WIN_L8-4SC_17	8	6.102	206	9.6	6.0	53.1	44.2
WIN_L9-FS_17	9	6.64	0	4.6	2.4	31.9	21.2
WIN_L9-1SC_17	9	6.637	2	4.7	2.5	31.9	21.2
WIN_L9-2.2_17	9	6.187	50	8.6	5.3	48.4	39.4
WIN_L9-2.5_17	9	6.288	77	7.5	4.6	43.8	34.6
WIN_L9-3C_17	9	6.191	105	8.6	5.3	48.4	39.4
WIN_L9-4C_17	9	6.303	206	7.4	4.4	43.8	33.7
WIN_L10-FS_17	10	6.447	0	6.1	3.6	39.5	29.8
WIN_L10-0.5_17	10	5.405	74	18.4	12.6	81.6	69.2
WIN_L10-1SC_17	10	5.887	131	12.8	7.8	62.7	50.0
WIN_L10-2_17	10	6.047	250	10.5	6.5	57.4	47.1
Minimum				4.0	1.8	24.1	19.2
Maximum				32.1	29.0	100.0	100.0
Mean				8.1	5.1	45.3	35.6

4.2 Ecomorphodynamic Analysis

The study area was divided into five discrete sections for analysis and discussion. As mentioned previously, due to the increased spatial coverage and accuracy of the 2017 orthomosaics and DSM compared with 2016, the boundaries of these sections were expanded, offering a more comprehensive analysis (Figure 16). Section 1 focused on the Tide Gate Channel (Figure 15), Section 2 addressed the dynamic confluence of the Tide Gate Channel of the Avon River and a side channel from the St. Croix River south of the Newport Bar. This section also included foreshore marsh adjacent to Elderkin Marsh (Figure 6). Section 3 focused on the Newport Bar that began to develop in the mid-1990s downstream of the main Windsor Salt Marsh. Section 4 encompassed the northeastern section of Windsor Salt Marsh along the St. Croix River and near the former Tourist Bureau. Section 5 focused on the Eastern Tidal Channel adjacent to the Highway 101 Exit 6 ramp which previously handled the flow from the now decommissioned aboiteau and sewage outflow from the town of Windsor.

Figure 15 View of high tide at causeway on October 20, 2017 from above Elderkin Marsh.

Figure 16 Delineated sections of study area used for the ecomorphodynamics analysis. 1) Tide Gate Channel; 2) confluence Avon and St. Croix Rivers; 3) Newport Bar; 4) St. Croix and East marsh and 5) Eastern Tide Channel.

Intertidal Channel Morphodynamics

Intertidal channels are by their nature inherently dynamic, exhibiting cycles of erosion and progradation in response to changing forcing conditions and sediment supply. The Avon Estuary is no exception. Overall the net sediment budget for the un-vegetated portions of the study area (Figure 16) indicated a gain of 1.3 million m^3 of sediment (Figure 17a) over approximately the last 10 years. The total (absolute) change in sediment volume, was much greater (2.7M m^3) (Figure 17b) reflecting differences in erosion and infilling between and within sections. It should be noted, however, that this positive sediment budget differs from the analysis reported in the previous year due to the inclusion of the entire Newport Bar and a more comprehensive network of GCP supporting the low-altitude aerial photography.

The greatest changes in net sediment volume were recorded in sections 2 and 4 (Avon-St. Croix confluence and St. Croix-East Marsh, respectively; Figure 17a). Section 2 also reported the largest absolute change in volume with 841,300 m^3 of infilling and 167,400 m^3 of sediment export (erosion). This represents the most dynamic section within the study area. Much of the change has occurred at the confluence of the Avon River Tide Gate Channel and a secondary tidal flood channel connecting to the St. Croix River (Figure 20, Figure 21). Comparison of cross-sectional profiles from 2007 to 2017 (lines 2.2 and 2.3) illustrate close to 2 m of vertical sediment accretion on the Newport Bar (Appendix B, Figure B1c,d). High levels of erosion were also recorded downstream on the western un-vegetated tidal channel bank (~40 m at Line 2.2; Appendix B Figure B1c) and continued downstream into Section 3, further eroding the western bank of the main channel (Figure 21,Figure 22,Figure 23). This was countered somewhat with rapid progradation of salt marsh in the southern end of this section (Figure 19, Figure 36). Line 2.2 recorded close to 6 m of sediment accumulation (Appendix B, Figure B1c).

The next largest net increase in sediment volume (643,800 m^3) was recorded in Section 4 at the northeastern edge of the Windsor Salt Marsh along the St. Croix River (Figure 17a, Figure 24). The budget is dominated by a gain of sediment (716,800 m^3) with very little loss of sediment (73,000 m^3). In 2007, the marsh edge was an erosional scarp (van Proosdij and Baker, 2007) but by 2012, a marked mudflat bank had developed and was well established in 2017 (Figure 25). This represents close to 6 m of vertical accretion of fine sediments and lateral extension of the mudflat surface by approximately 400 m (Line 2 Appendix B Figure 1b). It is unclear at this time what has driven this shift in sedimentation patterns, however, it is noted that the former sewage outflow and aboiteau channel near the former tourist bureau is no longer being used (Figure 27), and that dredging at the Hantsport wharf has been suspended due to the closure of Fundy Gypsum Company, both of which are major potential drivers of change in this system. This new accumulation of material has forced a shift in the main tidal creek outlet channel (Figure 25d), forcing it to run parallel to the edge of vegetation. This is resulting in bank erosion and slumping as that channel deepens (Figure 25d).

With the inclusion of the northern tip of the Newport Bar which is rapidly eroding, Section 3 is the only area to record a net negative sediment budget (Figure 7a) with 382,500 m^3 of sediment eroded laterally, offset by 266,600 m^3 of sediment deposited on top of the bar. Lines 2.3 to 2.7 illustrate over 1.5 m of sediment accumulation on top of the bar over the last 10 years (Appendix B, Figure 2B). The growth of the Newport Bar has increased channelization of the Avon Tide Gate Channel and induced scour and erosion on the western bank. The channel has increased in width by approximately 30 m (Appendix B Figure B1d Line 2.3; Figure B2a Line 2.5), mostly at the expense of foreshore marsh on the western bank (Figure 23, Figure 36). The expansion of the river channel and the lose of foreshore marsh threatens the integrity of the NS14 Elderkin Marsh dyke system. Attempts at armoring the foreshore or base of dyke have not been successful and are unlikely to be successful due to the depth and unconsolidated nature of this macrotidal floodplain and river channel (pers. comm. Kevin Bekkers, NSDA 2017).

While Section 1 exhibits much less net change in sediment volume (Figure 17a), the shifting patterns of erosion and progradation in the main western Tide Gate Channel of the Avon River should be examined closely since foreshore erosion can threaten the integrity of the dykes on Elderkin Marsh. In addition, the morphodynamics of that channel are highly influenced by the freshwater discharge through the tide gate structure, orientation of the gate openings and the secondary tidal currents that develop on flood tides when the gates are shut. The current orientation of the tidal channel immediately adjacent to the gates is directing ebb currents towards the eastern channel bank and has eroded approximately 32 m of salt marsh vegetation over the last 10 years (Figure 18, Figure 19). This bend in the channel thalweg and marsh erosion has, however, facilitated the formation of accretionary tidal flats on the western bank that are rapidly becoming vegetated, effectively creating new foreshore marsh to protect the Elderkin dykes along that section (Figure 19). Transect line 0.7 records a shift in the channel banks by approximately 30 m while maintaining a relatively similar cross-sectional channel profile (Appendix B Figure B3b). Scour is evident along both banks immediately downstream of the gate structure resulting from secondary tidal currents and eddies that continue to develop (Figure 15). These eddies and higher velocities on the ebb tide as the primary tidal creek parallel to the causeway drains, are also causing slumping and marsh erosion (Figure 18). This parallel channel is gradually narrowing and shallowing towards the east (Appendix B, Figure B3c, d).

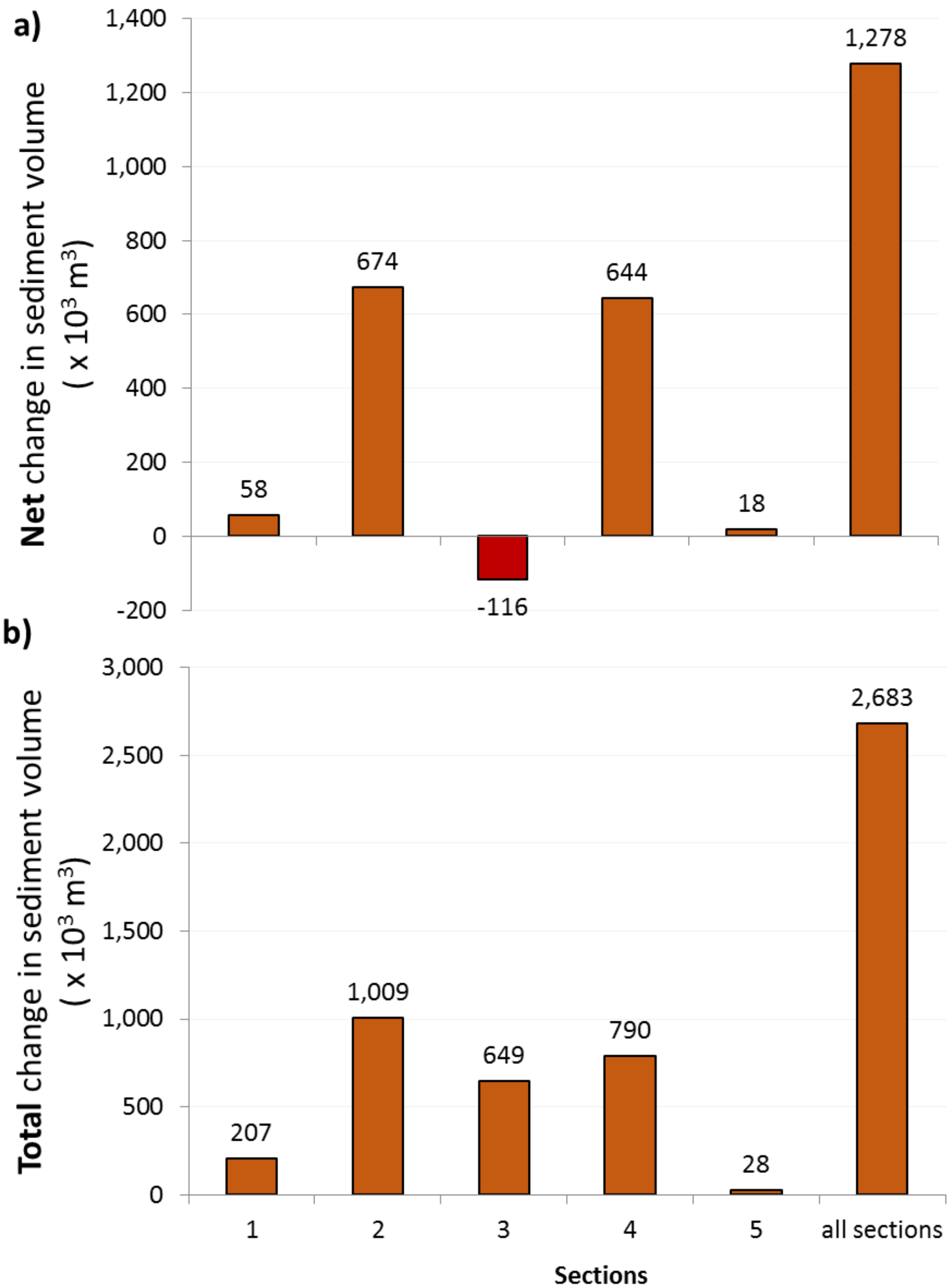


Figure 17 Calculated changes in sediment volume between 2007 and 2017 unvegetated intertidal surfaces. a) negative values indicate sediment loss or erosion, positive values indicate infilling, b) total change in sediment volume calculated as the total (absolute).

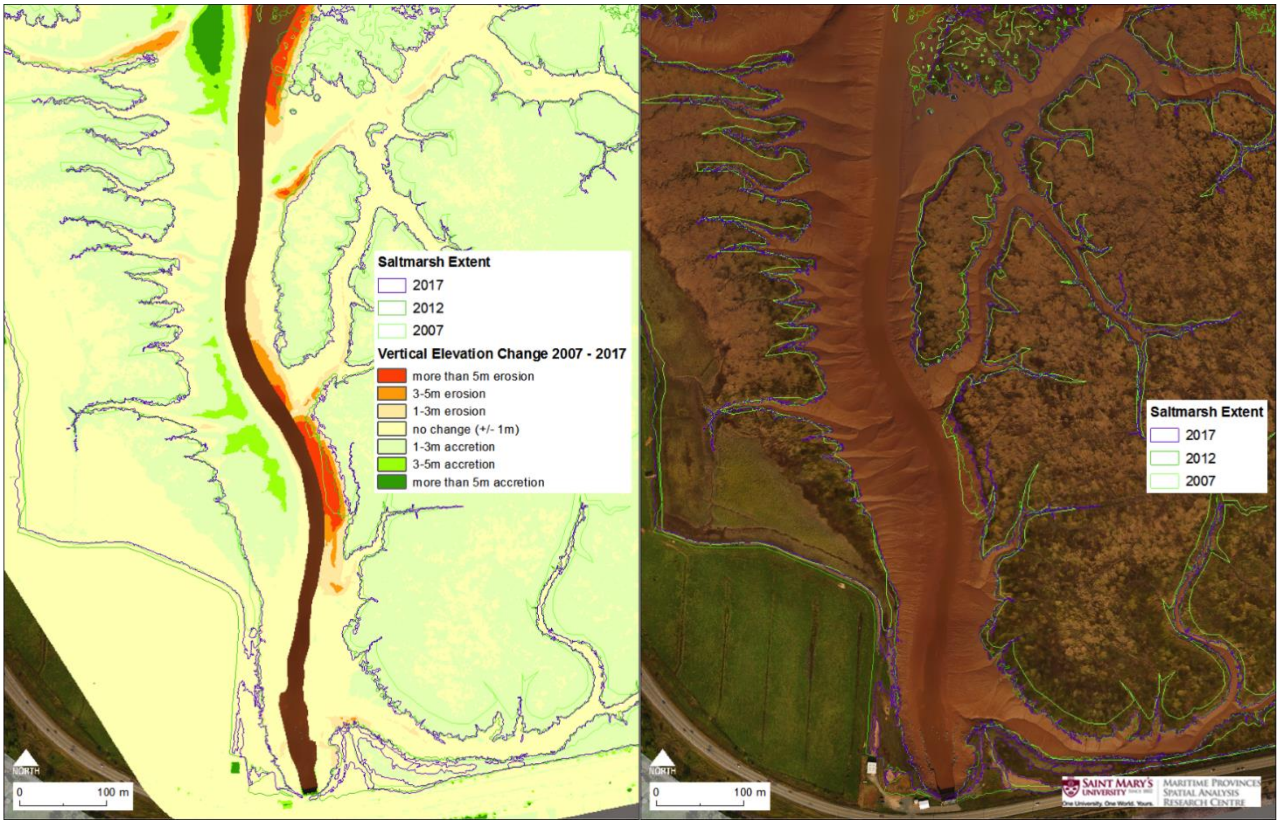


Figure 18 Change in surface vertical elevation between 2007 LiDAR surface and 2017 UAV flight in section 1. Marsh area polygons are provided for reference based on digitized aerial imagery.

