Examination of the Morphodynamics of the Upstream Portion of the Avon River

Causeway and tide gate with drill rig. Image taken May 23, 2019 by Greg Baker with DJI Phantom 4 RTK RPAS

Final Draft Report Submitted to:

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Introduction

The Avon River estuary is a very dynamic system and has a long history of morphodynamic change in response to natural and anthropogenic driving forces such as causeway construction, dredging, dyking and sewage outflow modifications (van Proosdij and Baker, 2007; van Proosdij and Bowron, 2017). It is well known that the construction of causeways across tidal estuaries causes significant, often negative, impacts to the physical and biological conditions of the system (van Proosdij et al., 2009; Gerwing et al., 2016; Gerwing et al., 2020). Salt marshes and mudflat complexes tend to experience the most dramatic and observable effects of the resulting change in the movement of water and sediment. The Avon estuary is a dynamic, coastal system that has a long history of morphodynamic change in response to natural and anthropogenic driving forces. Morphodynamics refers to the change in morphology (form) of coastal features such as salt marshes, tidal creeks and mudflats over time as sediment is re-distributed. The change in morphology then alters the hydrodynamics and sediment transport processes within the coastal system (van Proosdij et al., 2020). Ecomorphodynamics incorporates the interaction and feedback of vegetation establishment on morphodynamic change.

The former tidal river and wetland system upstream of the Avon River Causeway has been highly modified as a result of historical agricultural dyking (wetland loss), changing land use practices, hydroelectric dams and the original causeway construction (i.e., converted to a freshwater lake and river). While the historical downstream impacts of the construction of the causeway and associated ecomorphodynamic adjustments in salt marsh habitat, tidal flats and river channel are relatively well documented (van Proosdij et al., 2006; van Proosdij and Baker, 2007; van Proosdij et al., 2009; van Proosdij and Bowron, 2017; Graham et al., 2018; van Proosdij et al., 2020.), limited data are available, therefore, minimal analyses have been conducted upstream of the causeway structure. Understanding the ecomorphodynamics and evolution of the Avon River system in response to associated changes in human activities has been a core research program for Dr. van Proosdij since 2002. At the time of the 2005 study, Dr. van Proosdij was able to collect all available data for both upstream (for research purposes) and downstream historical surveys however analysis of the upstream section was outside of the scope of the original NSPW (formerly NSTAT) morphodynamic analysis and data upstream remained raw and unprocessed. In order to begin to understand how the river system upstream of the causeway has changed over time, the historical data would need to be processed, analyzed and compared to the current conditions. This project, solicited by the Confederacy of Mainland Mi'kmaw (CMM) provides an opportunity to examine the morphodynamic changes in the Avon River system upstream since completion of the Windsor causeway in 1970. This will serve as a baseline for further manipulations of the gate structure and return of partial or full tidal exchange.

Scope

The scope of this analysis is limited to processing and analysis of available historical data and comparing it to a contemporary survey conducted in 2020 to determine the degree of bed elevation change at cross sectional profiles. This analysis will be able to determine the extent of change and where sediment has been deposited upstream of the causeway.

Limitations

This analysis is limited to changes that have occurred at pre-established cross sections where the historical posts have been able to be accurately re-located and for the time periods in which data are available. The analysis was not able to accurately infer changes between profiles or determine an accurate sediment budget (e.g., input and output of sediment). Nor was this study comparing recorded changes in cross sectional area with frequency of gate openings (tidal inputs), variations in suspended sediment concentrations and freshwater discharge (seasonal precipitation). Those analyses are recommended for future studies.

Study Area and Methods

The study area extends approximately 7.2 km upstream from the existing causeway on the Avon River to Sangster's bridge (Figure 1). Since the causeway was completed in 1970, freshwater discharge on the Avon River has been controlled by hydroelectric and storage dams in its upper reaches and by tide gates located in the Windsor causeway. The Windsor Tide Gate was run on demand from its inception until 1981. This involved manually opening the gates fully on the outgoing tide when the lake level and river were equal. Since 1981, the gates have operated as an automatic system (with manual override) and is designed to maintain Pesiquid Lake at a set elevation. Lake levels would be reduced typically in March to allow for maintenance of gate infrastructure (van Proosdij and Baker, 2007). Gates would also be opened periodically for short periods to accommodate spring movement of gaspereau otherwise known as alewife (NSTIR, 2017). Sediment laden tidal waters would move upstream during these periods as well. Between 2016 (pers. Comm. Graeme Matheson, NSDA Feb. 28, 2022) and March 2021 the frequency of gate openings and tidal waters flowing upstream for short durations increased as a result of ongoing gate manipulations. A Ministerial order was issued by Minister Bernadette Jordan on March 19, 2021 dictating that the gates must be fully open during outgoing tides and for a minimum of 10 min on the incoming tides to allow salt water upstream. Detailed analysis of gate openings, sediment transport and freshwater discharge is outside of the scope of the current study however will be required to fully understand any changes in the morphology of the river system upstream of the current causeway.

Sediment samples (n=49) collected in 2019 to inform CBCL Ltd. modelling of aboiteau design options indicate that bed sediments closest to the causeway were classified as medium to coarse silt and sandy coarse silt and silty fine sand further upstream (van Proosdij et al., 2020).

