Examining Drivers of Ecomorphodynamic Change in the Avon River Estuary

By

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Abstract

The Avon River Estuary is a hypertidal, muddy estuary in the upper Bay of Fundy. The system has been in dynamic equilibrium since construction of the causeway in 1970, but recent construction activities and changes in tide gate management have caused an observable shift to disequilibrium. To assess the environmental consequences of these activities, we examine the relative influence of natural and anthropogenic drivers of ecomorphodynamic change within the Avon River, downstream of the Highway 101 causeway by comparing data from 2019-2023 to baseline conditions, 2007-2019. We hypothesize that system ecomorphodynamics will be strongly influenced by human activities. To evaluate changes in ecomorphodynamics occurring in the system we examined changes in channel cross-sectional profiles, cross-sectional area, changes in surface elevation, volumetric changes, sediment grain size, and vegetated area. These analyses were completed primarily through ArcGIS Pro and Microsoft Excel. We then compared these changes to tide gate manipulation information, construction activities, tidal cycles, and precipitation data to infer what may be influencing the change. Results indicate that there has been a quantifiable change in ecomorphodynamics between the baseline period and the study period. Additionally, most of the notable changes that occurred were concentrated around the Windsor Marsh and the Newport Bar, near the causeway. Based on patterns in natural and anthropogenic influences as well as the locations of changes, we believe that construction has had strong influence on the Avon River Estuary while the St. Croix River is mostly unaffected by anthropogenic interference and precipitation may be the dominant driver of change. While future studies need to be conducted and should be based closer to the causeway, these results provide insight from an environmental assessment perspective into how estuaries experiencing significant anthropogenic interference may respond and adjust.

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Table of Contents

1. Introduction 1
  1.1 Introduction and Rationale 1
  1.2 Dynamic Equilibrium 4
  1.3 Ecomorphodynamics 5
    1.3.1 Dynamic Processes 6
    1.3.2 Morphology 7
    1.3.3 Sediment 7
    1.3.4 Vegetation 8
  1.4 Human Influence 9
    1.4.1 Construction 9
    1.4.2 Aboiteaux and Dyking 10
  1.5 Natural Influence 11
    1.5.1 Water flow 11
    1.5.2 Ice 12
    1.5.3 Vegetation 12
  1.6 Objectives and Research Question 13
2. Study Site 15
  2.1 Study Area 15
    2.1.1 Tides 16
    2.1.2 Sediment 17
    2.1.3 Climate 17
  2.2 History of Anthropogenic Activity 18
3. Methods 21
  3.1 General Approach 21
  3.2 2023 Fieldwork 22
  3.3 Changes in Tidal Channel Morphology 27
    3.3.1 Cross-Sectional Profiles 27
    3.3.2 Cross-Sectional Area 28
  3.4 Changes in Erosional and Depositional Area 29
    3.4.1 Surface Elevation Changes 29
    3.4.2 Volumetric Changes 31

3.5 Grain Size Analysis 31
3.6 Changes in Vegetated Area 32
3.7 Timeline 33
4. Results 34
4.1 Changes in Tidal Channel Morphology 34
4.1.1 Cross-Sectional Profiles 34
4.1.1.1 Avon River Cross-Sectional Profiles 34
4.1.1.2 St. Croix Cross-Sectional Profiles 40
4.1.2 Cross-Sectional Area 43
4.1.2.1 Avon 43
4.1.2.2 St. Croix 47
4.2 Changes in Erosion and Deposition 50
4.2.1 Surface elevation changes 50
4.2.2 Volumetric changes 62
4.3 Grain Size Analysis 66
4.4 Changes in Vegetated Area 69
4.5 Timeline 77
4.5.1 Natural influence 77
4.5.2 Anthropogenic Influence 84
4.6 Ecomorphodynamics Summary 85
5. Discussion 89
5.1 Channel Infilling 89
5.2 Tide Gate Channel Changes 91
5.3 St. Croix River Influence 92
5.4 Vegetation and Sedimentation 93
5.5 Grain Sizes and Sediment Distribution 94
5.6 Implications 95
5.7 Limitations, Recommendations, and Future Work 96
6. Conclusion 99
7. References 101
8. Appendix 110

Table of Figures

Figure 1.1: The Avon River downstream of the Windsor Causeway. Study area is outlined by a black box, the intertidal zone extends approximately 8km downstream of the causeway. 3

Figure 1.2: Connectivity of hydrodynamics, sediment, vegetation, and channel morphology and descriptions of how each factor influences the other. 6

Figure 2.1: Study area extending from the causeway to Newport Landing and into the St. Croix River. Basemap provided by Esri Canada 16

Figure 2.2: Climatograph of average monthly temperatures and monthly total precipitation. Data obtained from Kentville CDA from 2019-2023. 18

Figure 2.3: Excavation of the Windsor marsh on June 22nd, 2020. Photo used with permission from Lachlan Rihel of the Confederacy of Mainland Mi'Kmaq (Appendix A).. 20

Figure 3.1 M9 ADCP attached to a fishing boat to complete the bathymetric surveys along transect lines. 23

Figure 3.2: Locations of GCPs deployed during RPAS. Base image is the orthomosaic collected during RPAS on August 4th, 2023, basemap provided by ESRI Canada... 24

Figure 3.3: Locations of transect lines with predetermined coordinates as well of the locations of sediment samples taken in 2019 and 2023. 26

Figure 3.4: Deep water preventing sediment sampling on the Newport Bar on August 4th, 2023. 27

Figure 3.5: Schematic of calculating wetted area. The HHWMT elevation is used to determine a level vertical maximum. The area is divided into trapezoids (example A, B, C, etc.) and the area of each trapezoid is then calculated and summed to determine total area. 29

Figure 3.6: Zones of study used for elevation and volumetric change. 30

Figure 3.7: Sediment samples dried in aluminum trays then powdered using a mortar and pestle. 32

Figure 4.1: Cross-sectional profiles of the first four transect lines within the Avon River based on surveys done prior to construction, 2005, 2007, and 2017, and during increased human activity, 2019, 2021, 2022, and 2023... 38

Figure 4.2: Cross-sectional profiles of transect lines within the Avon River based on surveys conducted prior to construction in 2005, 2007, and 2017, and during increased human activity in 2019, 2021, 2022, and 2023. 39

Figure 4.3: Cross-sectional profiles of transect lines within the St. Croix River based on surveys conducted prior to construction in 2005, 2007, and 2017, and during construction in 2019, 2021, 2022, and 2023. 42

Figure 4.4: Wetted area of the Avon River, lines closest to the causeway are at the bottom of the figure while lines furthest away are at the top. 44

Figure 4.5: Wetted Perimeter of the Avon River, lines closest to the causeway are at the bottom of the figure while lines furthest away are at the top. 45

Figure 4.6: Avon River cross-sectional width lines closest to the causeway are at the bottom of the figure while lines furthest away are at the top. 46

Figure 4.7: Avon River width/depth rations, lines closest to the causeway are at the bottom of the figure while lines furthest away are at the top. 47

Figure 4.8: St. Croix River profiles. A shows the wetted area of each transect line, B shows the wetted perimeter, C shows the width, and D shows the width/depth ratio. 49

Figure 4.9: Changes of elevation between survey years within Zone 1, nearest the causeway. 51

Figure 4.10: Changes in elevation of Zone 2 covering most of the Newport Bar. 53

Figure 4.11: Changes in elevation within Zone 3 which is the northwestern corner of the study area. 55

Figure 4.12: Elevation change within Zone 4 at the opening of the St. Croix River where it meets the Avon River. 57

Figure 4.13: Elevation change for Zone 5 located in the southeast corner of the study area. 59

Figure 4.14: Elevation changes within Zone 6 located in the northeast area of the study area. 61

Figure 4.15: Muddy midchannel bar at low tide developing within Zone 6 on August 3rd, 2023. 62

Figure 4.16: Location of sediment samples taken in 2019 and 2023. 67

Figure 4.17: Sediment category distribution for both 2019 and 2023. 68

Figure 4.18: Vegetated area across the entire study area during the four years of data collection during the study period. 70

Figure 4.19: Erosion along the eastern edge of the Newport Bar at low tide with blocks of vegetation being eroded on August 4th, 2023. 71

Figure 4.20: Changes in vegetation across the Newport Bar with emphasis on the southeastern channel infilling. Lines 2.5 and 3 are used for reference. 72

Figure 4.21: Changes in vegetation along the northern tip of the Windsor Marsh parallel to the channel along the south of the Newport Bar with Line 2 for reference. 74

Figure 4.22: changes in vegetation along the northern bank of the St. Croix River with Line T for reference. 75

Figure 4.23: Changes in vegetation on the bank of the northwestern corner of the study area with Line 3.5 for reference. 76

Figure 4.24: Tidal cycles and recorded precipitation for 2019. 78

Figure 4.25: Tidal cycles and recorded precipitation for 2020. 79

Figure 4.26: Tidal cycles and recorded precipitation for 2021. 80

Figure 4.27: Tidal cycles and recorded precipitation for 2022. 81

Figure 4.28: Tidal cycles and recorded precipitation from January to August 2023. 82

Figure 4.29: Ice distribution within the Avon River Estuary from 2020-2023. 83

Figure 4.30: Influence of channel infilling from the construction of the twinned highway in 2022 on the cross-sectional profile of Transect Line 1AA1A. 84

Figure 4.31: Notable changes throughout the Avon River Estuary between 2005 and 2023. 87

Tables

Table 3.1: Field work conducted prior to the increase in anthropogenic activity, 2005-2017, and after the start of increased anthropogenic activity, 2019-2023. 22

Table 4.1: Volume change by zone between 2007 and 2017 and approximate yearly change values. 65

Table 4.2: Annual volume changes by zone between 2021 and 2022. 65

Table 4.3: Annual volume changes by zone between 2022 and 2023. 65

Table 4.4: Summary of important changes observed within the Avon River Estuary between 2005 and 2023. 88

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1. Introduction

1.1 Introduction and Rationale

Coastal regions and estuaries around the world are highly susceptible to the impacts of climate change. Predicted effects of climate change include sea level rise, droughts, flooding, increased temperatures, and wildfires, all of which can have noticeable impacts on low lying estuaries (Collins et al., 2007; Cooley et al., 2022; Robins et al., 2016). Primary concerns within an estuary include sea level rise and changes in precipitation patterns as they will alter the fluvial discharge within an estuary therefore impacting erosion and deposition patterns which alters the equilibrium state of the estuary (Du et al., 2023). Atlantic Canada as a coastal region is home to many estuaries which are vulnerable to the impacts of climate change, the Avon River Estuary located in the Southern Bight of the Minas Basin, Nova Scotia is but one example of this.

In addition to impacts of climate change on estuaries, climate change is also affecting large populations of humans that inhabit coastal areas. Increased flooding and erosion can cause damage to infrastructure and severely disrupt day to day activities (Lemmen et al., 2016). As climate change continues to impact infrastructure, the general response is to strengthen existing infrastructure through hard engineering, which has been shown to have adverse effects within the intertidal zones of estuaries (Lemmen et al., 2016). Developing infrastructure, such as dams or bridges, within an estuary has been shown to alter flow velocities as well as sedimentation patterns both upstream and downstream of the structure (Isik et al., 2008). As populations surrounding the coast increase, we can expect infrastructure to increase as well and as a result, vulnerable estuaries will continue to be disrupted.

Estuaries are coastal environments located at the mouth of a freshwater river where there is mixing of salt and fresh water (Pritchard, 1967). This mixing of salt and freshwater leads to density stratification in the water column with the freshwater inputs from the river rising over the denser saltwater. Estuaries are classified based on the dominant hydrodynamic process that is shaping their morphology (Hume et al., 2007). These include river dominated estuaries which exhibit protruding birds foot deltaic morphology, wave dominated estuaries which exhibit a smooth shoreline, and tidal dominated estuaries which exhibit an open funnel shaped morphology at the mouth of the river (Bosboom & Stive, 2021). Tidal ranges are one of the defining characteristics for estuaries. Microtidal estuaries have tidal ranges less than 2 meters, mesotidal estuaries have tidal ranges between 2 and 4 meters, macrotidal estuaries have tidal ranges between 4 and 6 meters, and hypertidal estuaries have tidal ranges greater than 6 meters (Davidson-Arnott et al., 2019). The Avon River Estuary experiences a tidal range of 15m with strong currents and a tidal bore on the incoming spring tide (Desplanque & Mossman, 2004) which are both defining qualities of a tidally dominated estuary (Bosboom & Stive, 2021). As a result, the mouth of the Avon River discharging into the Bay of Fundy exhibits a wide, funnel shape. Due to the large tidal range, the Avon River Estuary has an extensive intertidal zone which spans the entirety of the study area and is exposed twice daily (Figure 1.1). Aerial exposure of the intertidal zone allows for water to evaporate from the sediments creating a layer of resistant sediment that will slow erosion on the incoming tide (Nguyen et al., 2020).

Figure 1.1: The Avon River downstream of the Windsor Causeway. Study area is outlined by a black box, the intertidal zone extends approximately 8km downstream of the causeway.

The Avon River Estuary is just one of many estuaries globally to be affected by climate change and anthropogenic activity. It is our hope that studying this system can provide a base of information that can lead to better informed management of hypertidal estuarine systems. While the effects of anthropogenic activities and natural forces on estuarine ecomorphodynamics have been well documented individually, there is a lack of literature, particularly studies that are focused on Canadian sites, that consider the influence of both at the same time. In addition to filing a knowledge gap, this study aims to provide useful information to aid in environmental and infrastructural decisions. The study of ecomorphodynamic change within the Avon River Estuary will provide useful information to develop an understanding of the relative influence of construction activities and gate manipulations on downstream changes in erosion and deposition patterns which may influence the structural integrity of new causeways, negatively affect fish passage, or increase environmental hazards, such as flooding. Examining how natural and anthropogenic events influence the ecomorphodynamics of the Avon River Estuary will provide important information from an environmental assessment standpoint regarding management of the system.

1.2 Dynamic Equilibrium

Dynamic equilibrium within an estuarine system occurs when the net change of a variable, such as vegetation, volume of sediment, or tidal prism, is zero (Zhou et al., 2017). Understanding dynamic equilibrium is important because it can be used as a measure of how balanced the system is. Due to the nature of estuaries and their fluvial, tidal, and anthropogenic influence, on both a microscopic and macroscopic level, the system can be observably altered. Examples of dynamic equilibrium states at differing levels can be found by examining the dynamics of a singular ripple, and intertidal bar, and an entire channel (Seminara, 2010). A ripple may be advancing across a bar during a flood tide. Considering the ripple alone there has been change, however, when considering the system to be the intertidal bar, there has been no net change. Additionally, an intertidal bar could migrate several meters over the course of a couple months. In terms of the intertidal bar, changes can be quantified, but there is no net change in the cross-sectional area or the quantity of sediment. A system that is in dynamic equilibrium is indicative of a stable system which is able to adjust to stressors in an efficient manner that is dependent on the energy available within the system (Nanson & Huang, 2018). Within an estuary, systems can exhibit differing equilibrium morphology based on if they are more strongly influenced by tides or waves (Z. Hu et al., 2018). Ideal tidal dominated systems will exhibit convex cross-sectional profiles in equilibrium while ideal wave dominated systems will exhibit concave cross-sectional profiles in equilibrium (Friedrichs & Aubrey, 1996 as cited in Hu et al., 2018).

1.3 Ecomorphodynamics

Estuaries are controlled by multiple feedback loops. The most influential inputs are dynamic processes, sediments, morphology, and vegetation (Figure 1.2). Considering all these variables and their interaction, while also quantifying how the estuarine system has changed is the study of ecomorphodynamics, allowing for consideration of the entire system, as opposed to more traditional studies on morphology without considering the effects of vegetation and other biota (Fagherazzi et al., 2005).

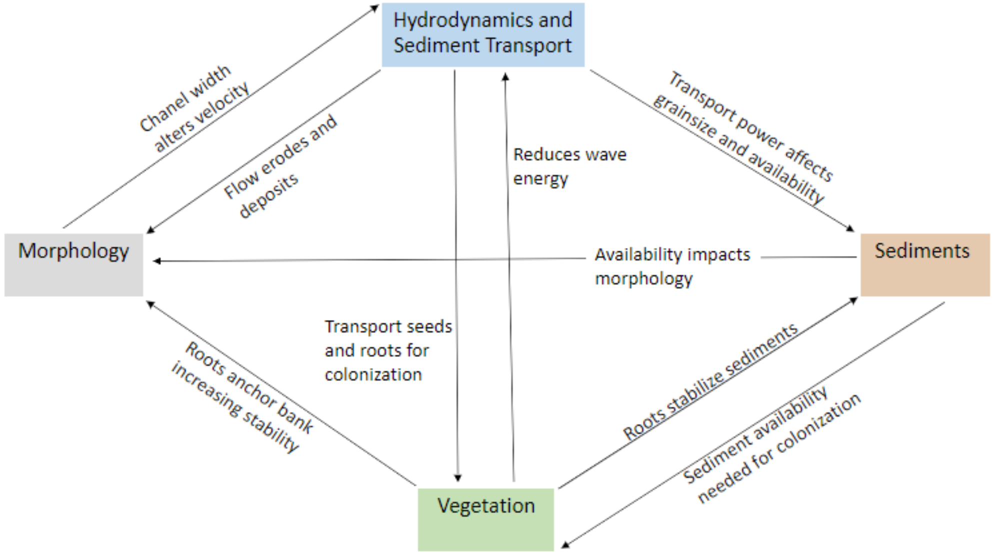

Figure 1.2: Connectivity of hydrodynamics, sediment, vegetation, and channel morphology and descriptions of how each factor influences the other.

1.3.1 Dynamic Processes

Dynamic processes encompass tidal prism and channel flow velocities. These processes are affected by the volume of water within an estuary, channel morphology, and vegetation (Figure 1.2). Morphology impacts dynamic processes as a narrow channel will concentrate the volume of water available resulting in higher flow velocities while a wider channel will spread the volume of water across the wider area resulting in lower flow velocities for a given discharge (Musa & Rusaldy, 2020). Vegetation will act to reduce the flow velocities by providing a greater surface area for the water to interact with. This increases friction and decreases energy (Hickin, 1984; Tambroni et al., 2022). It is important to consider that the extent of the effects of vegetation on velocity will be different from system to system. In rivers that have no tidal influence and water levels remain steady, vegetation that prefers to be constantly submerged can establish in the channel. This produces greater friction compared to an estuarine environment like the Avon River where the bottom of the channel is exposed twice daily, and vegetation is limited to the upper intertidal banks.

1.3.2 Morphology

Morphology is a combination of the shape and topography of the estuary. It is influenced by dynamic processes, vegetation, and sediments (Figure 1.2). Dynamic processes influence the channel morphology by eroding or depositing sediments based on the flow velocity. High velocities tend to erode banks while low velocities tend to encourage deposition of suspended sediment (Earle, 2019). This relationship creates a negative feedback loop since areas where deposition is favoured are wide areas where flow velocity drops, but the deposition of sediment will decrease the cross-sectional area of the channel, therefore increasing the flow velocity, which then has more energy to cause erosion. Vegetation affects morphology by anchoring the bank with roots, making erosion more difficult in vegetated areas compared to non-vegetated areas (Fagherazzi et al., 2020; Feagin et al., 2015; Hickin, 1984). Sediment availability is essential for deposition and infilling, if there is no sediment available, sediment cannot accumulate.

1.3.3 Sediment

Sediments in estuaries are typically composed of a combination of fluvial and marine sediment. The grain size and amount of sediment available in an estuary are dependent on dynamic processes and vegetation. Dynamic processes hold primary control over sediment in the system (Figure 1.2) (Earle, 2019). In areas where flow velocities are low, sediment falls out of suspension and deposition occurs. In estuaries where flow velocities are high across the estuary, sediment will be constantly eroding and may not accumulate anywhere. Dynamic processes also influence the grain size distribution of estuarine systems with high water velocities able to transport larger clast sizes than low flow velocities (Earle, 2019). By identifying areas of the sand flat that have below average grain size, it can be deduced that that area has lower than average flow velocities. The opposite can be said for areas exhibiting a higher than average grain size. Smaller particles would have been stripped from the area leaving behind the less mobile large clasts. Particles of sand can be defined as particles with a diameter between 2mm and 62.5um while silts have a diameter of 62.5um to 4um and clays have diameters less than that (Wentworth, 1922). Vegetation also can impact estuarine sediments by anchoring sediments in place and by attenuating wave energy which encourages deposition (Hickin, 1984; Moskalski & Sommerfield, 2012). As the vegetation creates increased friction, water carrying sediment loses velocity and in turn carrying capacity. This will lead to increased sedimentation in vegetated areas.

1.3.4 Vegetation

Vegetation within an estuary is typically halophytic. The colonization of vegetation is largely dependent on sediments and dynamic processes (Figure 1.2). Sediments are essential for vegetation to establish because the roots need an adequate growing medium. Marine and fluvial sediments are richer in nutrients than bedrock, and the unconsolidated nature is much more root friendly. Without the availability of sediments, vegetation would have a much harder time colonizing new areas of the estuary, and thriving when they did. Dynamic processes impact vegetation within an estuary by providing a method of transportation for seeds and roots (Vogt et al., 2004). These are typically picked up during a high tide when water levels are equal with vegetation and carried by the currents until competence is lost and the seeds and roots are deposited on the banks. Vegetation colonization would still occur without transport via tidal currents; however, the process is much more efficient when aided by dynamic processes and currents.

1.4 Human Influence

1.4.1 Construction

Human influence has been documented to affect morphology of river systems around the world (Blott et al., 2006; Cox et al., 2021; Isik et al., 2008). Examining how construction impacts systems around the world is important because it will act as a reference for what to expect from construction activities surrounding the Avon River. In the Mersey River Estuary, UK, there is a long history of dredging and training wall construction (Blott et al., 2006). Researchers conducted historical trend analyses on estuary bathymetry to quantify changes in the system and then examined the possible causes for these changes. They determined that based on available data, there had not been enough meaningful changes in natural factors so therefore, anthropogenic activity must be the driving factor of change in the system (Blott et al., 2006). In the Sakarya River, Turkey, most of the anthropogenic activity has come from dam and bridge construction, sand mining, and water withdrawal (Isik et al., 2008). They observed that again there were noticeable changes in morphology since the increase in human activity around 1965 (Isik et al., 2008). It was determined that most of the morphological changes were related to suspended sediment concentration and thalweg elevation. Since the construction of dams, the flow in the system decreased and fine sediments filtered out (Isik et al., 2008). Cox et al. (2021) determined that by dredging the Lower Rhine-Meuse delta, sedimentation patterns were being altered. The result of the dredging was an increase in sedimentation due to deeper channels acting as a trap as circulation patterns change (Cox et al., 2021). As construction was occurring in the area, there were brief periods of dredging to make room for the new section of causeway, but the infilling is more permanent. Numerical models run by Wang et al. (2016) suggest that decreasing channel width increases flow velocity, which has been known to increase erosional power, which is opposite to the effect of dredging. It is suspected that areas downflow of the newly infilled section may experience increased erosional rates (X. Wang et al., 2016).

1.4.2 Aboiteaux and Dyking

Dykes were originally constructed by the Acadians, sometime between their arrival in 1604 and their deportation in 1755, to create farmland on the fertile marsh surrounding the Bay of Fundy (Casbourn, 2022). Between 1701 and 1755, Acadian farmland had expanded by 1670 acres in the Grand Pré region due to dyking activities (Bleakney, 2004). The dykes were constructed using a mix of sod and brush. The sods provided a water resistant layer due to their high clay content and were held together by roots penetrating each layer (Bleakney, 2004). The brush packed within the dyke provided stability and prevented slumping, which occurred more commonly when settlers from New England took over the dyking practices after 1755 (Bleakney, 2004). The original aboiteau structures were composed of a hollowed log embedded near the bottom of the dyke which was fitted with a one-way valve to allow for freshwater to escape when large enough quantities were accumulated, but prohibited the flow of saltwater into the farmland (Bleakney, 2004). The modern aboiteau situated within the Highway 101 causeway is constructed similarly, however it contains a mechanically controlled tide gate. Freshwater is drained during the low tide as the gate is open. It is then closed as the tides change to prevent saltwater infiltration and flooding upstream. Under normal conditions, sediment travelling with an incoming tide would be prevented from reaching upstream when it reaches the tide gate, therefore the aboiteau is acting similarly to a dam which contributed to the development of the Windsor March by 1980 (Amos & Mosher, 1985). Changes in how the aboiteau is managed would likely lead to changes in how and where sediment is accumulating. If the tide gate is left open on an incoming tide, sediment is transported upstream, which could result in a change of depositional patterns downstream.

1.5 Natural Influence

1.5.1 Water flow

Natural factors impact channel morphology as well, particularly tides, storms, precipitation, and river discharge (Blott et al., 2006). All these factors work together to alter the dynamic factors of the system, being tidal prism, sediment transport, and bathymetry (Blott et al., 2006). Changes in natural factors will lead to a shift in dynamics as the system seeks to establish an equilibrium state. Altering water inputs, tides, river discharge and precipitation, will have the most influence on the tidal prism. Tidal prism is calculated by P=HA where P is prism, H is water height, and A is area (Jarrett, 1976). By increasing or decreasing the volume of water in a system while leaving the channel area the same, the tidal prism is going to increase which will give it more erosional power based on Bernoulli's equation (1) (Moebs et al., 2016). An increase in the water level in a channel area that remains the same will increase the flow of a river which is the primary erosional force of a river. However, once the channel is eroded, the cross-sectional area of the channel is increased decreasing the water height and the erosional power of the tidal prism. This results in a new system equilibrium. The inverse can happen if water inputs are decreased. The tidal prism would be decreased, decreasing the river's flow, causing sediment to fall out of suspension and decrease the cross-sectional area. Storms have a similar effect by increasing water level and discharge from heavy rainfall events. However, the main erosional forces come not from water levels, but from wave energy. The increased wave energy has a greater capacity for erosion which increases suspended sediment concentrations which are essential for sediment remobilization.

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \tag{1}$$

1.5.2 Ice

As ice is formed on the floor of the intertidal zone, sediments from that zone are incorporated into the ice block and plucked from the intertidal flat. By removing sediments, ice is acting as an erosive agent. The sediments that have been plucked from the bed are transported via ice rafts and subsequently deposited when an ice block melts, meaning that ice is also an agent of deposition (Kempema & Ettema, 2011; Rabinowitz et al., 2022; van Proosdij et al., 2006). Ice has also been documented to alter tidal cycles by reducing the amplitude of the tide through friction (R. Wang et al., 2012). This means that any driving force tides may have on the ecomorphodynamics may be reduced when ice is present. In the Nova Scotian climate, the presence of ice is generally limited to the months between December and early March. The majority of the ice that is present within the Avon River Estuary is formed in upper the intertidal zone in the creeks and channels or freshwater ends of tidal rivers, but as tidal cycles bring water in and out of the estuary, the ice gets transported with the tides outside of the intertidal zone (van Proosdij & Baker, 2007).

1.5.3 Vegetation

Vegetation plays an important role in shaping channel morphology. It has been found that vegetation can influence sedimentary bar formation, alter bank strength, and change flow resistance patterns (Hickin, 1984). It is thought that vegetation holds more influence in smaller channels than large river systems due to scale, so we expect to see less dramatic effects in the main estuary compared to some of the secondary channels (Hickin, 1984). The two main ways vegetation influences channel morphology is through their roots and their frictional properties. Roots act to stabilize the bank by penetrating sediments and holding them in place through a network of entangled roots acting as a screen. This will trap sediments and prevent erosion. Protruding vegetation influences sedimentation by decreasing water energy through increased friction (Vandenbruwaene et al., 2013). As energy decreases, carrying capacity also decreases, forcing sediment to be dropped from suspension. While vegetation does not necessarily affect the initial formation of bars, it does help them to grow at increased rates due to their frictional properties. As vegetation being transported by water gets stuck on a forming bar, it further increases the sedimentation rate by decreasing flow velocities around it, leading to deposition (Hickin, 1984). In addition to bar formation, friction provided by vegetation influences sediment deposition on the high marsh (Vandenbruwaene et al., 2013). Established vegetation will promote sedimentation and increase vertical accretion rates (Bass et al., 2022).