Figure 19 Screen capture of UAV-based video collected on Oct 20, 2017 illustrating eroding eastern bank as channel migrates, prograding western salt marsh and vulnerable dyke infrastructure at NS14 Elderkin.

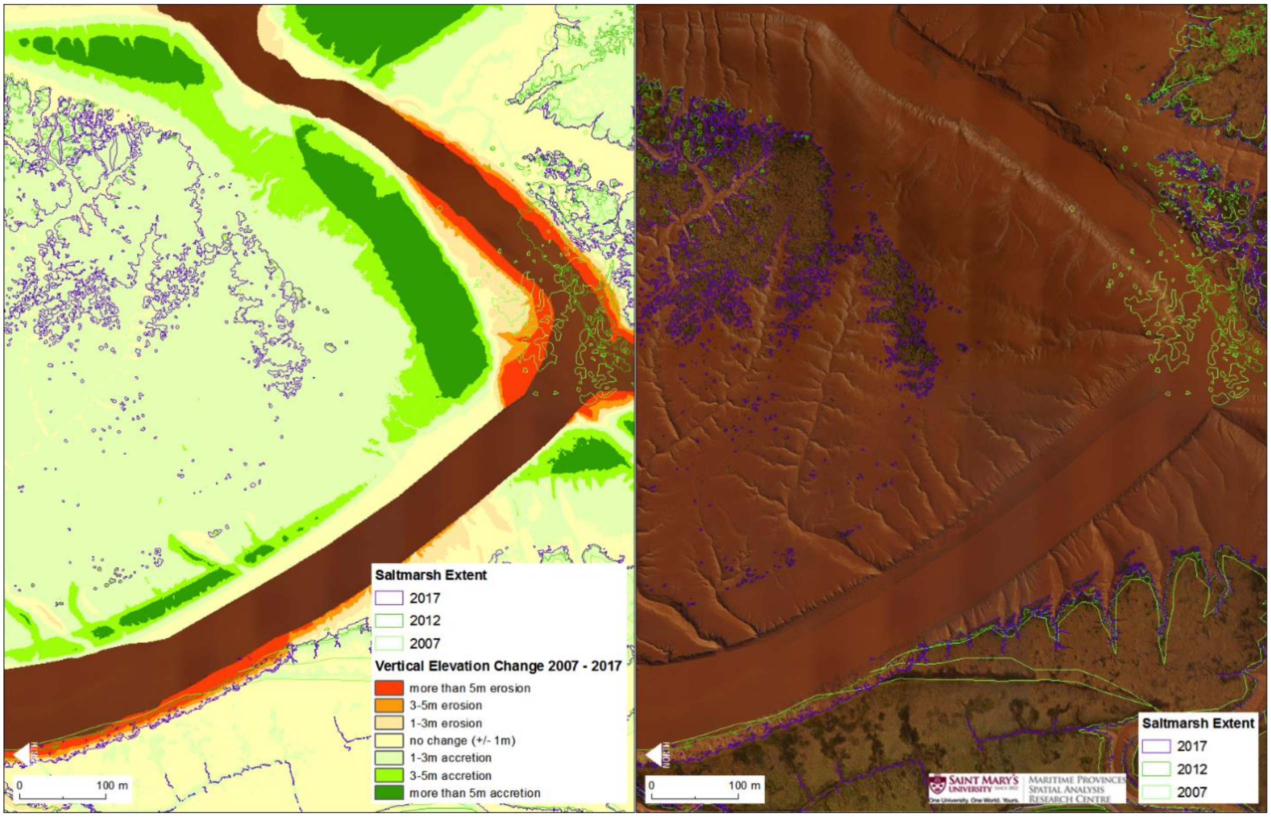


Figure 20 Change in surface vertical elevation between 2007 LiDAR surface and 2017 UAV flight in section 2. Marsh area polygons are provided for reference based on digitized aerial imagery. Note orientation of north arrow.

Figure 21 Screen capture of UAV-based video taken October 20, 2017 illustrating scour and erosion due to dominant tidal currents on flood tide turning east toward St Croix River.

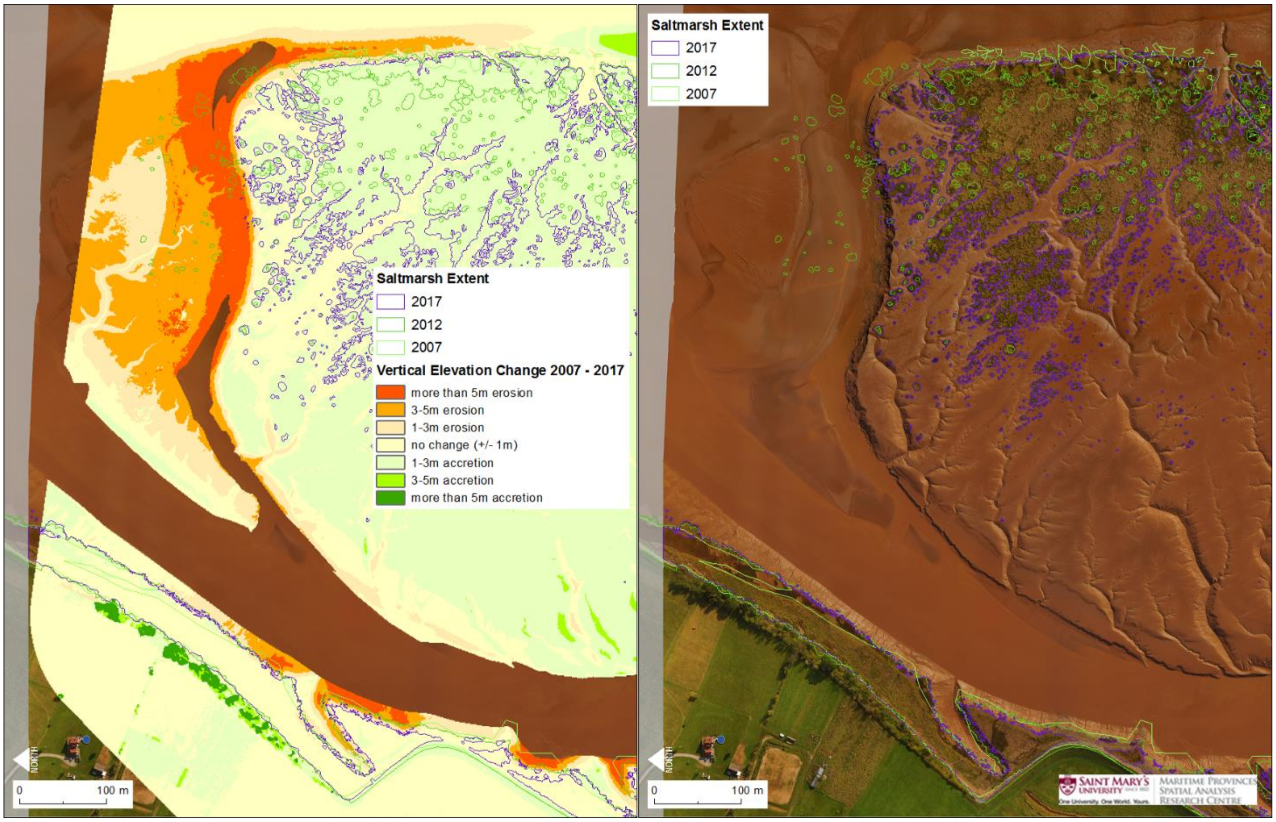


Figure 22 Change in surface vertical elevation between 2007 LiDAR surface and 2017 UAV flight in section 3. Marsh area polygons are provided for reference based on digitized aerial imagery. Note orientation of north arrow.

Figure 23 Screen capture of drone-based video of hydrodynamics along the Newport Bar and Elderkin Marsh on October 20, 2017.

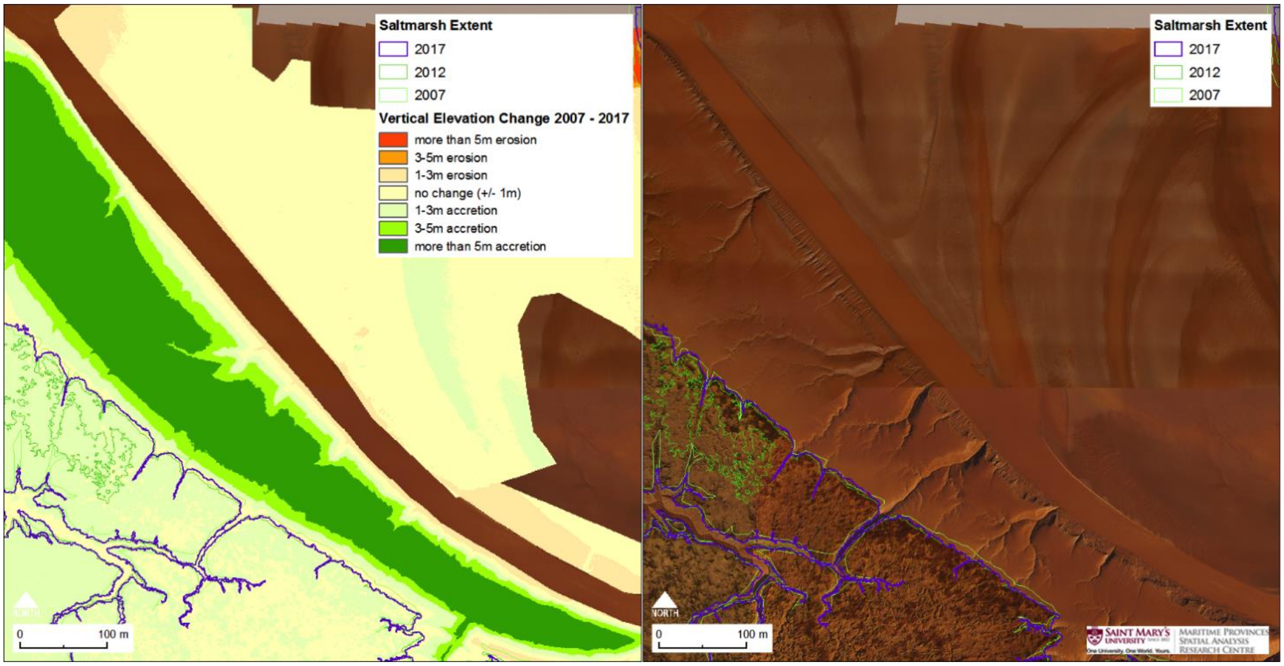


Figure 24 Change in surface vertical elevation between 2007 LiDAR surface and 2017 UAV flight in section 4. Marsh area polygons are provided for reference based on digitized aerial imagery.

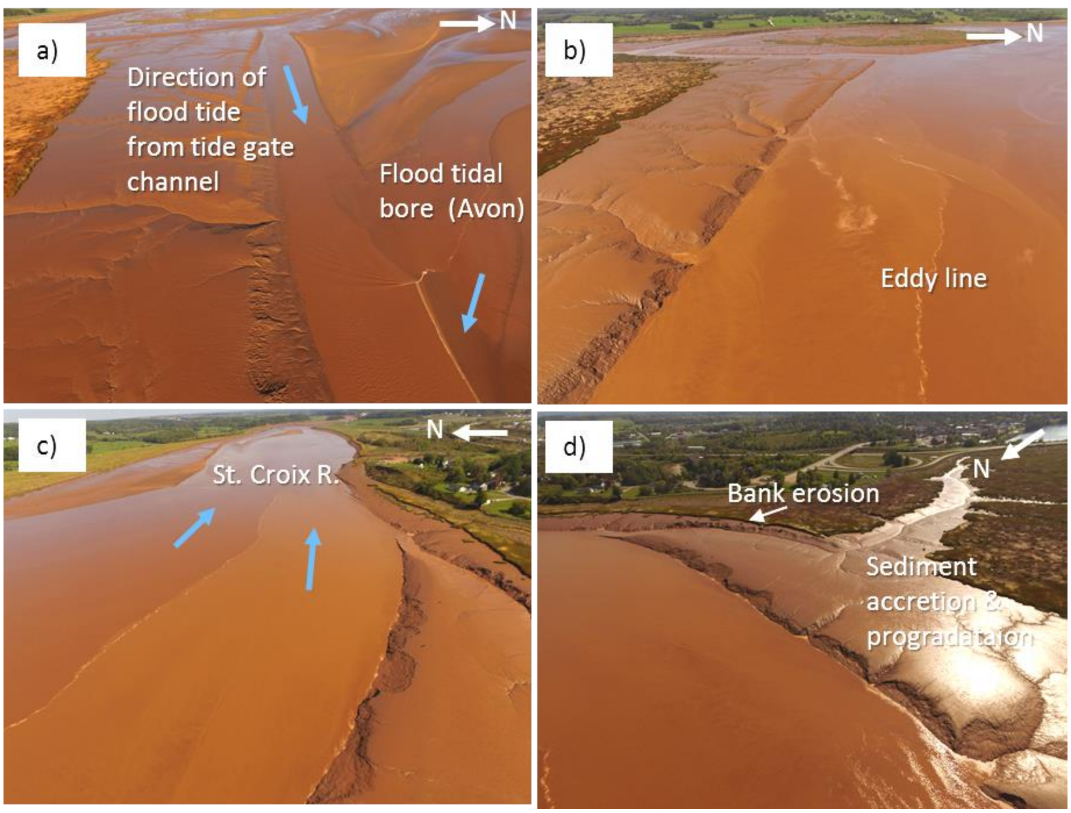


Figure 25 Oblique aerial images captured October 20, 2017 at section 4 on flood tide illustrating flow dynamics and geomorphic processes.