A combined total of 19 historical and contemporary cross-sectional surveys were found within the available records. Accurate comparison between years requires confidence in the historical and contemporary positions of start and end posts. These were assessed using field logs, historical and contemporary imagery, and historical notes. Twelve of the transects were deemed to be well (or somewhat well) estimated (Figure 1). Coordinates are provided in Table 1.

The earliest surveys available were collected by the Maritime Marshland Rehabilitation Administration (MMRA) in 1970 as the causeway was near completion. One transect (G aka US1) was also measured during construction in July and November 1969, similar to those collected downstream (van Proosdij and Baker, 2007). Surveys were conducted by MMRA survey technicians between two posts set on either side of the river. Bathymetry was recorded using an echosounder on a small open boat guided between posts at high tide. A detailed record of tide water levels during the survey was maintained to assist in interpretation of water levels. Profiles were extended on land using standard rod and level surveying techniques. These echo sounding profiles were drafted to scale on paper charts by the survey engineers and tied to geodetic datum (CGVD28). These paper charts were digitized at the Maritime Provinces Spatial Analysis Research Centre (MP_SpARC) at Saint Mary's University and brought into ArcGIS. Profiles were transformed into X,Y,Z coordinates using a customized script. Detailed procedures are provided in van Proosdij and Baker (2007). Elevations were converted to CGVD2013 using the National Conversion Model available through Natural Resources Canada, GPS-H[1] which calculates $H_{CGVD2013}$ as $H_{CGVD28} + N_{HTv2.0} - N_{CGG2013a}$ (NRCAN, 2020).