1.6 Objectives and Research Question

This study aims to examine the influence of both natural and anthropogenic drivers of ecomorphodynamic change in the Avon River Estuary after increased human influence on tide gate manipulation and construction activities. Based on the history of anthropogenic interference, two periods have been identified. The first being from 2007-2017, a period of routine human activity which will act as a baseline to determine what defines the ecomorphodynamics within the Avon River Estuary. Studies conducted prior to 2019 have indicated that the system appeared to be in a dynamic equilibrium state with routine gate manipulations and natural processes influencing ecomorphodynamic changes. The study period was identified as a period of increased change in 2019-2023. 2019 was identified as the beginning of the study period because it marked the beginning of the twinning of the Windsor Causeway, which we anticipate will have substantial impacts on the ecomorphodynamics based on previously conducted studies (Blott et al., 2006; Cox et al., 2021; Isik et al., 2008). While the periods have been divided based on anthropogenic change, natural factors will be examined as well. This study is important because it influences reporting on hazards in the area, enhances environmental assessment by providing a new perspective on effects to consider, and it is filling a knowledge gap by utilising improving technologies to inform new ideas concerning drivers of intertidal ecomorphodynamic change. We will complete this study by addressing the following objectives:

1. Compare changes in intertidal ecomorphodynamics from 2019-2023 to baseline (2007-2019) through making qualitative observations and quantifying changes in:
    a. Tidal channel morphology (cross-sectional area, wetted perimeter, width, and width to depth ratios)
    b. Spatial patterns of erosion and deposition
    c. Sediment grain size
    d. Marsh area:
2. Compare intertidal morphodynamics identified in Objective 1 between two periods of differing anthropogenic activities;
3. Compare patterns of natural drivers of change (precipitation and tides) recorded between 2019-2023 to baseline (2007-2019) in the Avon River estuary;
4. Determine the potential relative influence of natural versus anthropogenic drivers of change on spatial patterns of intertidal ecomorphodynamics downstream of the Windsor causeway.

2. Study Site

2.1 Study Area

The study site extends 3.5 km downstream of the Highway 101 causeway and about 1 km from reaching into the St. Croix River (**Error! Reference source not found.**). This area was selected for three main reasons. First, this area corresponds to the maximum area which can be effectively cover by a remotely piloted aircraft during surveying before the tide came back in and the area was covered by water. Second, this area has been studied extensively which resulted provided a rich data set. The quantity of data can help increase the validity of our findings by providing increased confidence in our assessment of spatial patterns. Finally, this area has been identified by previous studies as the area where most of the changes occur (van Proosdij & Baker, 2007). Examining this area in more detail will also provide valuable information on how the system is changing near the causeway which can aid environmental assessments. Embedded in the causeway is an aboiteau which manages the flow of freshwater coming out of Lake Pisiquid, located upstream of the causeway. The current tide gate is controlled mechanically to allow for opening and closure at desired intervals rather than traditional passive aboiteaux which are controlled by a unidirectional sluice gate which allows for freshwater to exit at low tide, but prevents saltwater from entering on a high tide (Bleakney, 2004).

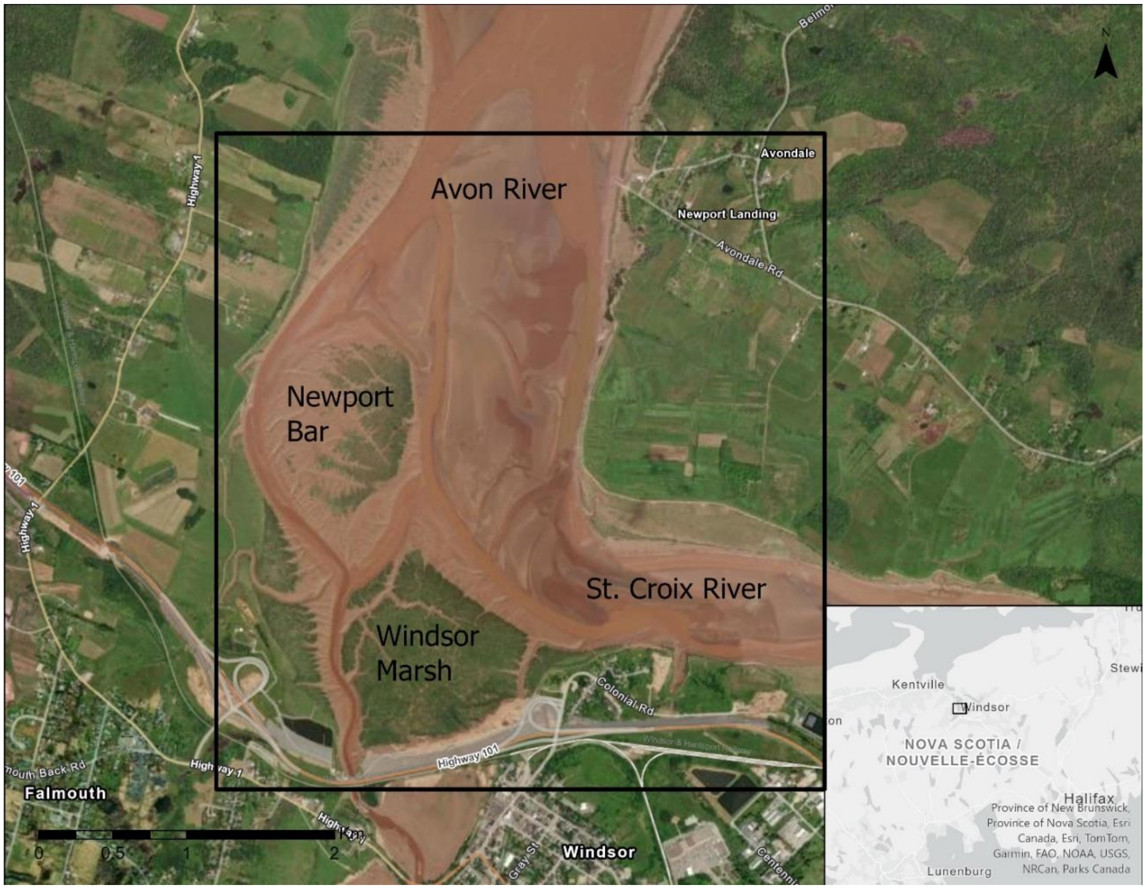

Figure 2.1: Study area extending from the causeway to Newport Landing and into the St. Croix River. Basemap provided by Esri Canada

2.1.1 Tides

The Avon River Estuary passes through Windsor, Nova Scotia. It is part of the Bay of Fundy and has a hypertidal range of approximately 15m (Desplanque & Mossman, 2004). The asymmetric semidiurnal tidal cycle of the Avon River Estuary means that the intertidal zone is exposed twice daily, but at differing levels of exposure (Desplanque & Mossman, 2004). In addition to the asymmetric exposure levels, the Avon River Estuary experiences uneven timing in the flood and ebb tide with the flood tide entering the estuary at a much higher rate than the ebb tide leaves, therefore the system is flood tide dominant (Archer, 2013). During spring tides when the tidal range is exceptionally high, a tidal bore can form as the incoming water forces itself up the river (Lambiase, 1980).

2.1.2 Sediment

Sediment within the Avon River estuary is sourced primarily from Triassic sandstone cliffs surrounding the area, but there are also marine and fluvial inputs (Amos, 1977). Undercutting of the sandstone cliffs paired with cliff recession and a dominant sand composition of the intertidal flats support the theorized sediment source (Amos, 1977). Studies have shown that grain size decreases moving upstream away from the mouth of the estuary (Pelletier & McMullen, 1972). Since the fluvial and marine sedimentary inputs must travel long distances carried in suspension with decreasing energy and carrying capacity, it is likely that the silts and clays within the estuary are sourced from either marine or fluvial sources rather than from the sandstone cliffs (Amos, 1977).

2.1.3 Climate

The Avon River Estuary is located in Nova Scotia near the coast. Nova Scotia has a temperate climate which is characterized by average temperatures around 0^{o}C in the coldest months, and average temperatures around 22^{o}C in the warmest months (SKYbrary, n.d.). Because it is also located in a coastal region, the water also acts to stabilize temperatures as it acts as a heat sink, cooling slower in winter compared to land masses and warming slower in summer (Proximity to Water Bodies, n.d.). Precipitation in temperate regions is characterized by predominantly rain, however snowfall is occasional in winter months (SKYbrary, n.d.). Using data from the Kentville weather station (Kentville CDA CS) for the years 2019-2023, climate information for Windsor Nova Scotia was complied to create a five-year representation of temperature and precipitation patterns (Figure 2.2). The maximum average temperature was 20.45^{o}C in July while the minimum average temperature was -3.39^{o}C in February. Total precipitation peaked in September with minimum precipitation occurring in March and May. Based on these characteristics, the area is described as type Dfb based on the Köppen Climate Classification system (Arnfield, n.d.).

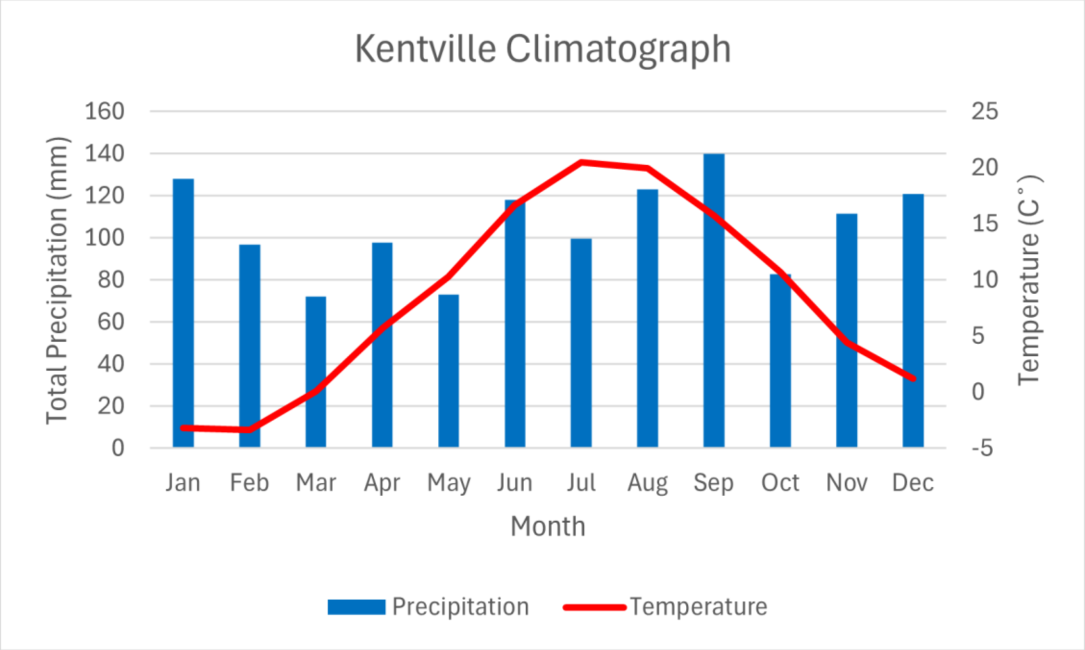

Figure 2.2: Climatograph of average monthly temperatures and monthly total precipitation. Data obtained from Kentville CDA from 2019-2023.

2.2 History of Anthropogenic Activity

The history of anthropogenic activity in the Avon River Estuary began with the Acadians as they began dyking to create farmland in the 1600s (section 1.4.2) (Bleakney, 2004). The construction of the Highway 101 causeway in 1970 had a significant impact on the ecomorphodynamics of the estuary, completely altering sedimentation patterns water flow, and vegetation (van Proosdij & Baker, 2007). Once construction on the causeway was completed, a mudflat began forming on the downstream side of the causeway and vegetation colonization started by 1981 (van Proosdij & Townsend, 2004). Today, this is known as the Windsor Marsh (**Error! Reference source not found.**). After the establishment of the main platform of the Windsor Marsh, the estuary reached a dynamic equilibrium. Downstream of the study area, Fundy Gypsum was shipping their product out of Hantsport. To accommodate the large ships, dredging needed to be conducted. While there are no available records on when this was done or how much was removed, the company was closed in 2011 and no dredging has been conducted since then (CBC News, 2011).

Changes in the system have been monitored extensively in the past to inform the Nova Scotia Department of Public Works of potential dangers their highway may face, but also for environmental assessment purposes. Extensive research and monitoring has been done within the Avon River estuary since the construction of the causeway which included bathymetry, sediment, vegetation sampling, and aerial photography (Desplanque & Mossman, 2004; Lambiase, 1977, 1980; van Proosdij et al., 2020; van Proosdij & Baker, 2007; van Proosdij & Townsend, 2004). From the 1970s to 2019, a period of dynamic equilibrium was established as shown by a stable sediment budget and cross-sectional areas of channel profiles (van Proosdij et al., 2020; van Proosdij & Baker, 2007). During that time, there was minimal human influence on the estuary, relatively speaking, with the aboiteau gate being managed on regular intervals to accommodate tidal cycles and prevent flooding in the town of Windsor. Construction activities in the area were also minor and included regular maintenance activities.

Since 2019 however, there has been a shift towards increased anthropogenic activity (section 1.5). In 2019, construction activities increased as the Department of Public Works started to twin Highway 101 from Three Mile Plains to Falmouth. The new highway extended onto the Windsor marsh which meant that dredging and subsequent infilling was required to build a stable foundation (Figure 2.3). Both the dredging and infilling affected the channel morphology, by increasing the channel cross-sectional profile, then decreasing it. In addition to increased construction activity, the management of the tide gate was altered on March 19, 2021 when the Department of Fisheries and Oceans (DFO) issued a Ministerial Order (Palmeter, 2021). This called for the aboiteau gate to be opened constantly on outgoing tides and for at least ten minutes on incoming tides to allow for adequate fish passage in accordance with the Federal Fisheries Act. This action was also to provide an opportunity to end the mass die-off events that were occurring downstream of the causeway when the tide retreated (Government of Canada, 1985). This

Ministerial Order was in effect for two years which may have been long enough to alter the equilibrium state of the estuary. In June of 2023, the 2021 DFO Ministerial Order was overturned by a provincial Ministerial Order which required the aboiteau gate to be closed and returned to its original operating schedule (Government of Nova Scotia, 2023). This was because Nova Scotia was in a State of Emergency due to extensive wildfires, however, the order was extended despite a lack of risk of wildfires and remains in place at this time (Gorman, 2023). These continuous changes in regulation associated with the aboiteau will likely impact the ecomorphodynamics of the Avon River.

Figure 2.3: Excavation of the Windsor marsh on June 22nd, 2020. Photo used with permission from Lachlan Rihel of the Confederacy of Mainland Mi'Kmaq (Appendix A).

3. Methods

3.1 General Approach

The methods for this study include field data collected jointly by Saint Mary's University and CBWES Inc, as well as laboratory analysis and is a part of a long-term monitoring project funded mainly through Nova Scotia Department of Public Works. This program consists primarily of bathymetric surveys, remotely piloted aircraft surveys (RPAS) or light detection and ranging (LiDAR) surveys, and sediment sampling. Collection of bathymetric and RPAS data is done once a year on a semi-annual basis, depending on circumstances, such as personnel and equipment availability as well as tidal and weather conditions. Bathymetric and RPAS data were used to create cross-sectional profiles along pre-determined transects established prior to 2005 that extend downstream of the causeway to the mouth of the Avon River, and into the St. Croix River (Appendix B). This thesis will consider lines R through 4 (Figure 3.3). In addition to bathymetric and RPAS data, sediment samples were collected in 2019 to aid CBCL Engineering Ltd in developing hydrodynamic and sediment transport models in the Avon River Estuary (van Proosdij et al., 2020). Data collection dates can be found in Table 3.1 and details of historical analyses can be found in van Proosdij et al., 2020; and van Proosdij & Baker, 2007. This thesis includes field data collected jointly by Saint Mary's University and CBWES Inc. in 2023 which consists of bathymetric surveys, RPAS, and sediment sampling which are then compared to data collected in previous years. Field work was always conducted during high spring tides to maximize exposed surface during low tide, and submerged area during high tide. Maximizing the areas that are exposed during low tide and covered during high tide allows for a greater area to be surveyed by RPAS and bathymetric survey. Following field collection, data is analysed using GIS software and used to create volume and surface elevation change models, as well as cross-sectional profiles. Sediment samples are processed in a laboratory setting to analyse grain size while changes in vegetation and position of channel thalweg are noted through qualitative observations.

Table 3.1: Field work conducted prior to the increase in anthropogenic activity, 2005-2017, and after the start of increased anthropogenic activity, 2019-2023.

	Preconstruction			Postconstruction			
	2005	2007	2017	2019	2021	2022	2023
Bathymetry	Dec 4th-5th		Dec 4th-5th	Aug 13th-15th	Oct 6th-8th	Completed	Aug 4th
RPAS				Jul 7th, Aug 8th	Nov 4th	Sep 12th	Aug 4th
LiDAR	Jul 12th	Apr 3rd		Jun-Jul			
Sediment				May 23rd-Aug 7th			Aug 3rd-4th

3.2 2023 Fieldwork

Fieldwork for the 2023 dataset was conducted August 2nd – 4th. It was broken up into three main tasks, bathymetric surveys, RPAS, and sediment sampling. Bathymetric surveys were conducted on all three days during high tide using a SonTek RiverSurveyor M9 Acoustic Doppler Current Profiler (ADCP) which has a reported accuracy of 0.5cm. This was mounted to a board which was attached to a fishing boat piloted by Darren Porter, a local fisher familiar with the area (Figure 3.1). The fishing boat provided stability and guided the M9 ADCP along targeted transect lines which were predetermined from historical surveys. The setup was calibrated according to the SonTek RiverSurveyor M9 ADCP manual (SonTek, 2011), and offsets were manually entered into the Hypack processing software to account for the difference in elevation between the Leica Geosystems GS18T global navigation satellite system (GNSS) unit and M9 ADCP unit (Appendix C). The survey lines from previous studies were uploaded to a Garmin GPS prior to entering the field. The M9 ADCP was connected to a Leica Geosystems GS18T GNSS unit via a custom-made splitter cable which allowed for connection from the M9 ADCP and GNSS unit to the Hypack processing software using Bluetooth. During data logging along transect lines, GPS coordinates as well as depth from five acoustic beams were measured and recorded in the Hypack software.

Figure 3.1 M9 ADCP attached to a fishing boat to complete the bathymetric surveys along transect lines.

RPAS were conducted on August 4th when there was minimal cloud cover and wind, while at low tide. The flight was conducted by Greg Baker from MP_SPARC (SMU) and Sam Lewis from CBWES Inc., who are both certified with advanced RPAS certification from Transport Canada. The flight was conducted simultaneously using a DJI Matrice 300 with real-time kinematic (RTK) positioning. One pilot was responsible for flying the north half of the study area, the other for flying the south half. This was done to maximize efficiency and area covered before the tide came in. The flight was conducted at 120m above ground with a 68% side overlap and an 80% front overlap. The images collected were used to create a study area orthophoto and digital surface model (DSM) with a ground resolution of 4cm. Before the flight occurred, 15 ground control points (GCPs) were deployed on the bed of the river and the dykes. Their location was the marked with a Leica Geosystems GS18T GNSS which has an accuracy of up to 5.1cm and a reliability of up to 99.4% (Luo et al., n.d.) (Figure 3.2). The coordinates measured with the Leica Geosystems GS18T GNSS unit were used as validation points when processing to correct any distortion in imagery.

Figure 3.2: Locations of GCPs deployed during RPAS. Base image is the orthomosaic collected during RPAS on August 4th, 2023, basemap provided by ESRI Canada.

Sediment sampling was conducted on August 3rd and 4th during low tide for maximum sediment exposure, and to make sure that people on the riverbed did not get stuck in an unsafe position on a rising tide. Field teams were divided into two groups so that everyone had a partner. Everyone was equipped with high visibility vests and life jackets, and each group carried a walkie talkie which was connected to the teams conducting RPAS on the marsh in accordance with safety protocol. Before conducting field work, coordinates of samples collected in 2019 were uploaded to a Garmin GPS. Sampling locations were adjusted in the field based on accessibility since some sample locations had been eroded, particularly those located on the Newport Bar, while others were not safe to access due to deep water (Figure 3.4). Once a sampling location was reached, the coordinates of the sample were recorded using a Leica Geosystems GS18T GNSS surveyor and field notes correlated sediment names on the sample bottles to point names stored in the Leica Geosystems GS18T GNSS unit database. A 250ml Nalgene bottle was filled approximately three quarters full of sediment that was scrapped from the surface layer of the riverbed. Five sample locations from 2019 were not able to be resampled in 2023 due to safety concerns, but eight new locations located near transect lines were added in 2023. This resulted in an overlap of six samples between the two sampling periods.

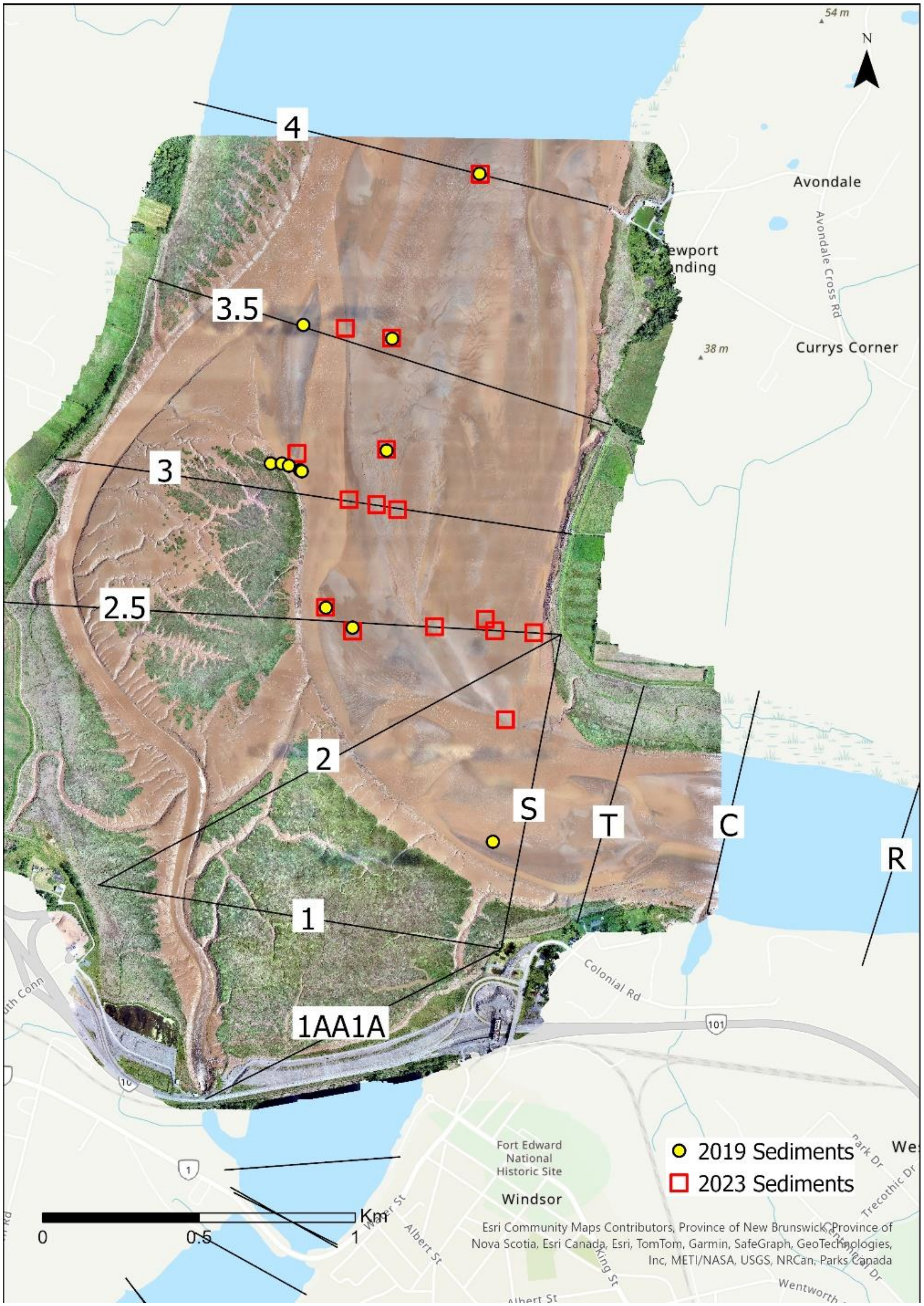

Figure 3.3: Locations of transect lines with predetermined coordinates as well of the locations of sediment samples taken in 2019 and 2023.

Figure 3.4: Deep water preventing sediment sampling on the Newport Bar on August 4th, 2023.

3.3 Changes in Tidal Channel Morphology

3.3.1 Cross-Sectional Profiles

Channel cross-sections were constructed using RPAS and bathymetric survey data. The RPAS data containing orthophotos and elevation data was uploaded into ArcGIS Pro version 3.1.2. First, elevation points that were associated with areas that were covered in water at the time of the survey were removed by creating polygons around the standing water. This was done because the LiDAR beams from DJI Matrice 300 cannot penetrate water, so the resulting elevations would be incorrect. The water polygons were then converted to a raster using the 'polygon to raster tool' in order to merge them with other raster layers in following steps. Bathymetric and RPAS data points were selected based on their proximity to the determined transect lines. RPAS data was the preferred source for elevations due to the higher resolution of data points, however bathymetric data was used where RPAS data was unavailable, like in standing water and beyond the edges of the RPAS. Elevation and coordinate data were exported to Excel where they were plotted and manually cleaned. Elevation points that were determined to be outliers due to unrealistic vertical positions, often well within the water column, were removed manually. These could have been several possible objects that prevented the RPAS or M9 ADCP beams from reaching the bottom of the riverbed such as fish, floating debris, or trees growing on the edge of the bank. Cross-sections from 2023 were plotted against cross-sections from previous surveys to examine changes in cross-sectional area.

3.3.2 Cross-Sectional Area

Once cross-sectional profiles were completed, each line was exported to an Excel sheet with customized scripts which calculated the wetted area (sum of the segmented areas), wetted perimeter (sum of the wetted segments), cross-sectional width (sum of the distance between wetted segments), and the width/depth ratio (width divided by maximum depth). First, a three-point running average was conducted to smooth out any noise in the data. These horizontal distances and bottom elevations of the smoothed data was then used with a higher high water mean tide (HHWMT) value of 5.26m based on values from CHS Hantsport-00282 in 2005 relative to CGVD2013 to calculate the area of a small trapezoid between two given horizontal distances and their corresponding elevations (Figure 3.5). The HHWMT value was selected as opposed to the higher high water low tide value because the HHWMT value encompasses more area and is more representative of average conditions. The calculation of area between the end points of a cross-section below 5.26m corresponds to the wetted area of a cross-section. Negative values occurred in segments that had an elevation greater than 5.26m and were then removed for the calculation of wetted perimeter. Wetted perimeter was calculated by finding the distance along the riverbed below the HHWMT level of the 5.26m. The width was calculated based on the distance between banks at the water line based on the HHWMT level of 5.26m. The width was then used along with the maximum depth to create a width/depth ratio which helps determine the general shape of a cross-sectional profile and how that is related to the area. In general, high ratios indicate a wide and shallow cross-section while low ratios indicate short and deep cross-sections.

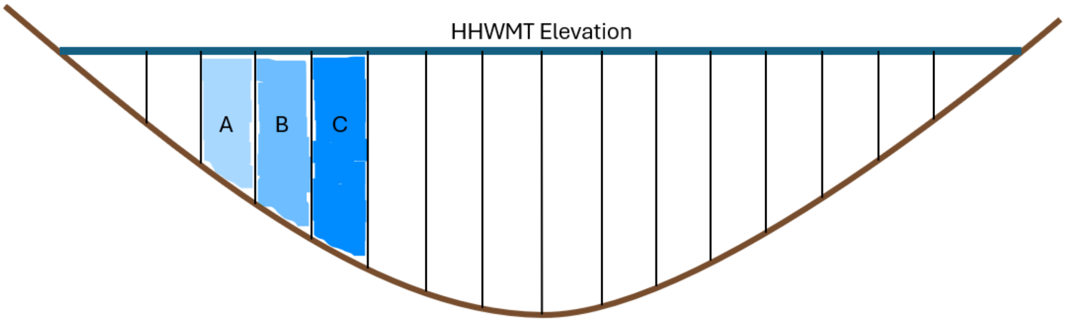

Figure 3.5: Schematic of calculating wetted area. The HHWMT elevation is used to determine a level vertical maximum. The area is divided into trapezoids (example A, B, C, etc.) and the area of each trapezoid is then calculated and summed to determine total area.

3.4 Changes in Erosional and Depositional Area

3.4.1 Surface Elevation Changes

Digital surface models (DSM) were created by first using ArcGIS Pro version 3.1.2. DSMs record the top of the surface which means that vegetation height is included in the reported elevation changes. The intertidal area was isolated by removing any elevation greater than 7.425m, which was determined during previous studies to be the maximum elevation of interest which corresponded to the base of a dyke, from the orthophoto. The area of interest was then converted to a polygon using ‘raster to polygon’ to easily remove any outliers of elevation points outside the intertidal area which may have presented as being lower than 7.425m. The remaining polygon was then converted back to a raster using ‘polygon to raster’. The areas of standing water were again eliminated by using the water polygon described in section 3.3 by creating null values where the water intersects the orthophoto. Elevations for the most recent year were subtracted from the previous year to obtain a change in elevation from year to year. Changes were mapped and assigned a colour value based on the amount of change. These categories included gains and losses of greater than 5m, between 1m and 5m, between 0.15m and 1m, and no detectable change which included changes between 0.15m lost and 0.15m gained. Zones of elevation change as determined in previous studies were divided into six change zones to allow for analysis in higher resolution (Figure 3.6).

