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CONTEMPORARY MORPHODYNAMICS OF THE AVON RIVER ESTUARY AND RECOMMENDED MONITORING PLAN BEFORE AND AFTER HIGHWAY 101 TWINNING

Maritime Provinces Spatial Analysis Research Centre

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CB Wetlands & Environmental Specialists

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Panoramic image of Avon River Salt Marsh

INTRODUCTION

It is well known that the construction of causeways across tidal estuaries causes significant, often negative, impacts to the physical and biological conditions of the system. Salt marshes and mudflat complexes tend to experience the most dramatic and observable effects of the resulting 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. One of the most significant impacts in the Avon estuary after initial dyking for agriculture was the construction of the Avon River tide gate and causeway between 1968 and 1971 to improve flood control for protected dykelands and provide a base for road and rail corridors. The causeway significantly affected the hydrodynamics and sediment transport processes resulting in the rapid accumulation of fine sediments in the 1970s and 80s with initial colonization by salt marsh vegetation (*Spartina alterniflora*) in 1992. The current vegetated marsh surface has grown significantly. A detailed historical analysis of the evolution of the Avon River estuary from the 1860s to 2007 conducted by van Proosdij and Baker (2007) revealed that while significant changes in the tidal prism were recorded within the first 2-5 km downstream of the estuary, the cross sectional area and tidal prism downstream had not varied significantly over the last 150 years. The findings of that study, based on significantly expanded spatial and temporal scope and intensity of sampling, demonstrated that the magnitude of impact of the construction of the Avon River Causeway was much less than originally postulated in the 1970s (van Proosdij and Baker, 2007; van Proosdij et al., 2009). The 'channel infilling' noted by Amos in 1977, 15 km downstream of the causeway, just north of the Kennetcook River was most likely a result of the natural migration of a large intertidal sand bar. The intertidal system accommodated changes in the hydrodynamics and sediment transport processes by cyclic changes in foreshore marsh erosion and progradation and raising or lowering the thalweg of the main channel. The Kennetcook and St. Croix Rivers were found to greatly assist in maintaining dynamic equilibrium (van Proosdij et al., 2009). As the marsh platform rose within the tidal frame and was less inundated by sediment laden tidal waters, a new intertidal bar (Newport Bar) developed downstream and started to vegetate (Figure 1). The cross sectional area of the channel however was maintained. However, since approximately 2012, marked infilling has been observed within the main salt marsh channels and a shift from a steeply cliffed to ramped marsh platform, suggesting that the marsh/mudflat system is still adjusting to a new equilibrium state. As such, planning for and constructing a new causeway and gate structure requires up to date information regarding the stability of the marsh, current changes within the tide gate channel and potential impacts of the construction process on the marsh system.

The main purpose of this project was to provide a comprehensive, updated analysis of the morphodynamics of the marsh and tidal channel system downstream of the existing causeway; assess the potential implications of twinning process and provide recommendations for monitoring impacts. This report examines changes in salt marsh and intertidal habitat in three dimensions using new (July 2016) high resolution low altitude unmanned aerial vehicle (UAV) imagery and a derived surface elevation model compared to historical data within ArcGIS 10.4. A sediment budget (net and total gains or losses of sediment) was determined within unvegetated tidal creek channels and mudflats using a 2016 surface elevation model derived from UAV imagery and a digital elevation model (DEM) generated from the 2007 LIDAR data. All changes are placed within the context of human and natural drivers of change in the system and how these may be affected by, and affect the, construction process. The final section of the report will provide recommendations of transects for future baseline and post-construction monitoring of the salt marsh and adjacent mudflats.

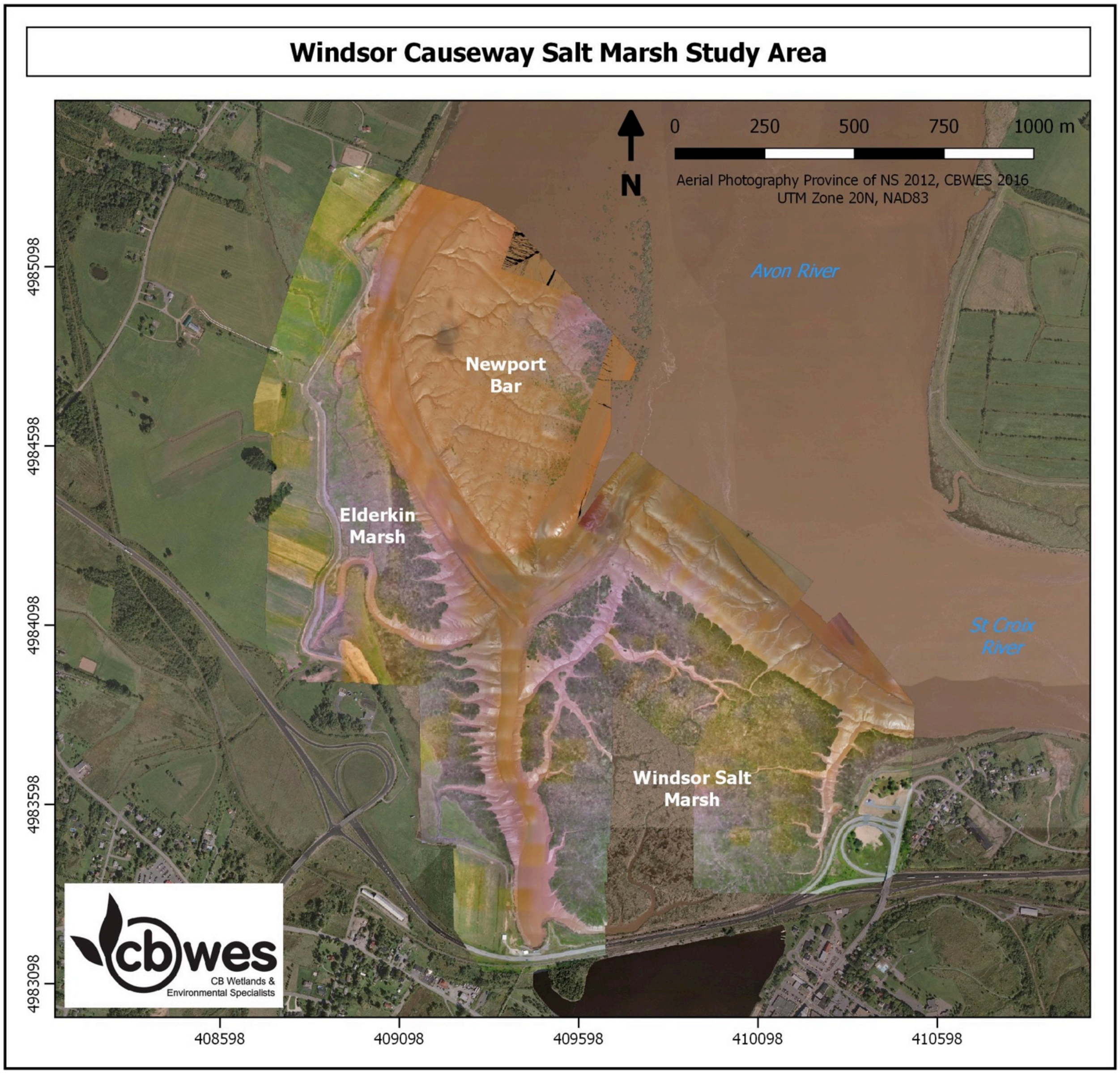

FIGURE 1: EXTENT OF STUDY AREA AND ORTHOMOSAIC DERIVED FROM JULY 2016 UAV FLIGHT SUPERIMPOSED ON 2012 PROVINCIAL AERIAL PHOTOGRAPHY.

PROCEDURES

A digital surface model (DSM) of the main tidal creek channels was derived from a series of aerial flights using a DJI Phantom 3 professional lightweight UAV and post-processed using industry approved software and surveyed ground control monuments. UAV flights were conducted on July 27-28, 2016 with over 1000 vertical and oblique photos taken covering 185 hectares. An example of oblique image is provided in Figure 2. High resolution orthomosaics with a 4 cm horizontal pixel resolution and 1.2 cm RMS error based on 26 ground control points (GCP) were generated.

Figure 3 outlines the 'valid' footprint of the 2016 image capture overlaid on the 2012 satellite imagery and resultant 2016 mosaic. Spatial extent was constrained by radio communication between operator and UAV as well as regulations regarding line of site for safe operation.

FIGURE 2 OBLIQUE AERIAL IMAGE TAKEN JULY 27, 2016. UAV HOVERING OVER NORTHEAST MARSH ON ST. CROIX RIVER. VIEW TOWARDS SOUTHEAST AND HWY 101.

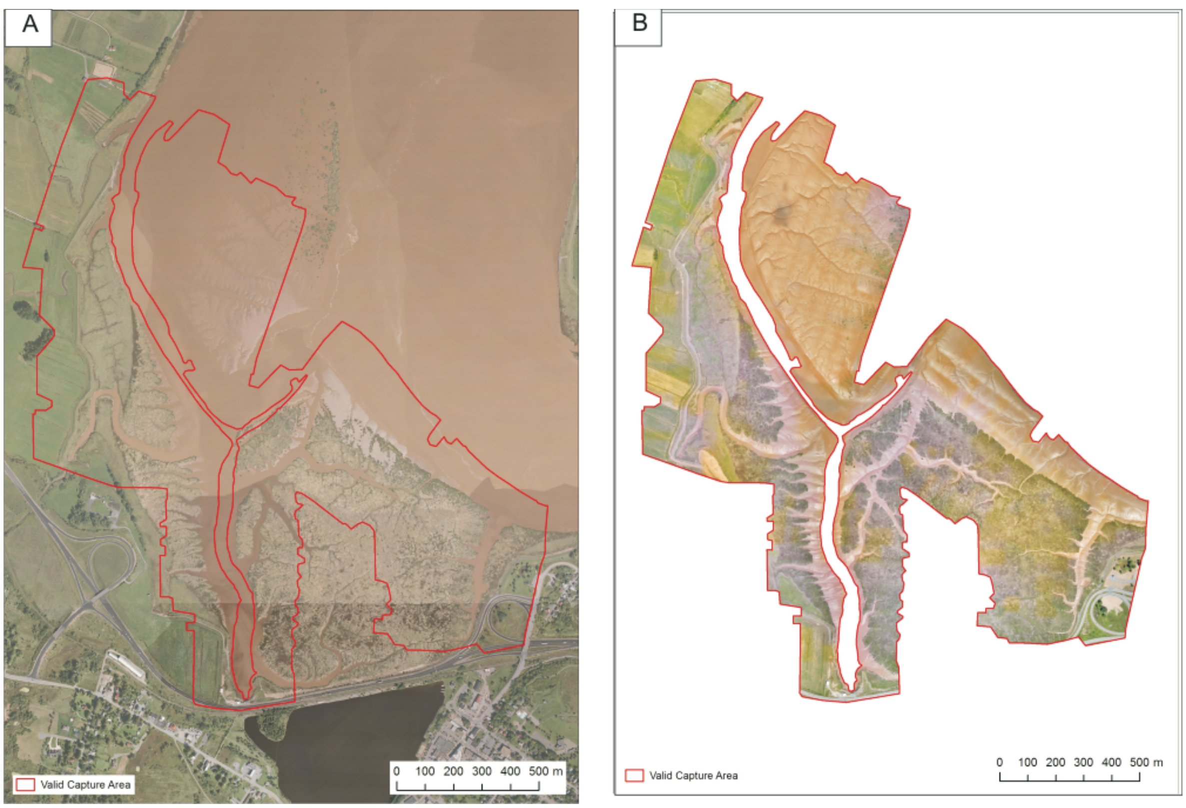

FIGURE 3 A) VALID CAPTURE AREA BASED ON GCP DISTRIBUTION, WATER LEVELS, AND PIX4D PROCESSING SHOWN ON 2012 IMAGERY. B) ORTHOMOSAIC GENERATED FROM CALIBRATED JULY 2016 IMAGERY.

The surface generated using the UAV imagery and Structure for Motion algorithms (Westoby et al., 2012) are DSMs not bare earth elevation models; therefore, cannot be used to determine marsh surface elevation since they include the height of the vegetation canopy. However, the DSM is excellent in bare mud channels and un-vegetated marsh surfaces (Figure 4). The 2007 LIDAR data were collected at low tide in May 2007 by the Advanced Geomatics Research Group (AGRG) at the College of Geographical Sciences, as a collaborative initiative with Saint Mary's University (SMU), NS Department of Transportation and Infrastructure Renewal (NSTIR) and NS Department of Agriculture (NSAg). LIDAR data were processed by AGRG (Webster et al., 2011). In the present study, a basic subtraction surface was calculated within ArcGIS 10.4 to delineate areas of vertical erosion and accretion based on the 2016 DSM and the 2007 1 m resolution LIDAR DEM. The resultant difference surface has 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 2016 elevation models in ArGIS (Figure 5) (Appendix B). Five of the profiles were identical to those surveyed immediately after causeway construction and in 2005, reported in van Proosdij and Baker (2007). The remainder were added to provide greater detail in areas of potential relevance for highway twinning. The geographic coordinates of the beginning and ends of all lines are provided in Appendix A.

Vegetated areas of salt marsh were digitized from the 2016 aerial photo mosaic and used to mask vegetated areas in the 2016 DSM. This permitted the most accurate direct comparison of changes in volume in tidal channels or cross sectional profiles between 2007 and 2016. 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 photos 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.