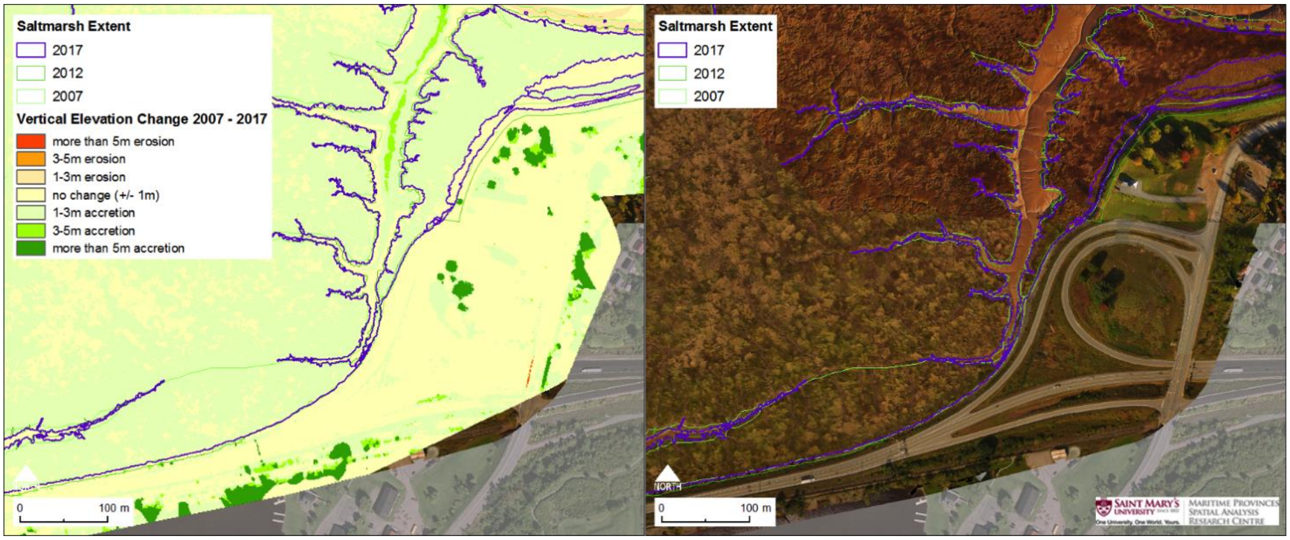


Figure 26 Change in surface vertical elevation between 2007 LiDAR surface and 2017 UAV flight in section 5. Marsh area polygons are provided for reference based on digitized aerial imagery.

Figure 27 Oblique aerial image captured October 20, 2017 of Eastern Tidal Channel and former sewage and aboiteau outflow.

4.3 Bathymetric Analysis

Comparison of the 2017 bathymetric profiles to those recorded in previous years supports the visual observations of changes in the patterns of sedimentation and erosion in both the St. Croix and the Avon Rivers. The greatest changes were recorded in the St. Croix River, which is not surprising given the construction and potential disturbance associated with construction and relocation of the sewage outlet. In addition, intertidal rivers in particular are sensitive to changes in heavy freshwater discharge events, which can relocate the river thalweg. This is evident along Line 1 of the St. Croix River where since December 2005, the deepest part of the channel has migrated to the northern bank, deepening by close to 1 m and eroding the southern bank by close to 50 m (Figure 28). This location is close to the relocated sewage outflow, which may account for the 14% increase in cross-sectional area of the main river channel at this location. Lines 2 and 3, however, decreased in cross-sectional area by 16 and 13% respectively (Table 6). Based on analysis of the 2005/2006 seasonal surveys, approximately up to 4% change in cross-sectional area can be considered due to seasonal variability. All three of these Lines exhibit changes that exceed this value. Lines 2 and 3 recorded large accumulations of sediment along the northern bank (Figure 28). Closer to the Avon River, however, on Line 4, the shore eroded by approximately 50 m over the last 10 years, accumulating material on the southern bank as seen in Figure 24, Figure 25 and resulting in a 3% increase in cross-sectional area.

Lines 5, 6 and 7 all cross over some portion of the Newport Bar and changes in the profiles reflect the high rates of accretion over the last decade and support results of the volumetric changes reported earlier. Approximately 2 m of sediment has accumulated on top of the bar with an expansion 200 m to the east at Line 5 (Figure 29). Progradation (Line 5) and erosion (Line 6) of the tide gate channel western bank at Elderkin is also noted and supports other measurements (Figure 29). Lines 5 and 7 saw 7 to 5% decreases in cross-sectional area when compared to the December 2005 survey (Table 6). This is generally associated with a decrease in depth by approximately 0.7 m. A low intertidal sand bar becomes evident at Line 8 with a shift in thalweg and channel deepening to the east (Figure 29). The tail of this bar is also seen at Line 9 but the 2% decrease in cross-sectional area falls within the range of seasonal variability. Line 10 is positioned just upstream of the Kennetcook River and recorded a deepening of both east and western thalwegs and overall mean depth (Figure 30). This results in an increase in cross-sectional area by 5% (Table 6).

The patterns of change further downstream of the Kennetcook River are consistent with findings of previous years. Minor changes in cross-sectional area between 2005 and 2017 (less than 1%) for Lines 15, 16, 17 and 20 (Figure 6 , Figure 31, Table 6). On Line 15, sediment accumulation along the eastern portion of the channel and decreased channel width (90 m) is offset by deepening of the river thalweg by over 1 m (Figure 30).

The changes (or lack of changes) in the cross-sectional profiles provide insight into the response of the river system to changes in tidal prism, freshwater discharge and sediment supply. These profiles set a new baseline for comparison of changes that may or may not occur post-causeway expansion.

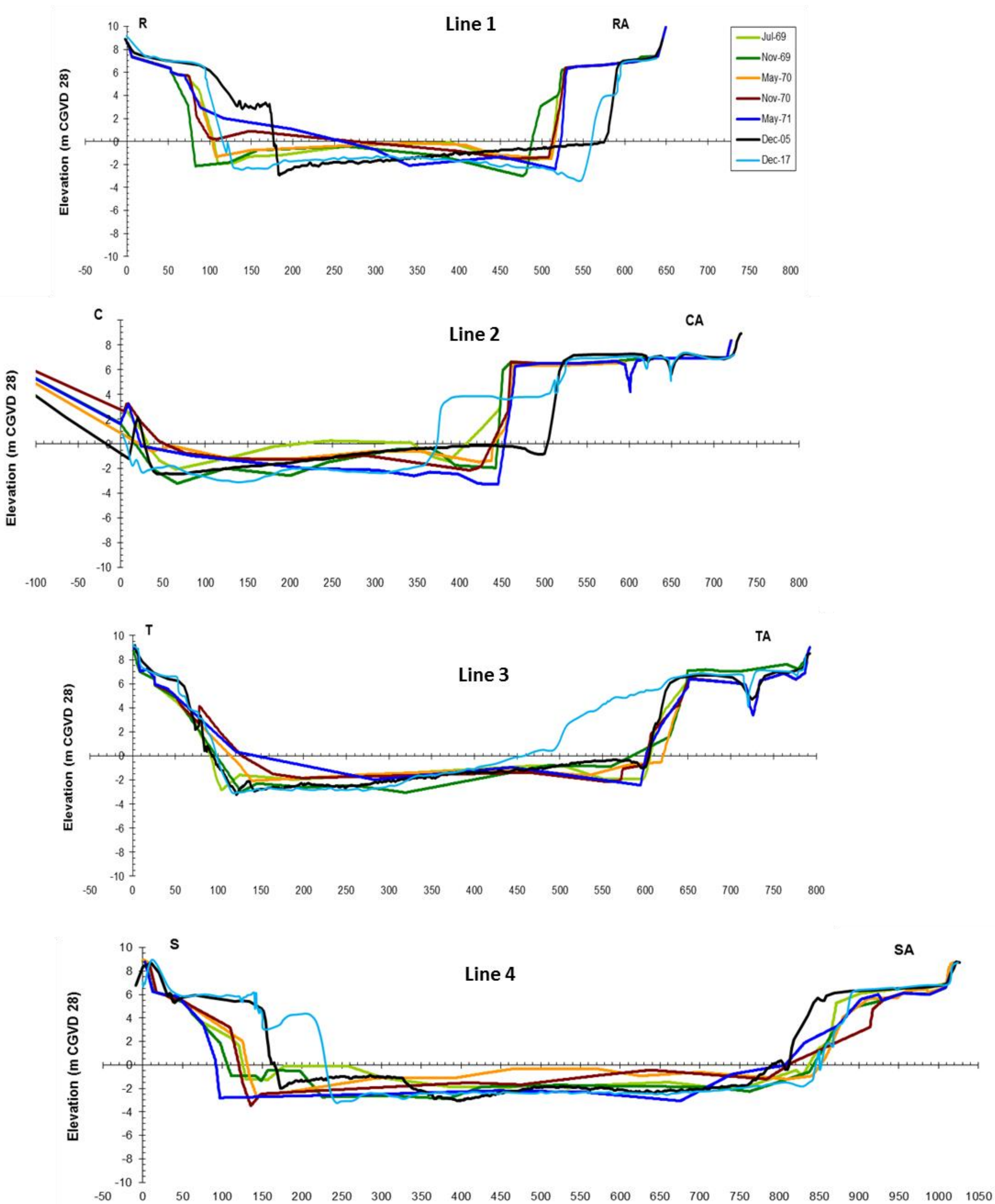


Figure 28: Comparison of historical cross sectional bathymetric profiles with 2017 survey for Lines 1-4 on the St. Croix River. Location of transects illustrated in Figure 5.

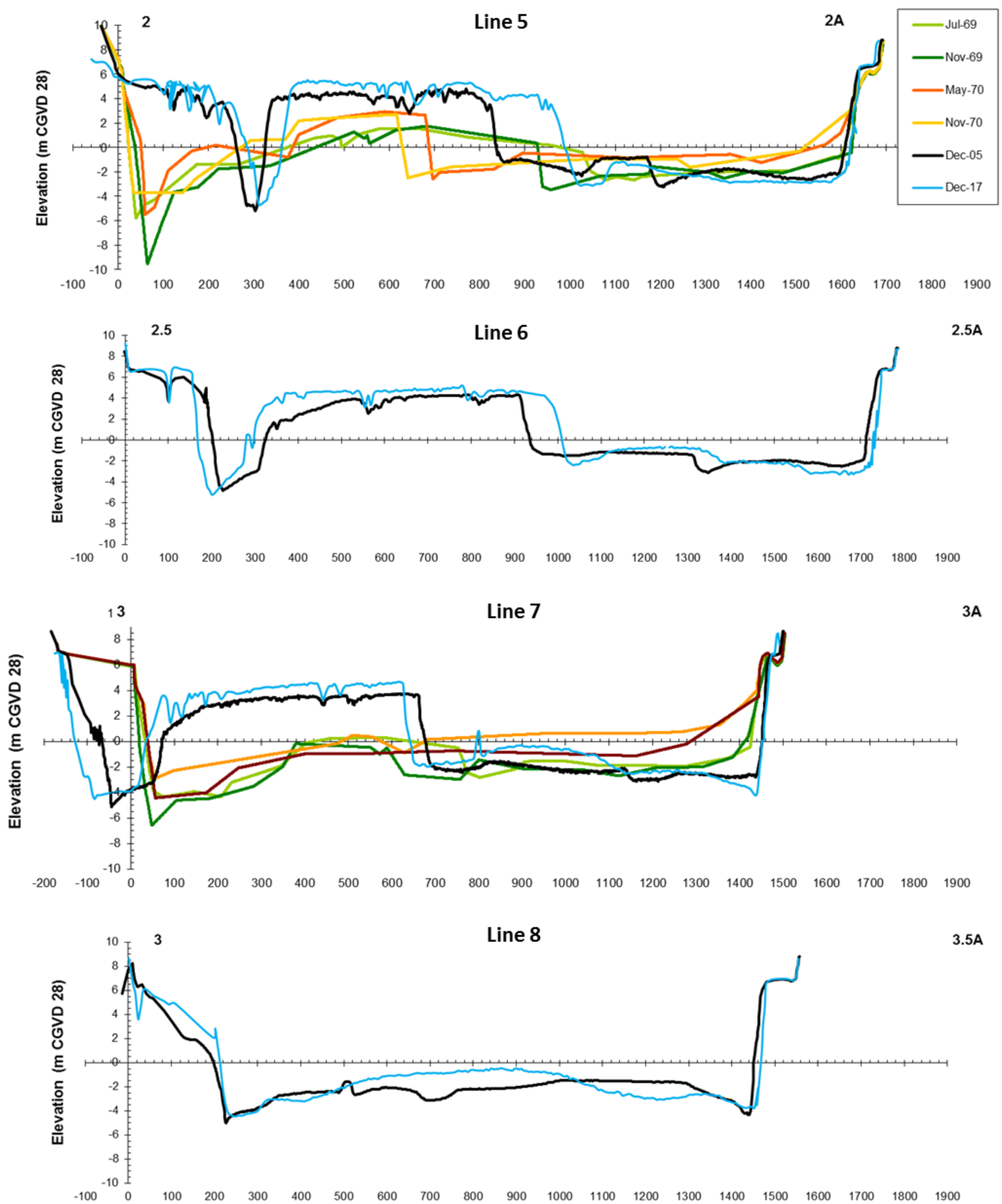


Figure 29: Comparison of cross sectional bathymetric profiles along Lines 5 to 8 on the Avon River. Location of transects illustrated on Figure 5.