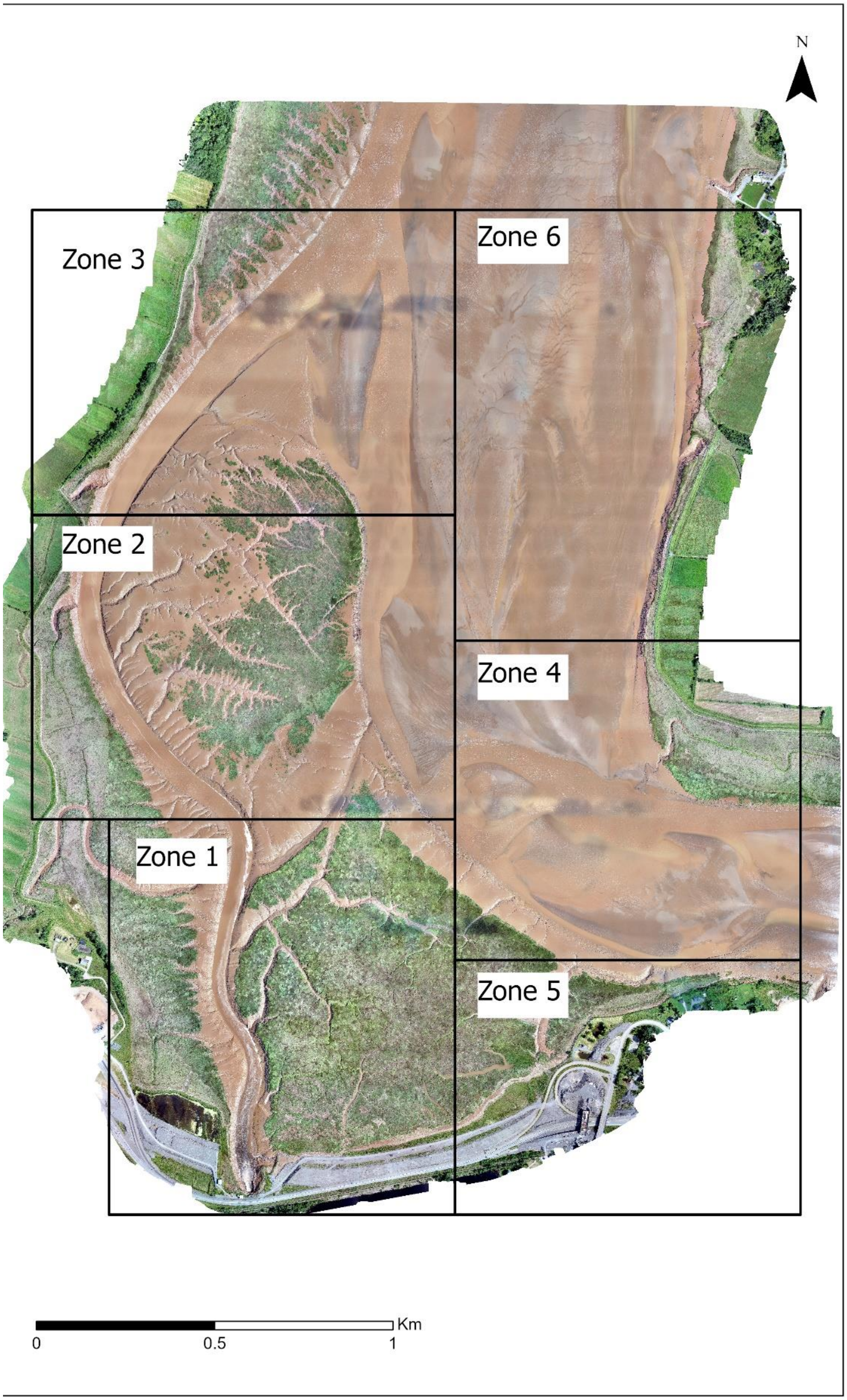

Figure 3.6: Zones of study used for elevation and volumetric change.

3.4.2 Volumetric Changes

Volumetric changes were calculated using the 'cut fill' tool. The area was once again divided into the six change zones where the volume gained, and volume lost were calculated (Figure 3.6). The volume gained and lost were converted to percentages to better compare changes between multiple years. The total changes were calculated by adding the volume of sediment gained with the absolute value of the volume of sediment lost ($TC = volume\ gained + volume\ lost$). Net changes were calculated by subtracting the volume gained from the volume lost ($NC = volume\ gained - volume\ lost$). Negative values indicate a loss of sediment while positive values indicate a gain in sediment. The values of net change are used to determine balance within the system while values of total change are used to determine the movement of sediment in the system.

3.5 Grain Size Analysis

Grain size analysis was completed by first drying the collected sediment in an Isotemp oven at 45^{o}C for at least five hours in washed aluminum trays. Sediments were then lightly ground with a mortar and pestle (Figure 3.7). Once the sediments were prepared, the initial weight of each sample was recorded to the nearest hundredth of a gram. Sediments were then sieved at half phi intervals using a vibrating sieve stack for ten minutes (Blott & Pye, 2001). The largest sieve was -1Φ and the smallest was 4Φ, everything smaller was collected in the bottom pan. After the ten minutes, sediment within each sieve was weighed and recorded. The final weight of the entire sample was measured and compared to the final weight. The initial weight, final weight, and weight within each individual sieve was entered into Gradistat which delivered information on sieving error, textural group, mean grain size, sorting, skewness and kurtosis (Blott & Pye, 2001). Data from 2023 was compared to data from samples taken during field work conducted in 2019.

Figure 3.7: Sediment samples dried in aluminum trays then powdered using a mortar and pestle.

3.6 Changes in Vegetated Area

Changes in the vegetated area were based on qualitative observations due to time constraints. Observations were made by uploading orthophotos from 2019-2023 in ArcGIS Pro version 3.1.2 and overlaying one year with the next year. The ‘flicker’ tool was then used to determine if there had been any change to the vegetation in the area. Changes that were looked for included a decrease in vegetation within an area, an increase in vegetation within an area, changes in the distribution of vegetation, or the establishment of vegetation in a new area. Since changes in vegetation were at a much finer scale than changes in surface elevation, areas of change were not confined to the same six zones of change identified in section 3.4.1. Instead, much smaller areas of change were identified based on qualitative observations such as increased, decreases, thickening, or thinning of vegetated area.

3.7 Timeline

The timeline of possibly influential events was constructed based on known gate manipulations, tide data, precipitation data, available construction information, and Sentinel-2 imagery. Satellite photos from Sentinel-2 were used to observe ice distribution within the estuary in the winter. These images were downloaded from Copernicus Open Access Hub. Images had a 10m resolution and were selected based on minimal cloud cover and presence of ice, regardless of tide level. Precipitation data was collected from the Kentville weather station (Kentville CDA CS), while tidal maximums and minimums were collected from predictions based on the Hantsport tidal station (Hantsport 00282). These were both then plotted to determine patterns precipitation and tidal cycles through the year. Information on tidal gate manipulations and construction activities was gathered using a combination of news articles and RPAS orthophotos.

4. Results

4.1 Changes in Tidal Channel Morphology

4.1.1 Cross-Sectional Profiles

4.1.1.1 Avon River Cross-Sectional Profiles

Line 1AA1A is the closest transect line to the causeway located within the Avon River (Figure 4.1a). It was not surveyed in 2017 but has been surveyed both before and after the construction of the twinned highway (Table 3.1). The newly constructed highway can be seen crosscutting the transect line where the deepest channel was before 2022. After the newly twinned highway was established and this western channel was filled, the deepest point in the channel within the cross-section was the eastern channel, in the same location as the position of the thalweg in 2007 (Figure 4.1a). Transect Line 1AA1A is located primarily across the Windsor Marsh, so elevation changes that are derived from RPAS data are highly influenced by changes in vegetation height, rather than erosion and deposition of sediments as seen with transect lines that cross mostly riverbed (Figure 3.3). These changes in vegetation height can be seen through the middle of the cross-section as elevation is highly variable over short distances within a single survey period and changes slightly from year to year (Figure 4.1a).

Line 1 is again located across the Windsor Marsh and exhibits the same pattern of vegetation elevation change as Line 1AA1A (Figure 4.1b). This transect line intersects the channel created from water discharging from Lake Pisiquid through the tide gate, which is about 220m away from the east survey stake (Figure 3.3). Within this channel, the most change occurred in 2017 where the channel deepened by about 2.5m between 2007 and 2017. In 2019, the channel depth had returned to an elevation of about -4.5m CGVD2013 where it has remained since. Channels within the Windsor Marsh have remained in approximately the same location from 2005-2023 with slight fluctuation from east to west and elevations remaining within a meter. Although much of the change in elevation across the marsh can be attributed to changes vegetation height, between 2007 and 2017 there was greater than 1m of elevation gain which can likely be attributed in part to an increase in sediment as opposed to an increase in vegetation height. The most eastern channel of the marsh has seen the most changes within Line 1. It reached its deepest point in 2007, followed by a substantial infilling event in 2017 which narrowed the channel. In 2019, the channel widened again, but retained the same maximum depth as 2017, where it has remained.

Line 2 is located on an angle which intersects the channel created from tide gate discharge as well as where the St. Croix meets the Avon River (Figure 3.3). Changes within the sluice gate channel are much more pronounced than changes observed closer to the gate in Line 1 (Figure 4.1c). The channel depth has greater changes on a survey-to-survey basis as opposed to in Line 1 where most of the changes occurred in 2017. Between 2007 and 2017, the channel shifted about 20m towards the east. Across the Windsor Marsh, there has been an elevation gain of about 2m between 2005 and 2023 which includes a change in vegetation height, so sedimentation is lower. Between 2007 and 2017, there was an increase in elevation of about 1m which was followed by a stable elevation with fluctuations in vegetation height until 2022 when about another meter of elevation was gained. Along the bank where the Avon River meets the St. Croix on the eastern edge of the line, there has been substantial change between 2005 and 2023. Between 2007 and 2017, there was 180m of lateral deposition. This new area was deposited at the same elevation as the Windsor Marsh and remained at this elevation, despite an increase in elevation on the Windsor Marsh in 2022. However, in 2022, approximately 30m which was followed by another 10m was laterally eroded from the St. Croix bank, which occurred at the same time as elevation was increasing on the Windsor Marsh.

Line 2.5 is the first transect line to cross the Newport Bar (Figure 3.3). Between 2007 and 2017, the western edge of the channel which connects to the sluice gate shifted further west due to erosion while the eastern edge of the channel experienced some infilling (Figure 4.1d). On the Newport Bar, most of the change is concentrated on the western edge, with both lateral and vertical growth. Between 2005 and 2023, there was a total of about 3m vertical growth, including changes in vegetation height. Based on the variation in elevation on top of the Newport Bar, it appears that vegetation is spreading further west between 2005 and 2023. The position of drainage channels on top of the bar remains the same from 2005 to 2023, however, the channels appear to be deepening. The absolute depth remains very close from year to year, however vertical accretion exaggerates the channel depths. Observing the changes in the bank position from survey to survey, the Newport Bar appears to be migrating west across transect line 2.5 from 2019-2023 due to erosion of its eastern edge and accretion along its western edge.

Line 3 also cuts across the Newport Bar, further north (Figure 3.3). The western channel retains its general shape but shifts position both vertically and horizontally (Figure 4.2a). Once again, the Newport Bar is showing evidence of accretion on the western side of the bar between 2017 and 2023. The only exception is 2019 where there was a period of erosion, and the bank was eroded back to 2005 position. On the eastern edge of the Newport Bar, erosion is consistent between 2005 and 2023. On top of the bar, channel positions remain in the same position, but they deepen with vertical accretion between 2007 and 2023. Considering the similarities between lines 2.5 and 3, there is evidence that the Newport Bar as a whole, and not just individual lines is migrating west and experiencing vertical accretion, as evidenced by the deepening marsh channels. Within the main river channel, another midchannel bar begins developing in 2019 800m from the eastern stake. In 2022 and 2023, the midchannel bar increases in size and shifts further east.

Line 3.5 crosses the main sand flat past the edge of the Newport Bar (Figure 3.3). The banks on both the west and the east side of the river remain in the same position from survey to survey (Figure 4.2b). On the west bank, there has been about 4m of elevation gain on top of the bank between 2005 and 2023 with minimal erosion. Most of the changes occur on the riverbed with changes in the placement of midchannel bars. In 2007, there was a midchannel bar approximately 450m away from the western stake and 2m above average bed level. In 2017, the bar was the same height, but spanned almost twice the distance. In 2019, the width of the bar shrank, but the height was about 3m above average bed level. The midchannel bar in 2021 was the same size and a similar shape, however, the bar shifted position so that it was further east than in 2019. In 2022, the size and shape of the bar was similar to that of 2017, but it exhibits the same steep western bank as seen in 2021. In 2023, the elevation of the bar increased to about 4m above average bed level. The steep western bank persisted, but the top of the bar was more rounded.

Line 4 is located at Newport Landing and shows similar riverbank erosion to Line 3.5 (Figure 3.3). The east bank remains stable with minimal erosion or accretion while the west bank experienced about 20m of erosion between 2005 and 2023 (Figure 4.2c). On top of the marsh platform on the west bank, 40m in from the edge of the bank, there has been about 4m of elevation gain between 2005 and 2023. In this area, channel position and absolute depth remained the same, but vertical accretion give the illusion of deepening channels, similar to what was observed on the Newport Bar in Lines 2.5 and 3. Further west, the most consistent elevation change occurred between 2007 and 2017 where about 2m of elevation was gained and remained stable until 2023 when another 2m was gained. On the riverbed, the midchannel bar which appears to be shifting in Line 3.5 also appears to be following similar patterns on a smaller scale until 2023 when there is an increase in elevation of between 2m and 3m compared to the average bed level.

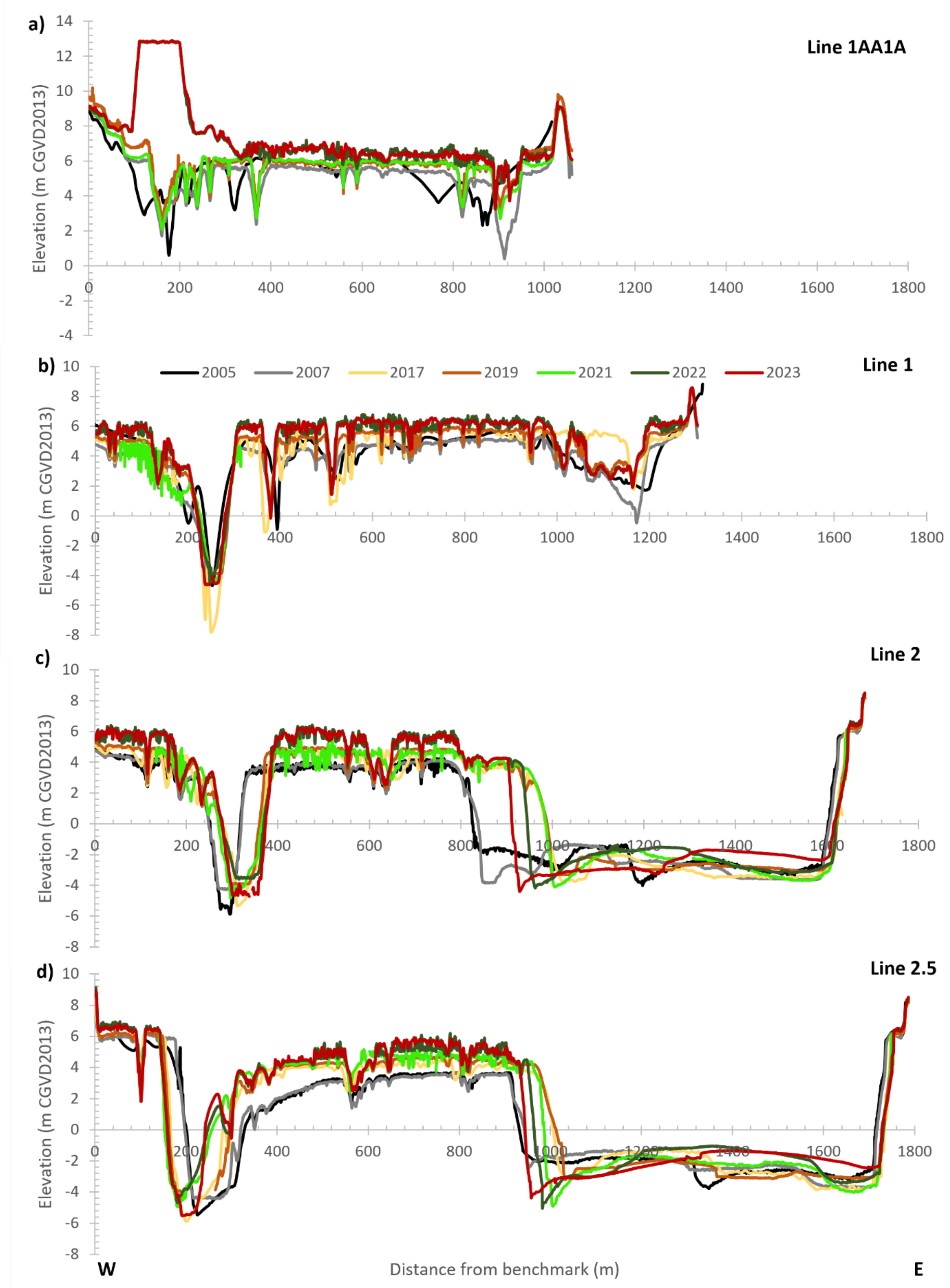

Figure 4.1: Cross-sectional profiles of the first four transect lines within the Avon River based on surveys done prior to construction, 2005, 2007, and 2017, and during increased human activity, 2019, 2021, 2022, and 2023.

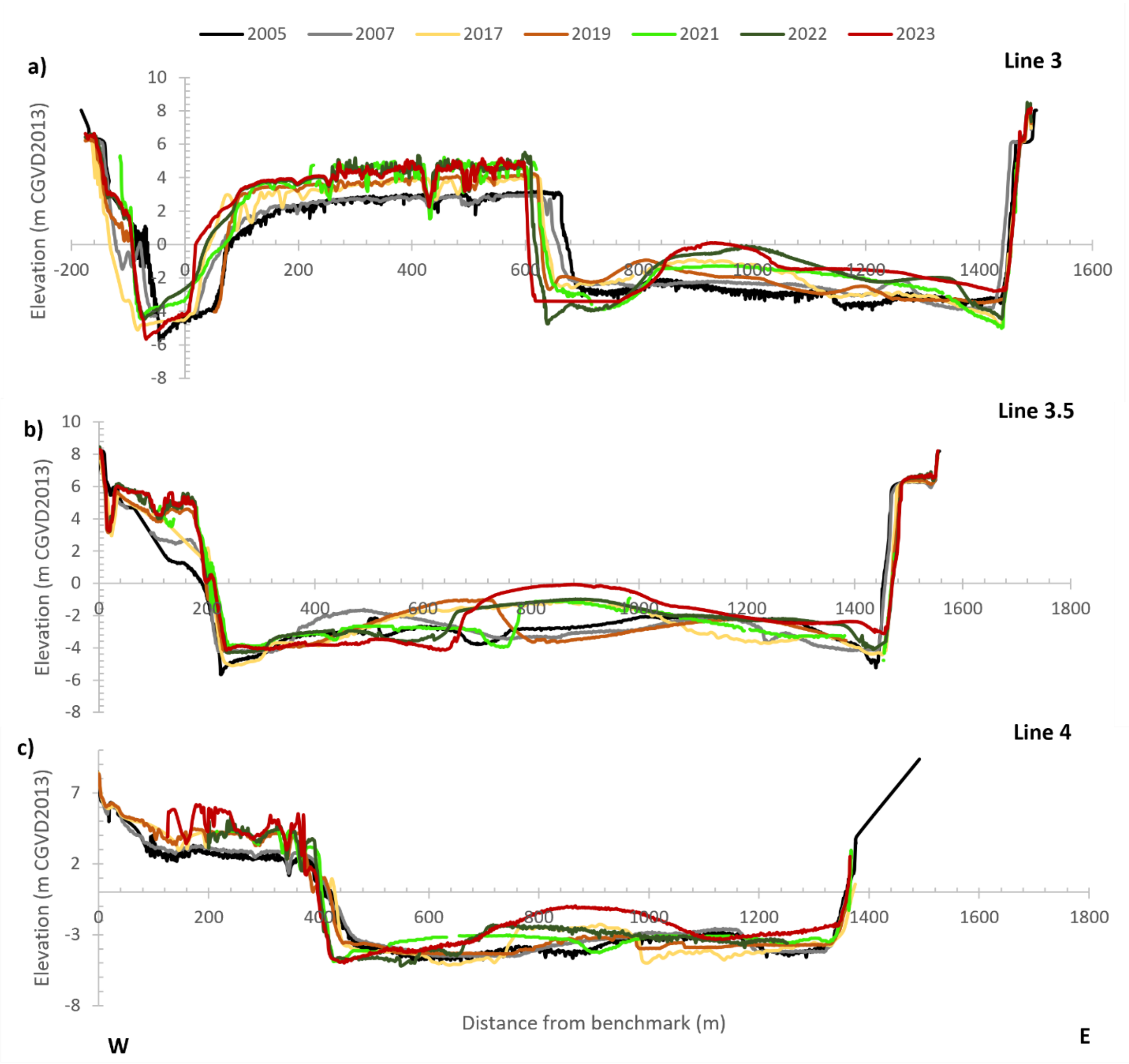

Figure 4.2: Cross-sectional profiles of transect lines within the Avon River based on surveys conducted prior to construction in 2005, 2007, and 2017, and during increased human activity in 2019, 2021, 2022, and 2023.

4.1.1.2 St. Croix Cross-Sectional Profiles

Changes along the St. Croix River were generally concentrated along the edges of the bank with more changes occurring further upstream than close to the Avon River (Figure 4.3). Line S is the closest to the Avon River and exhibits changes along both the north and south bank (Figure 3.3). The most notable changes occurred between 2007 and 2017 along the south bank (Figure 4.3a). During this period, deposition occurred off the edge of the south bank corresponding to expansion of the Windsor Marsh. The newly deposited area is about 60m across with a small channel cutting through and remained stable from 2017 to 2023. Along the north bank, about 40m of erosion occurred between 2005 and 2017. After 2017, the cross-sectional profile stayed stable.

Line T is one line upstream from Line S (Figure 3.3). The south bank has remained stable for all survey years until about 400m away from survey stake (Figure 4.3b). After 400m, channel elevations begin to deviate each other. Between 2005 and 2018, accretion occurred which moved the bank out nearly 100m into the channel. After 2018, the north bank began eroding and by 2023, the bank had eroded by about 40m. The main tidal channel within the Windsor Marsh has remained in a constant position since 2005, but it has been experiencing steady infilling.

Line C again saw few changes along the north bank with the majority of substantial changes being concentrated in the southern half of the channel (Figure 4.3c). Between 2005 and 2021, the south bank experienced about 100m of accretion. In 2021, a midchannel bar also began developing after the erosion of the south bank which had developed between 2007 and 2017. After 2021, the bank began eroding again and retreated nearly back to 2005 position.

Line R is the furthest upstream within the St. Croix River (Figure 3.3). Most of the changes were along the north edge of the bank (Figure 4.3d). Surveys in 2005, 2007, and 2017 reached the survey stake on the north bank, while surveys from 2019-2023 started between 100m and 200m away from the stake.

The north bank fluctuates between periods of erosion and deposition with erosion between 2007 and 2017 followed by deposition between 2019 and 2022. Since the 2021 survey started 200m in from the stake, it is unclear from the cross-sectional profiles if the north bank was stable between 2019 and 2021, or if there was erosion or deposition. On the southern bank, changes remained relatively stable with slight elevation fluctuations from year to year. In 2021 however, there was a substantial increase in elevations which corresponds to the increase in elevation and mid channel bar development that was observed in Line C in 2021.

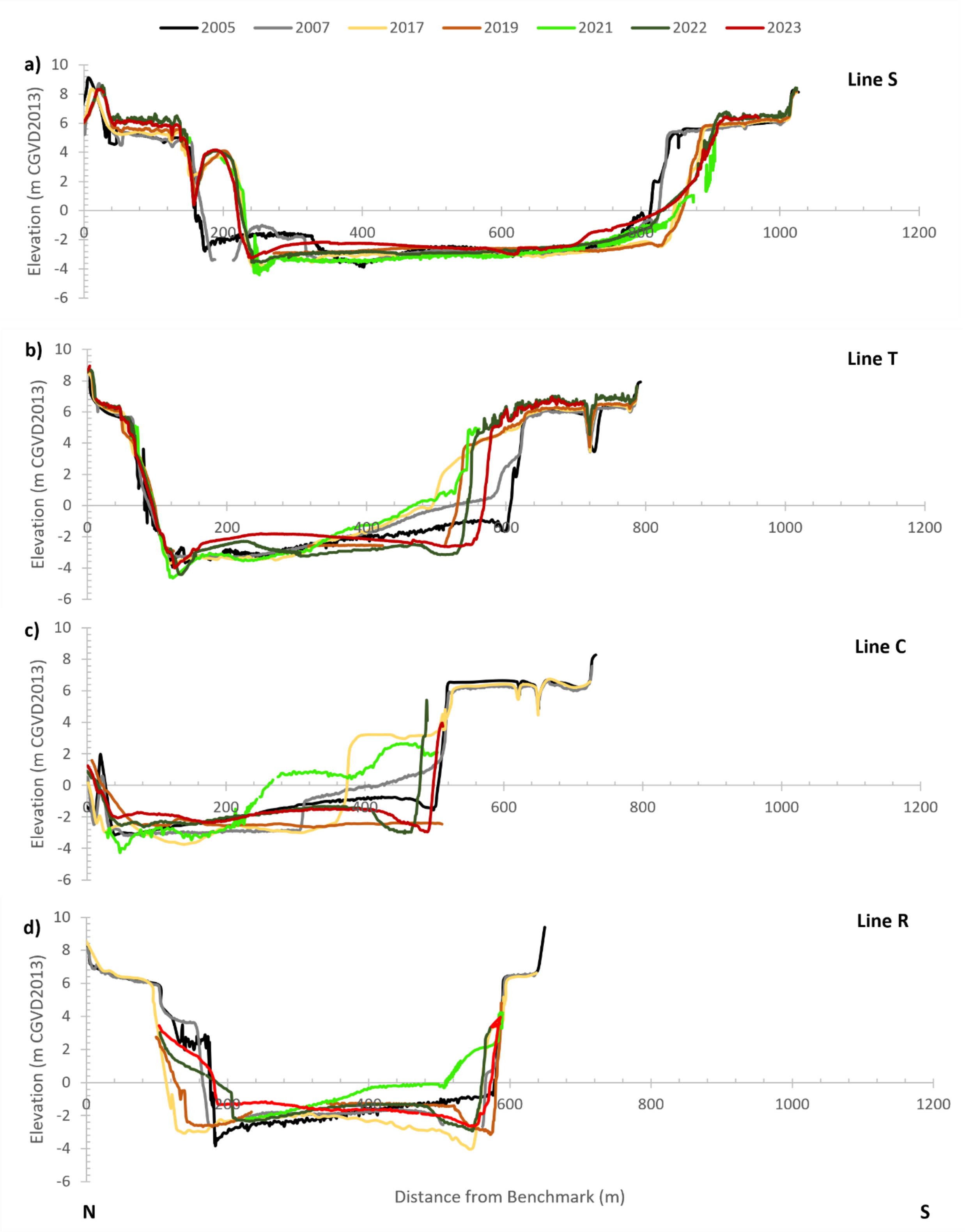

Figure 4.3: Cross-sectional profiles of transect lines within the St. Croix River based on surveys conducted prior to construction in 2005, 2007, and 2017, and during construction in 2019, 2021, 2022, and 2023.

4.1.2 Cross-Sectional Area

4.1.2.1 Avon

The wetted area of the Avon River generally shows a decreasing trend from 2005 to 2023 (Figure 4.4). Lines that are furthest away from the causeway are fairly consistent in this trend while lines close to the causeway are much more variable. While a decreasing trend is visible, it is important to note that in 2023, the wetted area of many transect lines increases compared to 2022. Lines 1AA1A and 1 are closest to the most variable and intersect both the Windsor Marsh and the main sluice gate channel. Because a substantial portion of both transect lines is on the Windsor Marsh, the wetted area is much lower than other transect lines which mostly cover riverbed. Line 1AA1A also intersects the twinned section of Highway 101, so when construction of the highway occurred in 2022, there was a decrease in wetted perimeter (Figure 3.3). Line 1 displays a decrease in a decrease in wetted perimeter until the lowest wetted area is reached in 2021 and was followed by an increase in wetted area. Since the primary area of interest across Line 1 is the tide gate channel, it is possible that the change in wetted area can be attributed to a change in this area.