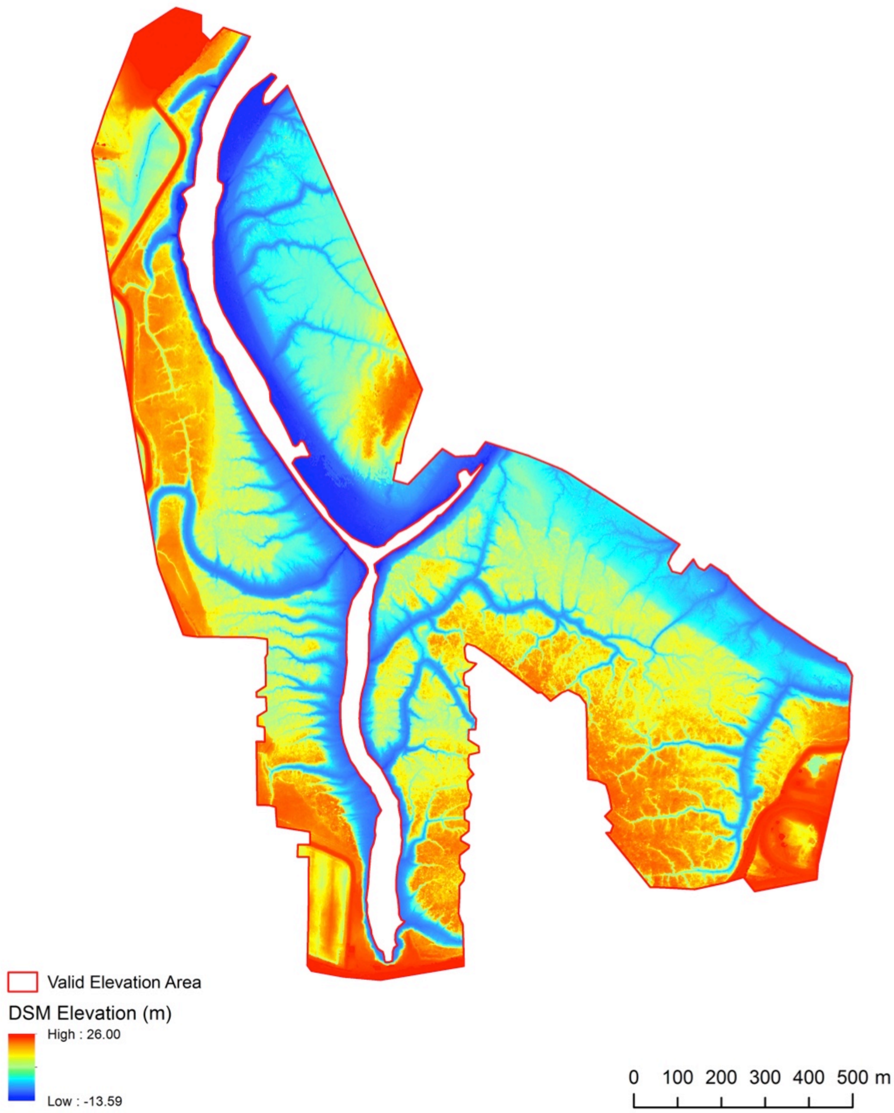

FIGURE 4 DIGITAL SURFACE MODEL (DSM) GENERATED USING PIX4D ILLUSTRATING ELEVATIONS RELATIVE TO CGVD28 (RED HIGH TO BLUE LOW) IN VALID SURFACE AREAS ONLY.

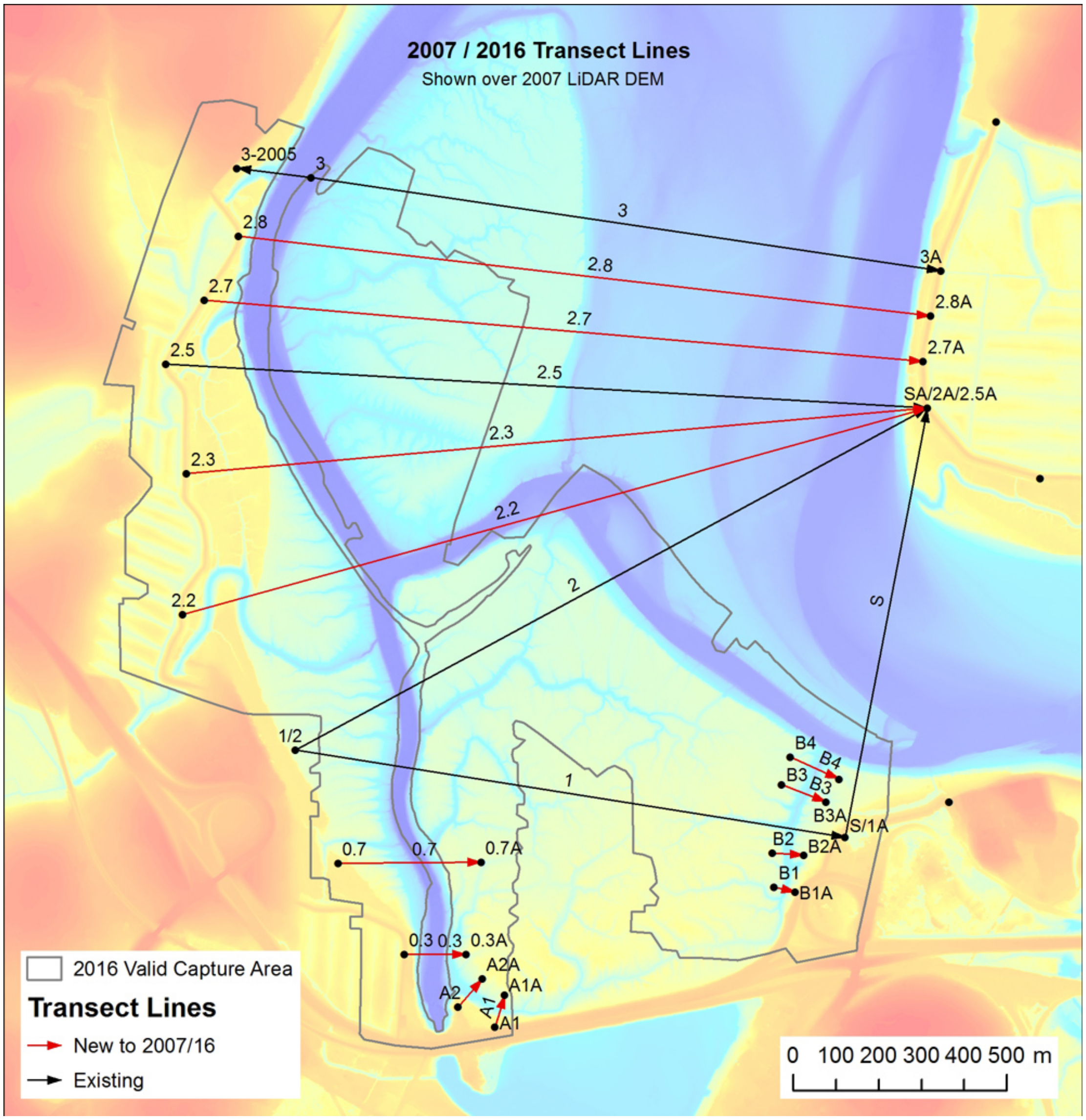

FIGURE 5 TRANSECT LINES USED TO DERIVE CROSS SECTIONAL PROFILE COMPARISONS. LINES OVERLAIN ON 2007 LIDAR DEM FROM AGRG.

FINDINGS

The study area was divided into five discrete sections for analysis and discussion. These sections are illustrated in Figure 6. Section 1 focuses on the tide gate channel, Section 2 addresses 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 includes foreshore marsh adjacent to Elderkin marsh. Section 3 focuses on the Newport Bar that began to develop in the mid-1990s downstream of the main Windsor salt marsh. Section 4 encompasses the northeastern section of Windsor marsh along the St. Croix River and near the former Tourist Bureau (Figure 7). Section 5 focuses on the eastern tidal channel with the recently decommissioned aboiteau, sewage outflow and adjacent Exit 6 of Highway 101.

FIGURE 6 DELINEATED SECTIONS OF STUDY AREA USED FOR ANALYSIS. 1: TIDE GATE CHANNEL; 2) CONFLUENCE AVON AND ST. CROIS RIVERS; 3) NEWPORT BAR; 4) ST. CROIX AND EAST MARSH AND 5) SEWER OUTFLOW AND ABOITEAU CHANNEL.

FIGURE 7 VIEW UPSTREAM TOWARD TIDE GATE (SOUTHEAST) ON JULY 27, 2016 FROM ABOVE ELDERKIN MARSH. VIEW OF NEWPORT BAR ON LEFT (EAST) AND EXPANDING LOW MARSH ON ELDERKIN FORESHORE ON RIGHT (WEST).

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 4) indicates sediment loss of (-)19,242 m^3 (Figure 8a) over approximately the last 10 years. The total (absolute) change in sediment volume, however, was much greater (1.35M m^3) (Figure 8b) reflecting marked differences in erosion and infilling between and within sections. It should be noted, however, that the eastern portion of the Newport Bar was excluded from the volume analysis due to a slight distortion at the edges of the 2016 DSM resulting from inadequate control monuments on the inaccessible Newport Bar.

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 8a). Section 2 also reported the largest absolute change in volume with 227,461 m^3 of infilling and 423,095 m^3 of sediment export (erosion). This represents the most dynamic section within the study area. The majority of 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 9; Figure 10). Examination of change in marsh area suggests that the majority of change occurred between 2012 and 2016 (Figure 11). 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 1c) and continued downstream, further eroding the western bank of the main channel (Figure 12; Figure 13; Figure 14).

The greatest increase in sedimentation (276,847 m^3) was recorded in Section 4, at the northeastern edge of the Windsor marsh along the St. Croix River (Figure 15). 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 2016 (Figure 16). This represents more than 5 m of vertical accretion of fine sediments and lateral extension of the mudflat surface by approximately 70 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 17, Figure 18), 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 16b), forcing it to run parallel to the edge of vegetation. This is resulting in bank erosion and slumping as that channel deepens (Figure 15).

While Sections 1 and 3 exhibit much less net change in sediment volume (Figure 8), 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 9). This bend in the channel thalweg and marsh erosion has, however, facilitated the formation of accretionary tidal flats on the western bank which are rapidly becoming vegetated, effectively creating new foreshore marsh to protect the Elderkin dykes along that section (Figure 9). Transect line 0.7 records a decreasing slope gradient and expansion of the toe of the channel by 19 m (Appendix B Figure 3b). Scour is evident along both banks immediately downstream of the gate structure as a result of secondary tidal currents and eddies that continue to develop (Figure 10a). 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 10b).

Further downstream, the growth of the Newport Bar has increased channelization of the Avon tide gate river channel and induced scour and erosion on the western bank. The channel has increased in width by approximately 30 m (Appendix B Figure 1d Line 2.3; Figure 2a Line 2.5), mostly at the expense of foreshore marsh on the western bank (Figure 14). The river channel is increasingly threatening the integrity of the dyke system in that area. Attempts at shore 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 river channel.

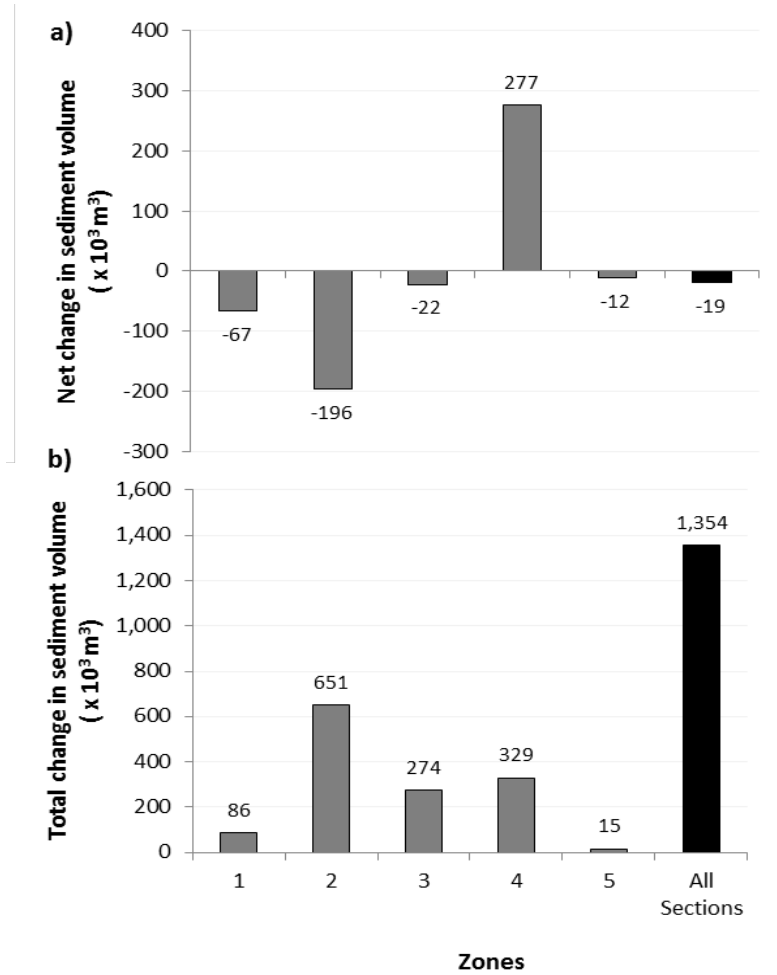

FIGURE 8 CALCULATED CHANGES IN SEDIMENT VOLUME BETWEEN 2007 AND 2016 UNVEGETATED INTERTIDAL SURFACES. A) NEGATIVE VALUES INDICATE SEDIMENT LOSS OR EROSION, POSITIVE VALUES INDICATE INFILLING, B) TOTAL CHANGE IN SEDIMENT VOLUME CALCULATED AS THE TOTAL (ABSOLUTE) AMOUNT OF CHANGE WITHIN EACH SECTION.

FIGURE 9: LOW ALTITUDE NADIR AERIAL MOSAIC OF AVON RIVER CAUSEWAY TIDE CHANNEL FROM JULY 27, 2016 WITHIN SECTION 1.

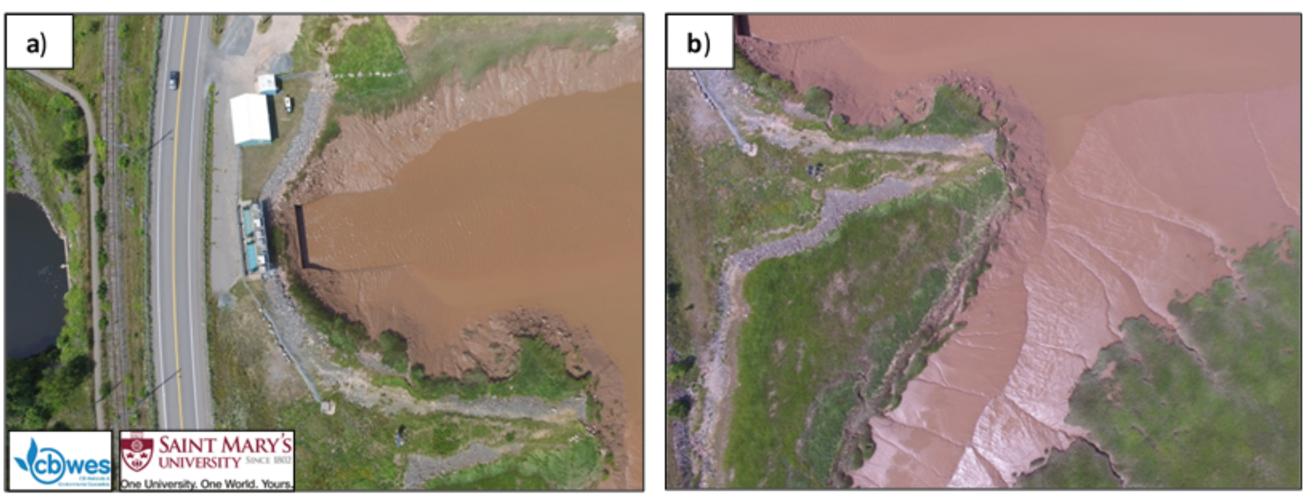

FIGURE 10 NADIR (VERTICAL) AERIAL PHOTO TAKEN BY UAV ON JULY 27, 2016 AT A) AVON RIVER CAUSEWAY TIDE GATE, B) CAUSEWAY CHANNEL.