[1] https://webapp.geod.nrcan.gc.ca/geod/tools-outils/gpsh.php

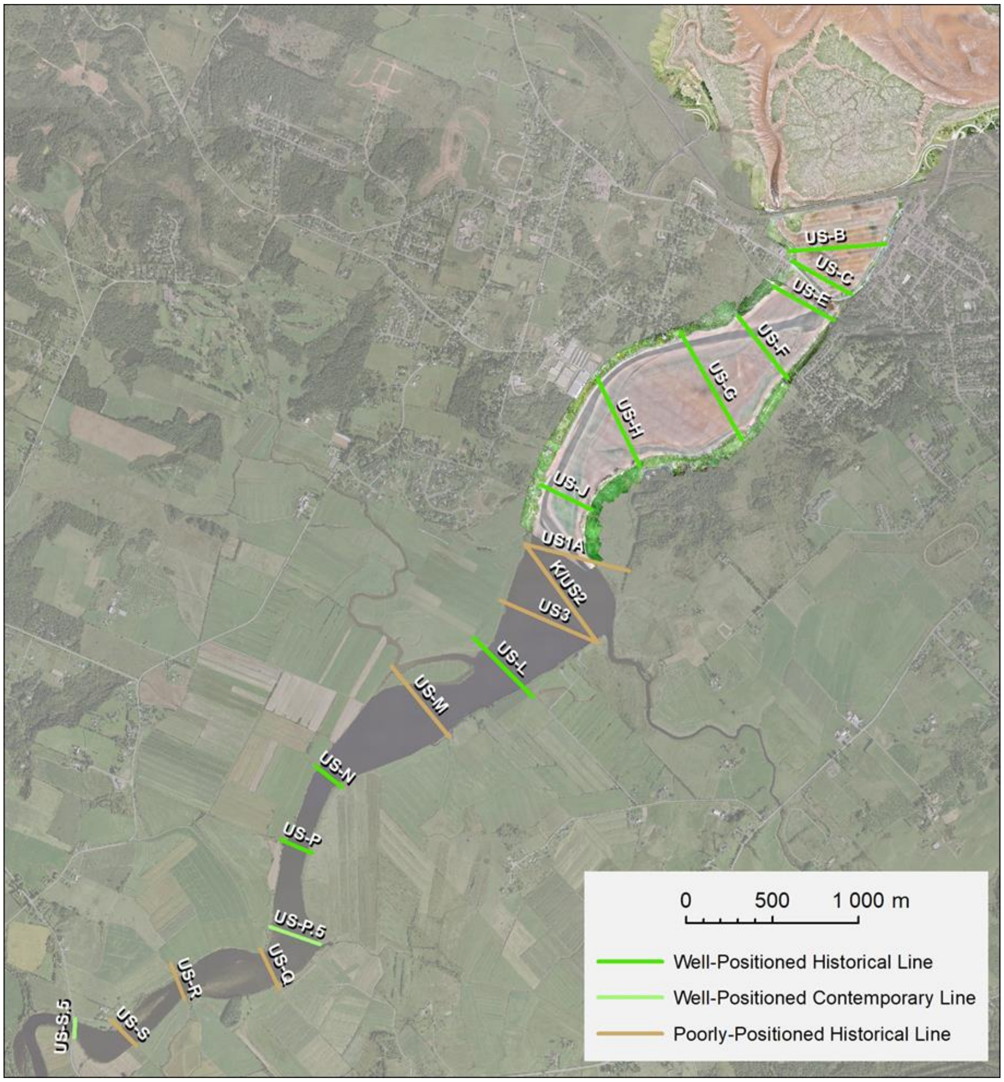

FIGURE 1: HISTORICAL AND CONTEMPORARY CROSS SECTIONS USED FOR UPSTREAM MORPHODYNAMIC ANALYSIS

TABLE 1: COORDINATES OF HISTORICAL AND CONTEMPOARY SURVEY LINES

Line ID	Post A (easting/northing) (m)	Post A' (easting/northing) (m)	Dist. from causeway (m)	MMRA (echo, terrestrial)	NSDA (2005) (terrestrial)	2007 lidar	May 2019 (RPAS/ sonar)	Dec 2020 (sonar)
B	409541.27274 E 4982944.9663 N	410101.73131 E 4982986.9383 N	260	1970	-	Y	Y	Y
C	409571.5061 E 4982872.3080 N	409910.2891 E 4982702.4399 N	450	1970	-	Y	Y	Y
E	409450.9714 E 4982741.6234 N	409807.9347 E 4982543.0797 N	630	1970	-	Y	Y	Y
F	409250.1644 E 4982566.4844 N	409533.7101 E 4982210.1208 N	950	1970	-	Y	Y	Y

G (US1)	408908.5362 E 4982476.4008 N	409271.0610 E 4981851.9870 N	1320	1969,1970	-	Y	Y	Y
H	408434.3128 E 4982205.7529 N	408677.4654 E 4981700.9004 N	1900	1970	-	Y	Y	Y
J	408106.3607 E 4981591.5388 N	408401.5868 E 4981446.7646 N	2450	1970	-	Y	Y	Y
L	407717.2805 E 4980705.6517 N	408059.1882 E 4980365.3750 N	3560	1970	Y	Y	Y	Y
N	406799.4023 E 4979961.0117 N	406952.0217 E 4979840.0576 N	4690	1970	Y	Y	Y	Y
P	406599.9813 E 4979534.6547 N	406778.5225 E 4979458.4545 N	5130	1970	Y	Y	Y	Y
P.5	406534.0165 E 4979031.2804 N	406821.8837 E 4978928.6219 N	5660	-	-	Y	-	Y
S.5	405406.9443 E 4978497.2179 N	405399.7344 E 4978390.9742 N	7140	-	Y	Y	Y	Y

A topographic survey was conducted on 4 lines (L,M,P and S.5) at the furthest upstream end of the river in 2005 (Figure 1). The survey was conducted by Darryl Hingley (NSDA) using a differential GPS system. The survey was conducted by foot therefore presumably would have been conducted in early spring when the water levels were typically drawn down for gate maintenance. Additional details are not available. Vertical elevations were originally referenced to CGVD28 and converted in this study to CGVD2013 using GPS-H (NRCAN, 2020).

Lidar data were collected at low tide in May 2007 by the Advanced Geomatics Research Group (AGRG) at the College of Geographical Sciences, as a collaborative initiative with Saint Mary's University (SMU), NS Department of Transportation and Infrastructure Renewal (NSTIR) and NS Department of Agriculture (NSAg). Lidar data were processed by AGRG into a 1m resolution digital elevation model (DEM) with a vertical accuracy of 0.15 m referenced to CGVD28 (Webster et al., 2011). Elevations were converted to CGVD2013 using GPS-H (NRCAN, 2020). Cross sectional profiles were extracted from the DEM as per van Proosdij et al., 2020. All lines were manually edited to remove areas of standing water.

On May 23, 2019, four flights were completed with the DJI Phantom 4 RTK (60 m altitude), and on May 27, 2019, three flights were completed with the WingtraOne PPK (120 m altitude) as part of the bathymetric model grid development for CBCL (van Proosdij et al., 2020). Flights were completed when the water levels were drawn down. Pilots for these flights were Greg Baker and Samantha Lewis, who both hold an RPAS Pilot Certificate – Advanced Operations from Transport Canada. Canadian Aviation Regulations were followed at all times during RPAS operations (Transport Canada, 2019).

All Phantom 4 surveys were completed using the Real-Time Kinetic (RTK) GNSS feature, providing survey-grade GNSS corrections to photo locations during each flight. During the collection, RTK connection was lost several times, but this was noted in the flight software and identified by the aircraft operator. All sections of the flight plans that were affected by the RTK connection loss were re-surveyed to ensure full coverage of the site with survey-grade geolocations for each image.

WingtraOne surveys were completed using the Post-Processed Kintematic (PPK) GNSS feature, providing survey-grade GNSS corrections to photo locations during processing in the lab, post-flight. Three processing projects were created in Pix4D, one for each RPAS flight day. Default settings were used for processing both the Phantom 4 and WingtraOne datasets. After initial processing, Ground Control Points (GCPs)s were added and the “Re-optimize” step was run to georeference the data. A digital surface model (DSM), orthomosaic, and set of las tiles were created for each project.

The Phantom 4 orthomosaic has a 2 cm resolution, is in coordinate system NAD83 (CSRS) UTM Zone 20N, had significant issues with sun glint in areas of water coverage and wet mud, and a lack of photo alignment due to water coverage in the southern portion of the dataset resulted in a data gap (Figure 2). The WingtraOne orthomosaics have a 2.5 cm resolution, in the NAD83 (CSRS) UTM Zone 20N coordinate system. These orthomosaics had no sun glint issues, but some striping is present due to variable light levels during collection, particularly in the orthomosaic created for the upstream section (Figure 3).