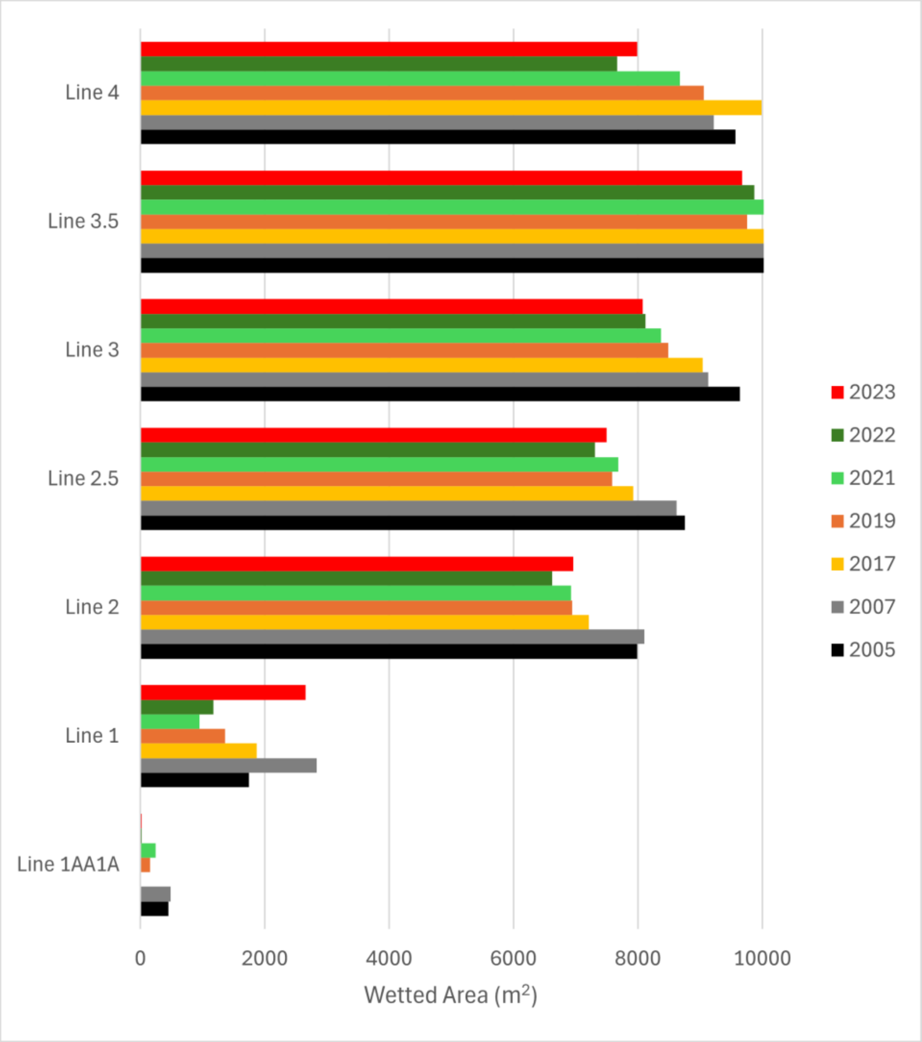

Figure 4.4: Wetted area of the Avon River, lines closest to the causeway are at the bottom of the figure while lines furthest away are at the top.

The wetted perimeter values mirror the trend of the wetted area values with many transect lines displaying a decreasing trend (Figure 4.5). Once again, transect lines further from the causeway display more stability while lines close to the causeway are highly variable. The wetted perimeter values for Line 1AA1A are impacted by construction in 2022 when wetted perimeter notably decreased. Line 1 shows high variability but it matches with trends seen in the wetted area data. Lines 2.5, 3, and 3.5 exhibit the most uniform wetted perimeter across surveys, they also either intersect or are very near the Newport Bar. It is possible that this stability comes from the bar expereincing similar amounts of erosion and accretion as well as minimal development of intertidal bars. With the exception the two lines closest to the causeway, all transect lines reach their peak wetted perimeter values in either 2017 or 2019. This maximum is before or very early into the period of notable human influence on the system and is followed by a decrease. It is also interesting to note that while wetted area seemed to be on the rise in 2023 for many transects, there are only three transect lines which show an increase in wetted perimeter between 2022 and 2023.

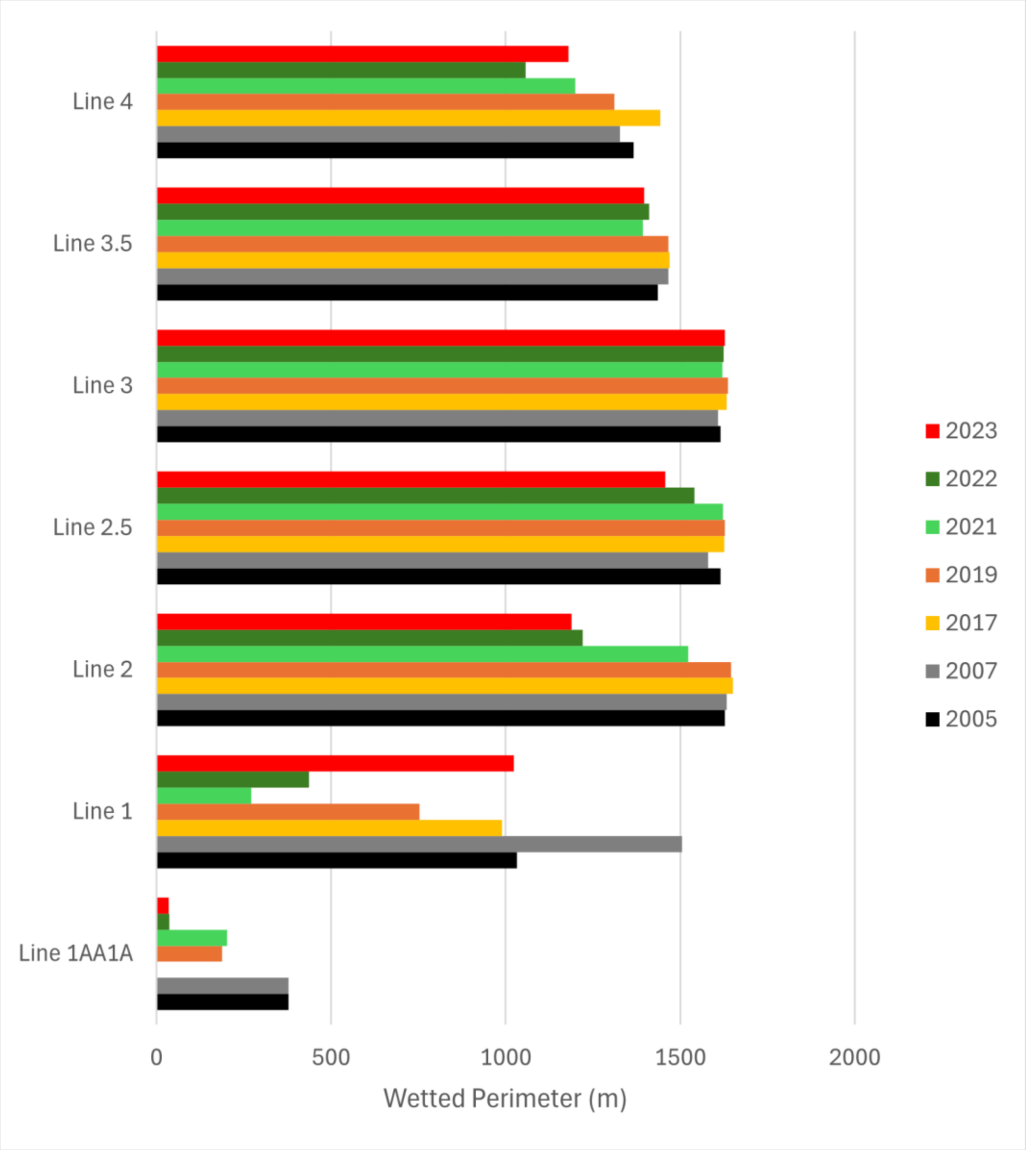

Figure 4.5: Wetted Perimeter of the Avon River, lines closest to the causeway are at the bottom of the figure while lines furthest away are at the top.

Since the wetted area and wetted perimeter are influenced by the width of a transect, the width follows many of the same trends (Figure 4.6). Line 1 shows the most notable deviation from wetted area and wetted perimeter trends since for both, 2023 was one of the higher values while 2023 had the second lowest width. The ratio of width/depth highlights changes in the transect line's morphology with high values being wide and shallow while low values are typically narrow and deep. Most transect lines are widest and shallowest in 2007 and 2019 with minor difference between 2023 being relatively narrow and deep (Figure 4.7). However, Line 1AA1A shows marked difference between 2007 and later years.

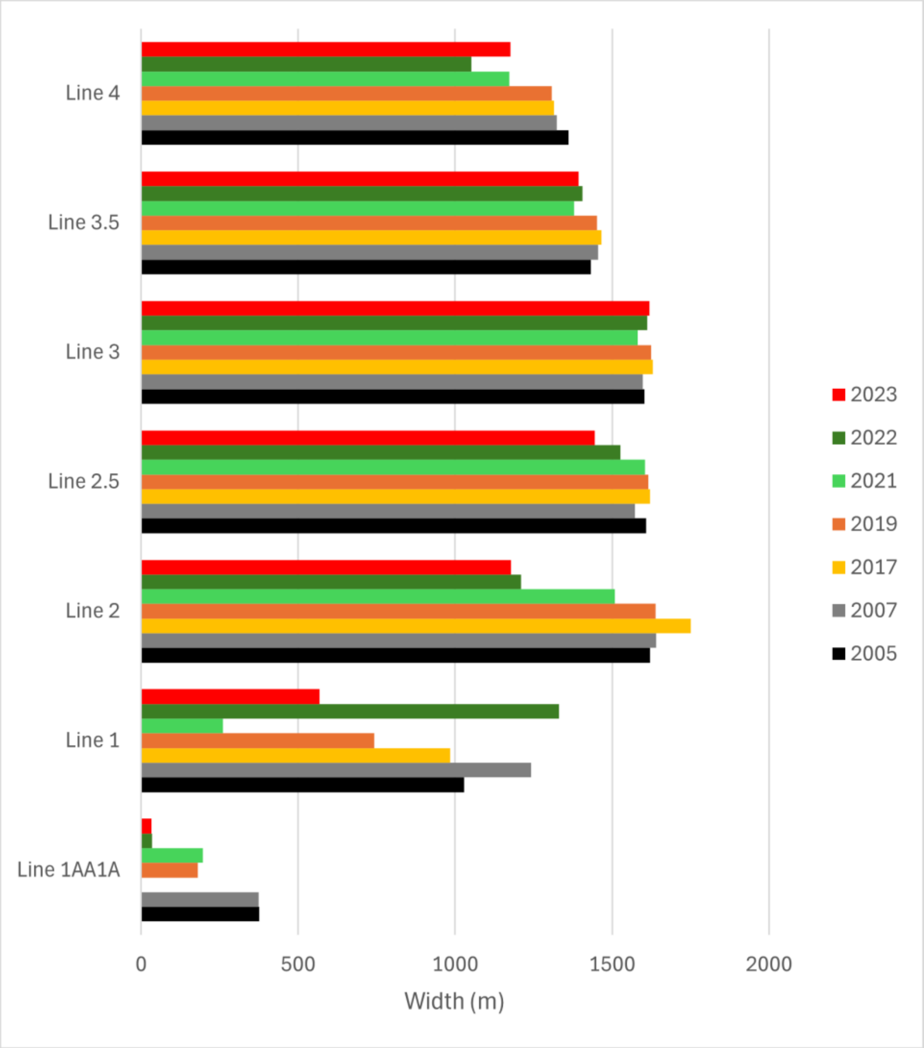

Figure 4.6: Avon River cross-sectional width lines closest to the causeway are at the bottom of the figure while lines furthest away are at the top.

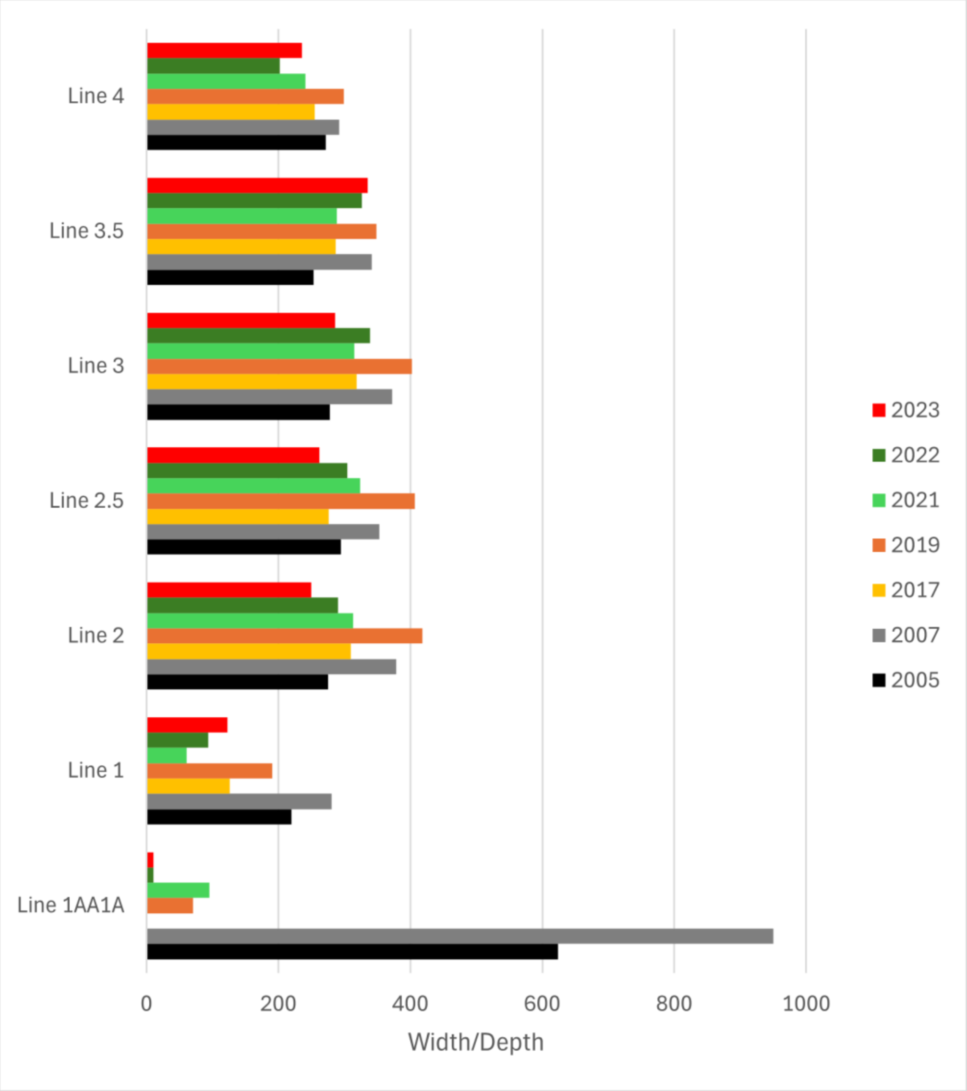

Figure 4.7: Avon River width/depth rations, lines closest to the causeway are at the bottom of the figure while lines furthest away are at the top.

4.1.2.2 St. Croix

The wetted area of all transect lines within the St. Croix all follow a general trend of a period of large area until either 2019 or 2021 when the lowest area is recorded, followed by period of increase in area (Figure 4.8a). Line T, near the causeway, experienced the lowest wetted area in 2019 while Lines C and R experienced their lowest wetted area in 2021. The lowest wetted area for Line S was 2023, however 2019 had the second lowest area which still mirrors the trend of a decrease in area followed by an increase as is seen in Line T. This trend of low area between 2019 and 2021 could be associated with the movement of an intertidal bar from close to the causeway to further upstream in the St. Croix. Line S had the least variation in wetted area while Line R experienced substantial variation compared to other transect lines within the St. Croix. Additionally, most transect lines exhibited the least difference between a single survey between 2022 and 2023 with the exception of line S, nearest the causeway, which had the least difference between surveys between 2005 and 2007.

Wetted perimeter is generally more stable between years than wetted area, with the exception of Line R (Figure 4.8b). Within transect Lines S, T and R which have the most variation between years, the trend in wetted perimeter follows the trend in wetted area. Line S experiences the highest wetted perimeter in 2021 which is matched by the highest wetted area in 2021. Similarly, Line R experiences the lowest wetted perimeter in 2021 which aligns with the lowest wetted area in 2021. However, a low wetted area does not always result in a low wetted perimeter as shown by Line T. 2021 showed the lowest wetted perimeter yet the highest wetted area while 2019 showed the second highest wetted perimeter and the lowest wetted area.

Both wetted perimeter and wetted area are affected by the width of a channel (Figure 4.8c). The trends are evident with Line S having the largest width and consistently the largest wetted perimeter and wetted area. The channel width also follows the decrease in 2019 or 2021 followed by an increase pattern that was observed in wetted area and wetted perimeter calculations, however 2021 was the dominant lowest value between transect lines. The width/depth is highly variable, but the ratios are generally greatest in Line S which indicates a wider and shallower channel compared to Line R which has lower ratios indicating a narrower and deeper channel (Figure 4.8d). Across all transect lines, the width/depth ratio is increasing from 2021 to 2023 indicating that all transects are getting wider and shallower since 2021 when most lines reached their narrowest and shallowest.

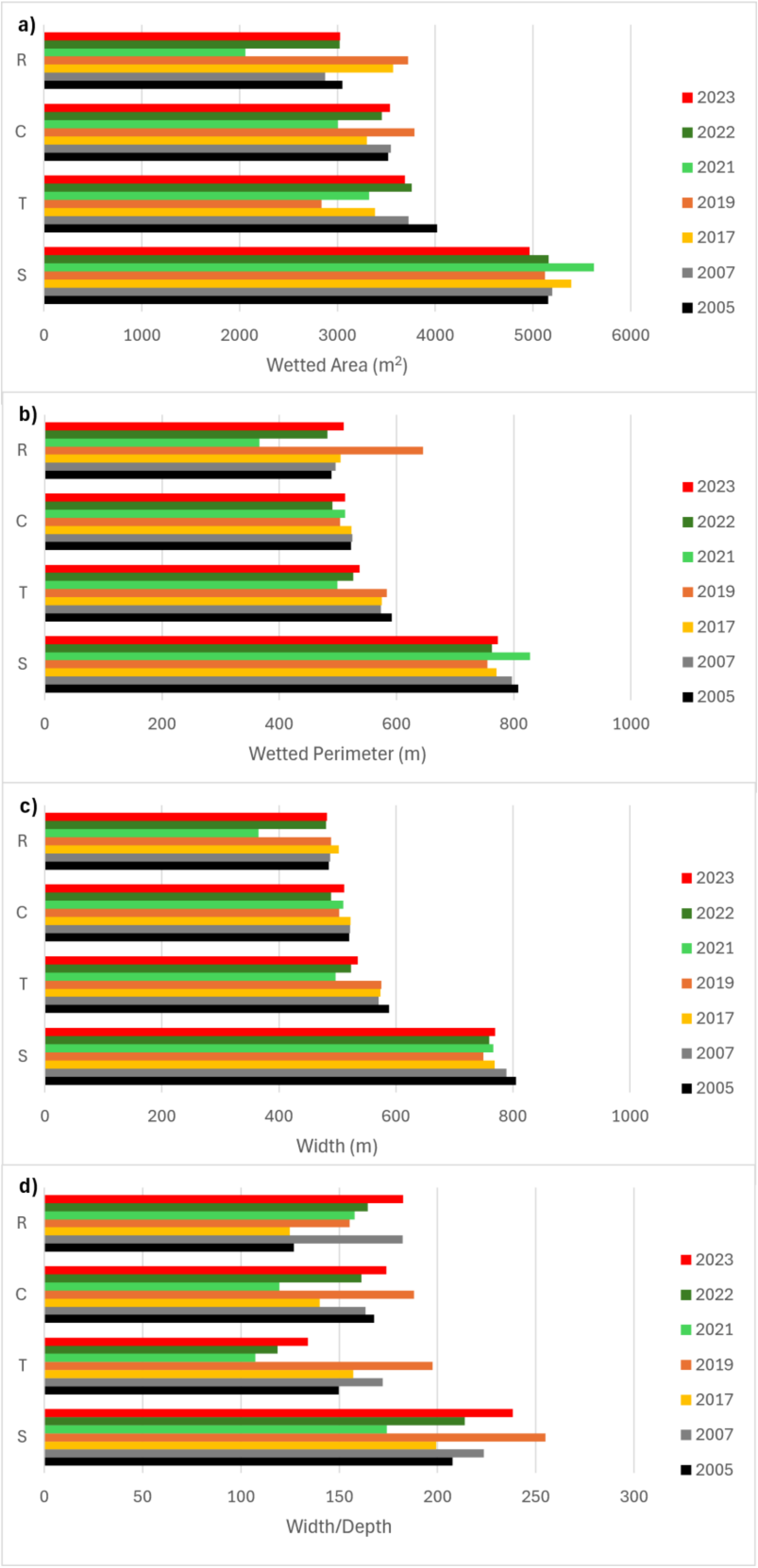

Figure 4.8: St. Croix River profiles. A shows the wetted area of each transect line, B shows the wetted perimeter, C shows the width, and D shows the width/depth ratio.

4.2 Changes in Erosion and Deposition

4.2.1 Surface elevation changes

Within Zone 1, changes are concentrated along the edges of the channel and created by water discharging through the tide gate, within the channel along the south edge of the Newport Bar, and along the west bank of the channel at the northernmost edge of Zone 1 (Figure 4.9). The most substantial changes along the main channel occurred between 2007 and 2019, with between 1m and 5m both lost and gained along the banks. Areas of the most change occur along the bends of the channel compared to banks running parallel which generally exhibited between 0.15 and 1m of elevation gain or loss. Likely the drastic changes in elevation compared to changes observed from one year to the next is due to the 12-year difference between the two sample years and the increased amount of time over which the system was allowed to change. More change is observed between 2022 and 2023 than between 2021 and 2022 along the edge of the main channel. On average, between 1m and 5m of elevation was lost between 2022 and 2023 while an average of only 0.15m to 1m was lost between 2021 and 2022. It is notable that neither comparison show an increase in elevation which is different than when the 2007 to 2019 period is compared. 2007-2019 also experienced the most changes within the channel south of the Newport Bar. Areas of greater than 5m of elevation loss were observed along with areas of between 1m and 5m of elevation loss. 2021 to 2022 experienced greater elevation changes within the southern channel than between 2022 and 2023. Between 1m and 5m of elevation was gained between 2021 and 2022 compared to an increase in elevation of between 0.15m and 1m between 2022 and 2023. The west bank at the northern edge of Zone 1 experienced the most changes between 2007 and 2019 within increases in elevation of between 1m and 5m on top of the marsh and decrease in elevation of greater than 1m loss within the main marsh channel. The period between 2021 and 2022 had more elevation gain within this area while 2022 to 2023 experienced elevation loss within the main marsh channel. Across the entire marsh platform, changes in elevation of between 0.15m and 1m are observed. These changes are small enough that they cannot necessarily be attributed to sedimentation or erosion but could be because of changes in vegetation.

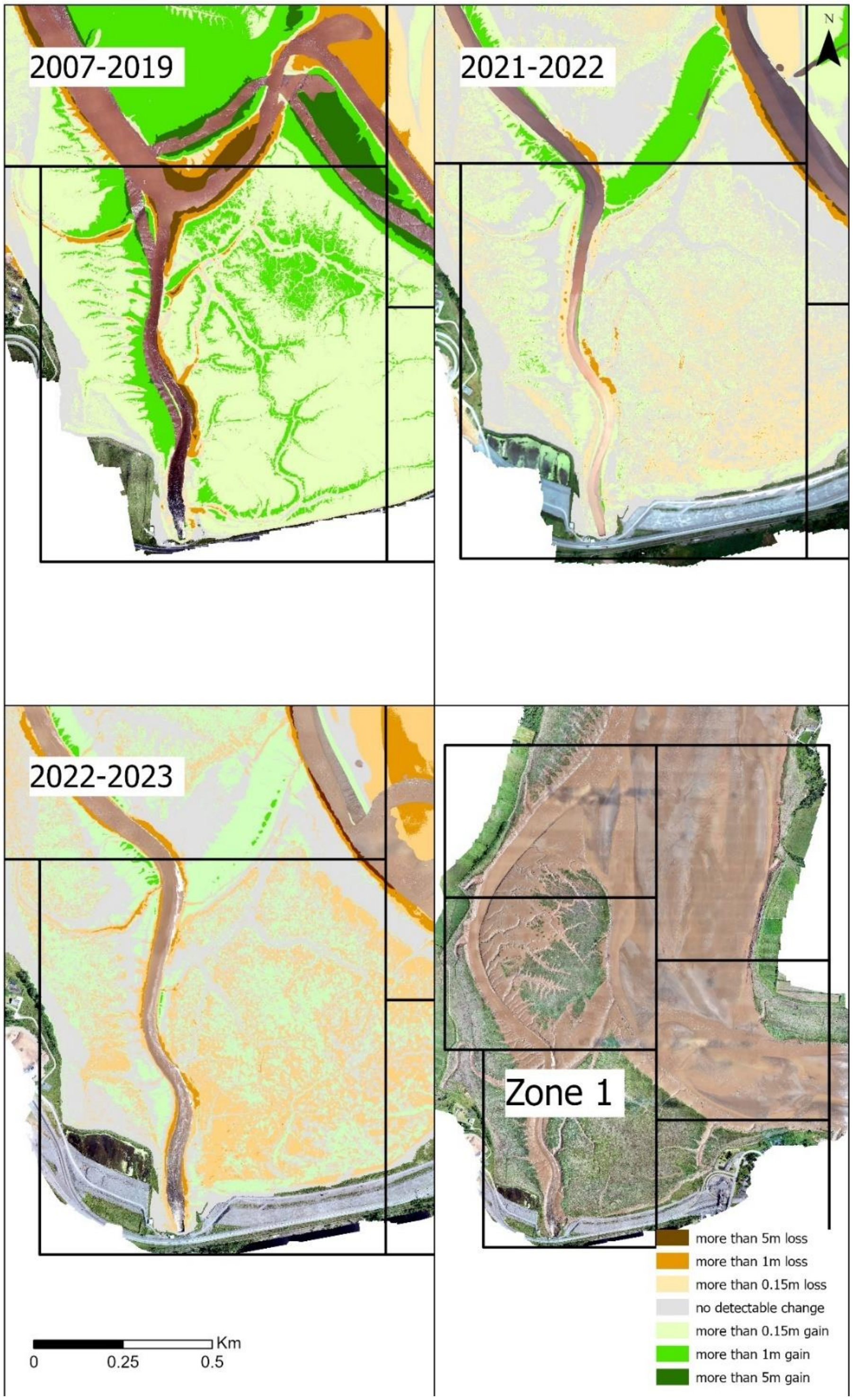

Figure 4.9: Changes of elevation between survey years within Zone 1, nearest the causeway.

Zone 2 encompasses the majority of the Newport Bar (Figure 4.10). Major changes within this zone are limited to the channel between the Newport Bar and the Windsor Marsh, as well as the banks along the Newport Bar. Patterns of elevation change within the channel south of the Newport Bar within Zone 2 are very similar to changes within Zone 1, however, greater than 5m of elevation gain can be seen closer to the Newport Bar. Depositional patterns within the southern channel in Zone 2 remain the same as in Zone 1 for both 2021 to 2022 and 2022 to 2023. Along the western bank of the Newport Bar, there is consistent elevation gain of between 1m and 5m while on the opposite bank of the channel erosional patterns are less consistent ranging from more than 0.15m of elevation loss to more than 5m of elevation loss. On top of the Newport Bar, elevation changes are much more noticeable between 2007 and 2019 with between 1m and 5m of elevation gain on average which can likely be attributed to sedimentation. In comparison, 2021 to 2022 and 2022 to 2023 have between 0.15m and 1m of elevation loss and gain which could be attributed to differences in vegetation height. Along the eastern bank of the Newport Bar, there is generally elevation loss greater than 1m. Between 2019 and 2021, the channel of standing water had shifted so that it runs directly next to the Newport Bar on the eastern edge, and elevation loss increases to be greater than 5m loss in many areas.