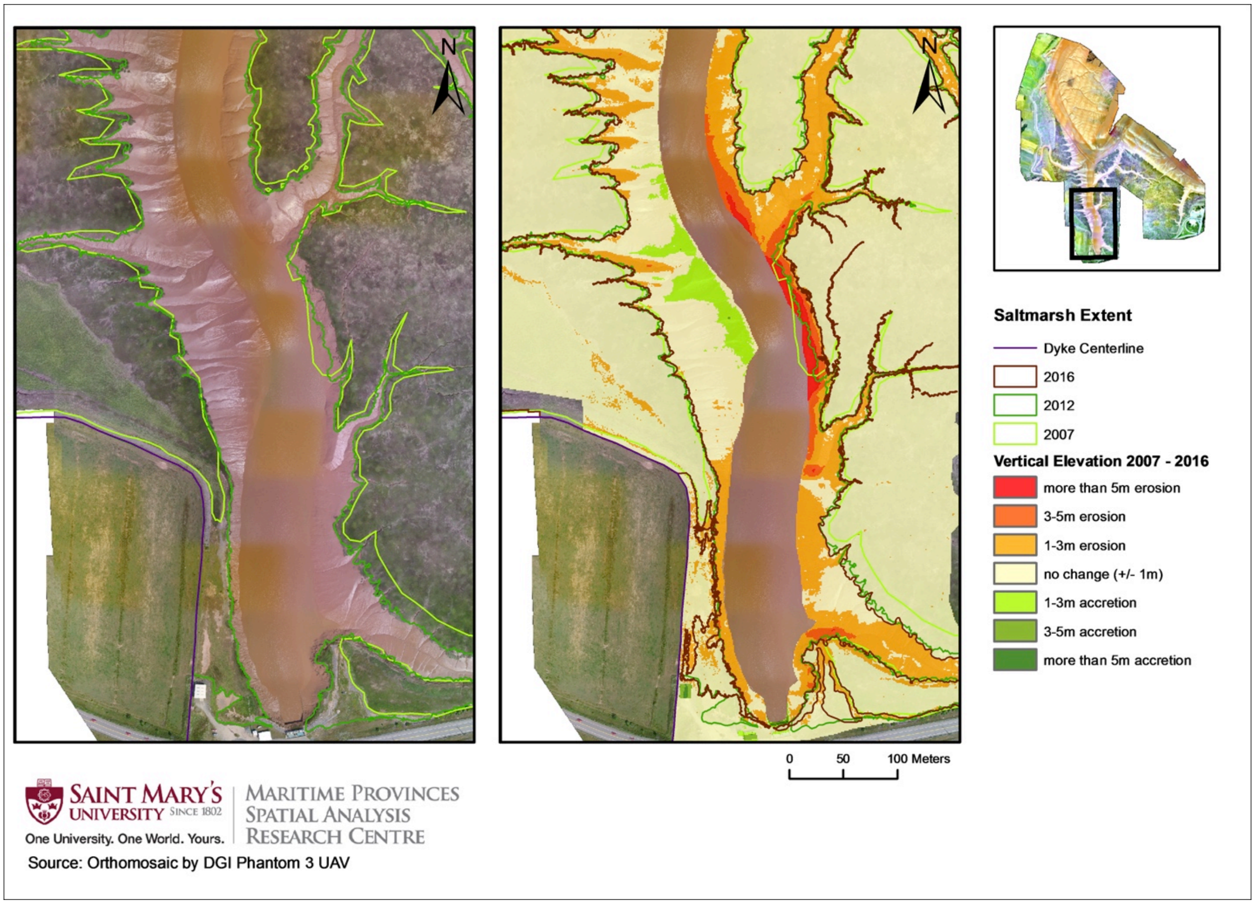

FIGURE 11 CHANGE IN SURFACE VERTICAL ELEVATION BETWEEN 2007 LIDAR SURFACE AND 2016 UAV FLIGHT IN SECTION 1. MARSH AREA POLYGONS ARE PROVIDED FOR REFERENCE BASED ON DIGITIZED AERIAL IMAGERY.

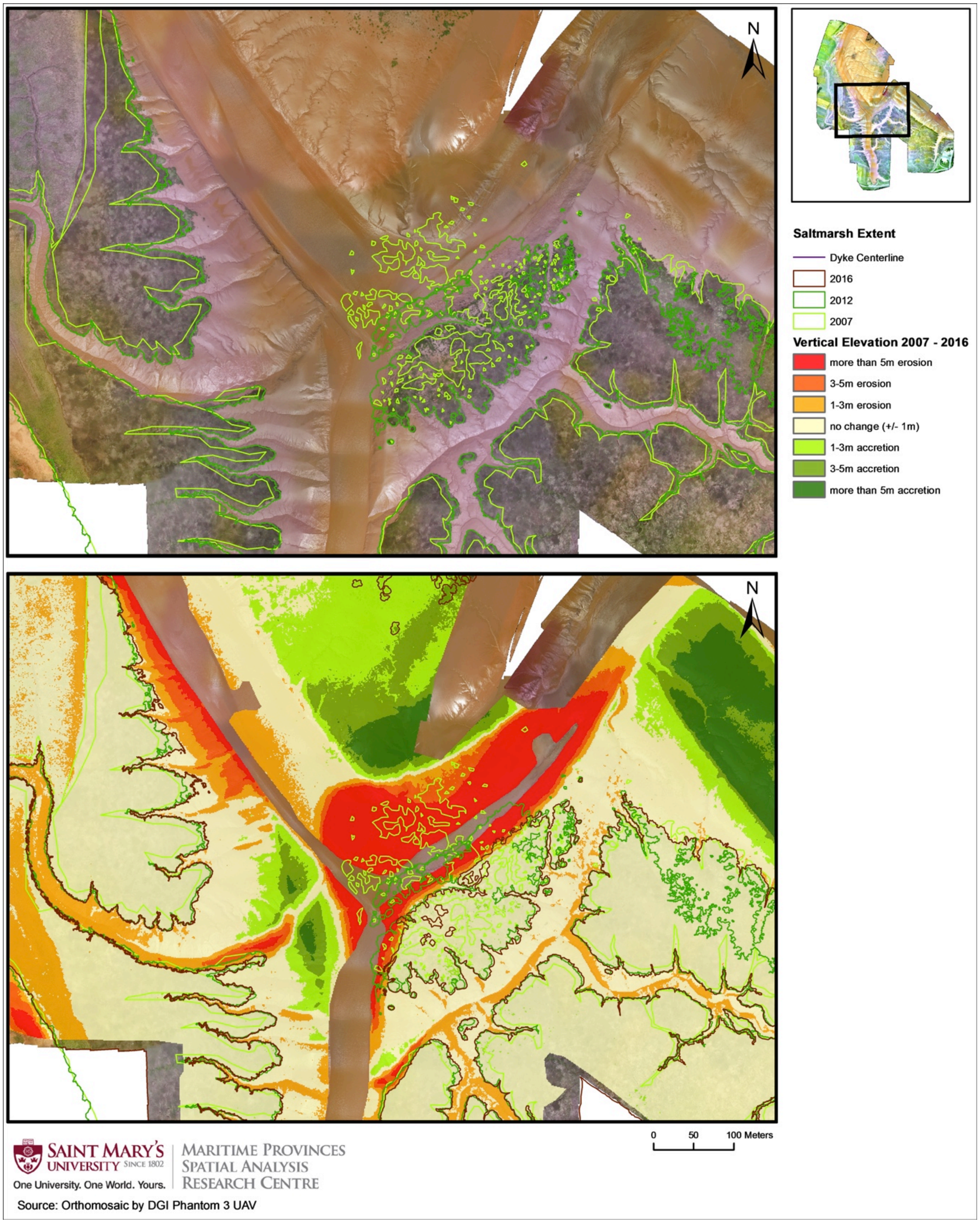

FIGURE 12 CHANGE IN SURFACE VERTICAL ELEVATION BETWEEN 2007 LIDAR SURFACE AND 2016 UAV FLIGHT IN SECTION 2. MARSH AREA POLYGONS ARE PROVIDED FOR REFERENCE BASED ON DIGITIZED AERIAL IMAGERY.

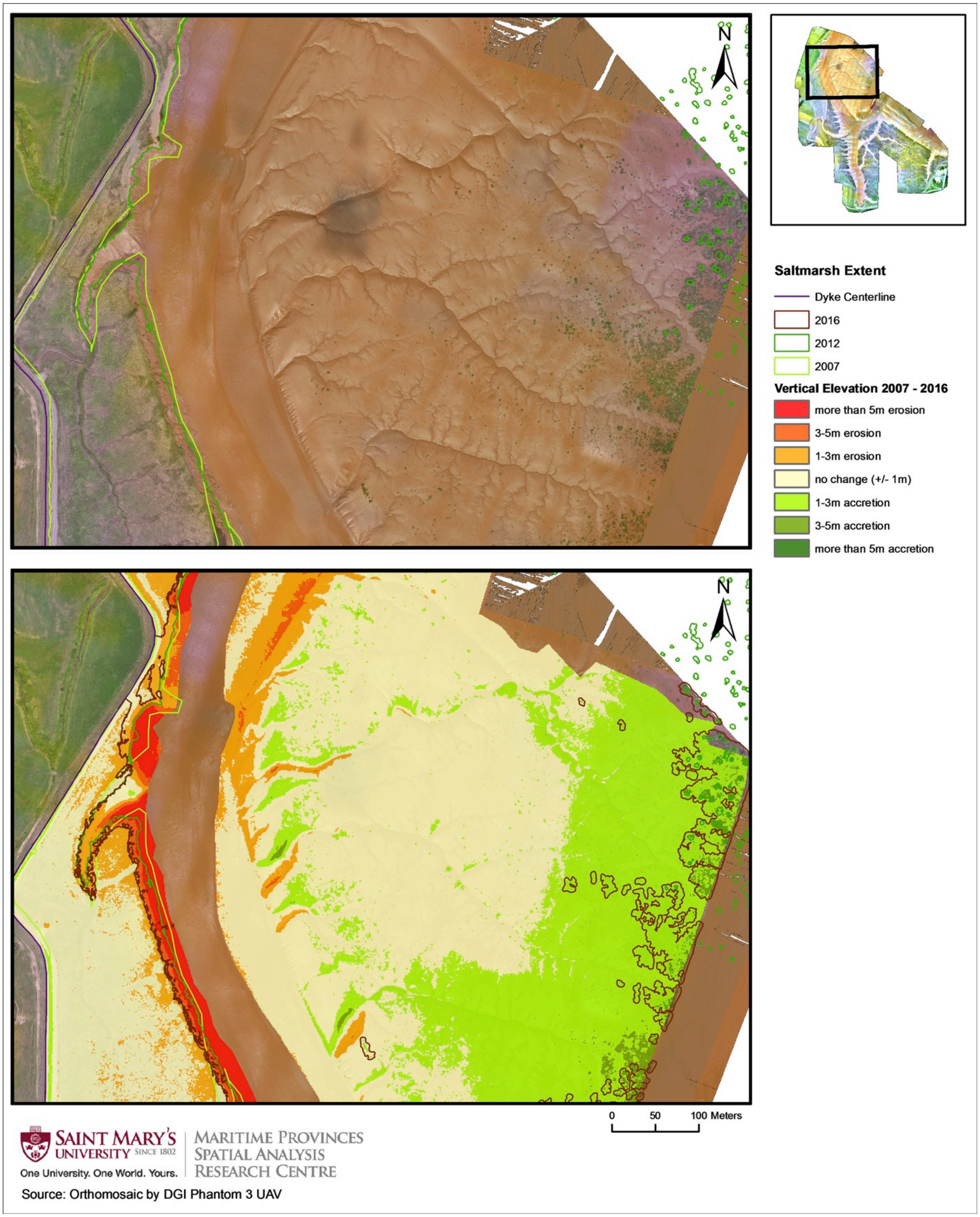

FIGURE 13 CHANGE IN SURFACE VERTICAL ELEVATION BETWEEN 2007 LIDAR SURFACE AND 2016 UAV FLIGHT IN SECTION 3. MARSH AREA POLYGONS ARE PROVIDED FOR REFERENCE BASED ON DIGITIZED AERIAL IMAGERY.

FIGURE 14 LOW ALTITUDE NADIR AERIAL MOSAIC OF AVON TIDE GATE CHANNEL JULY 28, 2016 WITHIN SECTION 3.

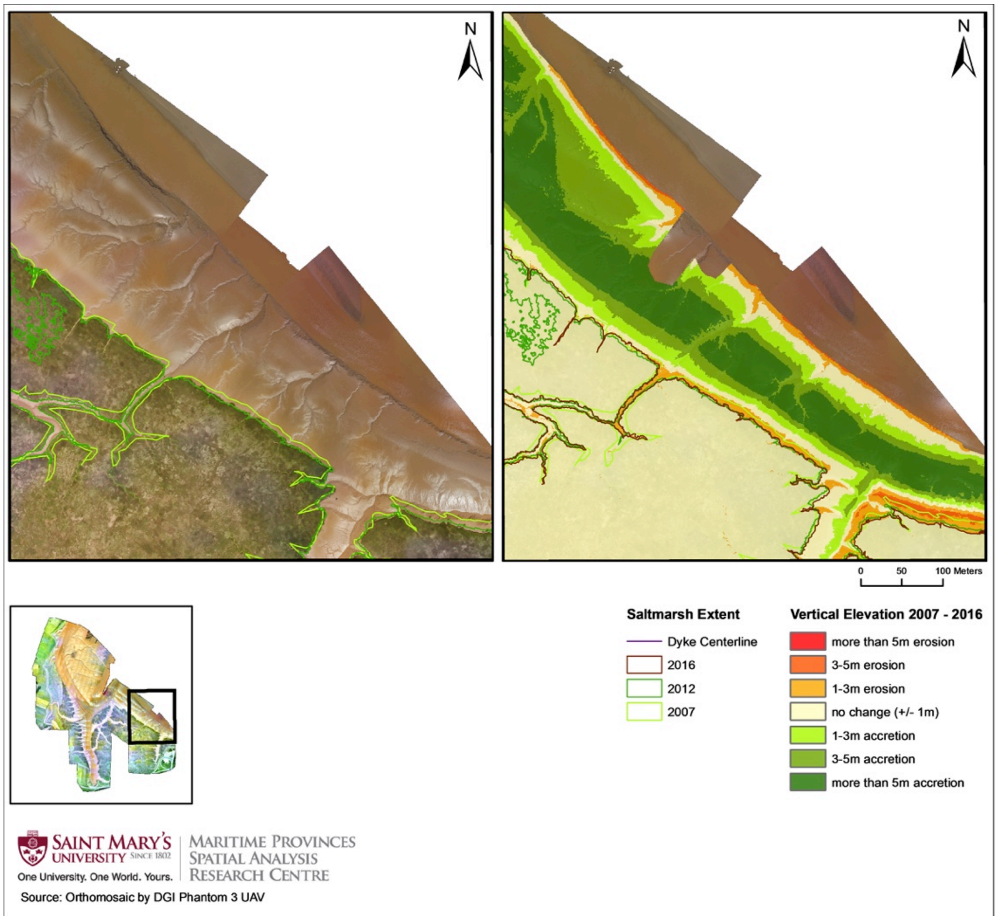

FIGURE 15 CHANGE IN SURFACE VERTICAL ELEVATION BETWEEN 2007 LIDAR SURFACE AND 2016 UAV FLIGHT IN SECTION 4. MARSH AREA POLYGONS ARE PROVIDED FOR REFERENCE BASED ON DIGITIZED AERIAL IMAGERY.