FIGURE 2: PHANTOM 4 ORTHOMOSAICS OF UPSTREAM SURVEY

FIGURE 3: WINGTRAONE ORTHOMOSAIC OF UPSTREAM SURVEY

Accuracy assessments for the RPAS DSMs were conducted by comparing DSM elevations to elevations collected with a Leica RTK GNSS antenna across the site. The accuracy assessment for the Phantom 4 DSM for the upstream survey reported a Root Mean Square Error (RMSE) of 0.03 m and a Mean Absolute Error (MAE) of 0.03 m. For the WintraOne DSM of the upstream, the RMSE was 0.09 m and the MAE was 0.08 m. Oblique images were also captured and are reported in van Proosdij et al., 2020.

Bathymetric data were collected on August 8, 2019 using a 16 ft. shallow water fishing boat (Carolina Skiff J16) in portions of the channel that had water, with a Sontek M9. The Sontek M9, which has five acoustic beams recording depth, operated with its HydroSurveyor functionality, and the Hypack software was used to collect that data. The M9 HydroSurveyor was paired with a Leica RTK GNSS for positioning. Portions of the channel that had water generally coincided with -0.5 m CGVD2013 (Figure 4). Cross channel surveys were conducted along each predetermined line, with a forward speed of approximately 7-8 km·hr^{-1}. In regions where RPAS flights resulted in the creation of a DSM, the DSM data was utilized due to the increased accuracy of the DSM model over M9 data.

To create the profiles, a Geographic Information System (GIS) was first used to create a polyline from the western bank to the eastern bank of the river between each historical post. The polyline vertices were densified to ensure a vertex interval of 50 cm along the line. The vertices of the polylines were then converted to a point feature class, and the elevation value of pixels coincident with each vertex were assigned as an attribute to those points. Regions of standing water were manually digitized and used to exclude elevation data from the RPAS DSMs. All profiles were examined individually, and elevation artifacts caused by trees, shrubs or woody debris were removed manually. Where the exclusion of standing water created a gap in the transect, nearby points from M9 data were added to the dataset to fill the gap. The XYZ coordinate for all lines were then exported from the GIS and entered into a custom spreadsheet designed to convert the XYZ coordinates to MZ coordinates for plotting as a vertical cross-section (van Proosdij and Baker, 2007).