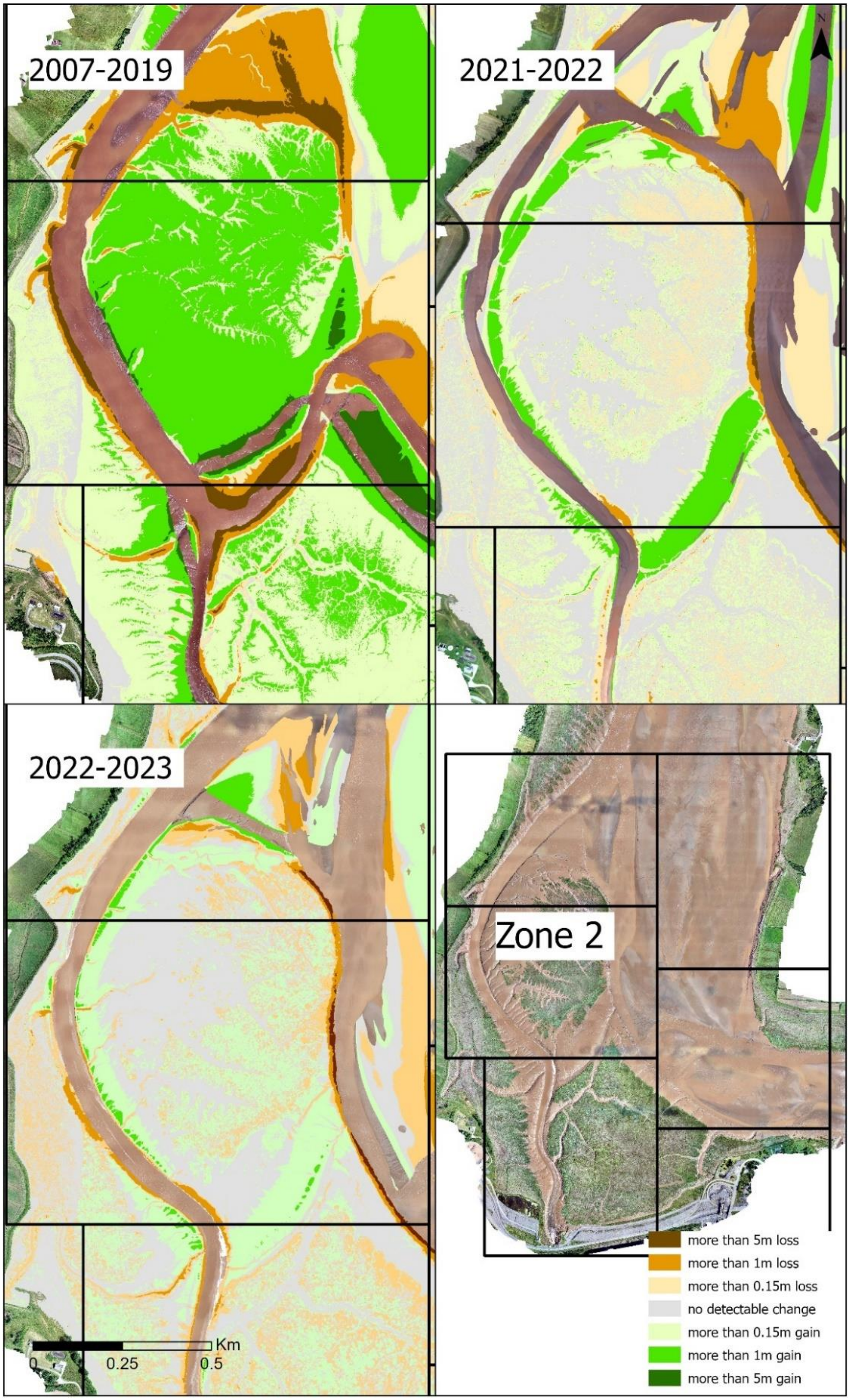

Figure 4.10: Changes in elevation of Zone 2 covering most of the Newport Bar.

Zone 3 highlights changes in the northern tip of the Newport Bar and the marsh bank in the northwestern corner of the study area (Figure 4.11). The northern tip of the Newport Bar exhibits more changes in elevation than on the top of the bar or the sides. Between 2007 and 2019, there were elevation losses of greater than 1m across the entire northern tip while sediment was depositing off the eastern edge of the tip creating an elevation gain of between 1m and 5m. Changes observed between 2021 and 2022 as well as 2022 and 2023 exhibit both elevation losses and gains. Increased elevation occurred closer to the western side of the northern tip while decreases in elevation occurred along the eastern edge of the tip. Between 2021 and 2022, there was elevation gain of between 1m and 5m off the edge of the northern tip as seen between 2007 and 2019. Between 2022 and 2023 however, this area of elevation gain had turned into primarily an area of elevation loss with a larger area of standing water. The northwestern marsh bank experienced changes similar to the top of the Newport Bar, with elevation gains between 1m and 5m between 2007 and 2019 and minimal changes between 2021 and 2022 as well as 2022 and 2023.

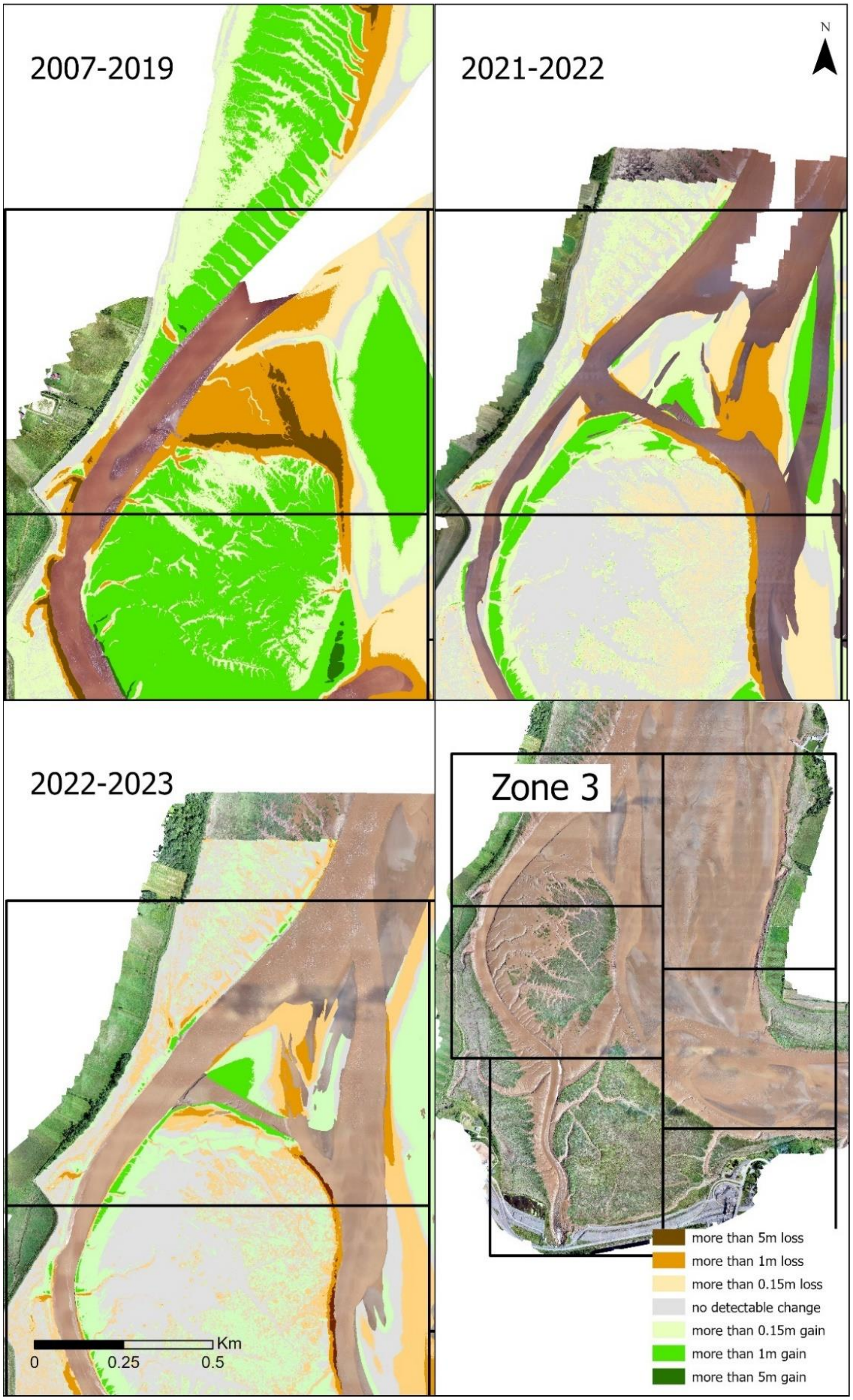

Figure 4.11: Changes in elevation within Zone 3 which is the northwestern corner of the study area.

Zone 4 captures the opening of the St. Croix River and is largely covered by standing water (Figure 4.12). As with most zones, substantial changes in elevation are concentrated along the edges of the banks. The only period that experienced a gain in elevation along the southwest bank was between 2007 and 2019. All other periods experienced losses of greater than 1m in elevation. Substantial elevation gain was also observed between 2007 and 2019 along the northern marsh of the St. Croix River where it meets the Avon River compares to minimal changes observed between 2021 and 2022 as well as 2022 and 2023. Despite the changes in elevation on the marsh, the bank is consistently losing elevation. The northeast corner of Zone 4 exhibited minimal changes between 2007 and 2019, however, there is between 1m and 5m of elevation between 2021 and 2022 as well as 2022 and 2023. Between 2021 and 2022, there was a large area of elevation gain while between 2022 and 2023, there was an elevation loss. In the center of the St. Croix opening, there is consistent elevation loss, but the amount lost between each period is shrinking.

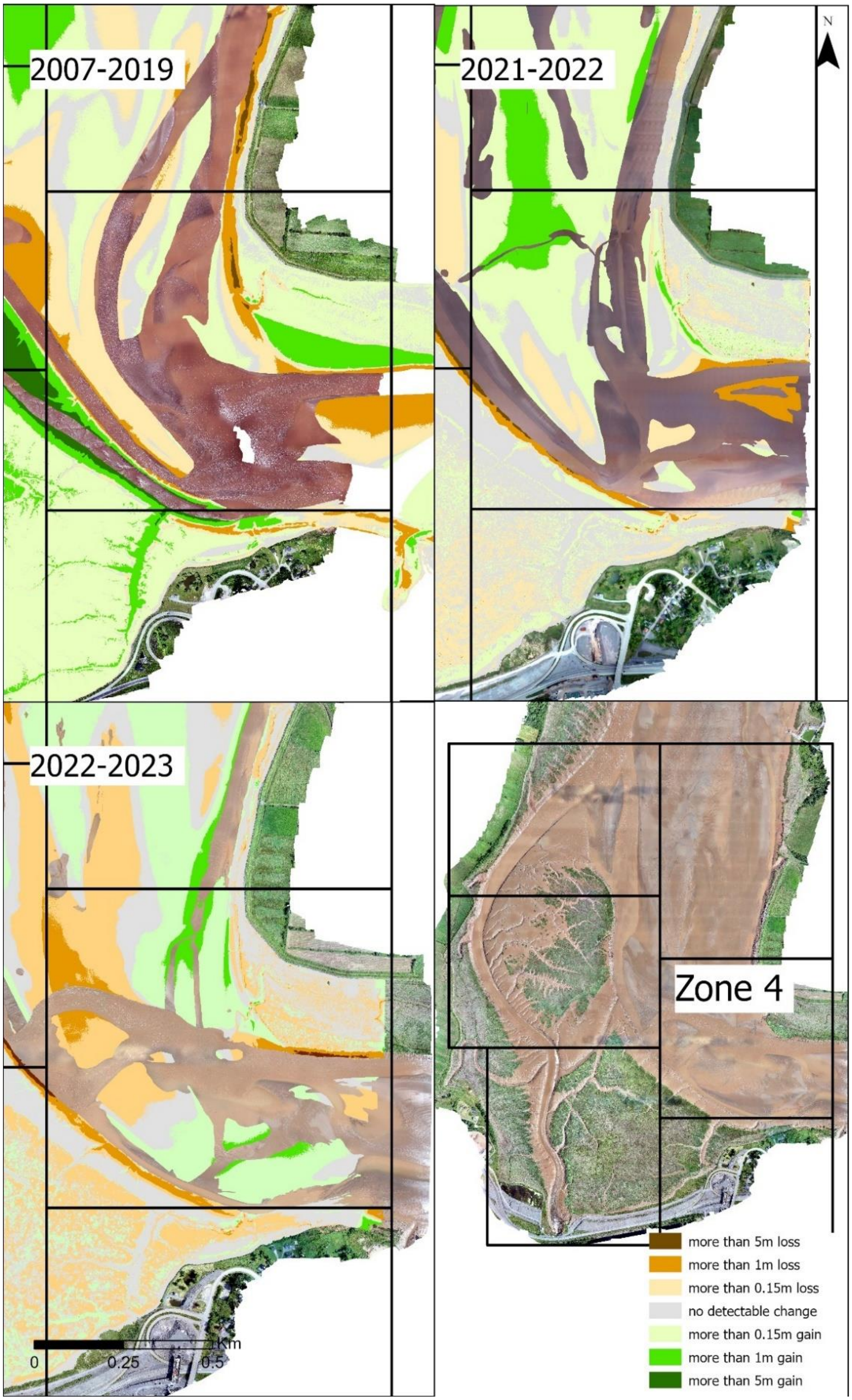

Figure 4.12: Elevation change within Zone 4 at the opening of the St. Croix River where it meets the Avon River.

Zone 5 is located near the highway and covers mostly marsh area of the central Windsor Marsh Complex (Figure 4.13). The most notable changes in elevation occurred between 2007 and 2019 when the main channel within Zone 5 which runs north to south increased in elevation by between 1m and 5m. After 2019 during the periods between 2021 and 2023, there was no detectable change within that channel. Also, between 2007 and 2019, there was a loss of elevation on top of the marsh between 1m and 5m while there was a gain in elevation greater than 1m along the bank. The decrease in elevation on top of the marsh can likely be partly attributed to changes in the height of vegetation, however a substantial component is possibly due to erosion since there is a decade between sampling periods, and changes in vegetation are typically less than 1m. The remaining area within Zone 5 is vegetated, and changes are all less than 1m, either gained or lost, and could reflect changes in vegetation height. Outside of the marsh area, it is also important to note the construction of the twinned highway in the south of Zone 5 which is shown in the orthophotos from 2022 and 2023.

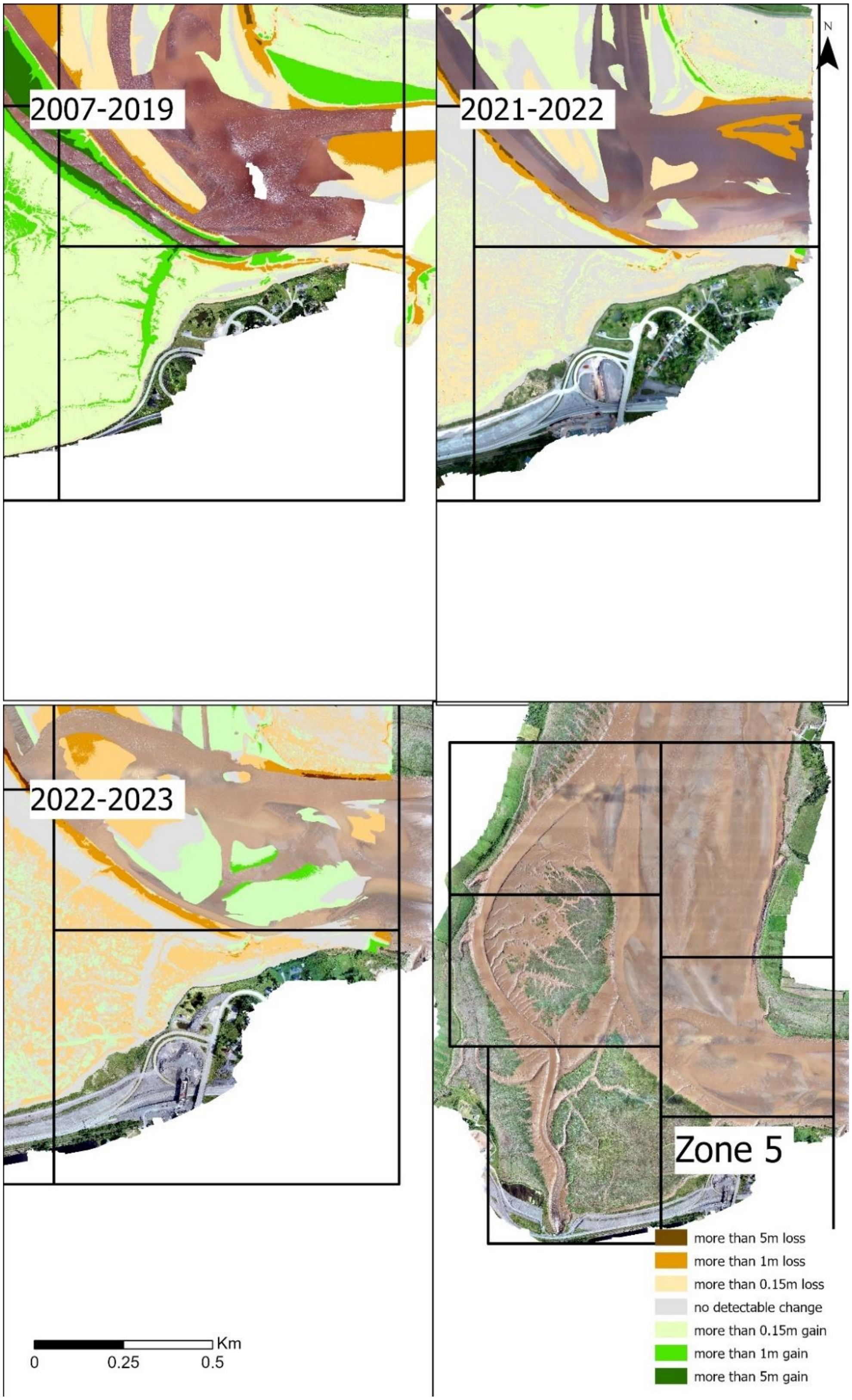

Figure 4.13: Elevation change for Zone 5 located in the southeast corner of the study area.

Zone 6 covers the northeastern segment of the study area and is primarily riverbed (Figure 4.14). Between 2007 and 2019, the eastern bank was losing greater than 1m of elevation while during the other two periods, there was minimal change. Along the riverbed, changes between 2007 and 2019 are minimal and generally less than 1m, with small exceptions in the center of Zone 6 where there is between 1m and 5m of elevation change. 2021 to 2022 and 2022 to 2023 have larger zones of elevation change. Between 2021 and 2022, a zone of between 1m and 5m of elevation gain developed in the southwest corner of the zone. This shifted to an area of less than 1m of elevation loss between 2022 and 2023. Between 2022 and 2023, there was also elevation gain in the northwest corner and the western side of the zone. The area of elevation gain along the western side was between 0.15m and 1m which corresponds to a muddy midchannel bar observed in 2023 (Figure 4.15). Elevation gained in the northwestern corner was more substantial, between 1m and 5m, between 2022 and 2023. This was the first time that substantial elevation gain was observed in that area, but it is possible that this could be attributed to the movement of an intertidal bar from Zone 3.

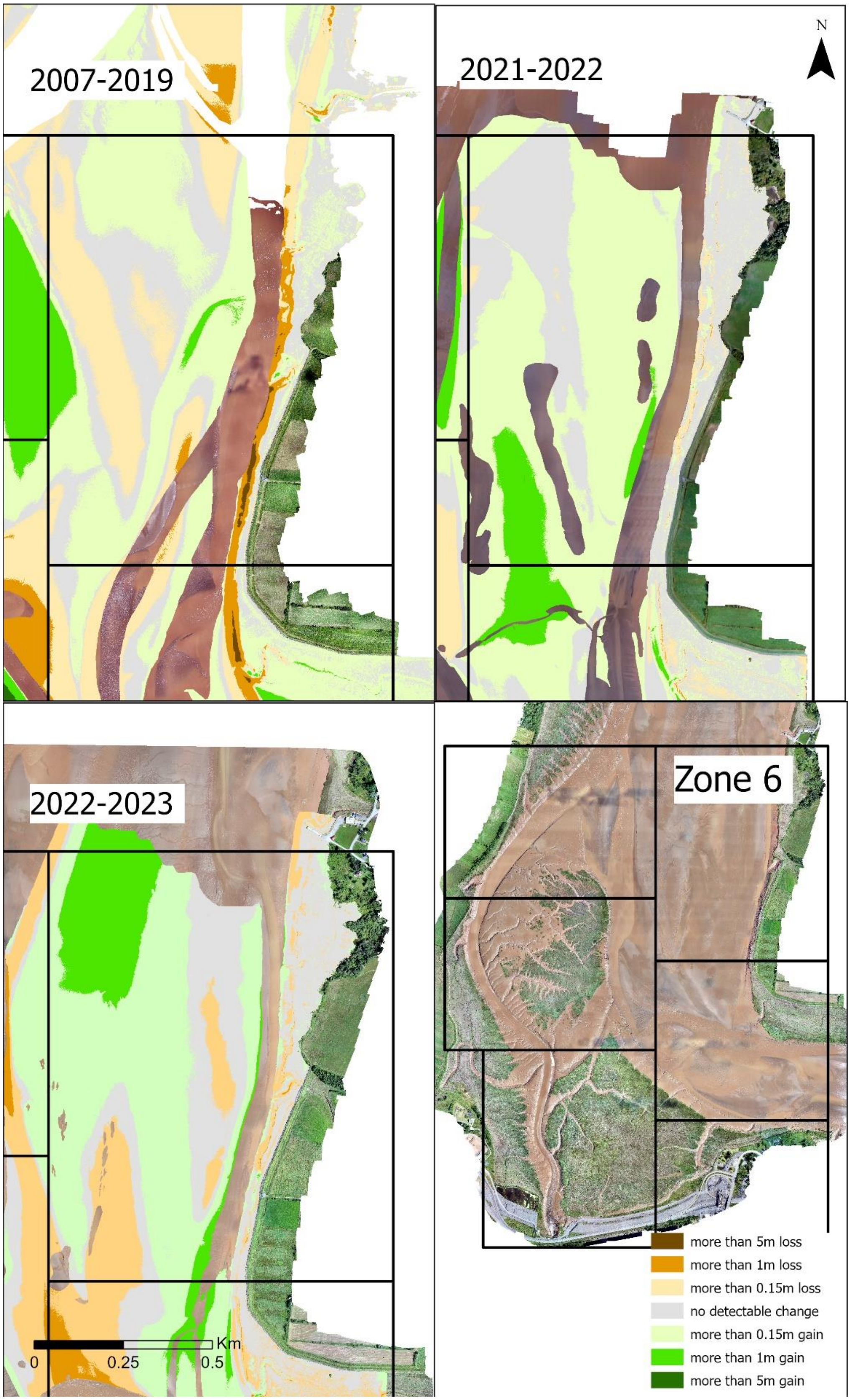

Figure 4.14: Elevation changes within Zone 6 located in the northeast area of the study area.

Figure 4.15: Muddy midchannel bar at low tide developing within Zone 6 on August 3rd, 2023.

4.2.2 Volumetric changes

Total and net recorded volumetric change between 2007 and 2017 was substantial compared to other periods, but there was a decade between sampling periods which would have allowed for more change compared to a difference between one year. To make sample sizes more accurate to compare, we divided the total and net changes by 10 to approximate how much the sediment volume was affected from year to year assuming uniform change. While the percentages of volume lost and gained by zone was not calculated, the most total change was in Zone 2 while the least total change was in Zone 5 (Table 4.1). Zone 5 had a total change of 28,000m^3. Having the least amount of total change is consistent with trends found between one-year periods of difference as Zone 5 also experienced the least change between 2021 and 2022 as well as between 2022 and 2023. Zone 2 had a total change of 1,009,000m^3 which was the most of any zone. Zone 3 was the only zone to experience a net loss of sediment between 2007 and 2017 while Zone 5 had the lowest net change of 18,000m^3. The entire system experienced a total change of 2,683,000m^3 and a net change of 1,278,000m^3 indicating that the system as a whole is gaining sediment. Comparing yearly estimated values between 2007-2017 and the other two sampling groups, the system experienced less total and net change from year to year before the increase in human influence.

Volumetric change calculations between 2021 and 2022 show that overall, the study area had a positive net gain of sediment (Table 4.2). The zone with the highest gains to losses ration was Zone 6 which experienced a 95% gain of 244,384m^3 and a 5% loss of 12,267m^3 resulting in a net gain of 232,117m^3. Zone 5, located in the southeast corner of the study area and covering mostly marsh was the only zone that experienced a volume loss. The net loss was 4,748m^3 with a 56% loss of 23,225^3 and the net gain was 44% and 18,477m^3. While Zone 5 had the lowest net change in cubic meters, Zone 4 exhibited the lowest percent changes with 46% volume lost and 54% volume gained. Zone 1, located nearest the tide gate within the causeway had the second highest volume gains with 65% of volume gained at a total of 154,631m^3 and 35% volume lost at a total of 84,479m^3. This resulted in a net gain of 70,152m^3. Zones 2 and 3 experienced similar percentages of volume gained and lost with Zone 2 experiencing a gain of 61% and a loss of 39% while zone 3 had a gain of 59% and a loss of 41%. Zone two experienced a much higher net gain of 68,626m^3 while Zone 3 experienced a net gain of 50,479m^3. The total volume lost between 2021 and 2022 34% while the total volume gained was 66%. This was represented by total change volumes across the whole system as 1,387,330m^3 and a net change volume of 435,557m^3. It is difficult to compare values to values observed between 2007 and 2019 due to a lack of percent change data.

Change in volume by zones between 2022 and 2023 experienced more loss than between 2021 and 2022, despite the system as a whole still having a total net gain (Table 4.3). Zone 6 still experienced a net gain in volume with a 13% loss and an 87% gain. Although the volume of net change is greater, the percentage of area experiencing volume gains had decreased compared to calculations from 2021 to 2022.

The remaining five zones all experienced net volume losses between 2022 and 2023 with Zone 5 experiencing the greatest percentage of losses and Zone 3 experiencing the lowest percentage of losses. Zone 5 experienced a 70% loss of volume and a 30% gain in volume resulting in a net loss of 17,566m^3. Zone 3 on the other hand had a 51% loss of volume and a 49% gain in volume resulting in a net loss of 4,949m^3. Zone 1 had a similar ration to Zone 3 with a 52% loss and a 48% gain in volume which resulted in a net loss of 9,066m^3. Although both Zones 2 and 4 experienced greater net losses than Zone 5, their percentage of losses was much lower. Zone 2 experienced a net loss of 30,953m^3 but had a percent loss of 56% and a percent gain of 44%. Zone 4 experienced a net loss of 42,372m^3 and a percent loss of 58% with a percent gain of 42%. The large differences in percent changes and net changes between zones is likely due in part to the difference in the size of each change zone. The total volume lost within the system between 2022 and 2023 was 45% while the total volume gained was 55% which was represented by a total volume change of 1,317,787m^3 and a net volume change of 144,762m^3. This indicates that there was overall more balance within the system between 2022 and 2023 than between 2021 and 2022.

Table 4.1: Volume change by zone between 2007 and 2017 and approximate yearly change values.

Zone	**Total Change**	**Yearly Total Change**	**Net Change**	**Yearly Net Change**
	m^3	*m^3/year*	*m^3*	*m^3/year*
1	207,000	20,700	58,000	5,800
2	1,009,000	100,900	674,000	67,400
3	649,000	64,900	-116,000	-11,600
4	790,000	79,000	644,000	64,400
5	28,000	2,800	18,000	1,800
Total	2,683,000	268,300	1,278,000	127,800

Table 4.2: Annual volume changes by zone between 2021 and 2022.

Zone	**Volume Losses**		**Volume Gains**		**Total Change**	**Net Change**
	m^3/year	*%*	*m^3/year*	*%*	*m^3/year*	*m^3/year*
1	84,479	35%	154,631	65%	239,110	70,152
2	128,475	39%	197,101	61%	325,576	68,626
3	117,594	41%	168,073	59%	285,666	50,479
4	109,847	46%	128,778	54%	238,626	18,931
5	23,225	56%	18,477	44%	41,701	-4,748
6	12,267	5%	244,384	95%	256,651	232,117
Total	475,887	34%	911,444	66%	1,387,330	435,557

Table 4.3: Annual volume changes by zone between 2022 and 2023.

Zone	**Volume Losses**		**Volume Gains**		**Total Change**	**Net Change**
	m^3/year	*%*	*m^3/year*	*%*	*m^3/year*	*m^3/year*
1	112,523	52%	103,457	48%	215,981	-9,066
2	150,317	56%	119,365	44%	269,682	-30,953
3	101,281	51%	96,333	49%	197,614	-4,949
4	149,060	58%	106,688	42%	255,748	-42,372
5	30,379	70%	12,812	30%	43,191	-17,566
6	42,952	13%	292,620	87%	335,571	249,668
Total	586,512	45%	731,275	55%	1,317,787	144,762

4.3 Grain Size Analysis

In 2019, twelve sediment scrape samples were taken across the study area (Figure 4.16). Five of these were located on the Newport Bar while the remaining seven were located on the sandflat. Textural categories present included from coarsest to finest: fine sand, silty fine sand, sandy coarse silt, coarse silt, and medium silt (Figure 4.17). The coarsest sediment samples, fine sand, were located nearest to the opening on the St. Croix River. The finest sediments medium silt, coarse silt, and sandy coarse silt were located on the Newport Bar. The coarse silt was located on top of the bar, medium silt was located on the slope of the bar, and sandy coarse silt located towards the bottom of the slope of the bar closer to the water discharging from the St. Croix during low tide. This pattern indicates that sediments were becoming coarser moving from the top of the Newport Bar down slope towards the standing water. Sediments coarsen to a silty fine sand past the Newport Bar before fining to a sandy coarse silt in the outer reaches of the study area.