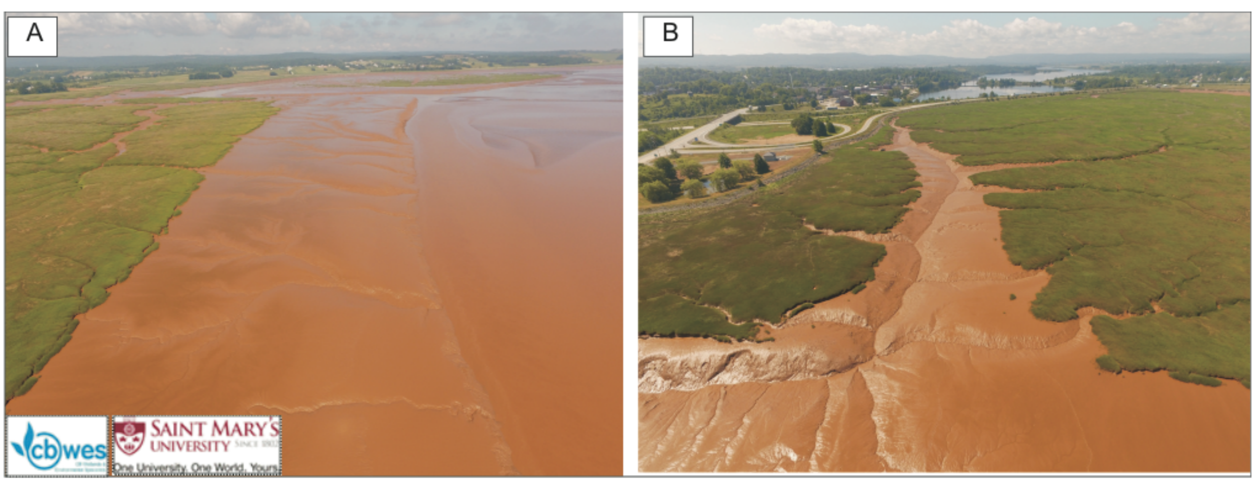

FIGURE 16 OBLIQUE AERIAL PHOTOGRAPHY OBTAINED BY UAV ON JULY 27, 2016 OF A) NORTHEASTERN EDGE OF WINDSOR MARSH COMPLEX AT ST. CROIX RIVER, AND B) NORTHEAST CHANNEL SECTION NEAR FORMER TOURIST BUREAU VIEWED FROM ST. CROIX RIVER.

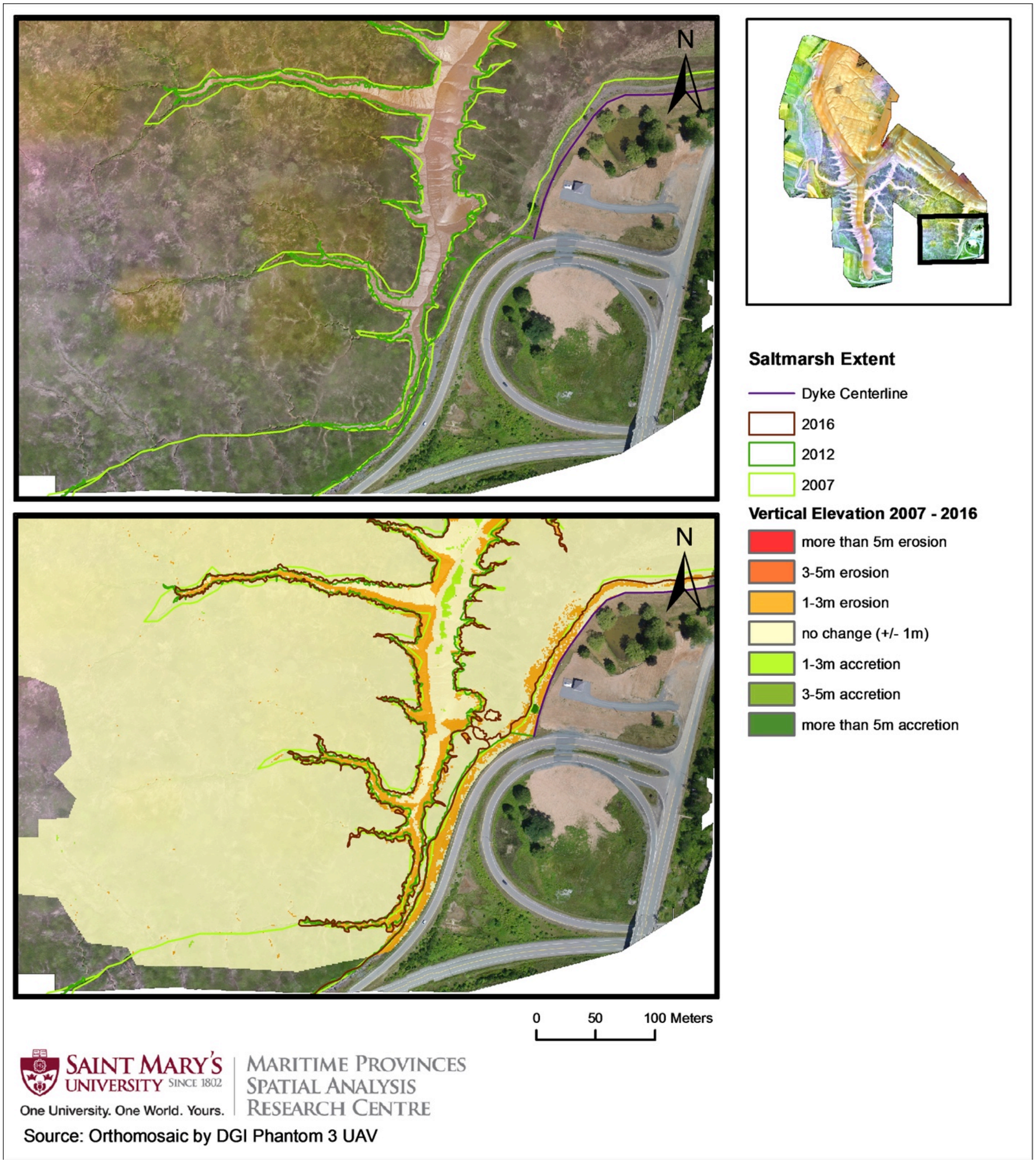

FIGURE 17 CHANGE IN SURFACE VERTICAL ELEVATION BETWEEN 2007 LIDAR SURFACE AND 2016 UAV FLIGHT IN SECTION 5. MARSH AREA POLYGONS ARE PROVIDED FOR REFERENCE BASED ON DIGITIZED AERIAL IMAGERY.

FIGURE 18 LOW ALTITUDE NADIR AERIAL MOSAIC OF EASTERN TIDAL CHANNEL AND FORMER SEWAGE OUTFLOW AND ABOITEAU CHANNEL ON JULY 27-28, 2016 WITHIN SECTION 5.

FIGURE 19 OBLIQUE AERIAL PHOTOGRAPH LOOKING DOWNSTREAM IN THE AVON TIDE GATE RIVER CHANNEL. NOTE SLUMPING AND EROSION OF LEFT BANK AND PROGRADATION ON RIGHT BANK OF NEWPORT BAR. PHOTO TAKEN JULY 27, 2016.

Salt Marsh and Intertidal Habitat

The construction of the Avon River tide gate and causeway facilitated rapid sedimentation and formation of a significant tidal flat which rapidly evolved into a vibrant, highly productive salt marsh habitat within a 40-year period (van Proosdij and Townsend, 2006; Daborn et al., 2004; van Proosdij and Baker, 2007) (Figure 20). Within the boundaries of the current study area, the greatest percent change in vegetated salt marsh habitat occurred between 1992 and 2003 (57%), followed by the 2003 to 2007 period (34%) (Figure 21). However, the greatest rate of change between time periods was 5.1 $Ha \cdot yr^{-1}$ between 2003 and 2007. Rates of increase in vegetated area have leveled off to approximately 0.2 to 1 $Ha \cdot yr^{-1}$ (Figure 21, Figure 22). Recall, however, that the absolute values from 2016 will be a slight underestimation of the amount of newly evolving *Spartina alterniflora* on the eastern edge of the Newport Bar due to the configuration of the study area (Figure 6). This leveling off is not surprising as the marsh platform raises within the tidal frame it will become less and less inundated. A lag also exists between growth of supratidal flats and vegetative colonization.

The growth in salt marsh area, however, is not uniform in space or time within all sections analyzed (Figure 22; Figure 23 to Figure 27). The greatest rate of change and largest vegetated area occurred in Section 2 (Figure 24) despite the significant scour and erosion illustrated in Figure 12. Section 3 saw a 4.8 Ha loss of foreshore marsh between 1992 and 2007 (Figure 22; Figure 25). The marsh edge at Section 4 has shifted from a cliffed to a ramped form with the rapid expansion of the tidal bank on the St. Croix channel (Figure 26). This surface will likely become vegetated within the next few years.

FIGURE 20 OBLIQUE AERIAL IMAGERY OF MAIN WINDSOR MARSH COMPLEX LOOKING SOUTHWEST FROM UAV HOVERING OVER THE ST. CROIX RIVER ON JULY 27, 2016.

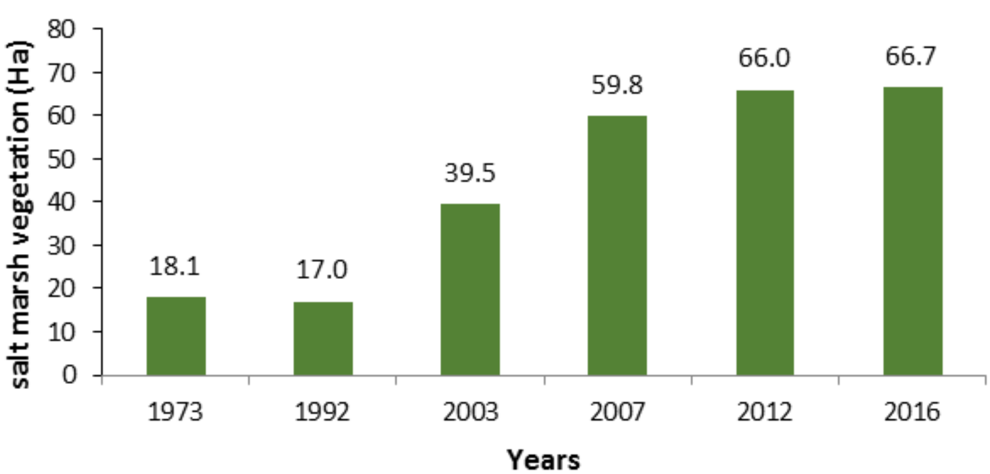

FIGURE 21 CHANGE IN VEGETATED SALT MARSH AREA FROM DIGITIZED AERIAL IMAGERY FROM 1973 TO 2016.

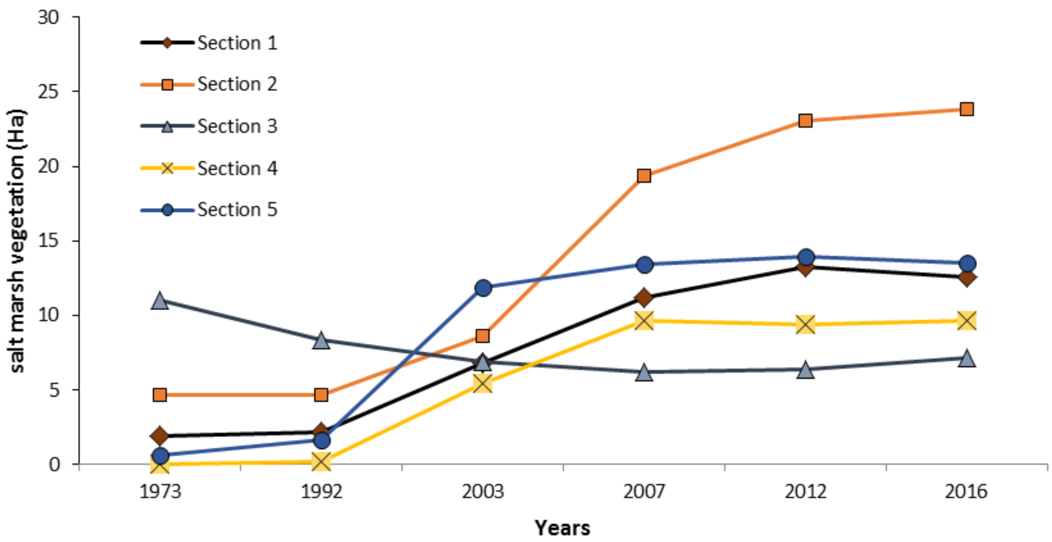

FIGURE 22 CHANGE IN VEGETATED SALT MARSH AREA OVER TIME WITHIN THE STUDY AREA FROM 1973 TO 2016.