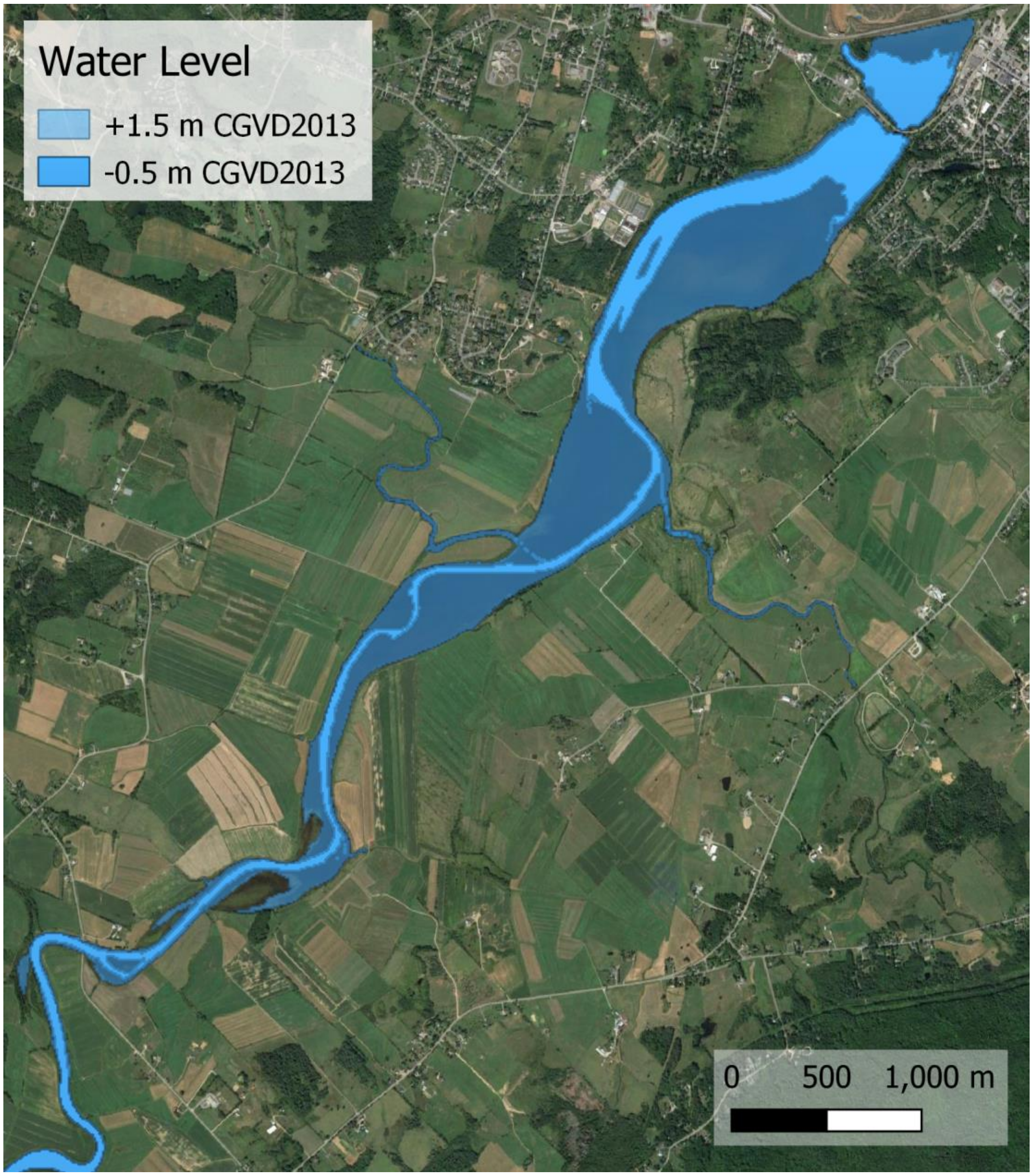

FIGURE 4: DELINEATION OF EXPOSED FLATS AND WATER FILLED MAIN RIVER THALWEG BASED ON RPAS IMAGERY IN MAY 2019.

The 2020 survey was conducted on Dec 11 by CBWES Inc. using a 16 ft. shallow water fishing boat (Carolina skiff J16), and Sontek M9 (Figure 5) at high water levels. Surveys were conducted cross shore along pre-established profile lines using posts and compass bearings for reference. The boat travelled between 7-8 $km \cdot hr^{-1}$ with data continuously recording resulting in data points spaced approximately 0.5-1 m apart. M9 elevation files were imported into an Excel spreadsheet template as Easting (x), Northing (y) coordinates with elevation (z) values and converted to a distance an elevation value suitable for comparison with the historical surveys. An additional distance filter was applied to the data which excluded any point which was more than 120m offline and points were 'snapped' to the established profile line. A resultant straight-line distance and associated elevation value were generated for each vertex. Data were filtered using a 5-sample running mean to smooth the data.

FIGURE 5: SONTEK M9 ON HYDROBOARD FOR BATHYMETRIC SURVEYING, DEC 11, 2020.

Results

Cross-sectional Profiles

Construction of the causeway, and removal of the upstream section of the Avon River from natural estuarine tidal circulation, significantly impacted the morphodynamics of the river system. In all cases, sedimentation and infilling was recorded between 1970 and 2005/2007. The most significant infilling occurred within the first 630 m upstream of the causeway and affected the entire width of the river, creating extensive flats and decreasing the depth of the main river thalwegs by 3.75 m, 3.9 m and ~ 5 m at lines B, C and E respectively (Figure 6a-c). The natural multi-channel tidal riverbed was reduced to one main river thalweg (Figure 4, Figure 6). Additional infilling of approximately 1 m was recorded between 2019 and 2020 (Figure 4a,b) expanding the flat near the boat club (Figure 9a). By Line F, 950 m upstream, a large central flat has emerged by 2007 with a lateral shift ~ 63 m east in the deepest river thalweg, shallowing by 1.1 m. The original western channel has almost completely infilled by 1.4 m of sediment by 2007 (Figure 6d). It should be noted that the maximum bed elevation of the central flat has not changed since 1970 and no discernable changes in bed elevation were recorded between 2019 and 2020 at Line E and further upstream.

Line G, 1320 m above the causeway (Figure 1, Table 1), provides a rare glimpse into the seasonal fluctuations in bed elevations that would be observed as construction progressed, while still permitting tidal flow upstream. The elevation of the main tidal flat decreased by approximately 0.70 m between July and Nov 1969 yet rebounded to the same elevation of approximately 0.8 m CGVD2013 that remains consistent between Jul 1969, Nov 1970 and all contemporary dates (2007, 2019 and 2020) suggesting some upper equilibrium elevation (Figure 7). The main river thalweg displayed approximately 0.6 m seasonal change in bed elevation between July 1969, Nov 1969 and 1970. However, between 1970 and 2007 the main channel narrowed by 150 m and infilled by 1.8 m and this position has remained consistent over time (Figure 7a).

The pattern of a consistent bed elevation of the main flat since 1970 continues further upstream. At Line H this is approximately 1.2 m CGVD2013 (Figure 7b). The main channel thalweg becomes narrower, but depth remains consistent at -2.3 m CGVD2013 (Figure 7b). At line J, 2450 m upstream, the river eroded laterally by approximately 40 m on the eastern bank and lowers the bed elevation of the main flat by 0.77 m between 1970 and 2007. The main river thalweg narrows significantly by ~ 30 m, remaining 34 m wide post 2007 and a consistent depth of -2.5 CGVD2013 (Figure 7c). Similarly, to Line L, the difference in the starting elevation of the transect may suggest removal of historical dyke infrastructure or errors in transect alignment however this hypothesis has not been thoroughly assessed at this time.