In 2023, fifteen sediment scrapes were taken. Unlike the samples taken in 2019, none of the samples were located on the Newport Bar for safety reasons (Figure 4.16). Instead, sample size was increased by sampling in new locations near the established transect lines. This has resulted in a more complete picture of the composition within the study area. Sediment textural categories in 2023 include from coarsest to finest: fine sand, very fine sand, and very coarse silt (Figure 4.17) (Appendix D). The very coarse silt makes up the newly developing intertidal bar and sample directly east of the bar. Samples of fine sand and very fine sand are located throughout the estuary. Generally, very fine sand is located to the west of the study area while the fine sand is located more toward the east, close to the Newport Bar with the exception of two samples. This is consistent with the grain sizes of samples collected in 2019, however, there were fewer samples collected in the eastern half of the study area during 2019 sampling, so it is difficult to define a pattern.

Comparing all samples from 2019-2023, there is a general coarsening pattern and less variability in grain size across the study area (Figure 4.17). In 2019, the coarsest sediments were fine sands while the finest were medium silts. In 2023, the coarsest samples were again fine sand, however the finest sediments were very coarse silts. Between 2019 and 2023 there were six samples taken at the same location. Examining these six samples, sediments in all locations became coarser.

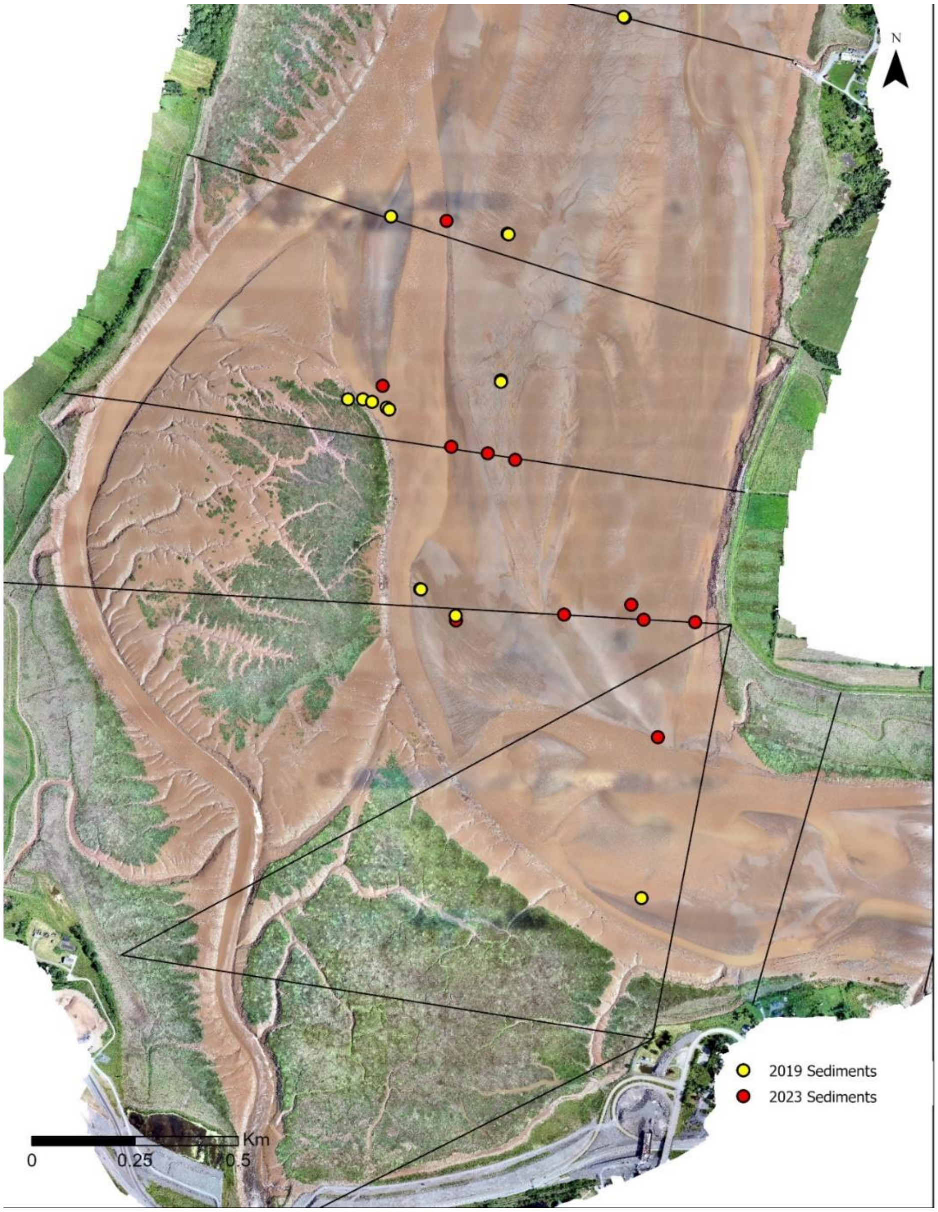

Figure 4.16: Location of sediment samples taken in 2019 and 2023.

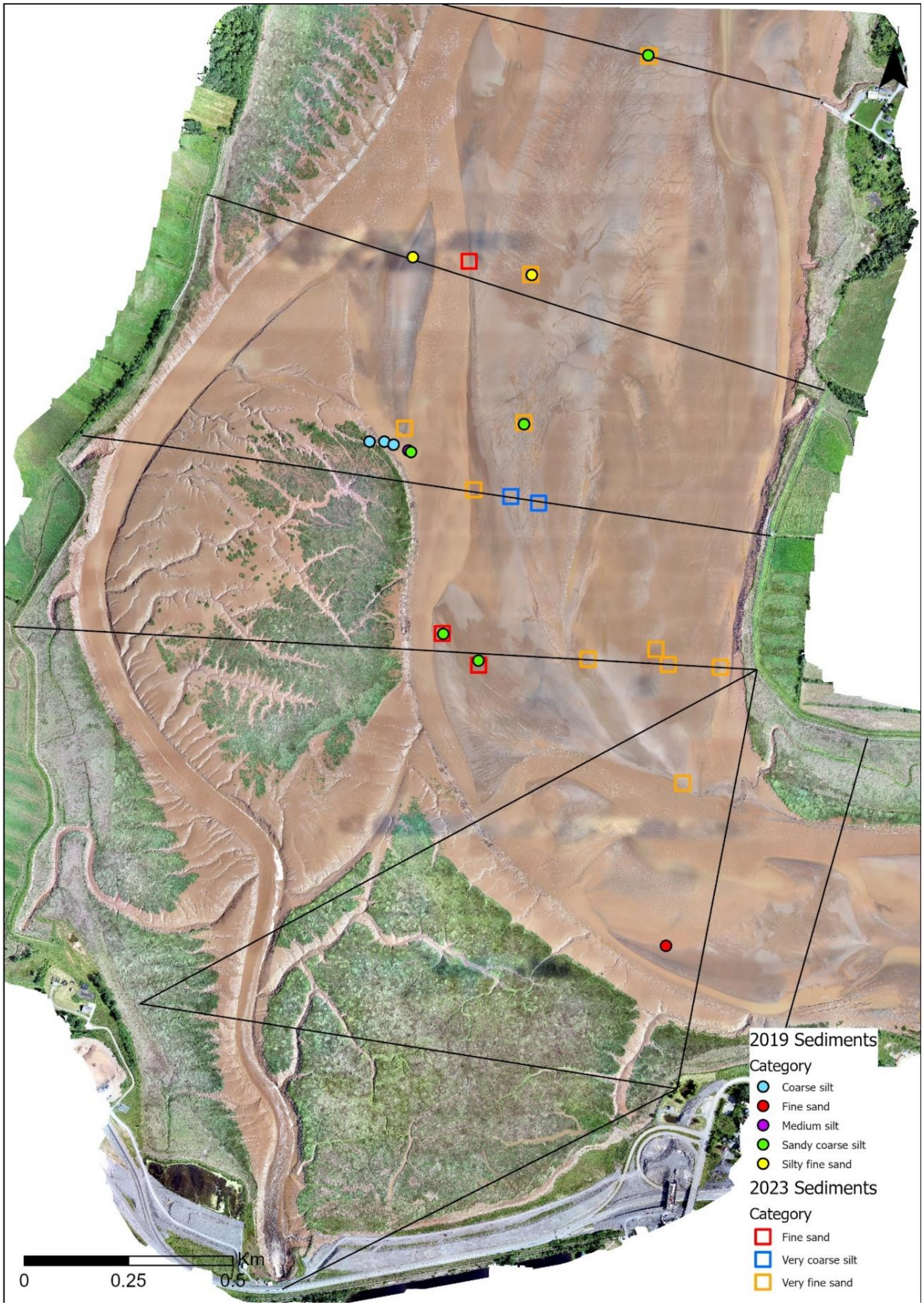

Figure 4.17: Sediment category distribution for both 2019 and 2023.

4.4 Changes in Vegetated Area

Across the entire system, the general pattern is that vegetation expands to establish in new areas, or the volume of vegetation increases within an area it is already established (Figure 4.18). In the few areas where vegetated area appears to be decreasing, it is usually along the edge of a bank. As sediment erodes, blocks of vegetation also calve off the edge as can be seen occurring along the eastern edge of the Newport Bar (Figure 4.19). Even though vegetated area appears to be decreasing along the erosive edge of that bank, vegetation on top of the bar is establishing further toward the west side and the density is overall increasing across the Newport Bar (Figure 4.20). Between 2019 and 2021, vegetation spread further south on the bar as well as further west. After 2021 however, the western extent of the vegetation remained relatively stable. The most notable change occurred along the Southeast edge of the bar between 2021 and 2023. In 2022, sparse vegetation began colonizing the area along where the edge of the Newport Bar was in 2019. As seen in section 4.2.1, the channel separating the Newport Bar from the Windsor Marsh began infilling in 2022 which created a greater surface area for vegetation to establish (Figure 4.10). Between 2022 and 2023, the vegetation density increased in this area and along the southern tip. Between the four years, the most consistent vegetated region of the Newport Bar is the northeast edge, which is remained largely unchanged with vegetated area primarily changing based on erosion.

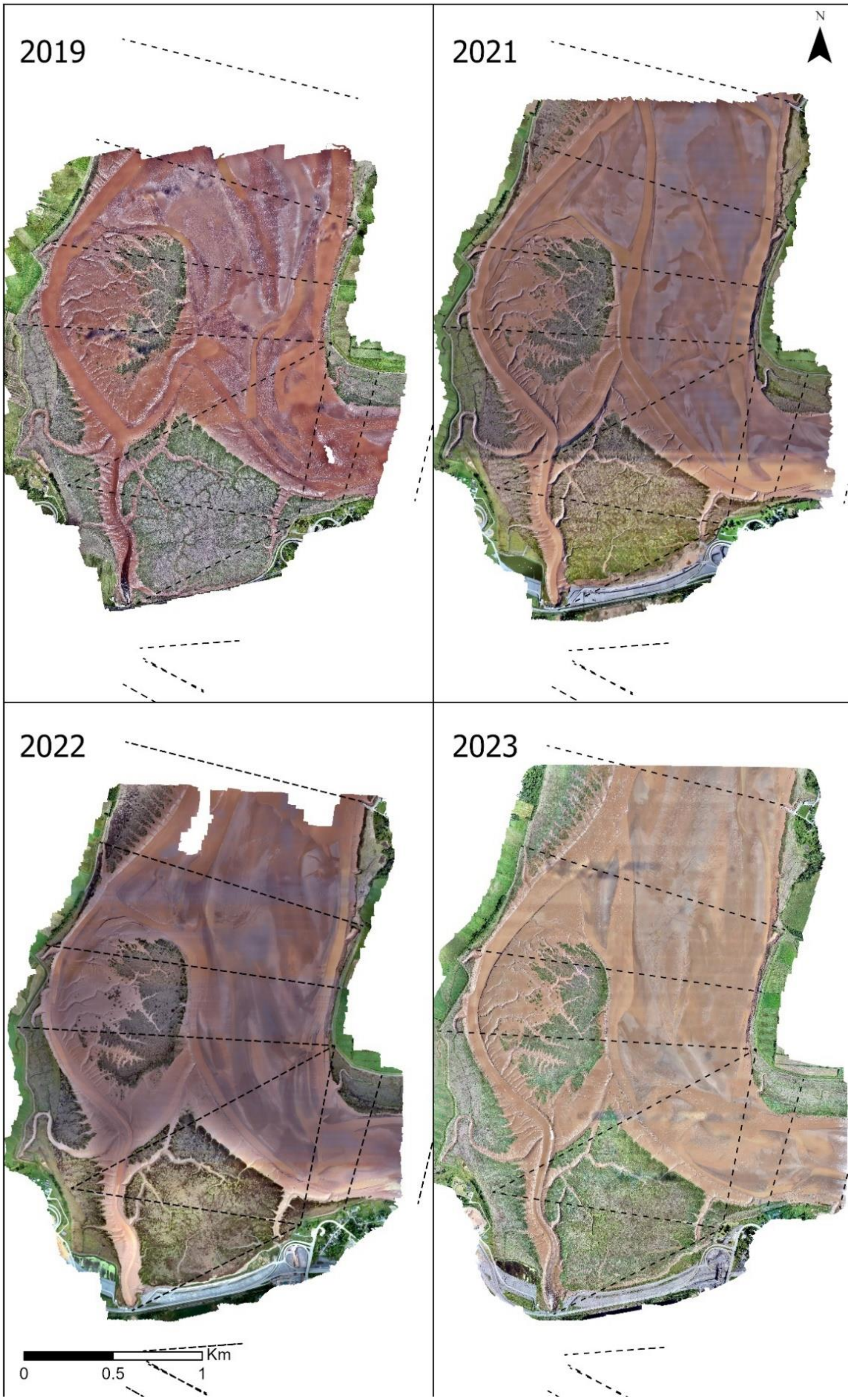

Figure 4.18: Vegetated area across the entire study area during the four years of data collection during the study period.

Figure 4.19: Erosion along the eastern edge of the Newport Bar at low tide with blocks of vegetation being eroded on August 4th, 2023.

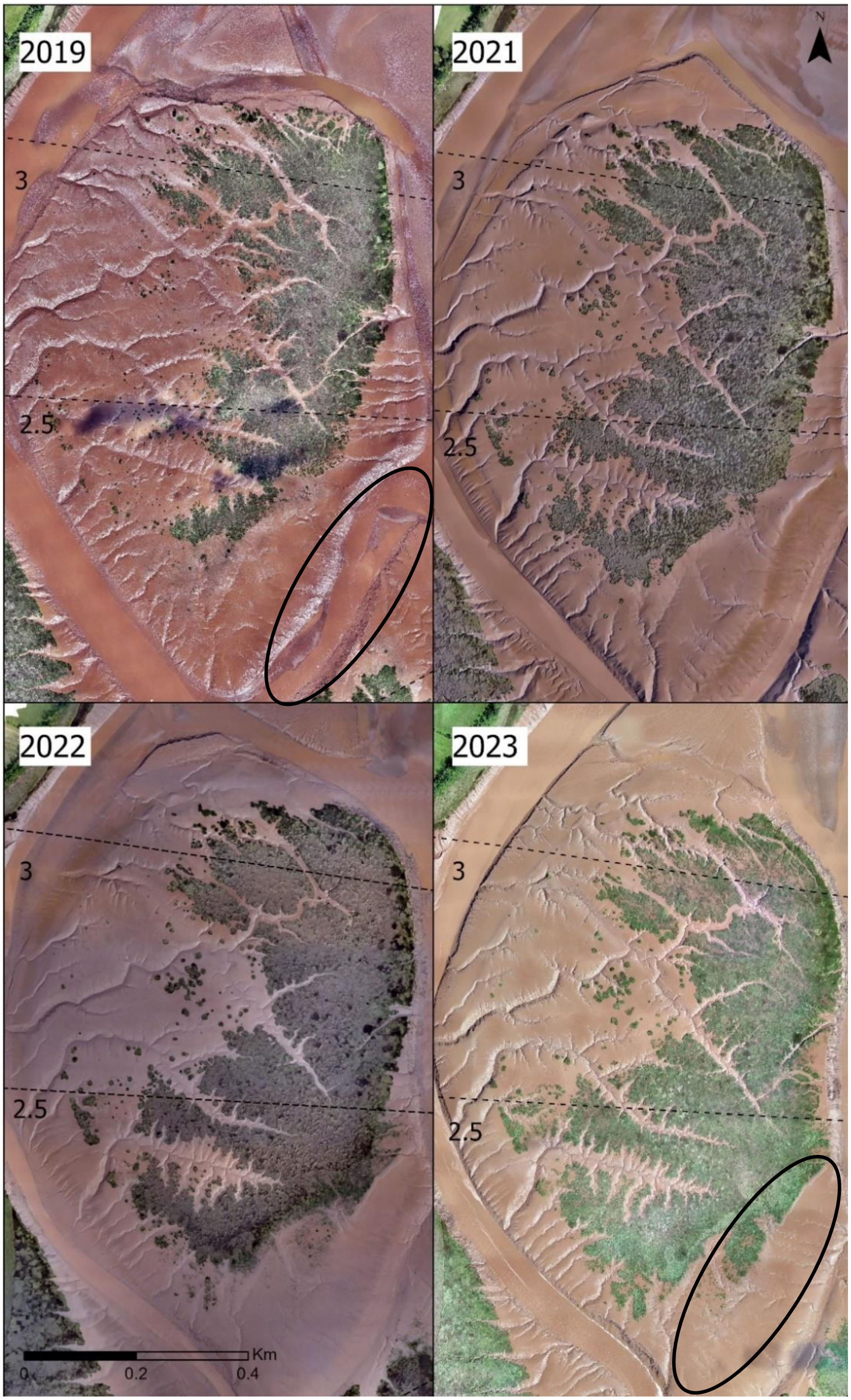

Figure 4.20: Changes in vegetation across the Newport Bar with emphasis on the southeastern channel infilling. Lines 2.5 and 3 are used for reference.

Along the Southeast bank of the channel that separates the Newport Bar from the Windsor Marsh, intersecting Transect Line 2, vegetation advanced northward by approximately 65m between 2019 and 2023 (Figure 4.21). Between 2019 and 2021, change was relatively minor with a small expansion of vegetation rimming the northern tip. Between 2021 and 2022, vegetation expanded much further than between 2019 and 2021, however the vegetation is very sparse. Between 2022 and 2023, the maximum reach of vegetation did not change substantially, but vegetation became much denser. The north edge of the St. Croix River where it meets the Avon River intersecting Line T experienced an expansion of vegetation which was associated with erosion of sediments (Figure 4.22). Unlike other locations of the study area, large changes occurred between 2019 and 2021. The southward expansion of approximately 25m was most notable during this period. Between 2021 and 2022, there was very minimal change in vegetated area. Between 2022 and 2023, the most notable change was a loss of vegetated area by about 30m at the direct intersection of Line T. This was the first case of vegetation loss that was not associated with erosion. Along the Northwest bank of the study area, changes in vegetated area are difficult to compare due to differences in area surveyed (Figure 4.23). For the areas that are comparable, between 2021 and 2022 vegetated area became denser while the extent of vegetated area did not change much. Between 2022 and 2023, there was minimal change in either density or vegetated area. This is a different pattern than the rest of the study area which saw either an increase or decrease in area between 2022 and 2023.

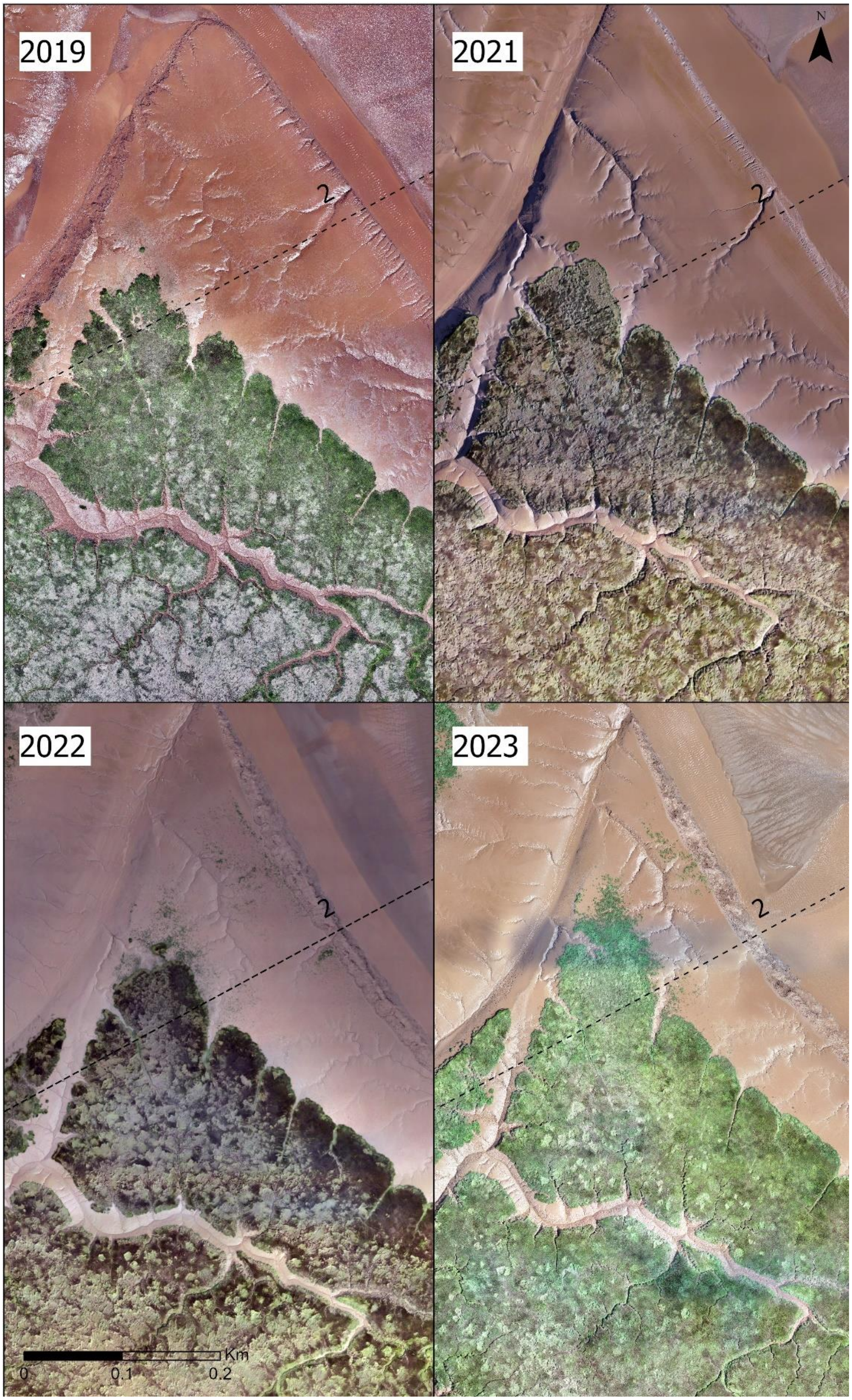

Figure 4.21: Changes in vegetation along the northern tip of the Windsor Marsh parallel to the channel along the south of the Newport Bar with Line 2 for reference.

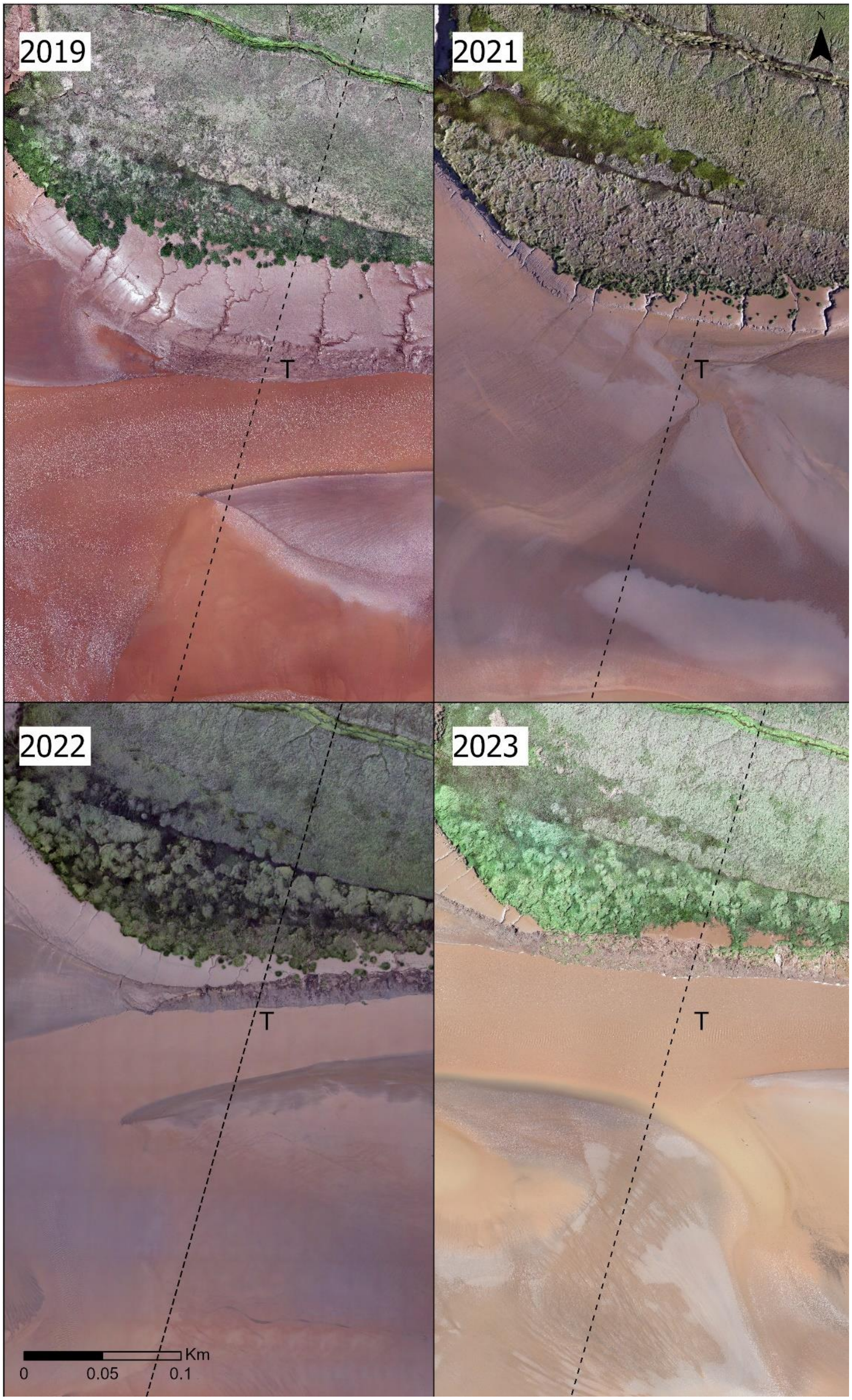

Figure 4.22: changes in vegetation along the northern bank of the St. Croix River with Line T for reference.

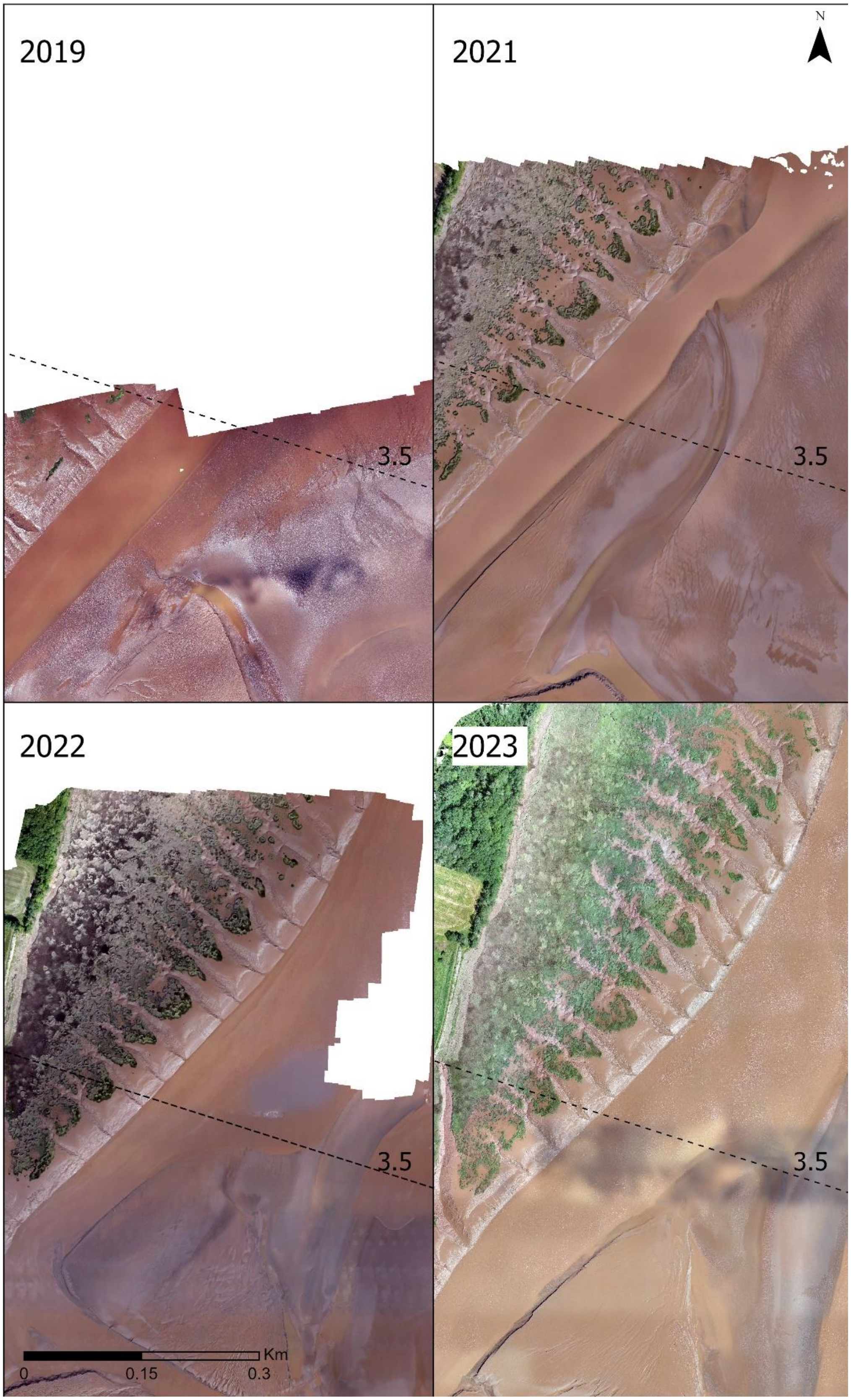

Figure 4.23: Changes in vegetation on the bank of the northwestern corner of the study area with Line 3.5 for reference.