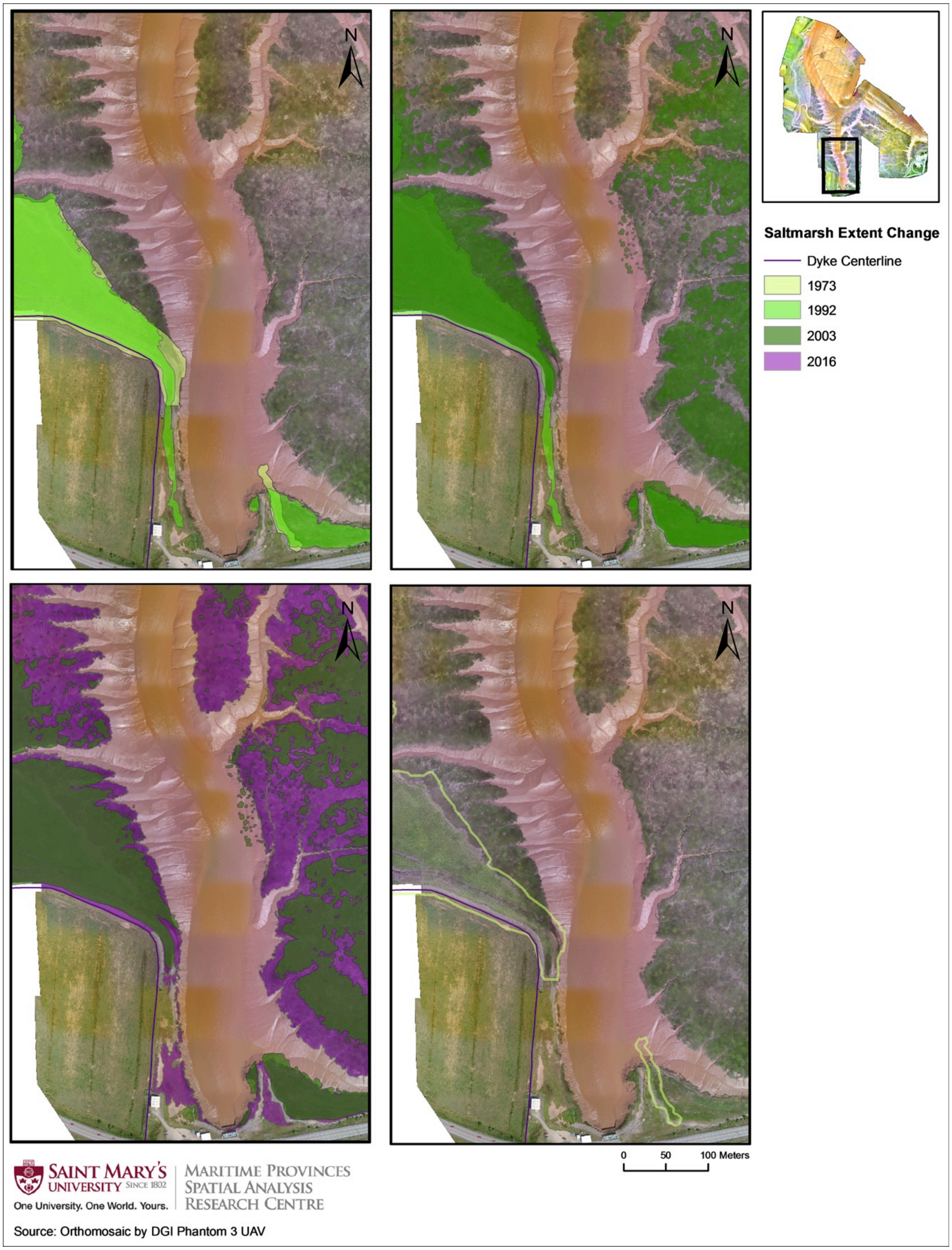

FIGURE 23: HISTORICAL CHANGE IN SALT MARSH AREA SINCE CAUSEWAY CONSTRUCTION, FROM 1973 TO 2016. POLYGONS OVERLAIN OVER 2016 ORTHOMOSAIC IN SECTION 1. FINAL PANEL ILLUSTRATES EARLIEST MARSH POLYGON FOR THE SECTION IN RELATION TO 2016 MARSH AREA.

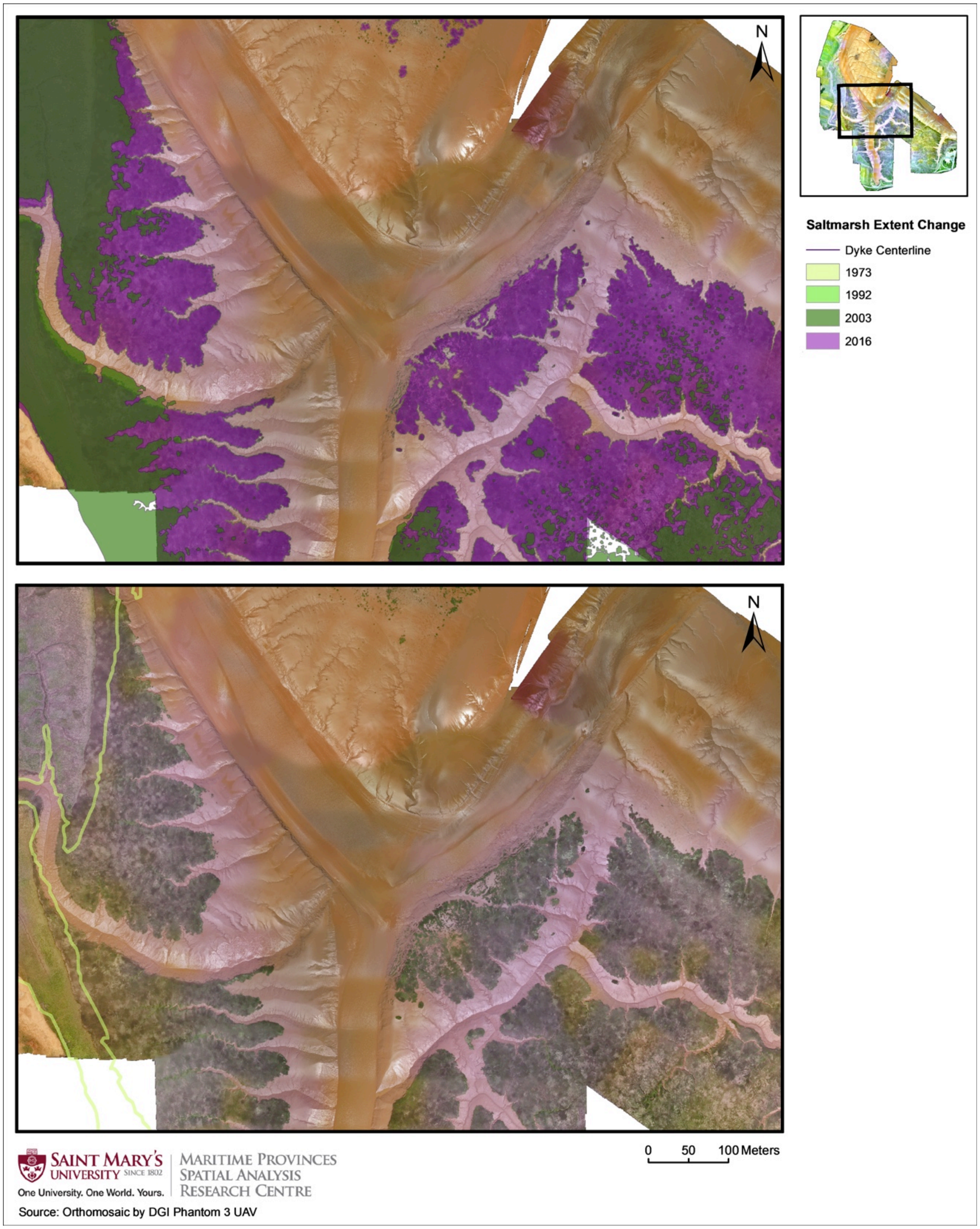

FIGURE 24: HISTORICAL CHANGE IN SALT MARSH AREA SINCE CAUSEWAY CONSTRUCTION, FROM 1973 TO 2016. POLYGONS OVERLAIN OVER 2016 ORTHOMOSAIC IN SECTION 2. FINAL PANEL ILLUSTRATES EARLIEST MARSH POLYGON FOR THE SECTION IN RELATION TO 2016 MARSH AREA.

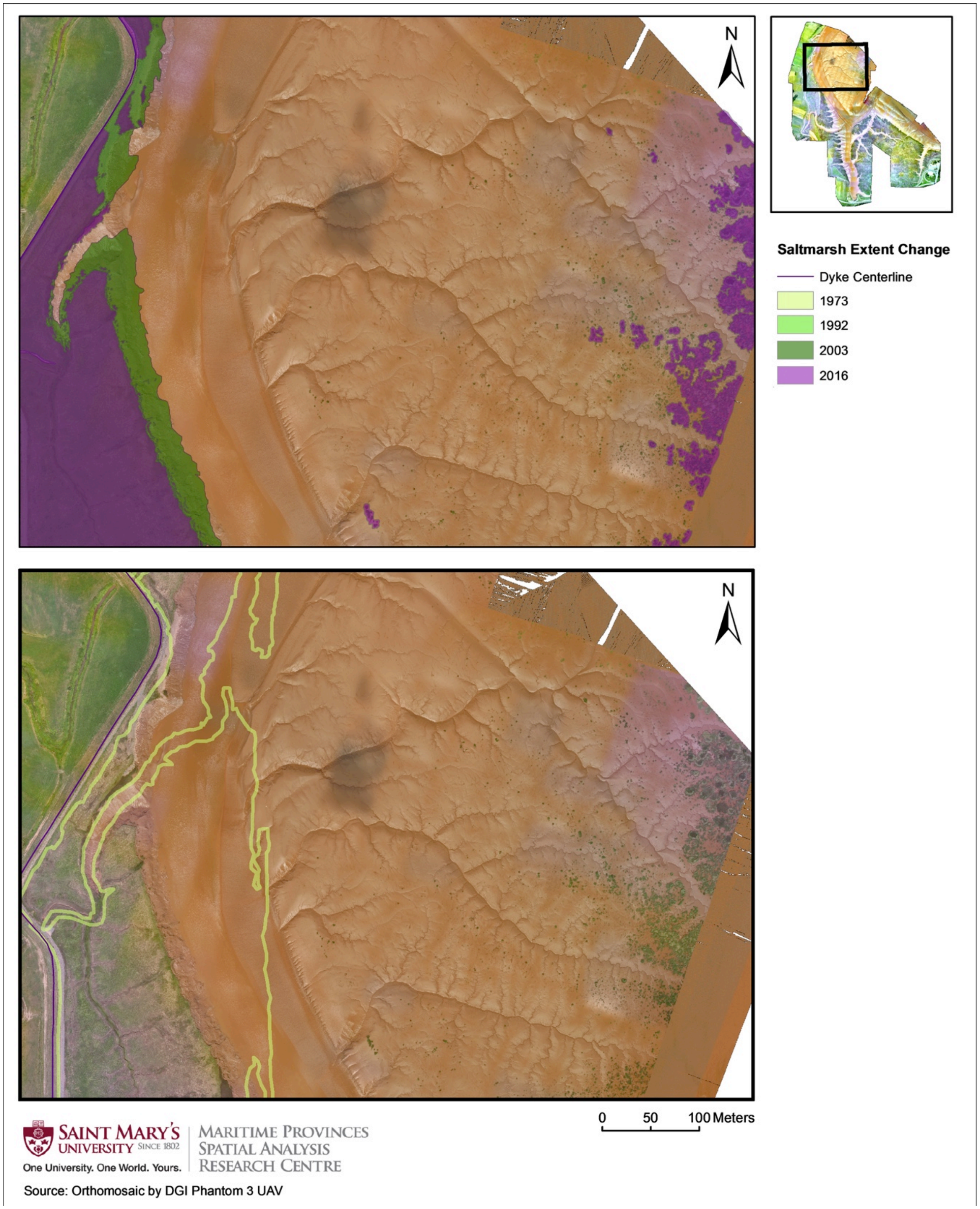

FIGURE 25: HISTORICAL CHANGE IN SALT MARSH AREA SINCE CAUSEWAY CONSTRUCTION, FROM 1973 TO 2016. POLYGONS OVERLAIN OVER 2016 ORTHOMOSAIC IN SECTION 3. FINAL PANEL ILLUSTRATES EARLIEST MARSH POLYGON FOR THE SECTION IN RELATION TO 2016 MARSH AREA.

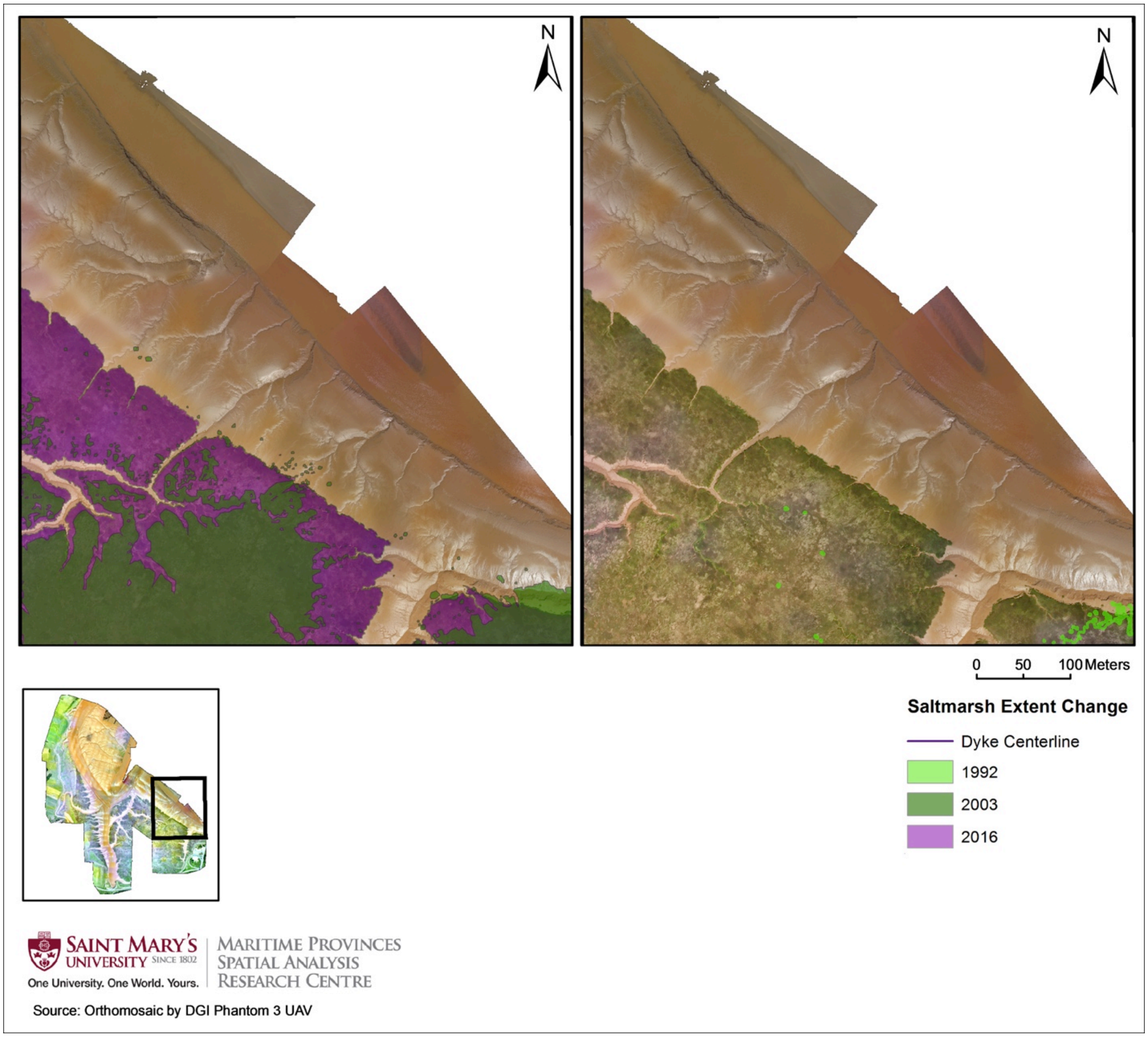

FIGURE 26: HISTORICAL CHANGE IN SALT MARSH AREA SINCE CAUSEWAY CONSTRUCTION, FROM 1973 TO 2016. POLYGONS OVERLAIN OVER 2016 ORTHOMOSAIC IN SECTION 4. FINAL PANEL ILLUSTRATES EARLIEST MARSH POLYGON FOR THE SECTION IN RELATION TO 2016 MARSH AREA.