Line N recorded 1.54 m decrease in depth of the main thalweg between 1970 and 2005 and the emergence of a secondary shallow channel, less than 1 m deep along the eastern bank (Figure 8I, Figure 9b). After 2005, the profile remains unchanged. At Line P, the river narrows between 1970 and 2005 with the development of a 40 m wide, 1.05 m high bed deposit along the eastern shore and deepening of the channel by 0.6 m between 1970 and 2005 (Figure 8j). The appearance of a bar on the western shore recorded in 2019 coincides with lateral erosion on the western side and re-establishment of the 2007 position by 2020 suggesting natural shift in intertidal bar features commonly observed in river systems (Figure 8j). This bar feature is also visible in Figure 9d. At the furthest reliable line upstream, approximately 0.15 m of accumulation and slight shift to the east was recorded at Line S.5 (Figure 8l). No 1970 profile was available for comparison at Line P.5. Limited changes were recorded at lines P.5 and S.5 from 2005 onwards (Figure 8k,l).

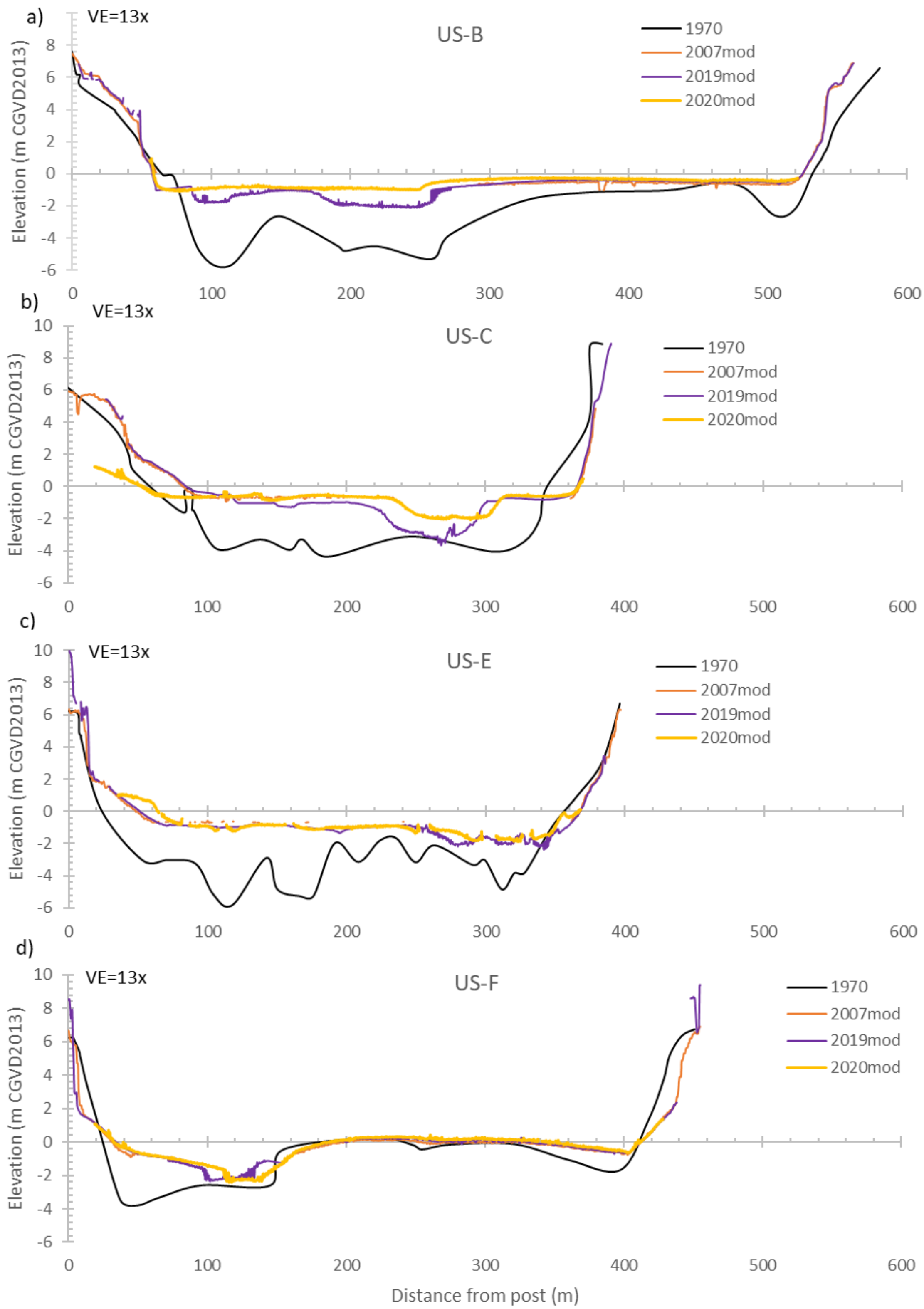

FIGURE 6: CHANGES IN CROSS SECTIONAL PROFILES AT A) LINE E - 260 M FROM CAUSEWAY, B) LINE C- 450M, C) LINE 3 – 630M AND D) LINE F- 950 M FROM CAUSEWAY