4.5 Timeline

4.5.1 Natural influence

The Avon River has an asymmetric, semidiurnal tide. Spring tides occur roughly once every two weeks, when tidal maximums and minimums are much more pronounced than during neap tides (Figure 4.24a, Figure 4.25a, Figure 4.26a, Figure 4.27a, Figure 4.28a). In addition to spring and neap tidal cycles, king tide cycles can be observed (Figure 4.24a, Figure 4.25a, Figure 4.26a, Figure 4.27a, Figure 4.28a). King tides occur twice a year and result in amplified spring tides. Between 2019 and 2023, king tides occur in the spring and fall early in the study period, and shift to winter and summer later in the study period (Figure 4.24a, Figure 4.25a, Figure 4.26a, Figure 4.27a, Figure 4.28a). On top of the spring tide and king tide cycles, there is also an 18-year saros cycle which amplifies tidal maximums and minimums again. The last Saros maximum was in 2015 while the last minimum was in 2006 (Robichaud, 2018) Although neither of these were years that data collection was done, sampling was conducted in both 2007 and 2017 which are still near the maximum and minimum of the Saros cycle, so patterns can be inferred.

Maximum precipitation often occurs in late summer to early fall, which is consistent with hurricane season in Nova Scotia. 2022 was an anomalous year where February had the highest single day precipitation (Figure 4.27b). Large precipitation maximums in the fall are often related to significant hurricanes. In 2019, Nova Scotia experienced Hurricane Dorian in early September which corresponds to the peak in Figure 4.24b. In 2020, Hurricane Teddy resulted in substantial rainfall in late September (Figure 4.25b). While there were no noteworthy hurricanes in 2021, significant rainfall consistent with levels similar to hurricanes still occurred in early September (Figure 4.26b). 2022 brought Hurricane Fiona in late September which again corresponds to a peak in precipitation (Figure 4.27b). 2023 had two significant precipitation events, the first being in early June which resulted in a daily precipitation amount of 70mm (Figure 4.28b) The second was in late July which resulted in extensive flooding in the upstream portions of both the Avon River and the St. Croix River (Figure 4.28b). Intense storms with a lot of precipitation seem to be becoming more frequent which could influence the ecomorphodynamics of the Avon River Estuary.

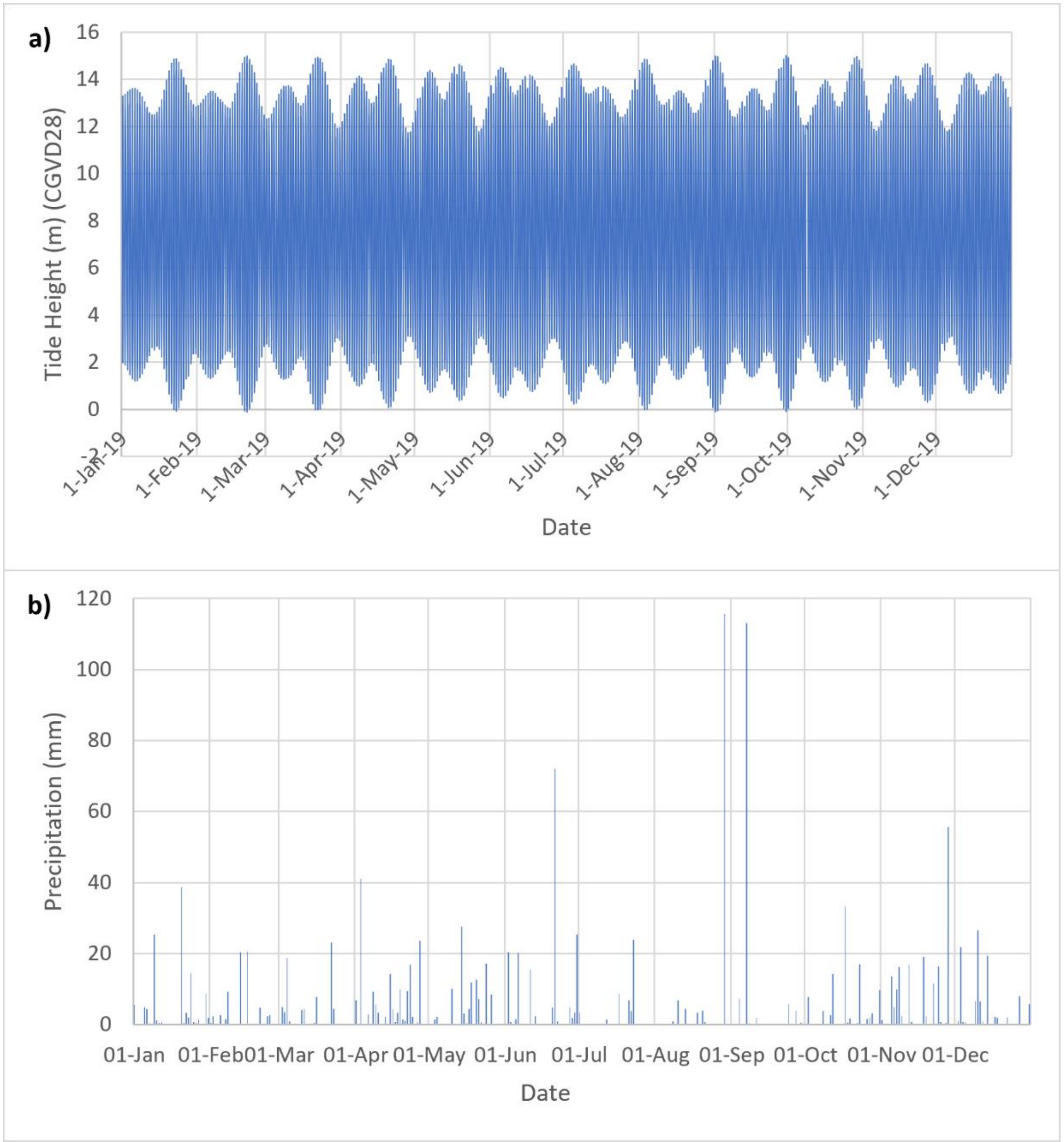

Figure 4.24: Tidal cycles and recorded precipitation for 2019.

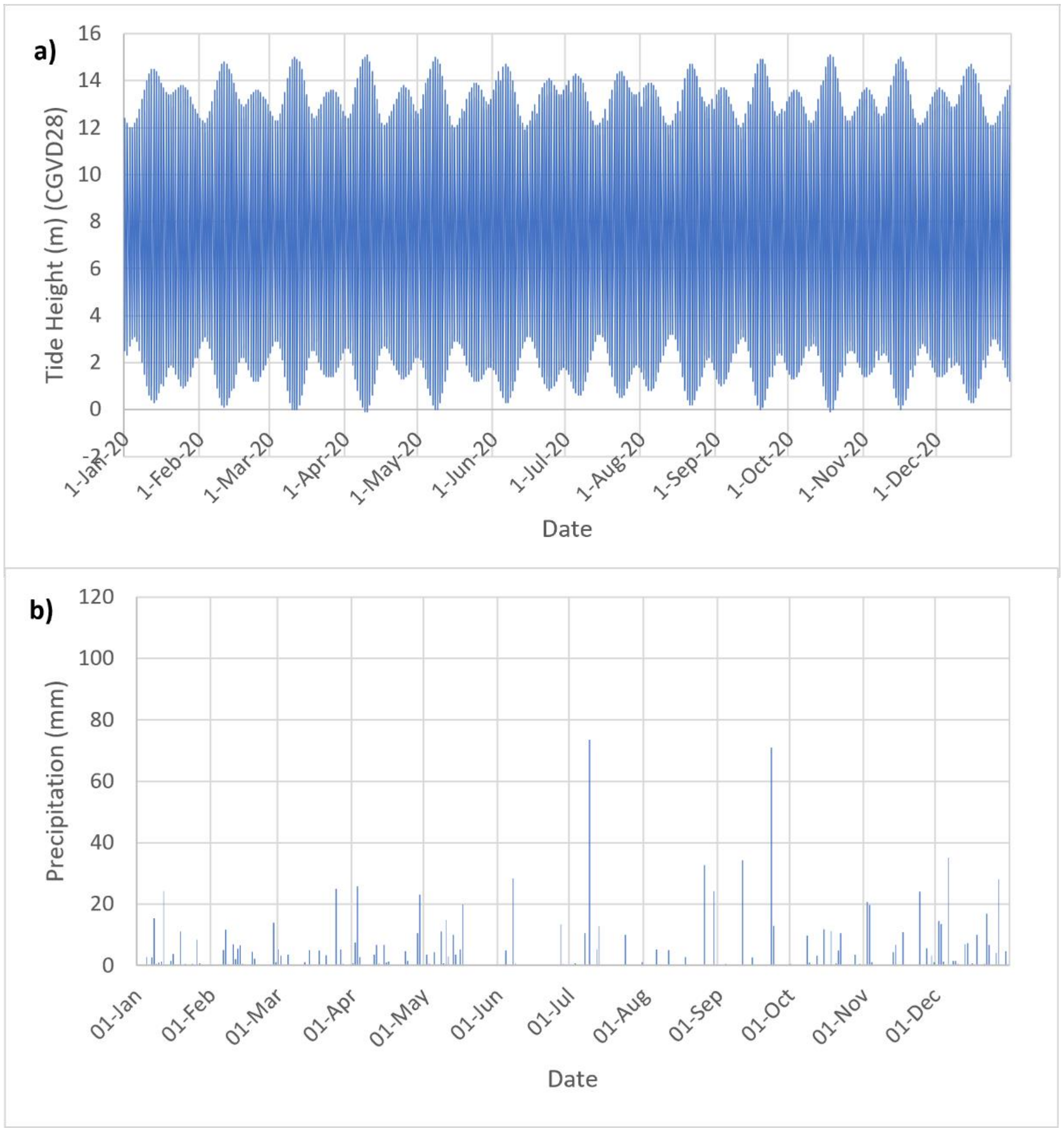

Figure 4.25: Tidal cycles and recorded precipitation for 2020.

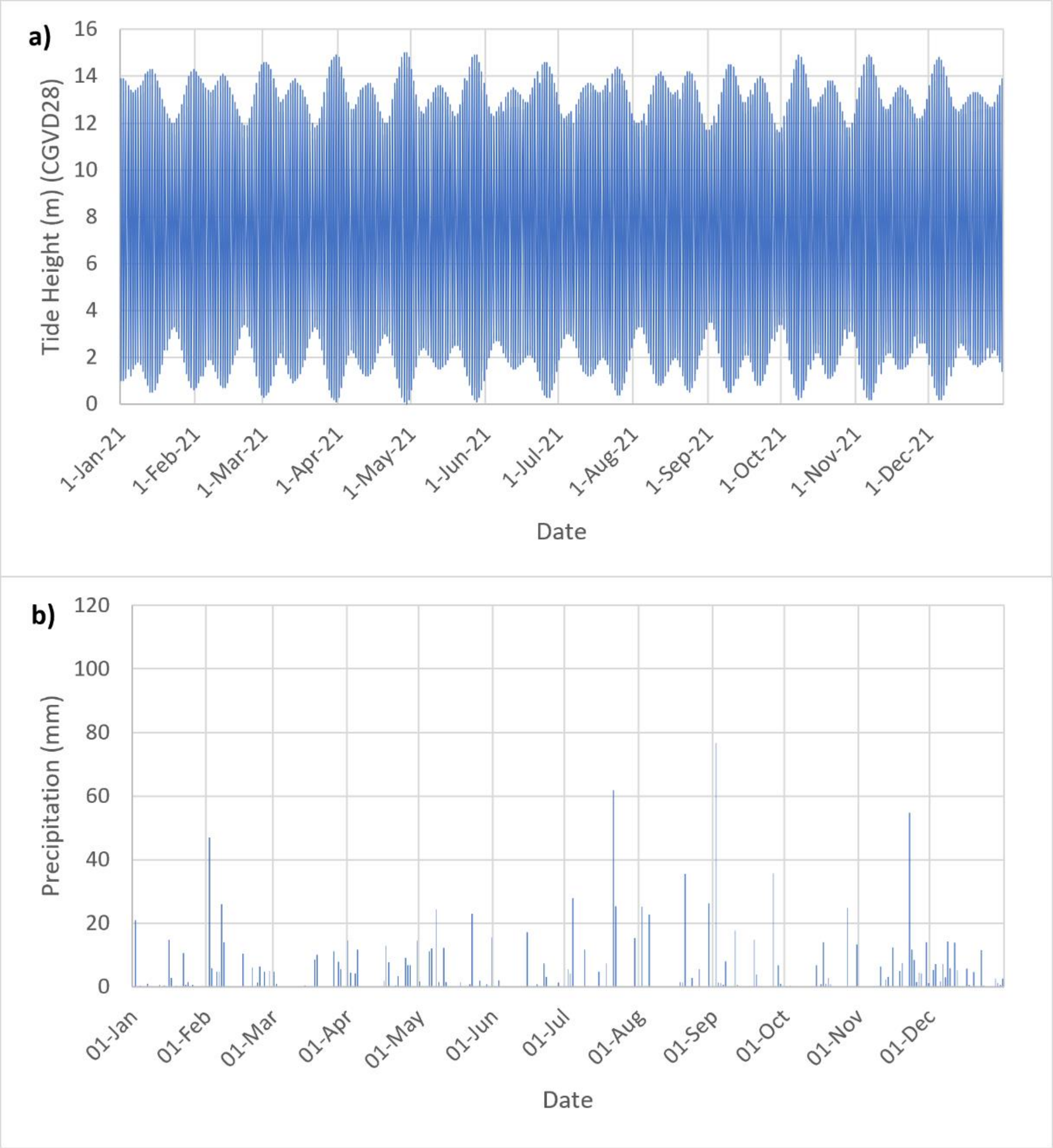

Figure 4.26: Tidal cycles and recorded precipitation for 2021.

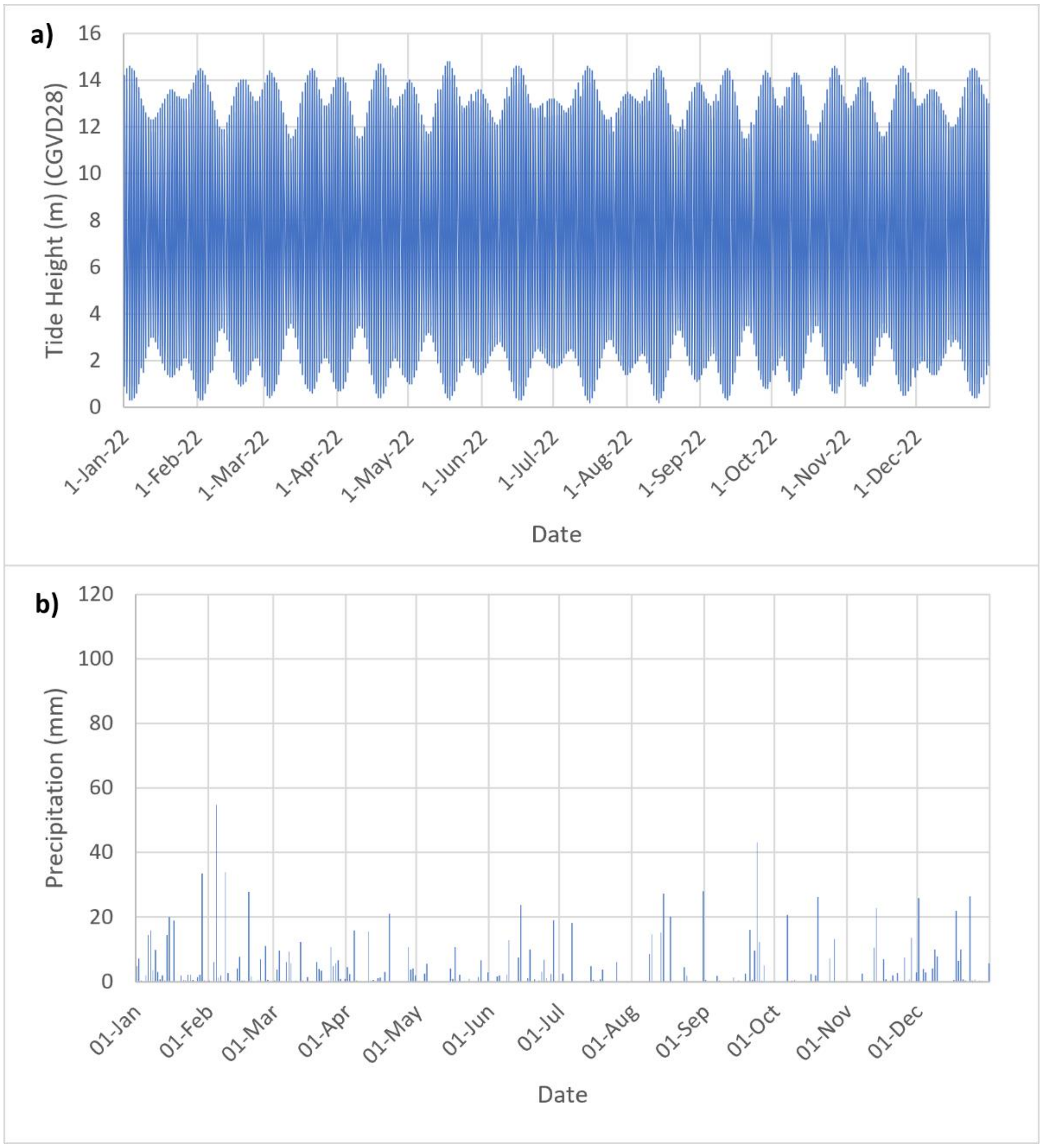

Figure 4.27: Tidal cycles and recorded precipitation for 2022.

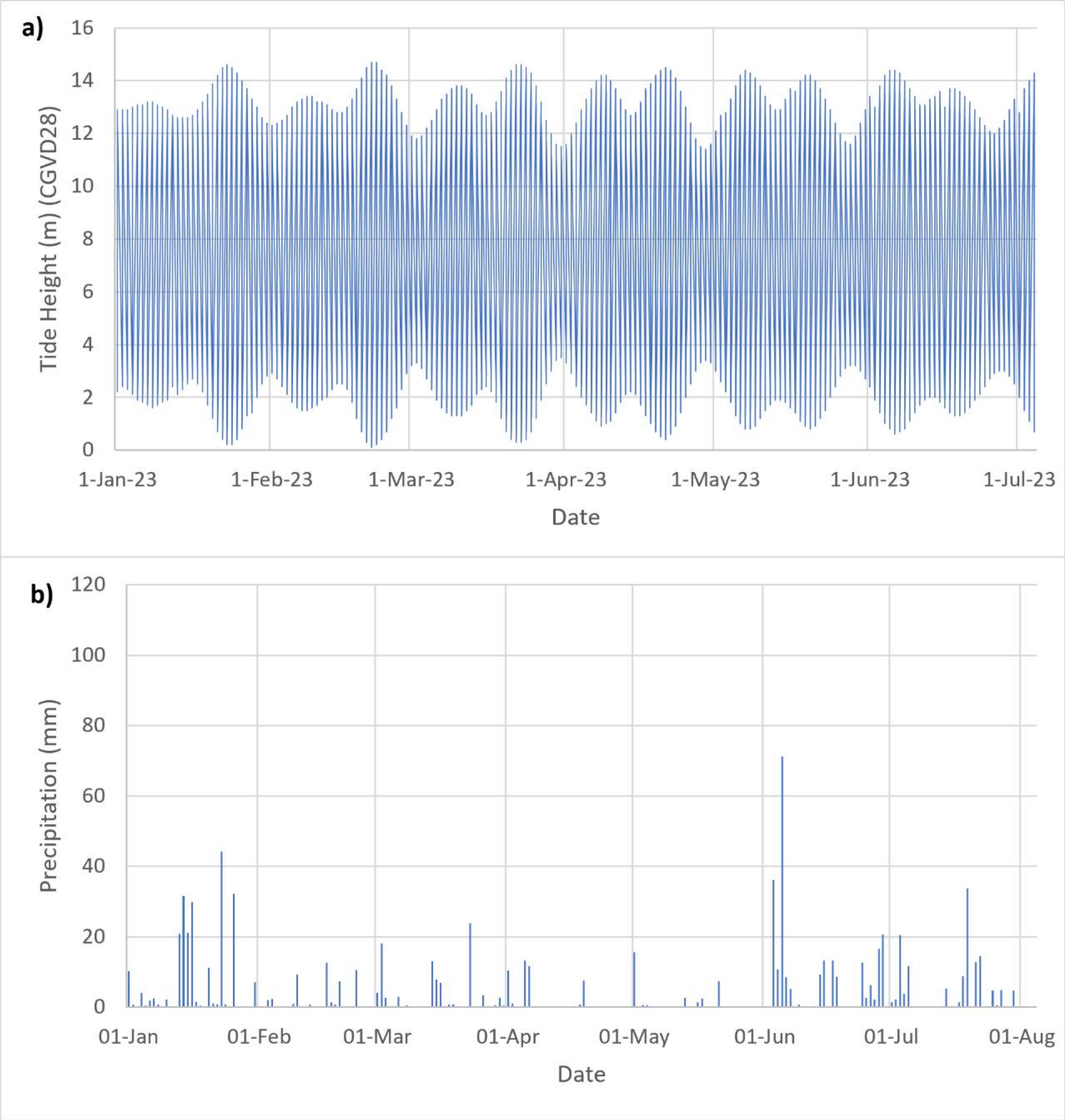

Figure 4.28: Tidal cycles and recorded precipitation from January to August 2023.

Ice patterns within the Avon River Estuary are difficult to quantify due to the nature of data collection. The Sentinel-2 satellite passes over the study area only once every 5 days which limits observation periods to begin with. Additionally, if there are clouds covering the study area, that imagery for that sample is unusable. Since we are interested in ice distribution, we are looking at months where cloud cover from winter storms is common. This means that there are very few viable images. However, based on the imagery available, it appears as though ice patterns within the system remain fairly similar with ice first appearing in the estuary around January with the last recorded ice in March (Figure 4.29).

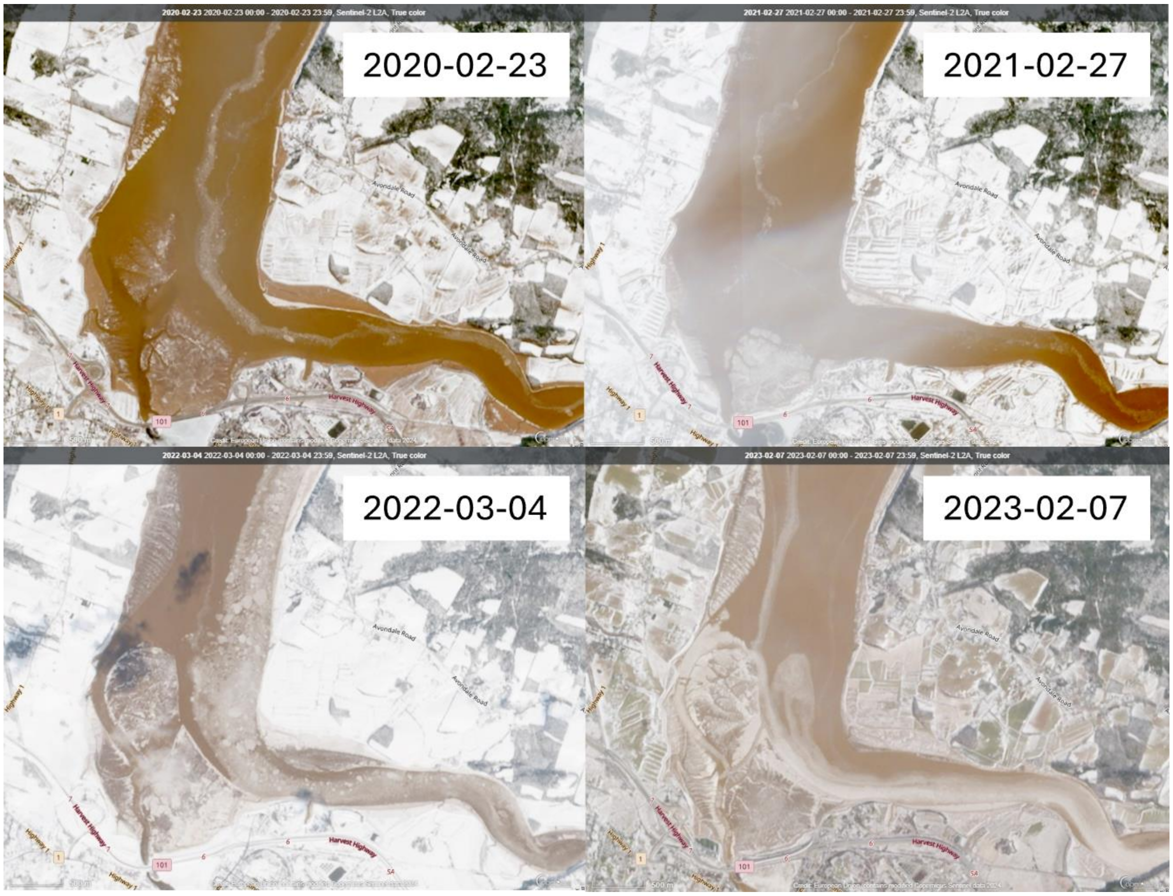

Figure 4.29: Ice distribution within the Avon River Estuary from 2020-2023.

4.5.2 Anthropogenic Influence

Human activities in the area began in 2019 when the first phase of construction on the twinned portion of highway began. Originally, it was estimated that the project could be completed by 2022, however disagreement on what should be done with the aboiteau has delayed the project. Initial planning and the start of construction was done between 2019 and 2022. In 2021, there was partial infilling as evidenced by Figure 4.18 along the southern edge of the orthophoto. While it appears as though the newly constructed road cuts through transect Line 1AA1A, there is no infilling as observed in 2022 (Figure 4.30). We believe that aggregates were placed down and allowed to settle during this period before paving the newly twinned section of the highway. In 2022, the channel was completely infilled, and the twinned highway structure was completed, with the exception of the portion that crosses the tide gate. Since 2022, not much has been done in the area, however the next phase of construction will encompass alterations to the aboiteau structure.