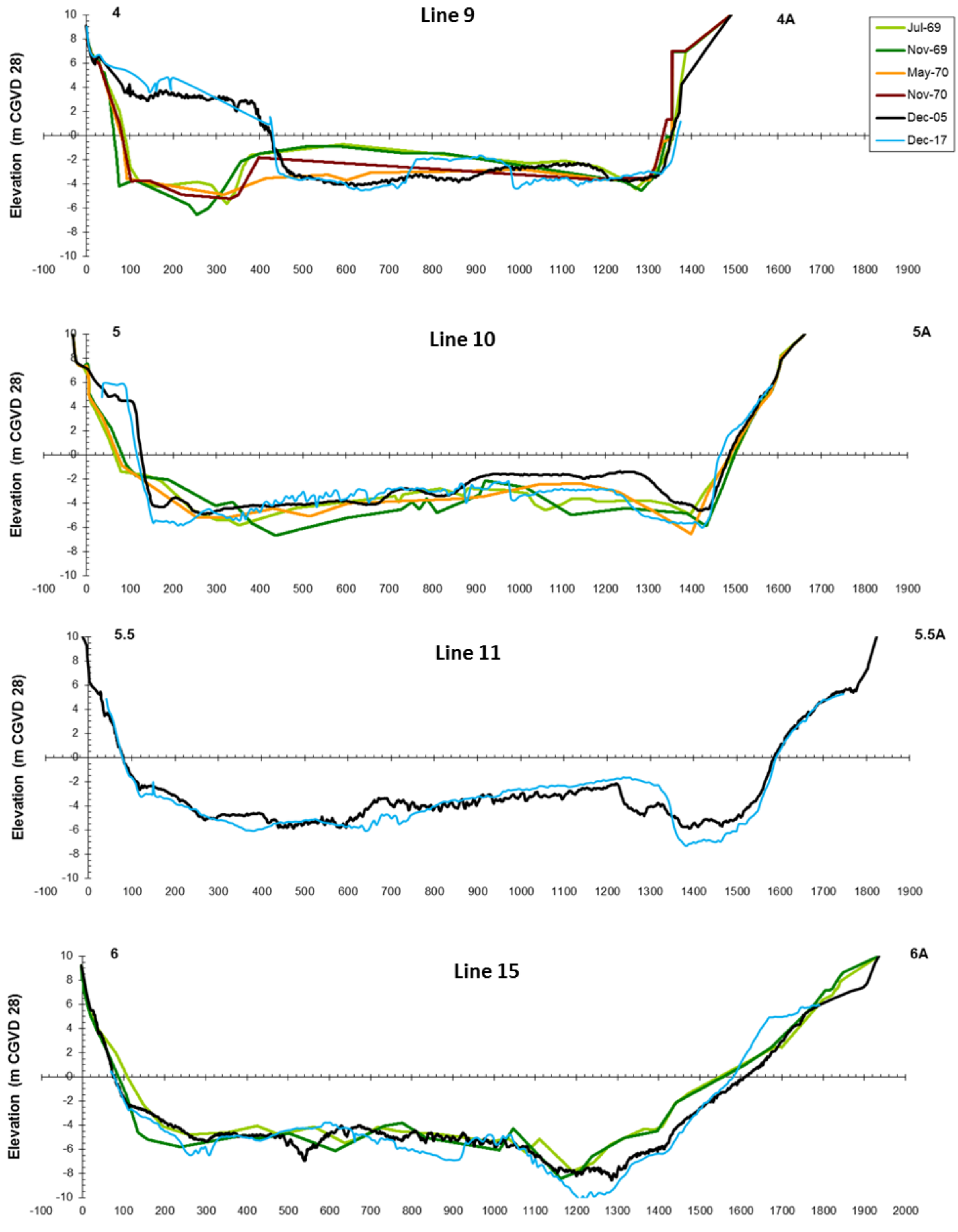


Figure 30: Comparison of historical cross sectional bathymetric profiles Lines 9 to 11 and 15. Note Lines 12-14 are on the Kennetcook River and not included in this analysis. Location of transects indicated on Figure 5.

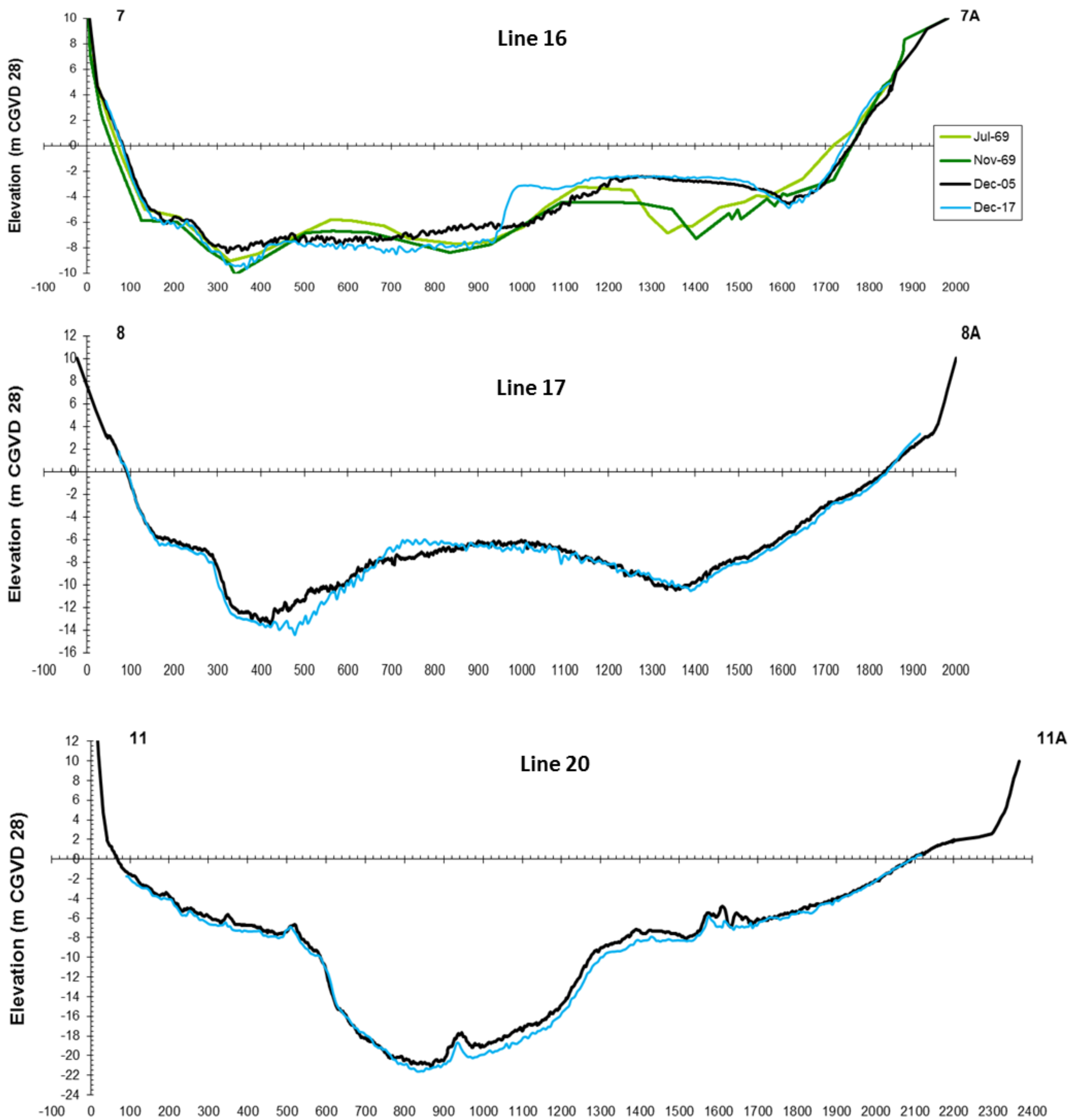


Figure 31: Comparison of historical cross sectional bathymetric profiles with 2017 survey on Lines 16,17 and 20 on the Avon River, downstream of the Kennetcook River. Location of transects illustrated on Figure 5.

Table 7 Comparison of cross-sectional area calculated for HHWLT as per van Proosdij and Baker, 2007. All comparisons relative to December 2005 survey. If +ve infilling, if –ve deepening. Note ~<4% change recorded 2005-2006 as seasonal fluctuations (Dec, Jun, Aug).

River	Line	X-sectional Area (m^2) (2017)	X-sectional Area (m^2) (2005)	% Change rel. to 2005	comments
St. Croix	L1_RRA	4487	3913	**-14.0**	Mean depth decreased by 30 cm, max by 80 cm
	L2_CCA	4342	5216	**16.0**	
	L3_TTA	4529	5183	**13.0**	
	L4_SSA	6958	6737	-3.3	
Avon	L5_22A	10071	10811	**6.8**	
	L7_33A	11825	12400	**4.6**	Mean depth shallower, by 70 cm, max depth ~0.8 m, width same
	L9_44A	11710	11953	2.0	Small intertidal bar appeared
	L10_55A	16093	16898	**-5.0**	Increase in max and mean depth, slightly narrower (~75 m)
	L15_66A	20346	20395	0.2	Although width decreased by 90 m, max depth increased by 1 m
	L16_77A	22120	22224	0.5	
	L17_88A	27323	27293	-0.1	
	L20_1111A	35799	35986	0.5	

4.4 Habitat and Vegetation

Habitat Map and Time Change Analysis

Surface cover and other habitat features delineated from the UAV orthomosaic are shown in Figure 32. The construction of the Avon River aboiteau/causeway facilitated rapid sedimentation and formation of a significant tidal flat which evolved over the course of the subsequent 48 years into a vibrant, highly productive salt marsh habitat (van Proosdij and Townsend, 2006; Daborn et al., 2004; van Proosdij and Baker, 2007) (Figure 34). Within the boundaries of the current study area, the greatest percent change in vegetated salt marsh habitat occurred between 1992 and 2003 (63%), followed by the 2003 to 2007 period (29%) (Figure 34). However, the greatest rate of change between time periods was 6.0 $ha \cdot yr^{-1}$ between 2003 and 2007. Rates of increase in vegetated area have levelled-off to approximately 2.0 to 2.1 $ha \cdot yr^{-1}$ (Figure 34). Much of this latter increase is associated with recent establishment of *Spartina alterniflora* on the eastern edge of the Newport Bar (Figure 23). This levelling off on the Windsor Salt Marsh is not surprising given the position of the marsh platform within the tidal frame. As the elevation of a mudflat increases and evolves into a vegetated marsh, the increase in elevation is reflected in a decrease in inundation frequency. Figure 33 illustrates the relative elevation difference between the Newport Bar and the main Windsor Salt Marsh platform. A lag also exists between growth of supratidal flats[1] and vegetative colonization.

The growth in vegetated salt marsh area, however, has not been uniform in space or time within all sections analyzed (Figure 35). The greatest rate of change and largest vegetated area occurred in Sections 1 and 5 (Figure 35). Section 2 saw a steady increase in salt marsh vegetation since 2003 (Figure 20) despite the significant scour and erosion illustrated in Figure 20. Overall marsh loss has been compensated by expansion of foreshore marsh and colonization of the Newport Bar (Figure 20, Figure 23, Figure 36). Section 3 saw a 3.3 ha loss of foreshore marsh between 1973 and 2007 (Figure 35, Figure 36). However, from 2012 to 2017, the rate of new vegetative growth per year more than doubled to 11.1 ha per year (Figure 22, Figure 35). The high mean end-point rate of erosion (-2 m/yr) between transects 40 to 50 is likely due to the formation of the Newport Bar and subsequent channelization of flow and tidal currents (Figure 23, Figure 38a). From 2012 to 2016 the rate of erosion was -2 m/yr and was offset by progradation (~1.7 m/yr) as the channel thalweg shifted to the east (Figure 38a). The marsh edge at Section 4 has shifted from a cliff to a ramped form with the rapid expansion of the tidal bank on the St. Croix channel (Figure 24, Figure 25). This surface will likely become vegetated within the next few years. On the opposite bank of the St. Croix River, the foreshore at NS27 Newport Town responded to changes in the main river thalweg, dyke armouring and the formation, movement and expansion of a tidal creek (Figure 37). This is particularly evident between transects 30 to 50 with a maximum mean endpoint change rate up to +13 m/yr that is a response to the migration of the tidal creek channel. This migration is also captured in a high standard deviation between years indicating variability. This section has also recently received some rocking and is therefore currently likely eroding. Between 2007 and 2012 Transects 1 to 32 have an end-point change rate of about -1.2 m/yr on average (Figure 38).

The current orientation of the river channel immediately downstream of the tide gate, is indirectly protecting newly developing foreshore marsh adjacent to the Elderkin dyke system. Care will need to be taken to ensure that changes to this channel, and thus risk to dyke infrastructure are minimal. Although potential extension of the spillway walls would help to alleviate some scour, it will likely have maladaptive (scour) impacts at the downstream edges. Design placement of construction pilings and associated hardened structures and materials will need to be mindful of the secondary tidal currents and eddies being generated as the rising tide is prevented from moving further upstream. Erosion of the foreshore marsh in Sections 2 and 3 in front of the Elderkin dyke is a concern and increased use of rock armouring is unlikely to be effective due to the deep tidal channel, unconsolidated muddy slopes and high tidal current velocities. Alteration or diversion of tidal flow will likely be the only alternative short of managed realignment of that section of dyke. This would increase the chance of the intertidal system shifting on its own as has been observed in many other parts of this river system (van Proosdij and Baker 2007). The intersection of the western Avon River channel within Section 2 with the secondary river channel entering from the St. Croix River is likely resulting in complex tidal current flow interactions. The use of the UAV video footage was very useful in understanding the complex flow dynamics within the study area. Timing of the video in relation to available daylight hours made it impossible to view and record the same tide draining on the ebb tide. It was evident from the video collected, however, that the

[1] Supratidal flats are tidal flats that are above the level of mean high water for spring tides and are inundated only occasionally by higher high water events or tides augmented by wind or storm events.

strongest currents arose during the flood tide as the tide waters are constrained between intertidal bodies and vegetated platform (Figure 21, Figure 25, Figure 39). Having now demonstrated the capabilities and benefit of UAV video footage for monitoring and analysing hydrology in a complex system like the Avon River, it is recommended that this be expanded upon in future studies.