FIGURE 27: HISTORICAL CHANGE IN SALT MARSH AREA SINCE CAUSEWAY CONSTRUCTION, FROM 1973 TO 2016. POLYGONS OVERLAIN OVER 2016 ORTHOMOSAIC IN SECTION 5. FINAL PANEL ILLUSTRATES EARLIEST MARSH POLYGON FOR THE SECTION IN RELATION TO 2016 MARSH AREA.

IMPLICATIONS

The salt marsh and intertidal habitats that have evolved downstream of the Avon River causeway continue to be very dynamic systems, and will very likely impact and be impacted by highway twinning and modification of the tide gate structure. 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 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 piling 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 re-alignment 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, which are worth investigating in more detail (Figure 28). The easiest way for this to be accomplished given the significant challenges of deploying hydrodynamic measurement instruments within this area, is to record an aerial video at this intersection as the tide shifts from flood to ebb. This would also be useful to view secondary flow currents and eddies around the tide gate structure at different stages of the tide. Given the macrotidal nature of this area and differences between tidal stages, it would be useful to do this on spring and neap tides.

FIGURE 28 OBLIQUE AERIAL VIEW OF NORTHWESTERN EDGE OF MAIN WINDSOR MARSH COMPLEX AND ERODING FLOOD CHANNEL FROM THE ST. CROIX RIVER, SOUTH OF THE NEWPORT BAR. IMAGE TAKEN BY UAV JULY 27, 2016.

RECOMMENDED MONITORING PROGRAM

Overview

It is well known that the construction of causeways across tidal estuaries causes significant, often negative, impacts to the physical and biological conditions of the system. Salt marshes and mudflat complexes tend to experience the most dramatic and observable effects of the resulting change in the movement of water and sediment. Given that the tidal system downstream of the Avon River Causeway has been highly modified as a result of the original construction and continues to be influenced by human activity, the system has yet to reach a new geomorphic equilibrium. Given this, predicting the future "response" of the system to causeway expansion is very difficult; however, it is anticipated that the biggest influence of construction and causeway expansion will be on the movement of water and sediment, particularly in close proximity to the crossing but also far-field. Changes in flow patterns, sediment mobility and deposition may result in changes in marsh surface elevation; channel location, stability and capacity; and surface cover (vegetation).

The proposed 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 Avon River salt marsh, mudflat and associated tidal channel system as a result of the proposed NSTIR-NSAg construction project. It builds upon the previous research and monitoring activities conducted by Saint Mary's University between 2002 and 2007 (van Proosdij, 2005; van Proosdij et al., 2006; van Proosdij and Baker 2007). The monitoring program is focused on four main objectives:

1. ***Measure changes in surface elevation*** using DEM and DSM derived from differential RTK elevation surveys along reproducible transections and georeferenced low-altitude aerial photography.

2. ***Measure changes in the location, stability and capacity of tidal channel networks***, particular 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 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 will encompass the entire Windsor salt marsh-mudflat system including the Elderkin Marsh and Newport Bar. The more detailed monitoring activities (elevation and vegetation surveys) will be focused 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 29). Attention will be 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.

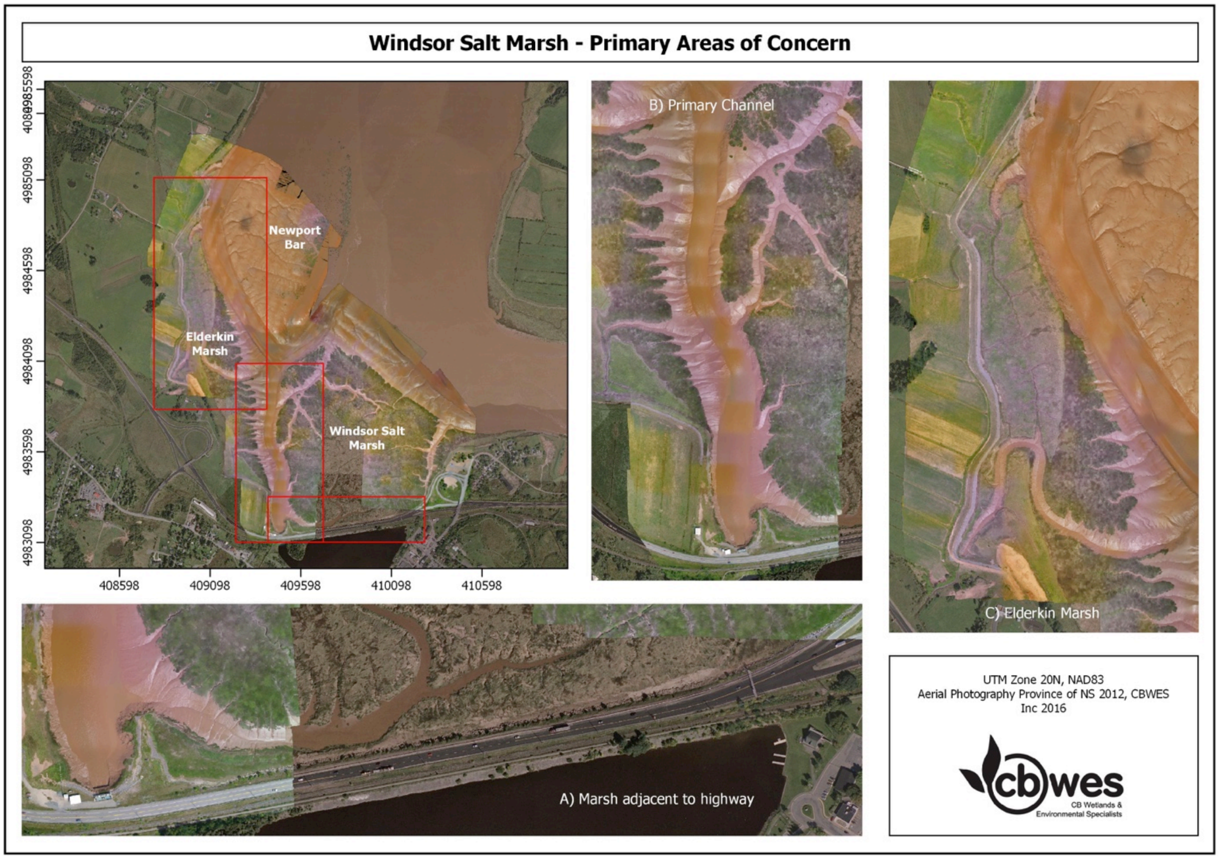

FIGURE 29: WINDSOR SALT MARSH SYSTEM AND AREAS OF POTENTIAL IMPACT.

Monitoring Framework

The monitoring program will be carried out in advance of causeway construction activities, with certain aspects of the program repeated during and immediately post-construction in order to quantify environmental impact predictions of the Environmental Assessment (EA) report and adequately offset the loss of salt marsh and fish habitat. Post-construction monitoring will continue on an annual basis for a minimum of 5 years. Effective monitoring also depends on the re-installation of tide gauges at the gate for accurate water level records (upstream and downstream), weather station and marsh/channel camera. This infrastructure is also essential for effective gate operation and emergency management. The proposed monitoring program is detailed below and summarized in Table 1.

Geospatial Attributes

Geospatial data are a key component of the monitoring program and serve as the foundation for all analyses. Several approaches will be used to create a robust dataset: on-site surveying, the creation of Digital Elevation and Surface Models (DEM & DSM), and acquisition of geo-referenced low-altitude aerial photography.

On-site mapping/surveying activities (i.e., elevation survey, digital mapping of sampling stations) will be conducted using a Trimble R8 GNSS RTK surveying system (or equivalent). A DEM will be generated in

ArcGIS using the topo to raster tool from survey data and NSTDB 1:10,000 data. Acquisition and geo-referencing of low-altitude aerial photography will be conducted using the CBWES-SMU aerial platform and Pix4d software (Figure 30). Multiple flights during each sampling year (i.e., spring before vegetation emergence for bare earth conditions; mid-late summer for habitat/vegetation community conditions). The resulting mosaics will be used to create layout, habitat, surface cover and change over time maps. In conjunction with orthomosaic processing a 3d model (DSM) can be generated using photogrammetric techniques (dependent on image quality, distribution, and vegetation conditions) and used to augment DEM and habitat mapping activities. When combined with RTK surveys and known vegetation heights, the DSM can be used to improve extrapolated surface elevations in un-surveyed areas of the DEM. During habitat mapping activities the community boundaries can often be identified from distinct changes in elevation and surface texture.

The DEM, DSM, habitat, and surface cover maps will be 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 will aid in the establishment of a more detailed picture of the sites geomorphic condition in advance of causeway expansion, against which post-expansion conditions can be compared.

Deliverable Products:

- Orthomosaics
- Low-altitude high resolution photographic imagery
- Layout map

FIGURE 30: EXAMPLE OF NADIR (VERTICAL) IMAGE FROM UAV THAT WOULD BE USED TO MONITOR VEGETATION CHANGE, PATTERNS OF SCOUR AND SEDIMENTATION. PHOTO TAKEN JULY 28, 2016 ADJACENT TO TIDE GATE CHANNEL.

Elevation, Bathymetry and Hydrology

In addition to DEM generation described above a series of transects, matching the location of the 2005 study transects, running perpendicular to the causeway and extending 200 m into the marsh will be used as the basis for a detailed elevation survey and vegetation monitoring (Figure 31) (van Proosdij 2005). A Differential RTK GPS will be used to map the beginning and end of each transect, vegetation sampling plots, and marsh surface elevation along each transect.

Flood mapping will be carried out using the DEM and flood levels obtained from the causeway tide gate automatic water level recorders (tide gauges)[1]. In addition to flood mapping, hypsometric curves and hydroperiod for sample stations will be calculated from DEM, station elevation and flood data. These metrics are important for both vulnerability assessment and vegetation community structure. Channel networks also play an important role in how the sites floods. They will be delineated using a combination of tools: the hydrology toolbox in ArcGIS will be used to delineate networks from the DEM, which can be further validated and refined using survey data, DSM, and orthomosaics.

In order to detect morphological changes in the Avon River channel, a subset of the cross sectional bathymetric surveys that were conducted in 2005 and new lines established in 2016 will be surveyed to assess changes in channel morphology and tidal prism (Figure 32). Stake coordinates of survey lines are provided in Appendix A.

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, should be monitored using video footage obtained by a combination of UAV and/or fixed camera stations.

Deliverable Products:

- DEM, DSM, transect elevation profiles
- Bathymetric analysis, tidal prism
- Flood maps, hypsometric curve, hydroperiod
- Tidal channel network delineation
- Video and analysis of tidal flow patterns

[1] The existing causeway tide gate has automatic water level recorders permanently installed on both the downstream and upstream sides. Assumption is that the new tide gate structure will also include tide gauges.

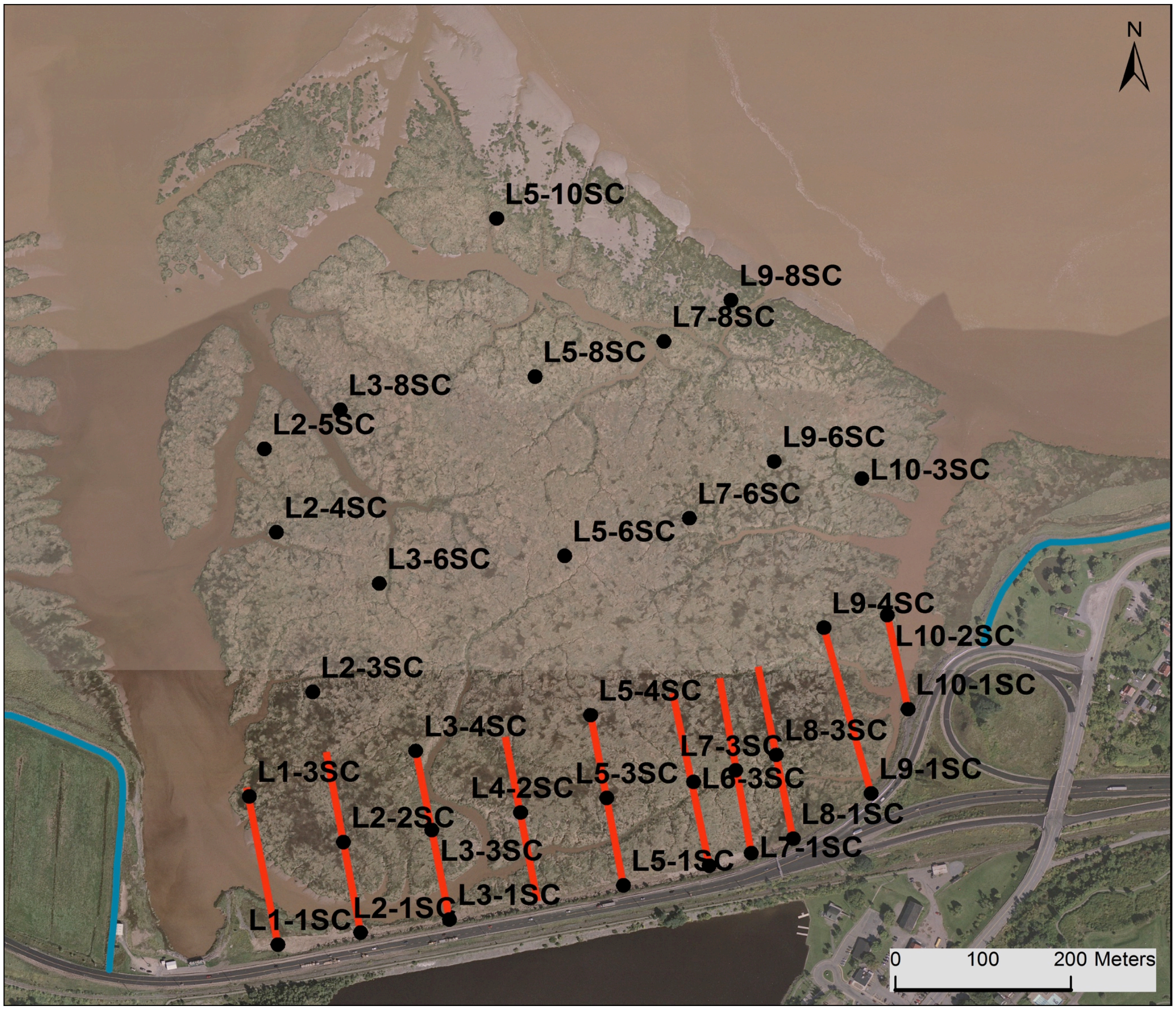

FIGURE 31: LOCATION OF SAMPLING LINES FROM 2005 STUDY OVERLAIN ON 2012 IMAGERY (VAN PROOSDIJ, 2005)