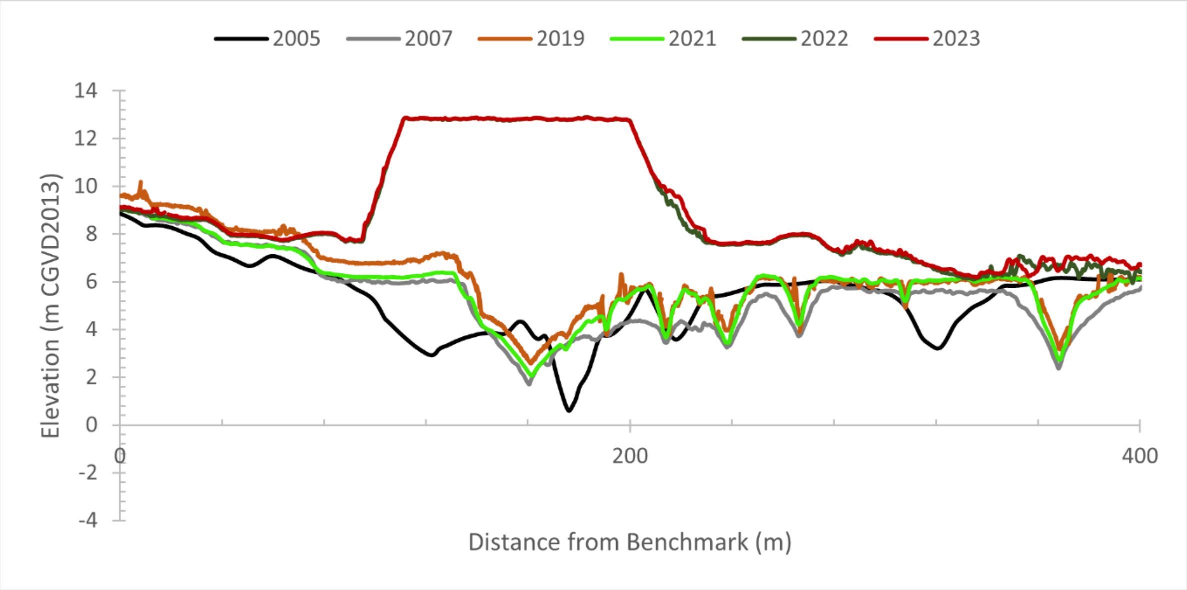

Figure 4.30: Influence of channel infilling from the construction of the twinned highway in 2022 on the cross-sectional profile of Transect Line 1AA1A.

Prior to 2021, the tide gate within the aboiteau was managed so that there was no saltwater intrusion into Lake Pisiquid on a rising tide, and the water level within the lake remained relatively constant. The DFO Ministerial Order of 2021 changed the gate management and called for the tide gate to remain open during low tides, and for a minimum of ten minutes on incoming tides (Palmeter, 2021). During this period, water would be exiting the tide gate more consistently which could have increased erosive power. Additionally, an open gate on an incoming tide would allow for sediment transport upstream of the causeway, instead of deposition being primarily concentrated downstream of the causeway. Gate operations were maintained in this order until June 2023 when a provincial Emergency Order overturned the DFO Ministerial Order. This reinstated the gate functions which were in effect prior to 2021. While it is beyond the scope of this study, quantifying openings and closures of the tide gate in relation to precipitation events, tide levels, and lake water levels would provide information on tidal prism exiting the tide gates. For the purpose of this study, we will treat May 2021- June 2023 as a period of opened gate and increased consistency in upstream discharge.

4.6 Ecomorphodynamics Summary

Most of the notable changes occur within one of four areas, the main sluice gate channel, the Windsor Marsh complex, the Newport Bar, or the northern bank of the opening of the St. Croix River (Figure 4.31). Within the main sluice gate channel, change is limited primarily to the banks of the channel and the opening of the marsh channel into the main sluice gate channel (areas A and B in Figure 4.31). The banks of the main sluice gate channel in area A have two main components. Within about the first 100m, the channel straightens between 2019 and 2023 which can likely be attributed to changes in the management of the tide gate due to the close proximity to it. Further down the main channel, there is increased sinuosity despite a primarily erosional environment, as evidenced from the decrease in elevation. Area B has exhibited substantial deposition at the opening of the marsh channel. Sediments have protruded into the channel and have likely impacted the increased sinuosity in the northern part of Area B.

The Windsor Marsh exhibits changes primarily along the northeast bank (area C in Figure 4.31). This area has seen substantial erosion between 2019 and 2023 which has resulted in a shift of the position of the channel thalweg within the St. Croix. The erosion of the bank has had minimal impact on vegetated area and overall, vegetation was found to be expanding in this area with notable increase in vegetation on the northern tip of the Windsor Marsh. The other difference in this area was a decrease in channel wetted area, wetted perimeter, and width in 2022 when the highway was twinned (area D in Figure 4.31).

The Newport Bar exhibited the most change within the system. The most prominent was the infilling of the channel that separates the Newport Bar from the Windsor Marsh which occurred primarily between 2021 and 2023 (area E in Figure 4.31). The infilling cut off a large portion of water flowing from the sluice gate and as a result more water is flowing to the west of the Newport Bar. This infilling also allowed for vegetation to expand and colonize the new area. Vegetation across the entire Newport Bar increases by colonizing new areas and filling in more sparsely populated zones (area F in Figure 4.31). Along the eastern edge of the Newport Bar, there has been erosion which ties into the erosion within area C (area G in Figure 4.31). However, since the Newport Bar is heavily vegetated, blocks of sediment that calve off the edge carry vegetation with them, providing new colonization opportunities. Finally, along the northern tip, there has been patterns of both erosion and accretion (area H in Figure 4.31). The eastern edge of the tip is more prone to erosion while the western edge has seen more accretion especially between 2022 and 2023.

Finally, the northern bank of the opening of the St. Croix has seen a gain of sediments followed by erosion between 2022 and 2023 (area I in Figure 4.31). While this area does not count for a substantial portion of the study area, it is interesting to note that this is one of the only areas where there has been a loss of vegetation. A summary of the most notable results can be found in Table 4.4.

Figure 4.31: Notable changes throughout the Avon River Estuary between 2005 and 2023.

Table 4.4: Summary of important changes observed within the Avon River Estuary between 2005 and 2023.

	Pre-construction			Post-construction			
	2005	2007	2017	2019	2021	2022	2023
Cross-sectional Profiles	Generally minimal change		More change, longer time period	Minimal changes, general vertical elevation gain, most changes occur around the edges of the bank			
Cross-sectional Area			High area and perimeter	High area and perimeter		Decrease near highway	
Surface Elevation Change		Elevation gained on top of the Newport Bar and northeast edge of the Windsor Marsh, elevation loss North Newport Bar and channel between Newport Bar and Windsor Marsh				Elevation loss eastern edge of Newport Bar, elevation gain in channel on western edge of Newport Bar and between Newport Bar and Windsor Marsh	Elevation loss along eastern edge of Newport Bar, northern edge of St. Croix
Volumetric Change		Highest total and net change, longest period, lowest yearly changes				66% volume gain, 34% volume loss	55% volume gain, 45% volume loss
Grain size Analysis				Newport Bar sediments, finer, more variable			General coarsening, samples added
Vegetation Changes				General expansion and thickening of vegetation across the study area			
Timeline		Hurricane Noel		Hurricane Dorian	DFO gate opening	Highway twinning, hurricane Fiona	Rainfall and flooding, gate closure

5. Discussion

This study set out to determine if there had been a change in ecomorphodynamics within the Avon River Estuary between a period of regular human influence, 2007-2017, and a period of increased human influence, 2019-2023. We made use of RPAS, bathymetric, and LiDAR data paired with sediment samples to identify changes in channel cross-sections, surface elevation, sediment volume, grain size, and vegetated area. We predicted that there would be a change in ecomorphodynamics during the period of increased human activity and that most of these changes would be related to anthropogenic influence, as opposed to changes in natural factors. Results showed that most of the notable changes within the system were concentrated between 2019 and 2023, and most were focused near the causeway where the human influence was occurring (Table 4.4).

5.1 Channel Infilling

One of the most obvious changes within the estuary was the rapid infilling of the channel between the Newport Bar and the Windsor Marsh between 2021 and 2022 (Figure 4.10). We believe that since this infilling corresponded to both the DFO Ministerial Order to open the gates in 2021, and marsh infilling due to highway construction in 2022, human interference may hold strong influence over the infilling. While there was not a loss in elevation within the channel between 2022 and 2023 (Figure 4.10), Zone 1 did experience a net volume loss during this time. This corresponded to the provincial emergency order in 2023 which returned gate operations to pre-2021 conditions, prioritize maintaining lake level through gate closure (Table 4.4). The net loss of sediment volume and the channel infilling when considered with tide gate operation schedules suggests that manipulation of the tide gate may influence sedimentation in that zone. Jinqiong et al., 2020, suggested that when tide gate management allows for storage of freshwater upstream by remaining closed, there is less sediment upstream than when ocean waters are allowed to intrude because the suspended sediment content of the Yongding River is less that the suspended sediment content of an incoming tide. As a result, freshwater that passes through on a falling tide is clearer and less sedimentation takes place (Jinqiong et al., 2020). If the suspended sediment concentrations of the Avon River were similar to those of the Yongding River, this could mean that during gate operations prior to 2021, discharging water was not carrying enough sediment to promote extensive deposition. However, several studies suggest that when the gate was operating so that it was mostly closed, sedimentation rates should have been higher since incoming, sediment laden seawater would have been blocked and velocities would have decreased promoting sedimentation (Mu & Huang, 2013; Tilai et al., 2020; Wu et al., 2020).

The construction and Windsor Marsh infilling in 2022 is a more likely explanation for how the channel between the Newport Bar and Windsor Marsh was infilled. Since the majority of the literature supports intense deposition downstream of structures due to loss of water velocity and promotion of sediment deposition (Mu & Huang, 2013; Tilai et al., 2020; Wu et al., 2020), the infilling of a tidal channel on the Windsor Marsh by the highway, which previously circulated incoming tidal water, is instead acting as a barrier. When the causeway was originally constructed in 1970, rapid sedimentation occurred immediately downstream, resulting in the establishment of the Windsor Marsh (van Proosdij & Townsend, 2004). It is likely that the stagnation of tidal waters is again promoting sedimentation near the new causeway. The stagnation of water likely occurs at high tide when the tide gates are closed so water now cannot move upstream or be distributed across the marsh platform as easily. Because of this, suspended sediment likely settled out of solution near the tide gate (Yang et al., 2020). However, since flow velocities exiting the tide gate are too high to allow for sedimentation, deposition is primarily occurring further downstream of the tide gate, within the channel between the Newport Bar and the Windsor Marsh. As this channel continues to infill, it is disrupting flow patterns as water exits the St. Croix River and the tide gate. Altered flow patterns could cause a change in sedimentation and erosional processes. For example, if water exiting the St. Croix River is not allowed to easily pass through, water could instead be concentrated along the eastern edge of the Newport Bar, which may be contributing to the westward migration that it is experiencing. Overall, more analysis needs to be done to determine if the infilling of the channel is correlated to a change in gate operation and if the infilling is causing a shift in flow patterns, altering sedimentation and erosion. We would recommend hydrodynamic data, such as water velocities and water currents, be monitored between the tide gate and the infilling channel. Additional monitoring of suspended sediment concentrations and the collection of surface sediment samples both upstream of the tide gate and in the infilling channel could also help determine what may be causing channel infilling.

5.2 Tide Gate Channel Changes

From 2019-2023 changes within the main tide gate channel have been minimal. There has been a consistent loss of elevation, however it is generally around 1m and concentrated immediately along the banks (Figure 4.9). While it may seem odd that the area closest to the highly manipulated tide gate experienced few changes, a combination of how the gate is managed and the construction of the new twinned section of highway can account for the lack of change. Under normal gate operations, in order to maintain the water levels in Lake Pisiquid, a minimal amount of water was allowed to pass through during low tides. This would not have created high energy flow with substantial erosive power and any erosion would have been centered in the channel thalweg where data is unavailable rather than on the banks. Once the tide gate operations changed in 2021, erosive power may have increased, but erosion still would have been concentrated in the lowermost portion of the channel immediately downstream of the gates. Prior to the infilling of marsh area for highway construction, tidal channels on top of the marsh promoted circulation and distribution on top of the Windsor Marsh. Infilling cut off the channel and promoted stagnation inducing sedimentation (Colina Alonso et al., 2021). This process likely helped fill the channel between the Newport Bar and Windsor Marsh at the end of the main tide gate channel, creating a feedback loop. Feedback loops are common in estuaries, particularly when examining sedimentation processes (Zhang et al., 2018). Within the Avon River Estuary, the infilling of the tidal channel on the

Windsor Marsh by the construction of the newly twinned portion of highway caused water velocities to decrease with nowhere to circulate. As a result, this promotes sedimentation within the main tide gate channel which then causes deposition between the Newport Bar and the Windsor Marsh. The infilling of that channel will likely cause further disruptions to flow patterns and cause further sedimentation. The depositional process near the main tide gate channel likely evened out any excess erosion caused by the increased discharge from the tide gate which explains why few changes were observed.

5.3 St. Croix River Influence

The St. Croix River remained relatively stable between 2007 and 2023, with the majority of the pronounced changes taking place in the upstream reaches, furthest from the causeway. The location of changes relative to sources of human interference suggests that the St. Croix River is mostly uninfluenced by anthropogenic activities. This is supported by van Proosdij and Baker, 2007, where they found the St. Croix River was influential in regulating the morphology of the Avon River Estuary, and instead exhibits relatively few changes. This was likely exaggerated after the channel between the Newport Bar and the Windsor Marsh infilled between 2021 and 2022. Because of this, we believe that natural factors, either tides or precipitation, hold more influence on morphology than anthropogenic factors, however, further analysis is required. The St. Croix River contributes 40% of freshwater inputs to the system, which is a substantial portion (van Proosdij & Baker, 2007). This level of discharge coupled with the fact that the St. Croix River heavily regulates the morphology of the Avon River near the confluence suggests that precipitation and river discharge may hold more influence over morphologic changes observed than tides. Work by Robins and Davies has suggested that the further landward tides move within an estuary, the more friction they will experience, and the more sedimentation will be likely over erosion (Robins & Davies, 2010). Instead, since 2017 the dominant trend has been erosion which would suggest that the sedimentation from slowing tidal velocities may not be dominant in the system. Studies have shown that in tidally dominated estuaries, river discharge from tributaries can have a large impact on channel morphology (Yu et al., 2020). Studies have also shown that increased precipitation can increase river discharge, which has been known to increase erosive power (Conway & Hulme, 1993). While the precipitation data for every survey year is not readily available, between 2019 and 2023, 2019 had the highest precipitation. 2019 also exhibited the largest wetted area for Lines C and R, which are the furthest upstream. To further our hypothesis, more precipitation data should be obtained and analyzed, and hydrodynamic monitoring should be conducted in the future.

5.4 Vegetation and Sedimentation

Within the system, changes in vegetated area are mostly associated with changes in elevation. On the Newport Bar and the Windsor Marsh, where elevation is increasing in association with sedimentation. Similarly, vegetation was lost along the northern bank of the St. Croix River where there was a decrease in elevation associated with erosion as well as block failure along the eastern edge of the Newport Bar due to erosion (Figure 4.19). Since expansion of vegetation remained fairly constant throughout the study period, we hypothesize that vegetated area is mostly uninfluenced by any of the influences we originally identified, human interference, tidal cycles, or precipitation patterns. Instead, we propose that sediment and vegetation exist in a feedback loop where the existence of one promotes the other. Multiple studies have shown that vegetation promotes sedimentation within estuaries by increasing friction and decreasing flow velocities while the root systems anchor sediments and prevent erosion (Bass et al., 2022; Hickin, 1984; Moskalski & Sommerfield, 2012; Vandenbruwaene et al., 2013). Additional studies have found that unstable and eroding sediment surfaces result in a decrease in vegetation as sediment is necessary for growth (M.-Y. Hu et al., 2019; Möller & Spencer, 2002). Within the Avon River Estuary, an expansion of vegetated area promotes sedimentation which will provide a base for more vegetation to colonize forming a positive feedback loop. Evidence of feedback loops found in estuaries around the globe supports our hypothesis which states that sediment and vegetation positively impact each other. However, it is important that while the two are currently not substantially impacted by outside factors, a shift which negatively affects vegetation can likely negatively impact sedimentation.

5.5 Grain Sizes and Sediment Distribution

Across the estuary, between 2019 and 2023 sediment has gotten coarser, in both repeated and new locations (Figure 4.17). Since this pattern occurred during the period of increased human activity, we believe that the coarsening of sediment is likely due to either alteration from construction activities, or changes in how the tide gate was managed. However, since changes are exhibited through the entire study area and grain size data is unavailable upstream, we cannot conclusively determine this. Between these two sample periods, the tide gates were required to open for a period of tide on the incoming tide. We hypothesize that the fine fraction which was present in 2019 sediments may have been transported upstream. While we do not have sediment data upstream of the causeway beyond the initial sediment sampling conducted in 2019 to support this, we would expect that with the opening of the tide gate, the fine-grained sediments that are carried in suspension with an incoming tide would be transported through the tide gate and deposited upstream. This would mean that sediments upstream of the causeway should be finer now than they were when sampling took place in 2019.

A study conducted in the Hudson River Estuary examined the effect of narrow openings of storm barriers on sediment dynamics. They found that upstream of the structures, fine sediment content was greater in areas of deposition compared to downstream of the structures (Ralston, 2023). While this study seems to support our findings, studies which focus on the construction of dams suggest that damming structures promote the collection of fine sediment upstream of the barrier, which could contradict our hypothesis (Grant et al., 2013; Liu et al., 2023). However, tidal gates allow fresh water, and any fine sediments carried in suspension to pass through on a falling tide which does not result in the same sediment accumulation found with dams. To thoroughly test the hypothesis that fine grained sediments were transported upstream through the tide gate, sediment grain size analysis would have to be conducted on the upstream portion of the Avon River.

5.6 Implications

The changes that have been observed within the Avon River Estuary represent a response to external pressure. Changes in vegetation reflect changes in sedimentation which can be influenced by external factors, such as construction activities, like we have seen in between the Newport Bar and the Windsor Marsh. Even though the system is no longer in dynamic equilibrium, it is difficult to determine if the system is healthier now than it was during our baseline period. The system has been subjected to some unfortunate external factors, however it is adapting and working towards establishing a new equilibrium, possibly with new ecosystems developing in association with the melding of the Newport Bar and the Windsor Marsh, which should be viewed as positive. Overall, this study has found that human activities, particularly tidal gate manipulations and construction activities, strongly influence the ecomorphodynamics of the Avon River Estuary. While vegetation and changes further downstream from the anthropogenic activity did not manifest in substantial changes, large changes were observed close to the source of human impact. Because most of the changes were concentrated so close to the causeway, the area which has experienced substantial change has shrunk compared to previous reporting done in 2007 (van Proosdij & Baker, 2007). The influence of channel infilling and highway twinning has been found to hold more influence over ecomorphodynamics than we had originally thought. This study is unique in the sense that so much anthropogenic activity has taken place in such a small area within a brief time period. Additionally, it provides a preliminary analysis of ecomorphodynamic changes in association with anthropogenic influence, namely construction activities and tidal gate manipulation. Therefore, it has the potential to translate to other studies which examine the impacts of shifting human influence on intertidal ecosystems downstream of constructed structures. We have found evidence of feedback loops present in the system from channel infilling promoting more sedimentation which can then cause more infilling, to vegetation colonizing newly deposited sediments and acting to promote more sedimentation. These processes highlight the interconnectedness of the estuary on both an internal and external level. Moving forward, this study has shown that in environmental assessments, it is essential to consider how cascading effects will impact the system. For example, when considering infilling tidal channel networks, it is important to think about what the effects of stagnant water will be on sedimentation patterns.

5.7 Limitations, Recommendations, and Future Work

The most significant limitation of this study is that no statistical analysis was done to determine if there was a statistically significant correlation between observed physical changes within the system and changes in both natural and anthropogenic influences. The analysis that was done during this study used available data to make informed conclusions as to what may be influencing major changes observed within the estuary, however we cannot say with certainty that there is a correlation. While the literature and the data support the likelihood that most of the changes are caused by human activities, statistical analysis should be conducted to prove that the two are related. We suggest that this study could be used as a starting point for further investigation which would apply statistical analyses to determine correlation between changes in morphology and changes in influencing factors. Studies have already been conducted which correlate the influence of natural factors, tides and precipitation, on sediment dynamics in estuaries (Dike & Agunwamba, 2012; Kido et al., 2023). However, there are some uncertainties in the quality of the detailed tidal gate openings which may make statistical analysis difficult.

Another limitation in the study was the failure to consider influential variables other than tidal cycles, precipitation, ice, gate manipulation, and construction activities. While these were the most important to consider, we did not take into account any activity further upstream than the causeway. The operations of the Avon Hydro System could have impacted the availability of water flowing from upstream. Additionally, activities in the upstream portion of the St. Croix River that we did not examine could have impacted the system. We also did not consider any possible activity further downstream, like the dredging by Fundy Gypsum in Hantsport. Even though this did not occur during our study period, there could have been lasting impacts.

There were also some gaps within the data. Data that is missing due to long periods between fieldwork, such as between 2007 and 2017, makes it difficult to interpret patterns. For example, when considering cross-sectional area of Line 1 (Figure 4.4), it appears as though there is a decrease in area between 2007 and 2017. Due to a lack of data in between, we are only able to interpret a decline between 2007 and 2017. However, it is possible that any number of increases and decreases in cross-sectional area could have occurred between these two time periods. Similarly, with only two periods of sediment sampling and six overlapping samples, determining a pattern is difficult. Additionally, because data collection dates vary throughout the year, environmental conditions at the time of the surveys can create differences in the data. For example, surveys conducted in July would have a vegetation artifact and the vertical elevation may seem higher compared to surveys conducted in December, when vegetation is not present. Similarly, the maximum depth of the channel thalweg can vary by up to 2m depending on the season (van Proosdij & Baker, 2007). Moving forward, we recommend yearly fieldwork for data collection within the whole system, similar to how it has been done in recent years. We also think it would be worthwhile to conduct sediment, RPAS, and bathymetric surveys close to the causeway, near the Windsor Marsh, once a year in addition to the regular surveying. This would give a better picture of how the system is responding to anthropogenic interference. It may also be interesting to start collecting hydrodynamic data in areas of interest near the causeway to determine how flow patterns have been altered. Incorporating hydrodynamic data would create an opportunity for collaboration with hydrologists and oceanographers who have more experience in the area.

While past gaps in data collection cannot be rectified, what is done with the data could be improved. Due to time constraints, we were unable to quantify vegetated area within the estuary, create a DSM between 2019 and 2021, or calculate the volume of water exiting the tide gate. All of these would have provided a clearer picture of what changes were occurring within the estuary, however, with the data that was available, sufficient analysis was still conducted and we were able to understand the overall patterns of the system.

The complexity of this system provides an opportunity for interesting future research. In addition to completing statistical analyses on the data presented in this study, we propose future work which focuses on how tide gate manipulation affects the tidal prism of the system. Since detailed records of gate openings are available, once the quality of data has been confirmed, it would be interesting to calculate the discharge from the gates and compare that to changes observed as well as how changes in discharge affects the tidal prism. Additionally, examining how the changes in morphology affect tidal prisms could provide interesting information on the evolution of erosional and depositional properties within the estuary.

6. Conclusion

In this study, we examined the ecomorphodynamics of the Avon River Estuary in two distinct periods, one being from 2007-2017 where there was relatively low anthropogenic interference, the other being from 2019-2023 which was characterized by high anthropogenic interference. Based on evaluation of channel cross-sectional profiles, cross-sectional area, changes in surface elevation, volumetric changes, sediment grain size, and vegetated area, we have determined that there has been a change in ecomorphodynamics since anthropogenic activities increased in 2019. After successfully determining changes in morphology and examining patterns in both natural and anthropogenic drivers of change, we were able to determine the relative influence of both. Since most of the observed changes were located near the causeway along the edges of the Windsor Marsh and the Newport Bar, and we believe most can be attributed to anthropogenic activities due to a combination of location and timing. We believe that the construction of the newly twinned portion of Highway 101 and associated marsh infilling has had substantial influence on the ecomorphodynamics of the Avon River Estuary and can be connected to both the infilling of the channel between the Windsor Marsh and the Newport Bar as well as the stability of the main tidal gate channel.

This thesis has supported research from numerous studies which conclude that the construction of barriers substantially influences the morphology of estuaries downstream. In addition to supporting other research, this study has provided an opportunity for future work which will be able to use the data synthesized in this thesis to further test our hypothesis that construction activities have had significant impact on the morphology of the Avon River Estuary, downstream of the Windsor Causeway. Moving forward, we suggest that data collection efforts be concentrated near the causeway, surrounding the Windsor Marsh, to clearly understand how anthropogenic activity is impacting the system. While sampling frequency has provided a sufficient level of analysis, increased frequency would make it much easier to align changes in morphology with changes in external drivers of change. This would allow for a better understanding of what may be causing changes and how the system is reacting. Additionally, adding hydrodynamic studies on flow patterns and velocities could provide an additional layer of detail into how the system is evolving. Overall, from an environmental assessment perspective, this study has shown that human activities can have substantial impacts on intertidal estuarian systems that are often difficult to predict. This study can hopefully be used in the future to inform others of how estuaries experiencing significant anthropogenic impact may respond and adapt.

7. References

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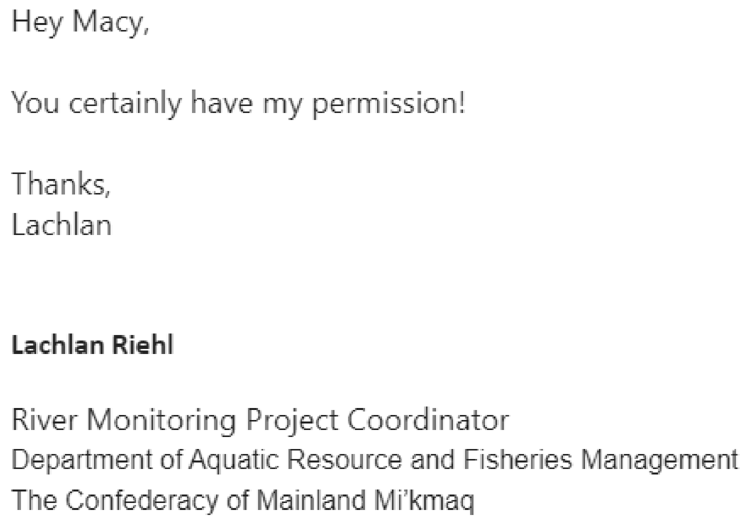
8. Appendix

Appendix A: Photo permission from Lachlan Riehl.

Hi Lachlan,

My name is Macy, I am an honours student working with Danika van Proosdij at SMU, we contacted you earlier in the year about records of construction work done near the Avon causeway and you provided us with some images. I would like to include the attached image in my thesis but I need written permission to do so. I would appreciate approval but if you are not comfortable with it I understand.

Thanks!
Macy



Hey Macy,

You certainly have my permission!

Thanks,
Lachlan

Lachlan Riehl

River Monitoring Project Coordinator
Department of Aquatic Resource and Fisheries Management
The Confederacy of Mainland Mi'kmaq

Appendix B: Coordinates of transect line stakes based on UTM zone 20.

End Stake 1	UTM x	UTM y	End Stake 2	UTM x	UTM y
R	411582.2798	4983599.379	RA	411773.2237	4984208.034
C	411085.9887	4983768.874	CA	411251.6124	4984476.552
T	410669.4499	4983735.175	TA	410883.1117	4984492.955
S	410426.5767	4983652.495	SA	410618.5623	4984658.368
1AA	409480.3588	4983171.805	1A	410426.5767	4983652.495
1	409138.7254	4983856.61	1A	410426.5767	4983652.495
2	409138.7254	4983856.61	2A	410618.5623	4984658.368
2.5	408835.1092	4984761.635	2.5A	410618.5623	4984658.368
3	409174.9765	4985197.805	3A	410650.5834	4984979.451
3.5	409298.5824	4985798.954	3.5A	410779.7347	4985328.721
4	409443.3796	4986361.558	4A	410767.9103	4986027.377

Appendix C: Offsets used in the setup of the M9 ADCP for bathymetric surveys.

	X offset from boat center (m)	Y offset from boat center (m)	Z offset from boat center (m)	Height above water (m)
HydroBoard	-0.175	0.000	0.075	0.118

Appendix D: 2023 sediment sample coordinates, category, mean grain size, sorting, skewness, and median grain size.

2023	Easting	Northing	Category	Mean	Sorting	Skewness	D50
A1.1_23	410375.889	4984706.94	Very Fine Sand	122.13	1.415	-0.543	140.98
A1.2_23	409939.358	4985089.652	Very Fine Sand	71.71	2.278	-0.301	76.00
A1.3_23	410027.763	4985073.736	Very Coarse Silt	43.48	2.701	-0.606	69.62
A1.4_23	409773.158	4985237.517	Very Fine Sand	121.21	1.422	-0.539	140.21
A1.5_23	410094.431	4985057.923	Very Coarse Silt	45.37	2.540	-0.638	70.28
A1.6_23	410213.011	4984683.046	Very Fine Sand	118.45	1.433	-0.536	137.65
A1.7_23	410405.654	4984670.521	Very Fine Sand	124.50	1.399	-0.562	142.88
A1.8_23	410530.705	4984664.013	Very Fine Sand	68.57	2.483	-0.349	77.31
A2.3	410359.572	4986131.026	Very Fine Sand	71.69	2.395	-0.343	78.90
A2.4	410075.617	4985606.455	Very Fine Sand	99.25	1.439	0.369	88.67
A2.5	409927.591	4985638.031	Fine Sand	145.65	1.245	-0.291	145.65
A2.8	410059.434	4985250.732	Very Fine Sand	78.81	2.104	-0.206	76.83
A1.7_23	409863.801	4984745.04	Fine Sand	150.94	1.217	0.272	150.94
A1.8_mud	409950.843	4984668.812	Fine Sand	147.34	1.230	-0.295	147.34
A1.12	410440.187	4984385.691	Very Fine Sand	92.34	1.940	-0.002	80.56