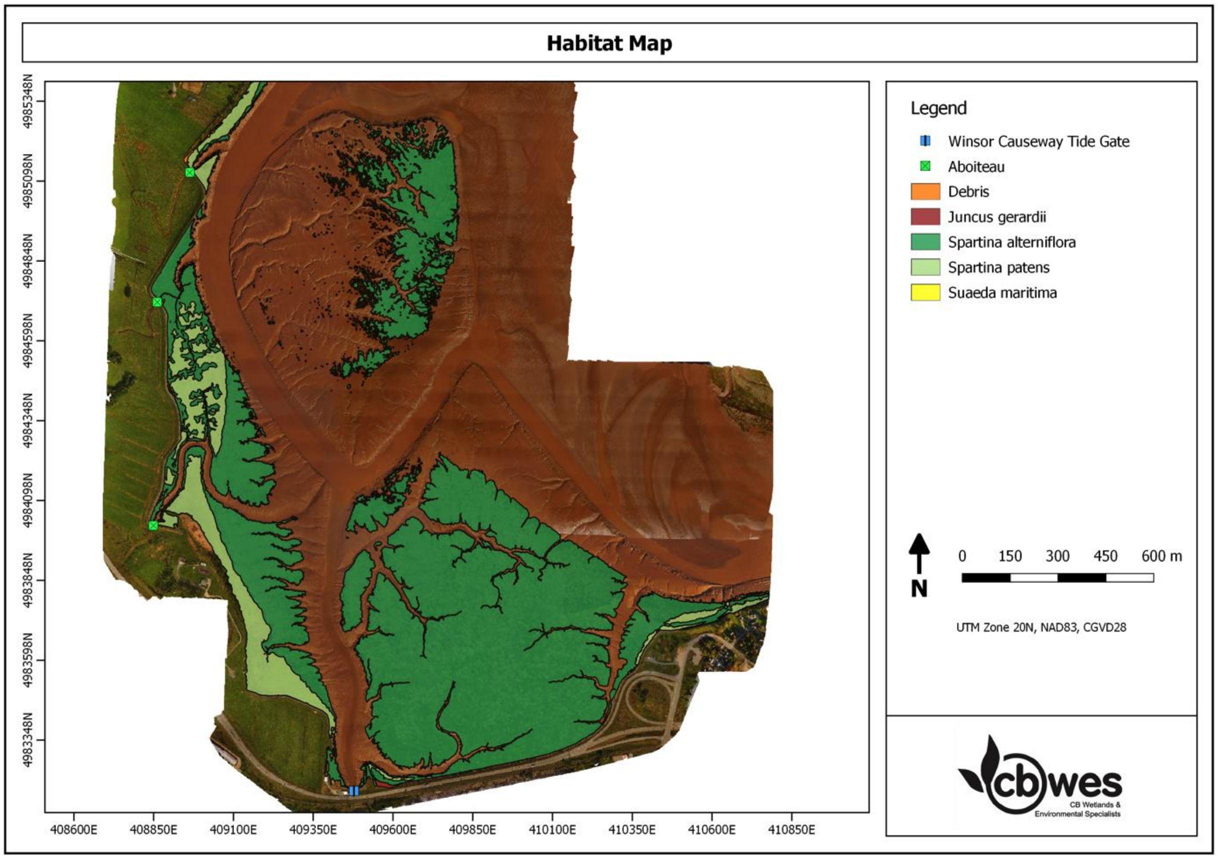


Figure 32 Habitat map of Windsor Salt Marsh, Elderkin Marsh and Newport Bar.

Figure 33 Oblique aerial image taken at high tide on October 20, 2017 looking North from tide gate. Note the fully submerged Newport Bar and tops of tall *Spartina alterniflora on both the Windsor and Elderkin Marshes.*

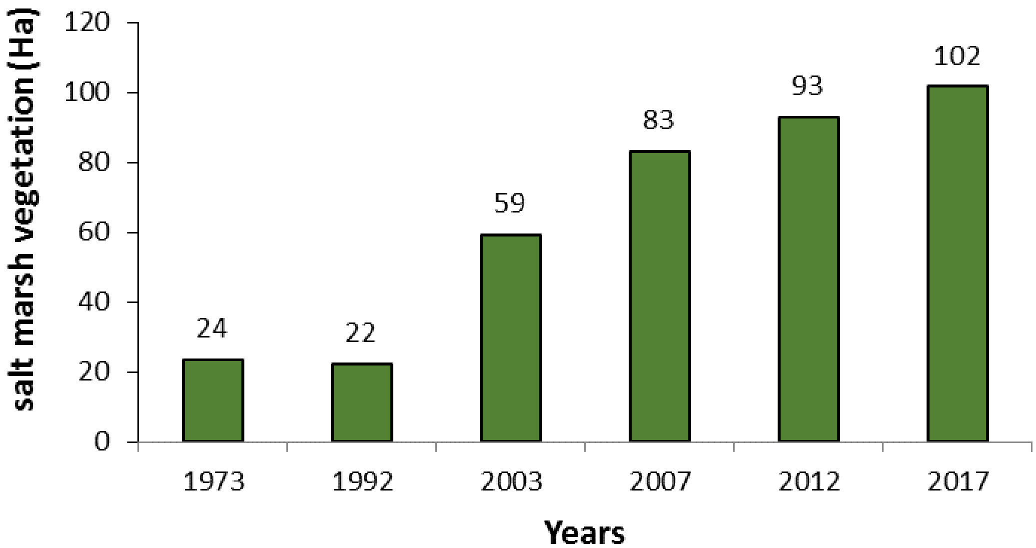


Figure 34 Change in vegetated salt marsh area from digitized aerial imagery from 1973 to 2017.

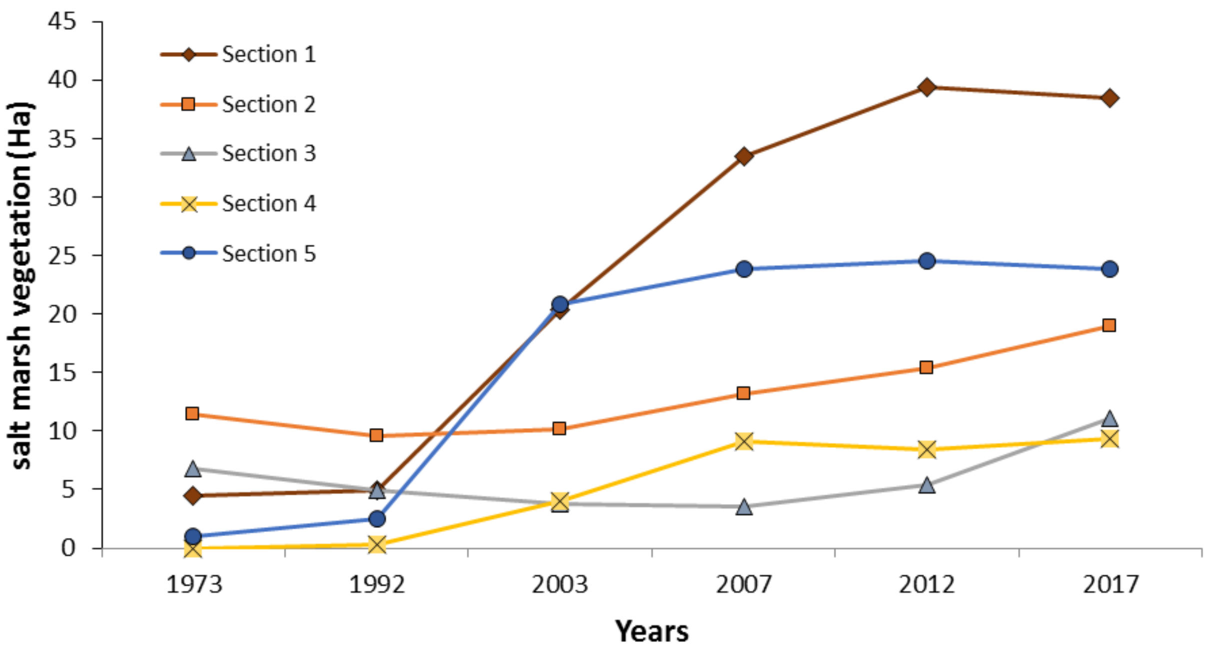


Figure 35 Change in vegetated salt marsh area over time per section within the study area from 1973 to 2017.

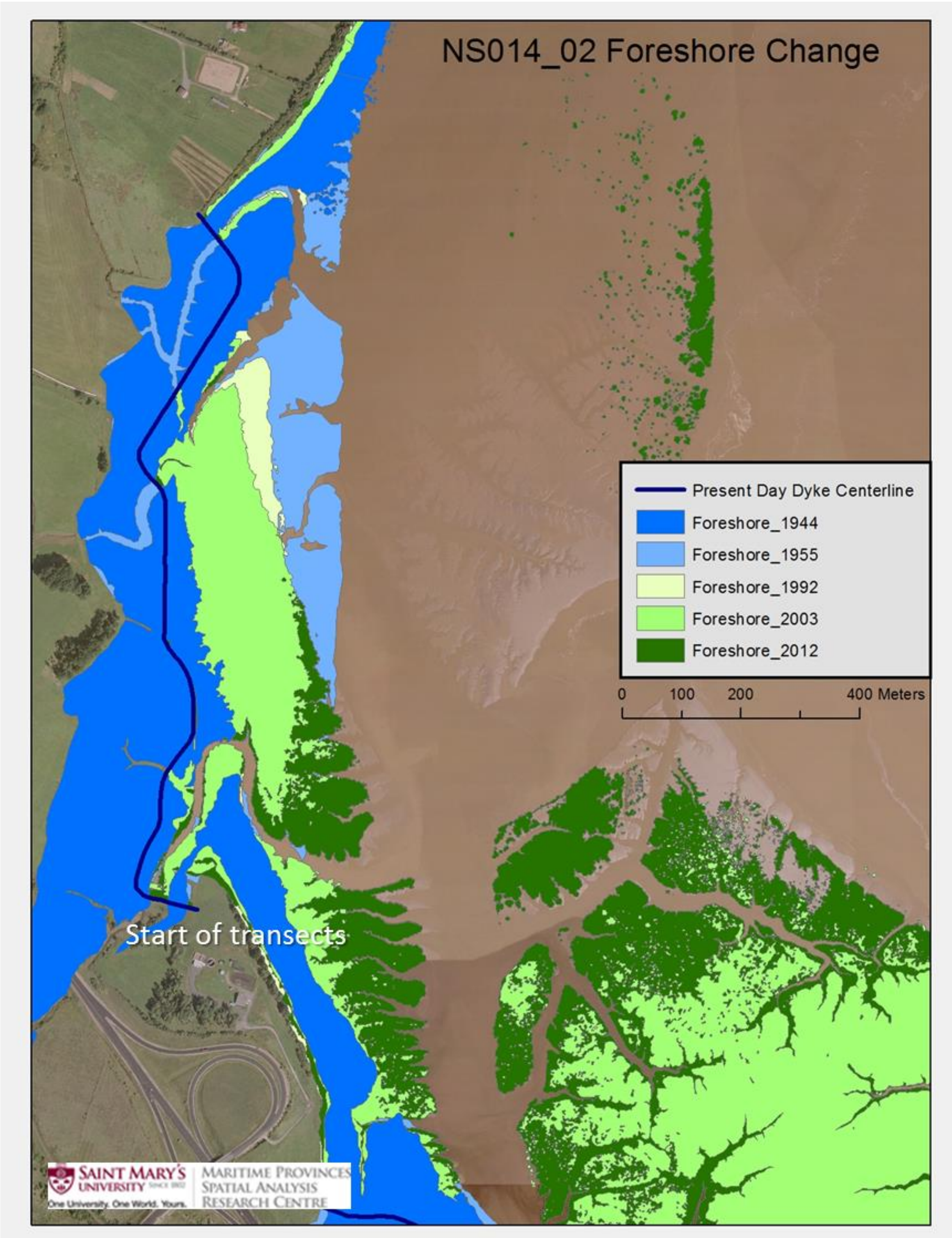


Figure 36 Digitized foreshore marsh polygons used for end-point change rate analysis using AMBUR adjacent to NS14 Elderkin Marsh. Note, foreshore 2017 not included in this analysis. Analysis performed by G. Matheson.