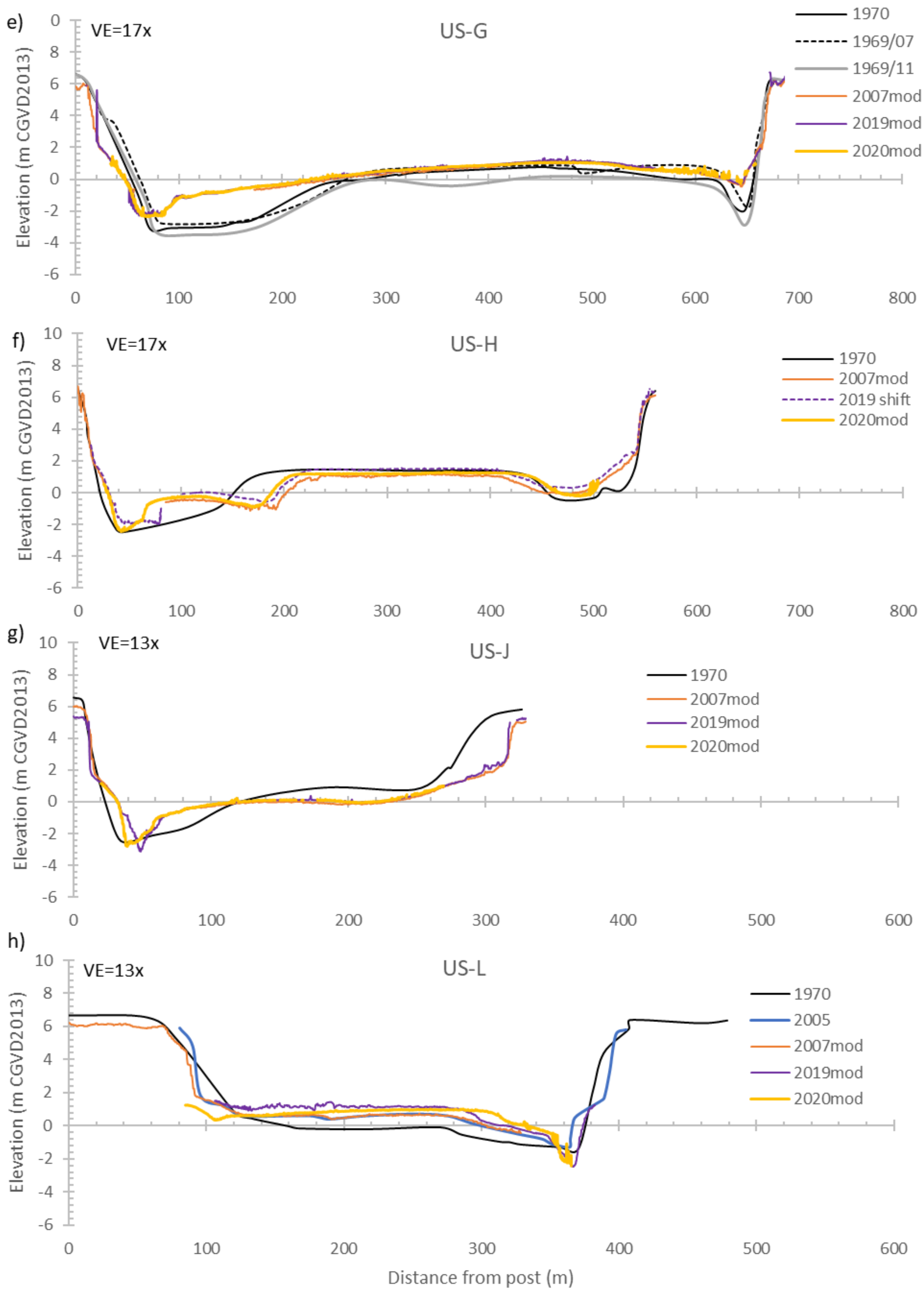

FIGURE 7: CHANGES IN CROSS SECTIONAL PROFILES FOR E) LINE G (ALSO US1) - 1320 M FROM CAUSEWAY, F) LINE H - 1900 M , G) LINE J - 2450 M AND H) LINE L - 3560 M UPSTREAM OF THE CAUSEWAY.