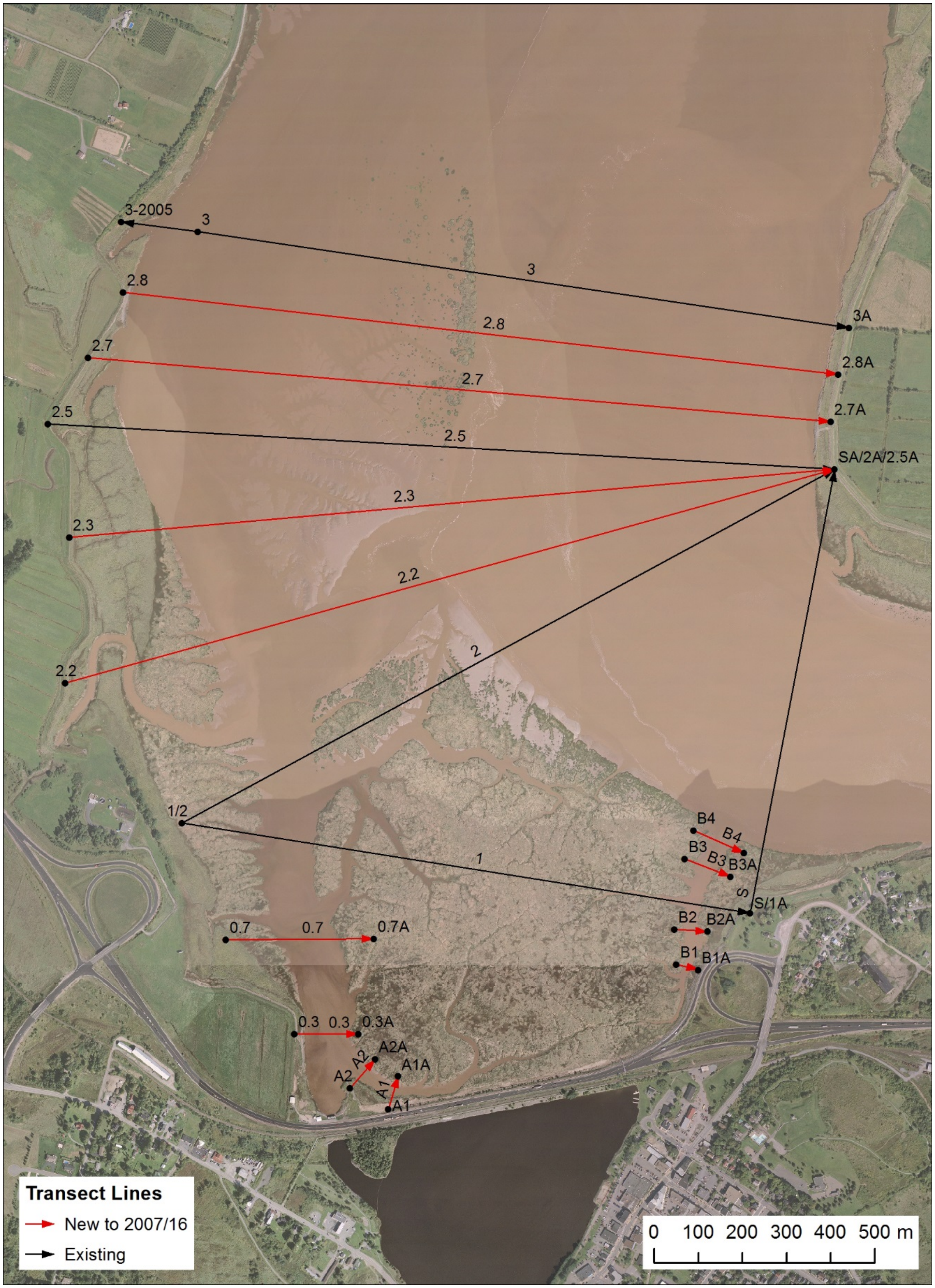

FIGURE 32: RECOMMENDED TRANSECTS FOR MONITORING BASED ON HISTORICAL AND CONTEMPORARY SURVEYS OVERLAIN OVER 2012 IMAGERY (VAN PROOSDIJ AND BAKER 2007).

Habitat and Vegetation

Changes in salt marsh habitat (vegetation) will be quantified using a combination of low-altitude aerial photography and a limited ground-based vegetation survey. Ground survey will be carried out at 1 m^2 veg plots located along the transects identified above, recording species composition, abundance, and height. Additionally, a qualitative vegetation survey will be conducted as part of all on-site activities, with emphasis on the identification of invasive/non-tidal wetland plant species. The presence, identity and location of any species of significance (i.e., salt marsh species representing high marsh development; invasive species) will be noted and mapped.

To map landscape scale change of salt marsh habitat low-altitude aerial photography will be collected annually and used to generate georeferenced orthomosaics and DSMs as previously described. Imagery and DSMs will include the entire salt marsh and mudflat complex and will be used to monitor the extent of vegetation cover, produce landscape scale habitat/surface cover maps, delineate channel network maps, and carry out time change analysis.

Deliverable Products:

- Vegetation Composition, Abundance and Height
- Habitat/Surface Cover Maps
- Delineated wetland area/cover types
- Tidal channels, creeks and open water network
- Additional wetland habitat features, structures, or things of note

Winter Conditions (Ice)

During the winter months, intertidal areas are covered with snow and ice that is rafted in with the tides and stranded on the marsh surface and within the tidal creek channels (Figure 33). This ice is ephemeral in nature and can appear and disappear within only a few tides (van Proosdij, 2005). However, it can also build up within the tidal creeks, altering patterns of flow and erosion/deposition of sediments. These ice blocks contain high concentrations of both sediment and plant rhizome material, which are importance inputs of the salt marsh system (Ollerhead et al., 1999; van Proosdij et al., 2006). In addition, it is not uncommon for coarse material and smaller armour stone to be displaced from the causeway by repeated stranding then re-floating of each ice block. This material is then deposited on the marsh surface in the spring.

As part of the monitoring program to complement the evaluation of habitat conditions conducted during the summer's activities, a structured winter walk (mid-winter) should be conducted in order to document and evaluate winter conditions at the site. Structured walk(s) will include 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.

Winter walks could be also supplemented by remote monitoring (presence/absence of ice) using the existing marsh video camera system (if this is replaced).

Deliverable Products:

- Brief description of site conditions, highlighting ice and snow conditions as well as any areas or issues of concern
- Photo-documentation of habitat conditions

FIGURE 33 RAFTED ICE BLOCKS ON THE WINDSOR MARSH AND METEOROLOGICAL STATION AT THE AVON RIVER CAUSEWAY ON FEBRUARY 24, 2005 (PHOTO BY D. VAN PROOSDIJ)

Thresholds and Adaptive Management

Salt marshes are critical habitat for many fish and bird species, however plant diversity is typically low due to the limited number of species able to thrive on the salt marsh. Furthermore, the majority of the Windsor salt marsh has not reached a mature condition and is dominated by a single species of halophyte, the low marsh cord grass *Spartina alterniflora*. In addition, sedimentation patterns vary both seasonally and annually leading to a higher degree of variability in surface elevation then may be observed in other habitats. For this reason, establishing meaningful thresholds indicative of significant changes which are a direct result of actions taken at the causeway are difficult. Changes in community structure, particularly when combined with changes in elevation or significant alteration of the channel network, may require further investigation. For example, the development of barren areas may be an indication of subsidence/erosion or may be a temporary condition resulting from winter conditions or wrack mats. This type of change would be best understood when examined in conjunction with elevation changes and larger marsh-scale processes.

TABLE 1: PROPOSED MONITORING PROGRAM FOR THE WINDSOR SALT MARSH POST-ALTERATION MONITORING PROJECT.

Category	Parameters	Sampling Method	Annual Sampling Frequency	Monitoring Year						
				Pre	Construction	Post-Restoration				
						Year 1	Year 2	Year 3	Year 4	Year 5
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
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
	Tidal Creek Network	DGPS/GIS; Geo-referenced low-altitude aerial photography	Annually, once per sampling year	X	X	X	X	X	X	X
	Sediment Dynamics	DGPS/GIS; Geo-referenced low-altitude aerial photography; volumetric calculations	Once per required sampling year	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	UAV based camera system	Twice per sampling year (spring,	X		X	X	X	X	X

Category	Parameters	Sampling Method	Annual Sampling Frequency	Monitoring Year						
				Pre	Construction	Post-Restoration				
						Year 1	Year 2	Year 3	Year 4	Year 5
	photography		mid-late summer)							
Vegetation	Composition	Transect based, Point Intercept Method (1 m^2 plots)	Once per sampling year (August)	X		X		X		X
	Abundance									
	Height									
	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-March)	X		X	X	X	X	X

REFERENCES

- Daborn, G.R.; van Proosdij, D. and M. Brylinsky. 2003. Environmental Implications of Expanding the Windsor Causeway (Part One). Report prepared for Nova Scotia Department of Transportation Contract # 02-00026. Acadia Centre for Estuarine Research Publication No. 72. 15 pp.

- Ollerhead, J.; Davidson-Arnott, R.G.D. and A. Scott. 2006. Cycles of salt marsh extension and contraction, Cumberland Basin, Bay of Fundy, Canada. In *Geomorphologia Littoral I Quaternari: Homenarge el Professor V.M. Rossello I Verger.* E. Sanjame (Ed.).

- van Proosdij, D., Daborn., G.R. and M. Brylinsky. 2004. Environmental Implications of Expanding the Windsor Causeway (Part Two): Comparison of 4 and 6 Lane Options. Report prepared for Nova Scotia Department of Transportation Contract # 02-00026. Acadia Centre for Estuarine Research Publication No. 75. 17 pp.

- van Proosdij, D. 2005. Monitoring Seasonal Changes in Surface Elevation in Intertidal Environments near the Windsor Causeway. Final report prepared for the Nova Scotia Department of Transportation 22 pp.
- van Proosdij, D. and S., Townsend. 2006. Spatial and Temporal Patterns of Salt Marsh Colonization Following Causeway Construction in the Bay of Fundy. Journal of Coastal Research, SI 39:1858-1862, ISSN 0749-0208.
- van Proosdij, D; Bambrick, J. and G. Baker. 2006. Spatial and Temporal Variations in the Intertidal Geomorphology of the Avon River Estuary. Final report prepared for the Nova Scotia Department of Transportation 82 pp.
- van Proosdij, D.; Ollerhead, J. and R.G.D. Davidson-Arnott. 2006. Seasonal and annual variations in the sediment mass balance of a macro-tidal salt marsh. *Marine Geology* 225:103-127.
- van Proosdij, D. and G. Baker. 2007. Intertidal Morphodynamics of the Avon River Estuary. Final report prepared for the Nova Scotia Department of Transportation 186 pp.
- van Proosdij, D.; Milligan, T.; Bugden, G. and C. Butler. 2009. A Tale of Two Macro Tidal Estuaries: Differential Morphodynamic Response of the Intertidal Zone to Causeway Construction. Journal of Coastal Research SI 56: 772-776. ISBN 0749-0258.
- Westoby, M.J; Brasinton, J; Glasseu, N.F.; Hambrey, M.J. and J.M. Reynolds. 2012. 'Structure-from-motion' photogrammetry: a low cost, effective tool for geoscience applications. *Geomorphology* 179:300-314.