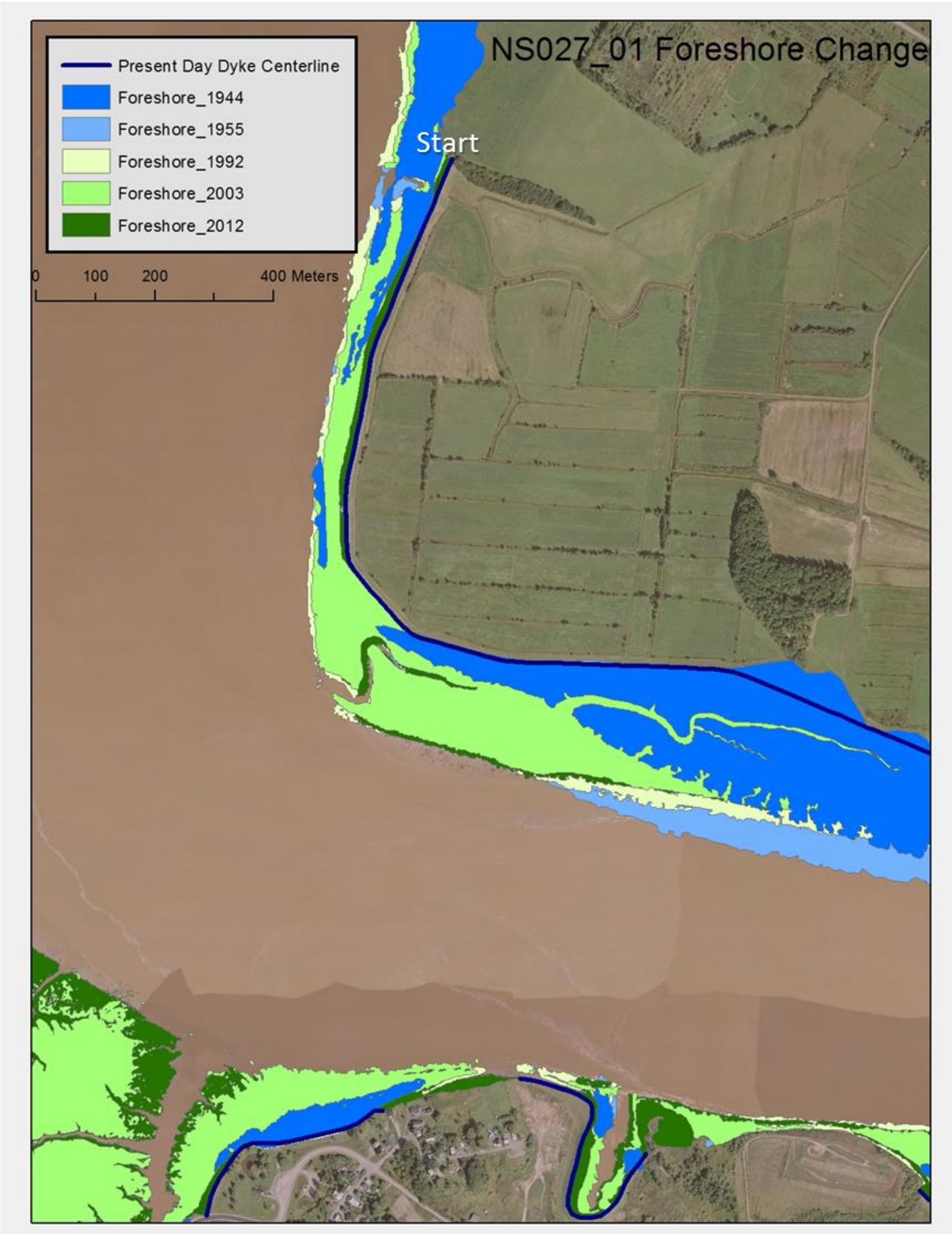


Figure 37 Digitized foreshore marsh polygons used for end-point change rate analysis using AMBUR adjacent to NS27 Newport Town marsh. Note, foreshore 2017 not included in this analysis. Analysis performed by G. Matheson.

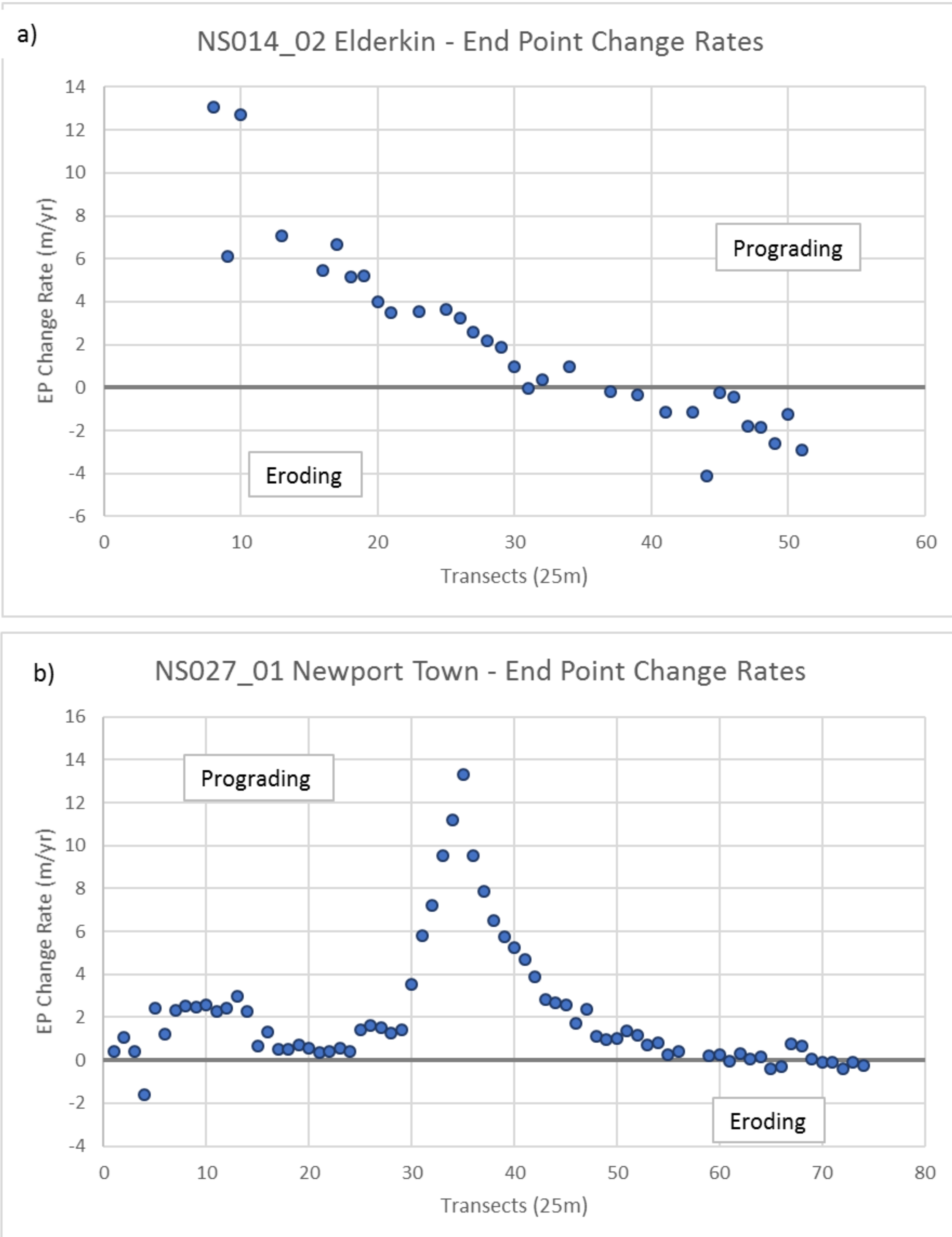


Figure 38 Mean end point change rate of foreshore marsh from 1944 to 2012 at a) Elderkin and b) Newport Town marshes. Rate determined using R statistical package "Adapting moving boundaries using R" (AMBUR). Script prepared by C. Ross, Analysis performed by G. Matheson, validated by D. van Proosdij. Transects cast every 25 m perpendicular to dyke centerline. Position and orientation of transects manually edited where needed. Start of transects indicated in Figure 36 and Figure 37.

Figure 39 Converging flow on flood tide from main Avon Channel and secondary channel parallel to main Windsor Salt Marsh, entering into the St Croix River on October 20, 2017.

Vegetation Survey Analysis

The reference plots and study site only contained 27 species, almost all halophytes (Table 8). Species designated halophytes included: *Atriplex glabrisculata, Carex paleacea, Distichlis spicata, Glaux maritima, Juncus gerardii*, *Limonium virginicum, Plantago maritima, Salicornia europea, Solidago sempervirens*, *Spartina alterniflora*, *Spartina patens*, *Spartina pectinata, Sueda maritima*, and *Triglochin maritima.*

Non-metric multidimensional scaling reveals that the Windsor vegetation plots mostly contain a low marsh community structure dominated by *S. alterniflora* (Figure 40). Reference sites had a greater range of salt marsh vegetation including high marsh communities dominated by *S. patens* and brackish communities with *Festuca rubra*, *Juncus gerardii* and other halophytes typically associated with higher elevations relative to the tidal frame.

As such the Windsor plots could be viewed as early successional vegetation that has not yet had a chance to develop the zonation pattern typical of reference marshes in the region. The study site has many plots that occur in regions of the tidal frame that could support high marsh and brackish communities but current vegetation at the study site remains dominated by *S. alterniflora*. Whether held back by environmental conditions or lack of propagules of later successional species is not clear but over similar ranges of elevation, inundation frequency and hydroperiod, the reference sites have a much broader range of tidal wetland communities represented.

References site plots had higher per plot species richness (Figure 41a), and halophytic richness (Figure 41b) ($P<0.05$) than the study site, largely as they had more representation of high marsh communities that draw from a larger species pool. Halophytic abundances were higher at the reference sites too (Figure 41c) ($P<0.05$), but this is partly an artefact of overall species richness. Since most of the study site plots just had a single species, even though average plant cover was high and only contained halophytes, the average abundance at the reference sites was higher as the abundance values are summed across all species and the reference sites contained more halophytic species. Vegetation cover was close to 100%

across all plots in both reference and study sites with no significant difference (average # hits of bare ground: 0 in both sets of plots).

Table 8 Plant species plot average abundance and frequency (# of plots at sites).

Plant species name	Code	Study site abundance	Study site frequency	Reference site abundance	Reference site frequency
Agrostis stolonifera	Agr.sto	0	0	1.55	12
Atriplex glabrisculata	Atr.gla	1.02	7	0.1	5
Calystegia sepia	Cal.sep	0	0	0.2	3
Carex paleacea	Car.pal	0	0	3.65	17
Distichlis spicata	Dis.spi	0	0	0.98	7
Eleocharis tenuis	Ele.ten	0	0	0.5	3
Elymus repens	Ely.rep	0	0	0.02	1
Elymus trachycaulis	Ely.tra	0	0	0.04	1
Festuca rubra	Fes.rub	0	0	2.04	11
Glaux maritima	Gla.mar	0	0	0.1	2
Hierochloe odorata	Hie.odo	0	0	0.33	3
Juncus balticus	Jun.bal	0	0	0.66	4
Juncus gerardii	Jun.ger	1.74	4	4.01	23
Limonium virginicum	Lim.nas	0	0	0.22	5
Dead spruce	Pic.ded	0	0	0.27	1
Plantago major	Pla.maj	0	0	0.25	2
Plantago maritima	Pla.mar	0	0	0.23	3
Potentilla anserina	Pot.ans	0	0	0.8	12
Salicornia europea	Sal.eur	0	0	0.11	4
Scirpus americanus	Sci.ame	0	0	0.54	3
Solidago sempervirens	Sol.sem	0	0	1.37	20
Spartina alterniflora	Spa.alt	23.25	51	8.89	56
Spartina patens	Spa.pat	0.4	1	12.42	60
Spartina pectinata	Spa.pec	0	0	0.83	7
Suaeda maritima	Sue.mar	0.21	2	0	0
Symphotrichum novi-belgii	Sym.nov	0	0	0.32	4
Triglochin maritima	Tri.mar	0	0	0.15	3

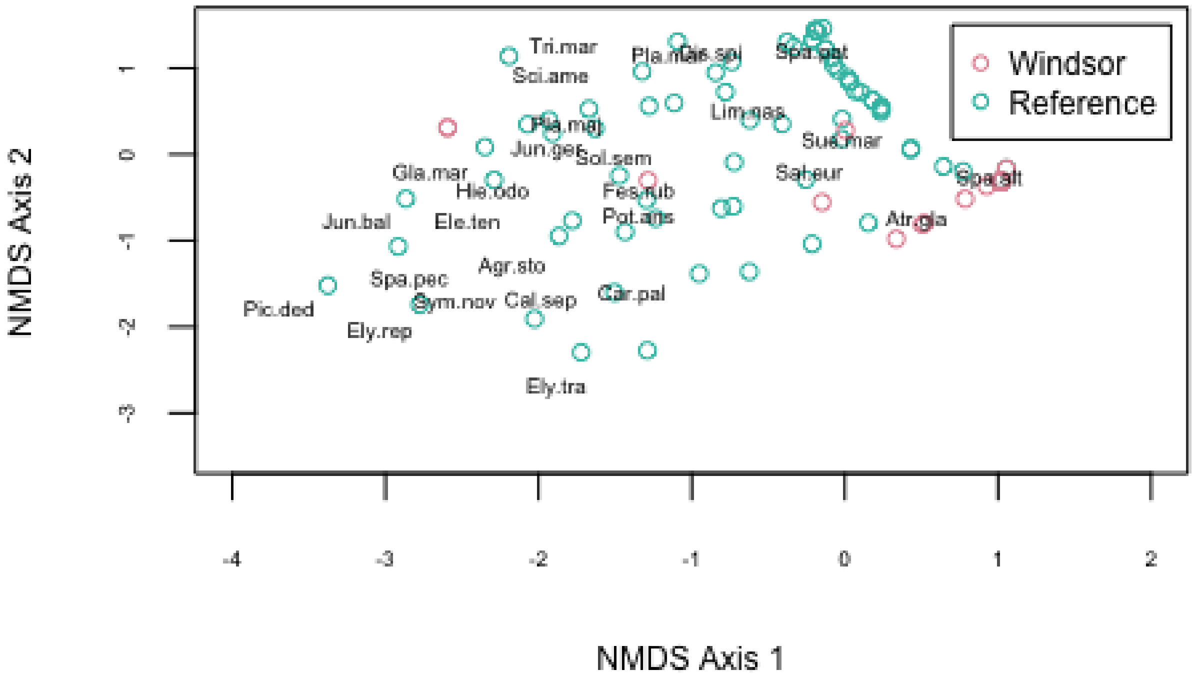


Figure 40 Non-metric multidimensional scaling analysis depicting plots in Windsor study site and reference plots (stress=9.2). Plant species codes above.

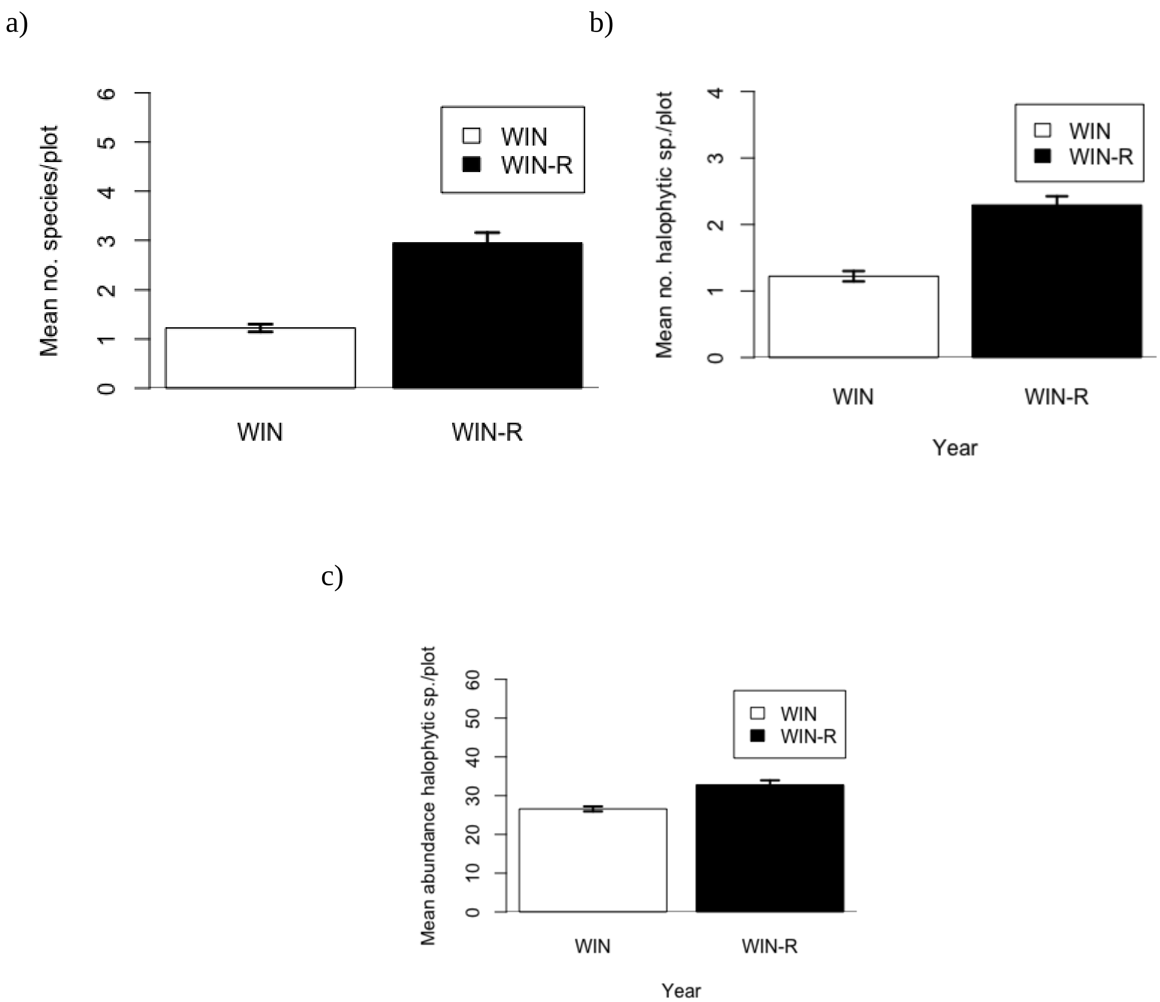


Figure 41 a) Plant species richness; b) Halophytic species richness; c) Halophytic species abundance at Windsor study site and reference plots for 2017.

Species of Special Concern

Several species of *Suaeda* have been observed in the Windsor area, one of which is a species at risk regionally (*Suaeda rolandii*). At present *Suaeda* are largely concentrated near the highway edge and scattered sparsely across the platform. In the past only *Suaeda martima* has been observed, however *Suaeda* can be difficult to identify in the field, particularly due to heavy sedimentation which can leave species coated in mud. *Suaeda* growing at the highway edge was observed to be shorter and more robust than that on the platform, however, the variation in form was suspected to be a response to the difference in conditions (i.e., presence/absence of tall *S. alterniflora*, elevation, inundation frequency). Samples were taken from the highway edge and from the platform, and in addition from two locations across the river near Avonport to confirm the absence/presence of *Suaeda rolandii*. Three of the four samples were identified in the lab as *Suaeda maritima ssp. maritima* (S5 – exotic), while a fourth (located on the Avondale side in the high marsh) was identified as *Sueada calceoliformis* (S3/S4).

4.4 Structured Winter Walk

Winter 2017/2018 experienced generally warm wet conditions punctuated by short intermittent cold periods. Ice formation was limited, and snow rarely accumulated with most precipitation falling as rain. The structured winter walk was conducted on February 7, 2018 on a clear day at low tide during one of the colder periods of the winter. Figure 42 shows the build up of ice cakes at the site and a thin ice crust that has formed over the banks of the channels. Ice cakes were mainly restricted to the lower sections of the marsh close to the river and tidal channels (Figure 43). There were some wrack and sediment deposits that indicated that larger tides and winter storms had moved ice and materials into the upper sections of the marsh (Figure 44). Many of the bamboo rods marking the transect end points and vegetation sampling stations were still present and intact, indicating that there had not been significant disturbance from storms or ice prior to the winter walk (Figure 46). During site visits by members of the research team in previous years during winter months, significant ice formation has been observed, with individual blocks greater than 10 feet high. Late February and March 2018 experienced several large winter storms with high winds and storm surges that may have changed the conditions observed at the site during the winter walk.

Figure 42 Eastern channel and foreshore marsh showing limited ice build-up on the platform or in the channels (7 February 2018).

Figure 43 Windsor Salt Marsh showing distribution of ice at the site (7 February 2018).

Figure 44 Exposed marsh surface with extremely limited ice rafting and minimal surface within the tidal channel (7 February 2018).

Figure 45 Sediment deposits in the upper section of the marsh (7 February 2018).

Figure 46 Bamboo transect marker (7 February 2018).

5.0 Summary

The salt marsh and intertidal habitats that have evolved since the construction of the Avon River Causeway (1968-71) continue to be very dynamic systems, and will very likely impact and be impacted by the planned Highway 101 twinning and associated modification of the tide gate structure. The monitoring program described in this report, has been developed to document any changes to the site as a result of construction activities and builds on previous research on the site (van Proosdij, 2005; van Proosdij et al., 2006; van Proosdij and Baker 2007). This program includes pre- and post-construction monitoring activities focused on the detection of changes in surface elevations, characteristics of tidal channel networks (location, stability, capacity), vegetated marsh vs. mudflat conditions, and changes in vegetation community structure.

This report documents the pre-construction conditions at the site. The data collected for geospatial attributes, hydrology, habitat conditions, and vegetation indicate that the Windsor Salt Marsh is a young marsh that is in the process of maturing and that the downstream system as a whole is still adjusting to a new equilibrium in response to the construction of the original causeway and tide gate structure. Elevation transects display an overall pattern of accretion (mean increase 0.26 ±0.17 m) on the marsh platform and a narrowing of tidal channels. The tidal channels themselves are highly variable and continue to experience large fluctuations in sediment volume, location, and morphology. The area at the confluence of the Avon and St. Croix Rivers has experienced the greatest net change in sediment volume within the study area (841,300 m^3 of infilling and 167,400 m^3 of export). Bathymetric data shows northward migration of the St. Croix River thalweg and an overall decrease in the cross-sectional areas of the channels, which supports the observed changes in sediment volumes.

Water levels upstream of the causeway are controlled primarily by the tide gate and do not correspond closely to downstream tide levels or precipitation. Downstream, the tide levels were found to be 0.25 m (CGVD28) higher than predicted with the highest observed tide measuring 8.22 m (CGVD28). A tide level of 8.22 m (CGVD28) would flood the entire marsh surface with a mean water depth of 2.55 m while the mean observed high tide (6.58 m CGVD28) would flood 92% of the marsh surface. These flooding patterns are not characteristic of a mature marsh where we would expect rapid increases in flooded area near the mean high tide and maximum flooding extent near the highest high tide.

Overall, the area of vegetated salt marsh has increased within the study area since 1992. Colonization of the Windsor mudflat by marsh grasses (primarily *S. alterniflora*) occurred rapidly at first and has since levelled off. Increases in salt marsh area are quite variable across the site with losses to erosion in some areas being offset by deposition and colonization in others (i.e., Elderkin Marsh and Newport Bar). Halophytic vegetation dominates the study site. The Windsor Salt Marsh contains mostly low marsh species with *S. alterniflora* dominating the site, while representative reference condition plots exhibited higher species richness mainly driven by high marsh species. This is an indication that the Windsor Salt Marsh has not yet matured to the point of developing the distinct high and low marsh habitat conditions and a level of habitat complexity that is typical of a salt marsh climax community in the region. The tidal flats, vegetated marsh and tidal channel networks throughout the study site continue to evolve in response to a variety of morphological and hydrological conditions which, in turn, continue to change in response to human activities within the watershed. Attention to modelling predictions during the aboiteau/causeway design phase will help to minimize adverse or unintended consequences to the tide channel network, flats and vegetated marsh communities during subsequent construction activities.

The results of baseline monitoring of the Avon River Estuary show a system in transition, that is still developing and attempting to reach an equilibrium state (ecological balance) in response to the construction of the original causeway almost 50 years ago, as well as more contemporary changes. This system is highly dynamic and continues to change in response to changes in human activities around the site such as shoreline armouring, discontinued dredging, and sewage treatments outflows. It is realistic to expect that the twinning of Highway 101 and the associated expansion of the causeway and tide gate structures will result in further changes to the downstream marsh and channel system. It is important to consider these possible changes in order to minimize adverse impacts to habitat and to avoid unintended damage to other infrastructure such as the downstream dyke system. Subsequent phases of this monitoring program during and following construction will be compared with the baseline data presented here to assess and quantify ecomorphodynamic changes at the site resulting from construction.

Reference List

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Appendix A - Geographic coordinates for the elevation/bathymetric surveys

	Coordinates		Surveys available				
PostID	**UTMx**	**UTMy**	**1969/72**	**2005**	**2007**	**2016***	**2017**
0.3	409393.710	4983378.641			X	X	X
0.3A	409538.983	4983378.244			X	X	X
0.7	409238.525	4983592.002			X	X	X
0.7A	409573.602	4983594.285			X	X	X
1	409138.725	4983856.610	X	X	X	X	X
1A	410426.577	4983652.495	X	X	X	X	X
2	409138.725	4983856.610	X	X	X	X	X
2A	410618.562	4984658.368	X	X	X	X	X
2.2	408873.928	4984174.567			X	X	X
2.2A	410618.562	4984658.368			X	X	X
2.3	408883.109	4984504.212			X	X	X
2.3A	410618.562	4984658.368			X	X	X
2.5	408835.109	4984761.635		X	X	X	X
2.5A	410618.562	4984658.368		X	X	X	X
2.7	408925.753	4984911.289			X	X	X
2.7A	410609.110	4984767.119			X	X	X
2.8	409005.536	4985060.120			X	X	X
2.8A	410626.368	4984873.978			X	X	X
3	409174.976	4985197.805	X	X	X	X	X
3A	410650.583	4984979.451	X	X	X	X	X
A1	409606.102	4983207.966			X	X	X
A1A	409628.539	4983283.531			X	X	X
A2	409519.021	4983255.614			X	X	X
A2A	409576.171	4983320.861			X	X	X
B1	410259.452	4983536.328			X	X	X
B1A	410309.300	4983523.839			X	X	X
B2	410255.325	4983615.306			X	X	X
B2A	410329.937	4983610.808			X	X	X
B3	410278.013	4983775.578			X	X	X
B3A	410381.928	4983734.898			X	X	X
B4	410297.923	4983839.938			X	X	X
B4A	410412.223	4983788.873			X	X	X
S	410426.577	4983652.495	X	X	X	X	X
SA	410618.562	4984658.368	X	X	X	X	X

*2016 elevation surveys had smaller spatial extent therefore 2017 values will be used for comparison in post monitoring.

Appendix B - Comparison of topographic surveys

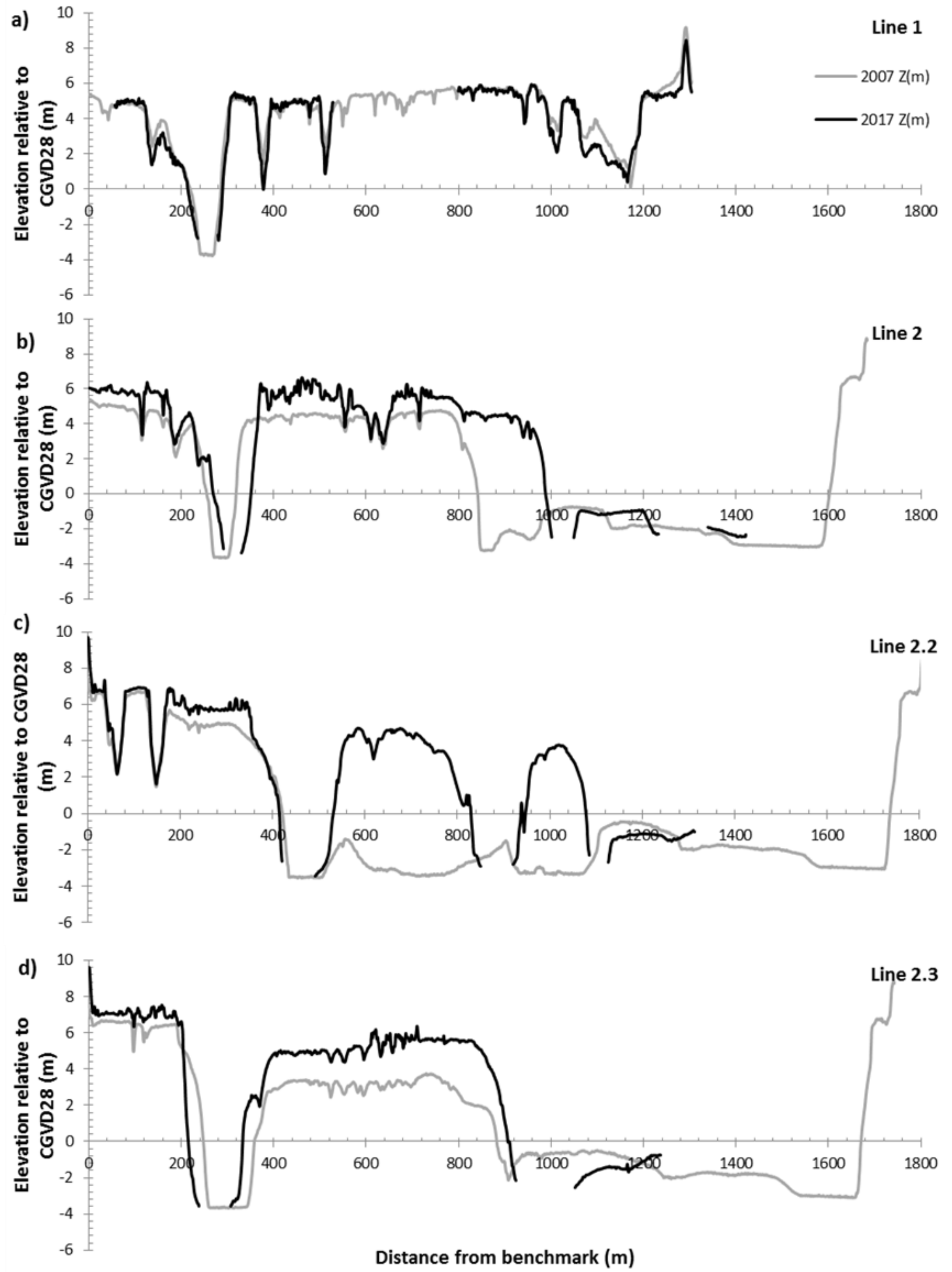

Figure B1 Comparison of topographic survey lines extracted from 2007 LIDAR surface and 2017 non-vegetated UAV DSM for Lines a) 1,b) 2,c) 2.2 and D) 2.3 illustrated in Figure 5.