APPENDIX A - GEOGRAPHIC COORDINATES OF ELEVATION/BATHYMETRIC SURVEYS

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

APPENDIX B - COMPARISON OF TOPOGRAPHIC SURVEYS

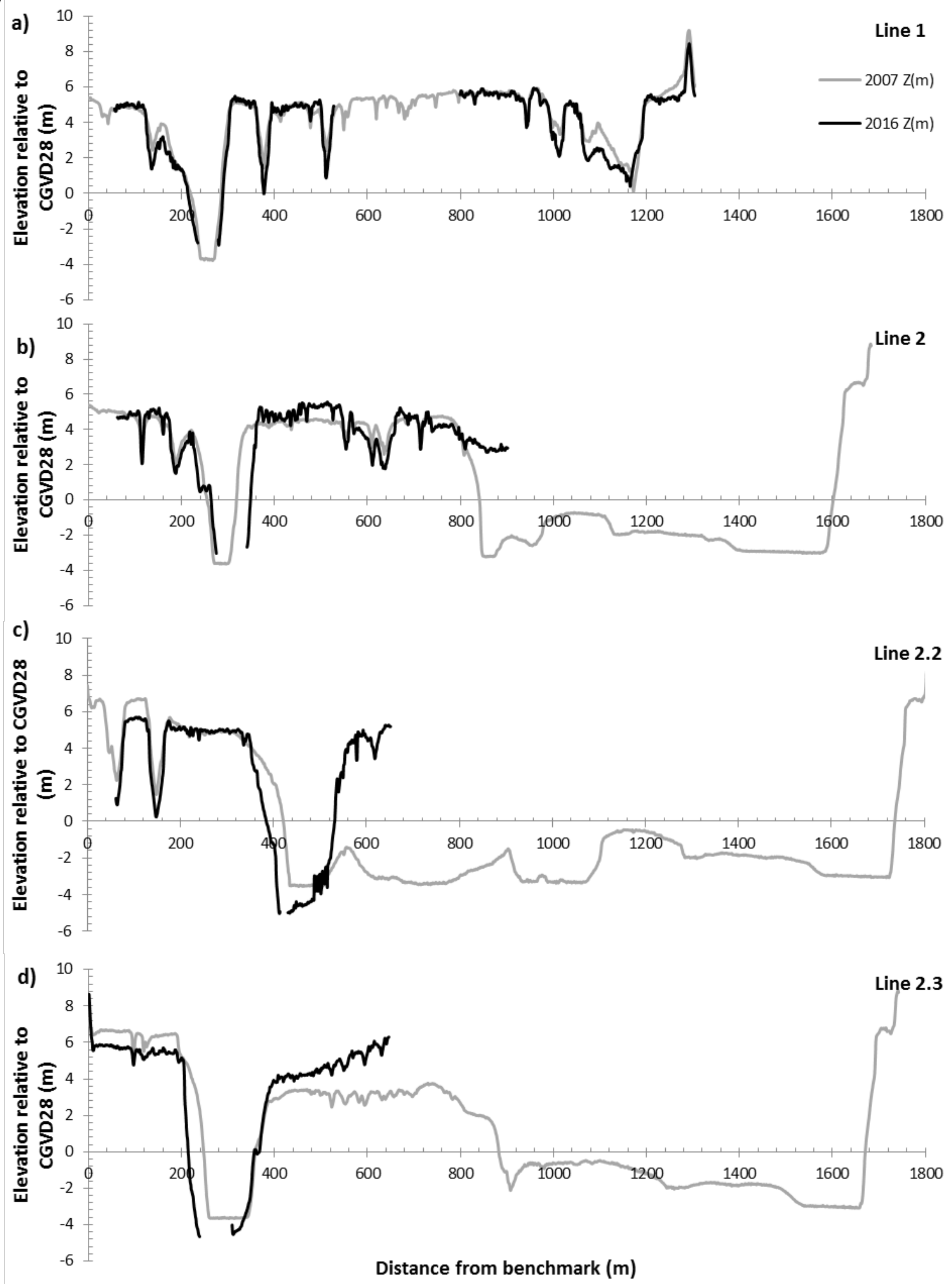

FIGURE 1 COMPARISON OF TOPOGRAPHIC SURVEY LINES EXTRACTED FROM 2007 LIDAR SURFACE AND 2016 NON-VEGETATED UAV DSM FOR LINES A) 1,B) 2,C) 2.2 AND D) 2.3 ILLUSTRATED IN FIGURE 32.

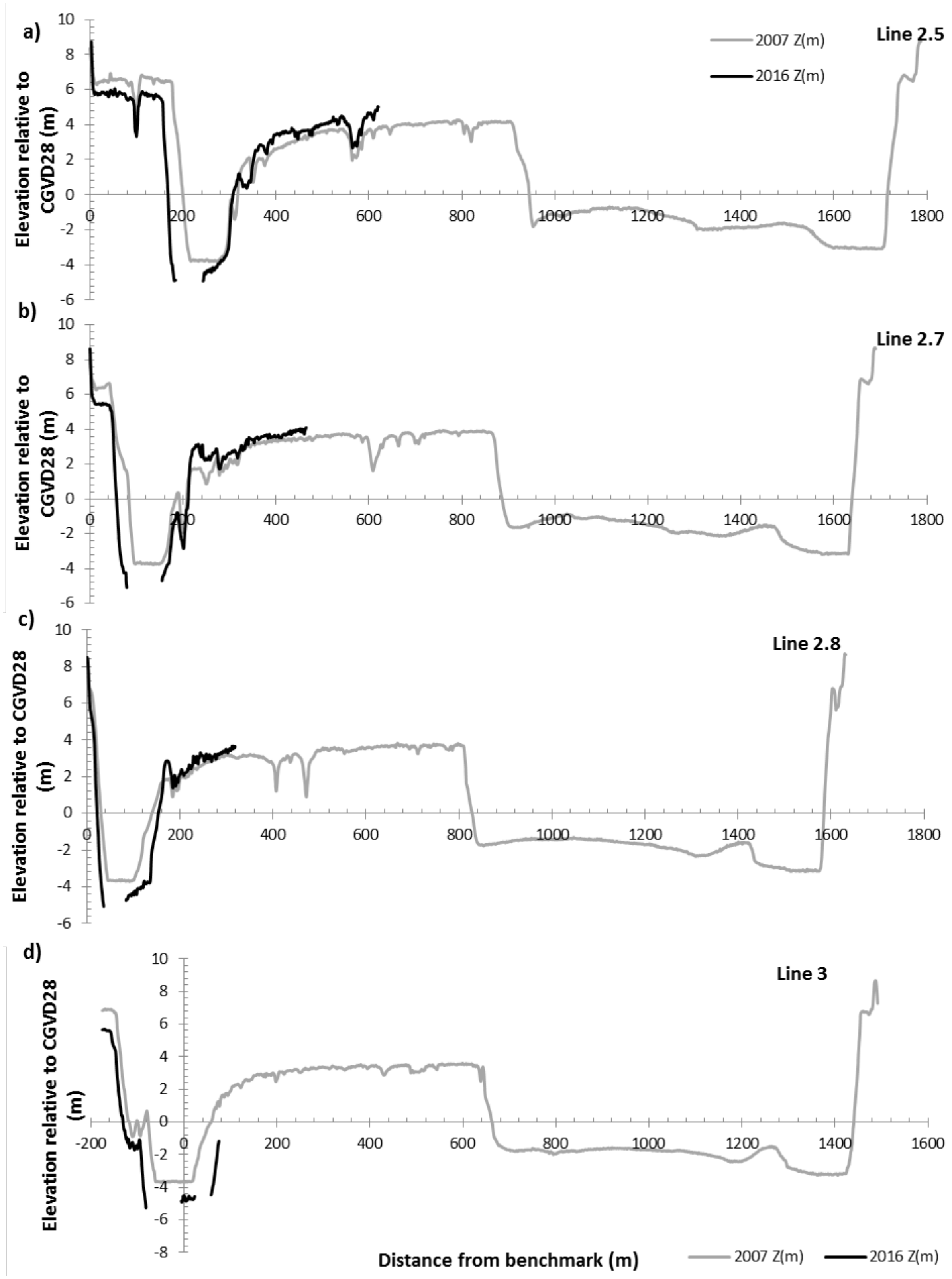

FIGURE 2 COMPARISON OF TOPOGRAPHIC SURVEY LINES EXTRACTED FROM 2007 LIDAR SURFACE AND 2016 NON-VEGETATED UAV DSM FOR LINES A) 2.5, B) 2.7C) 2.8 AND D) 3 ILLUSTRATED IN FIGURE 32.

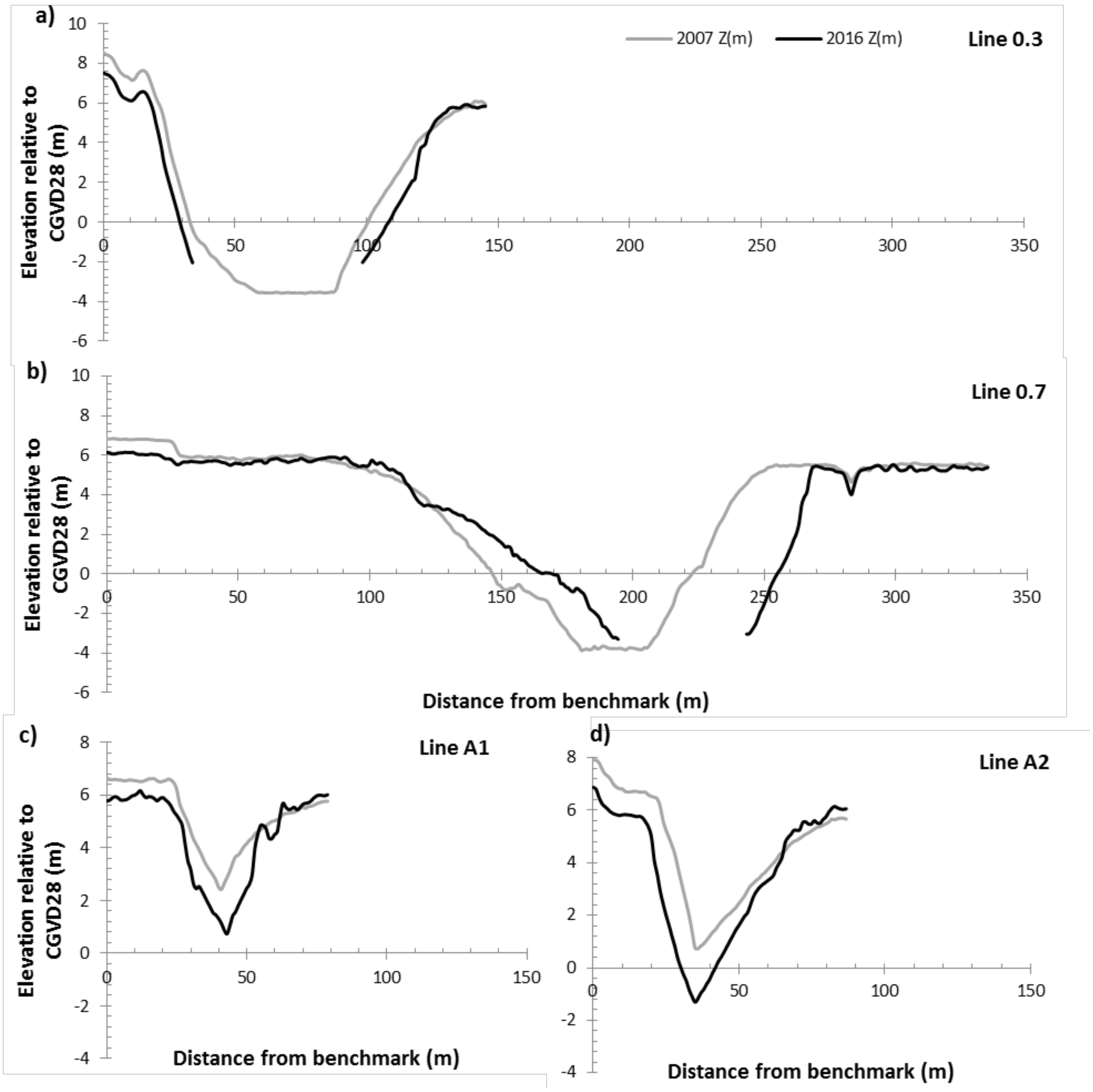

FIGURE 3 COMPARISON OF TOPOGRAPHIC SURVEY LINES EXTRACTED FROM 2007 LIDAR SURFACE AND 2016 NON-VEGETATED UAV DSM FOR LINES A) 0.3,B) 0.7,C) A1 AND D) A2 ILLUSTRATED IN FIGURE 32.

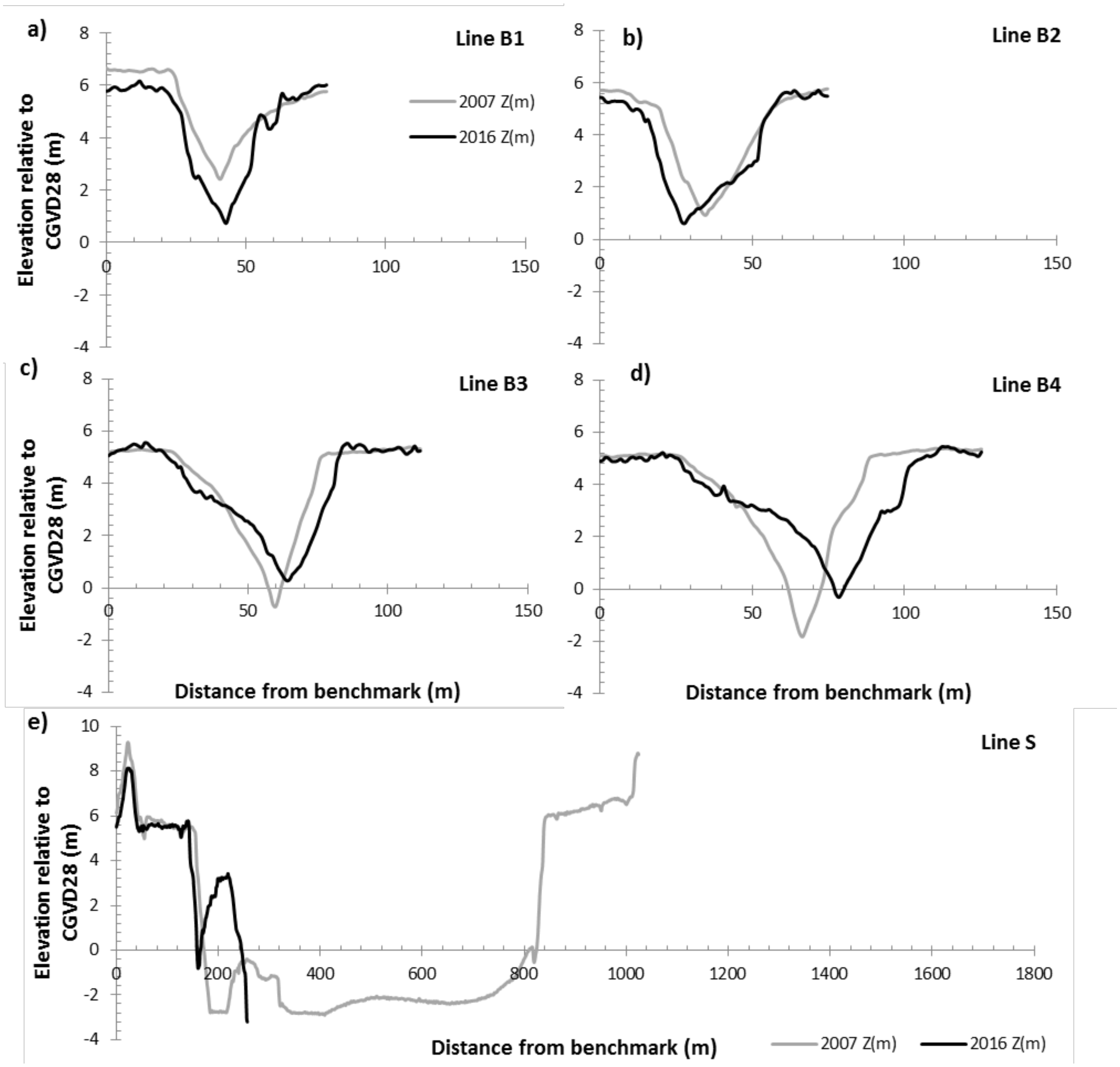

FIGURE 4 COMPARISON OF TOPOGRAPHIC SURVEY LINES EXTRACTED FROM 2007 LIDAR SURFACE AND 2016 NON-VEGETATED UAV DSM FOR LINES A) B1, B) B2, C) B3 D) B4 AND E) S ILLUSTRATED IN FIGURE 32.