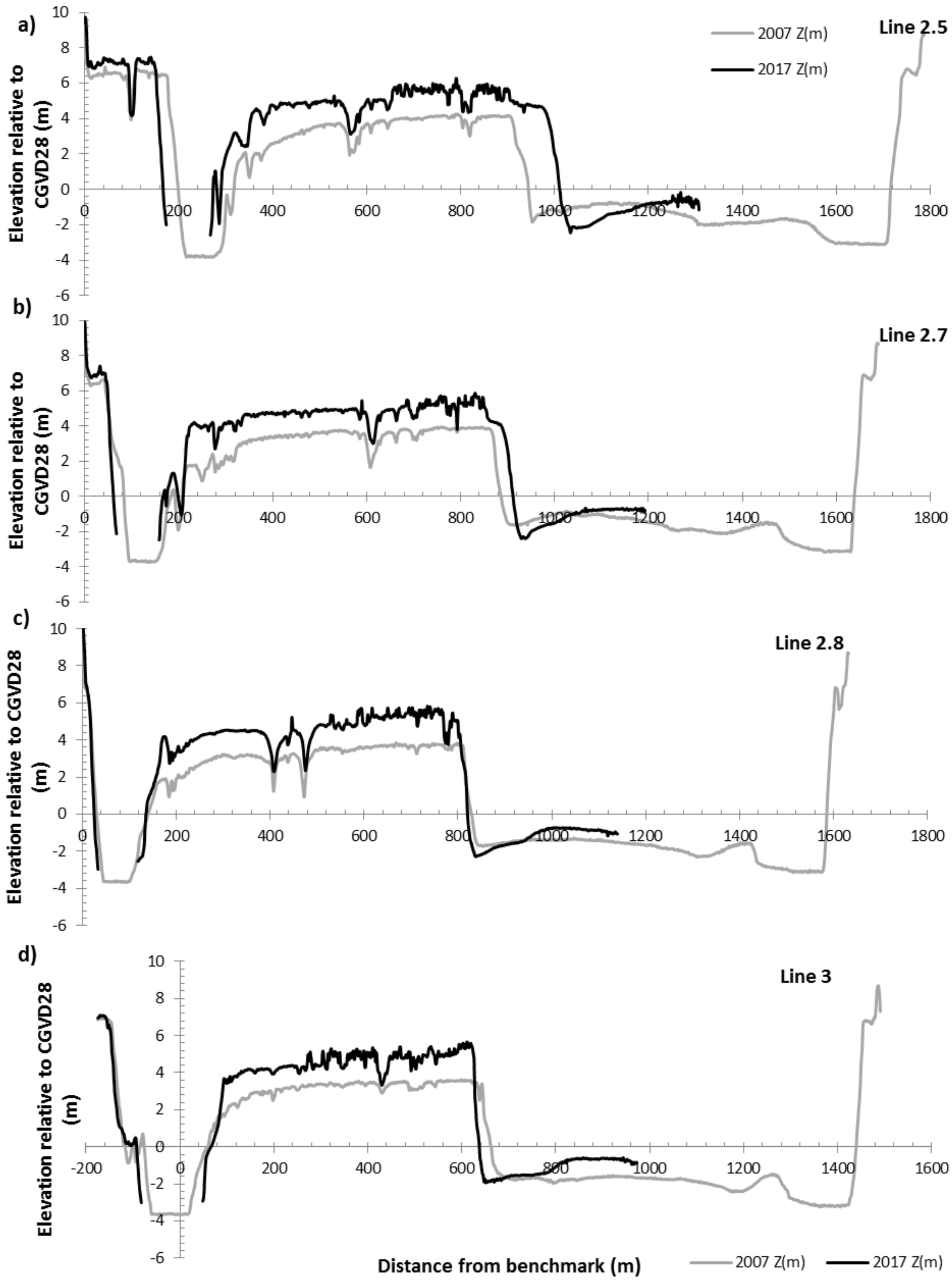

Figure B2 Comparison of topographic survey lines extracted from 2007 LiDAR surface and 2017 non-vegetated UAV DSM for Lines a) 2.5, b) 2.7c) 2.8 and d) 3 illustrated in Figure 5.

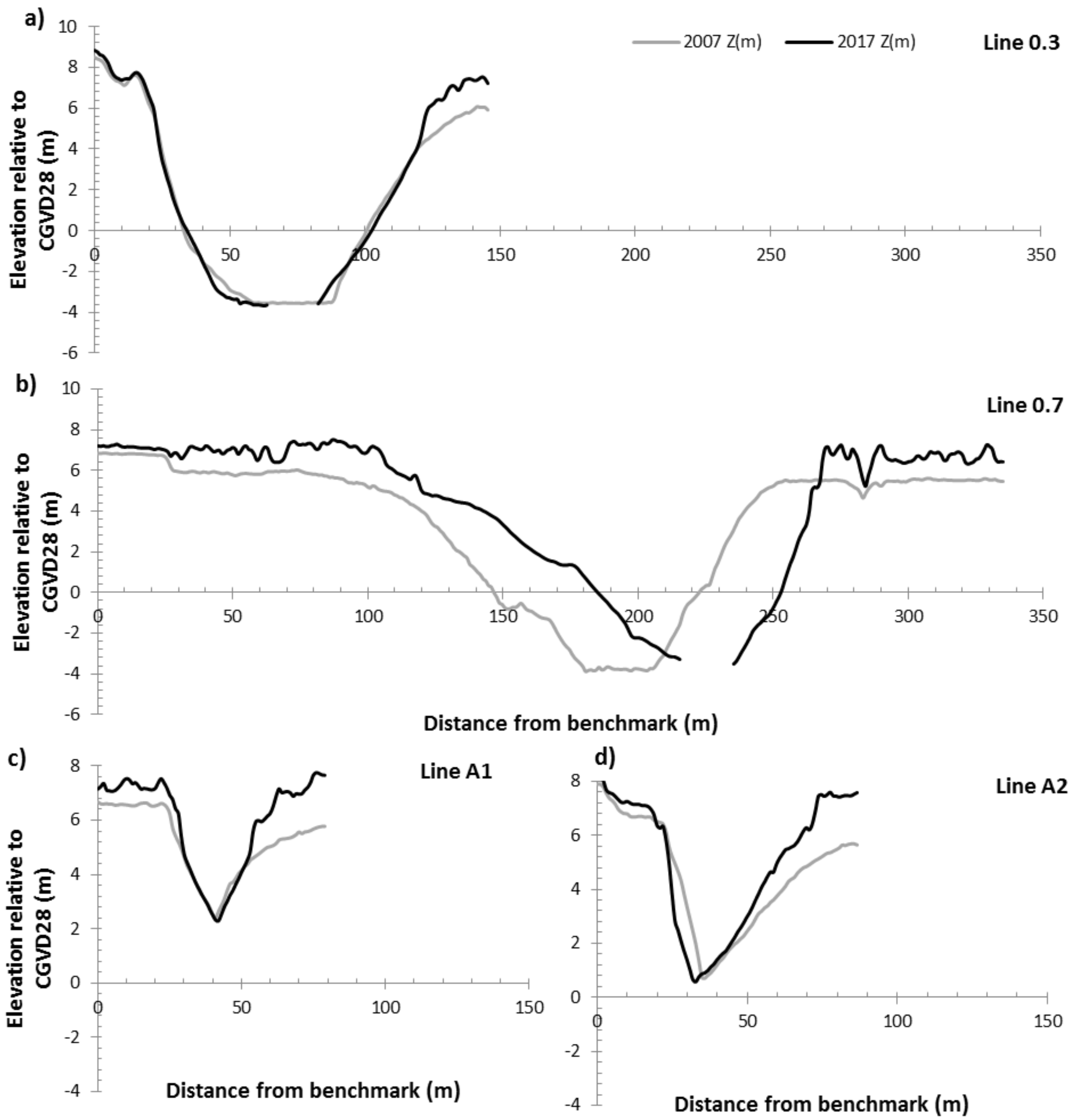

Figure B3 comparison of topographic survey lines extracted from 2007 LiDAR surface and 2017 non-vegetated UAV DSM for Lines a) 0.3,b) 0.7,c) a1 and d) a2 illustrated in Figure 5.

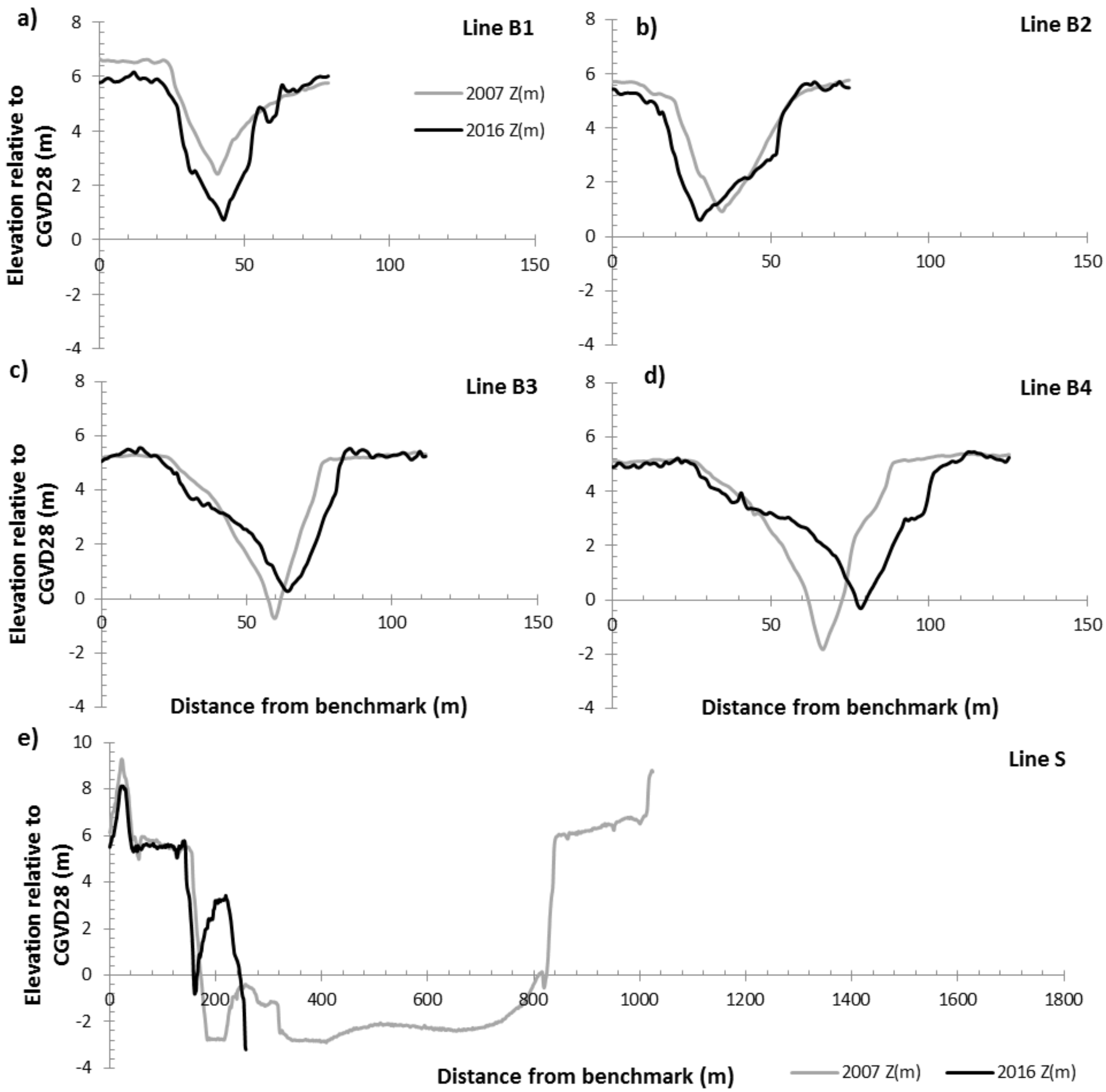

Figure 4 Comparison of topographic survey Lines extracted from 2007 LiDAR surface and 2016 non-vegetated UAV DSM for Lines A) B1, B) B2, C) B3 D) B4 and E) S illustrated in Figure 5.