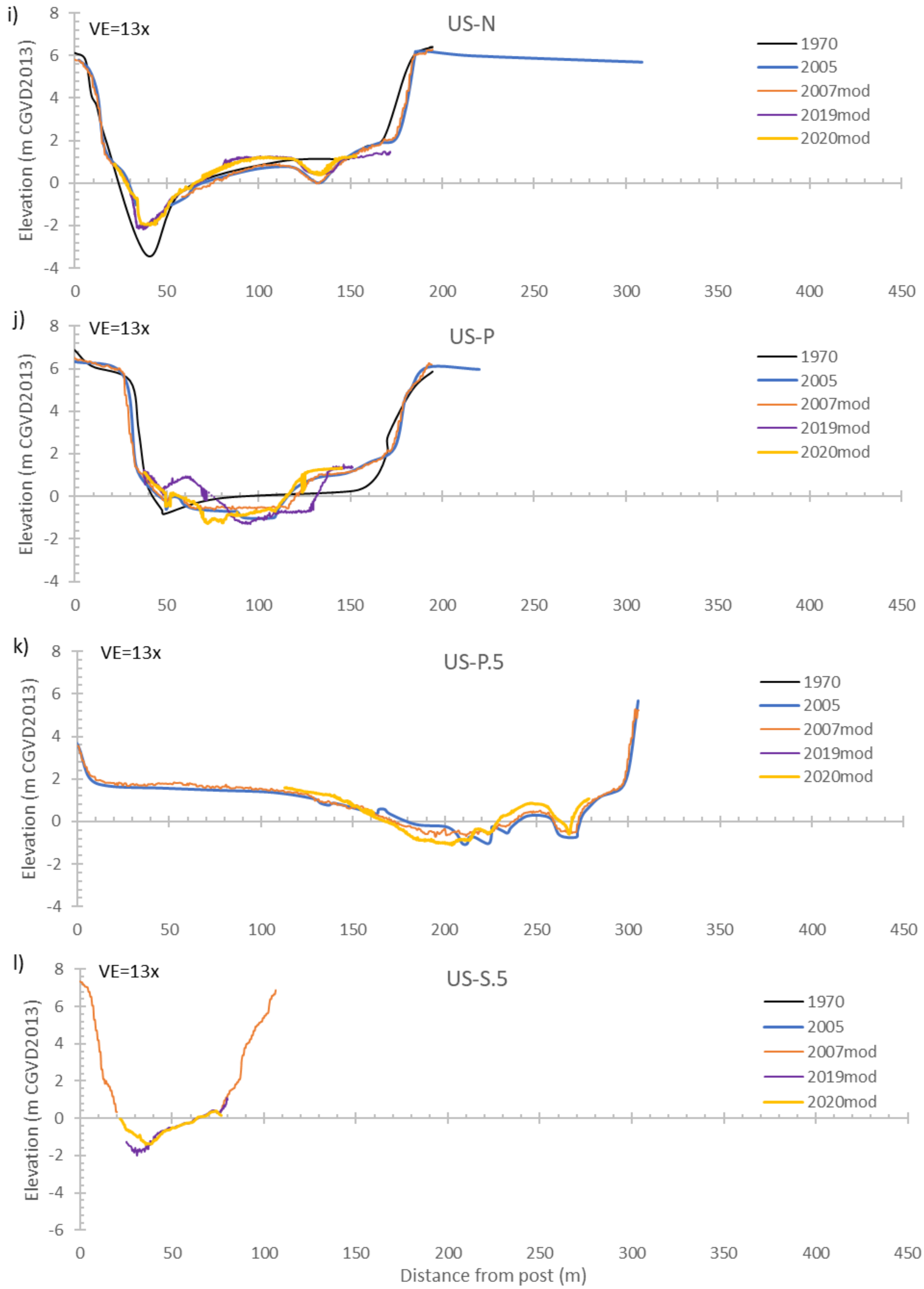

FIGURE 8: CHANGES IN CROSS SECTIONAL PROFILES FOR I) LINE N - 4690 M, J) LINE P - 5130 M, K) LINE P.5 - 5660 M AND L) LINE S.5 – 7140 M ABOVE THE CAUSEWAY.

Field and Satellite Observations

Limited data exist on upstream sediment characteristics prior to samples collected for the CBCL aboiteau modelling study in 2019. Details are provided in van Proosdij et al., 2020 and results are summarized here. Upstream of the causeway, sediment grain sizes range from silty fine sand to coarse silt. In the southern half of the upstream portion of the river, the three sediment samples were categorized as sandy coarse silt. In the middle section of the upstream portion of the river, samples varied from coarse silt to silty fine sand, with the coarse silt generally being closer to the banks and the sandy coarse silt generally being more in the middle of the river. In Lake Pisiquid, closer to the causeway, there were some finer samples, categorized as medium silt, most pronounced close to the Windsor Waterfront area, on the east side of the lake. The mean of all median diameter (d50) values for sediment samples upstream of the causeway was 41 µm, the finest sample having a d50 of 9 µm and the coarsest sample having a d50 of 266 µm (van Proosdij et al., 2020).

FIGURE 9: LOW ALTITUDE OBLIQUE AERIAL IMAGERY TAKEN ON MAY 23,2019 BY GREG BAKER WITH DJI PHANTOM 4 RTK RPAS, A) CAUSEWAY AND TIDE GATE; B) LOOKING NORTH (DOWNSTREAM) FROM ALLEN BROOK; PHOTOS TAKEN MAY 27, 2019 AT C) LOOKING NORTH FROM HV TRANSMISSION LINES AND D) LOOKING NORTH (DOWNSTREAM FROM SANGSTER'S BRIDGE).

Low altitude aerial imagery collected on May 27, 2019 illustrate the presence of persistent bar features within the upstream river system and infilling adjacent to the causeway (Figure 9). In order to roughly correlate sedimentation and intertidal bar formation associated with gate openings, publicly available satellite imagery was examined between 2018 and 2021. The Copernicus Sentinel 2 provides high resolution (10 m) images in the visible and infrared wavelengths and is used to monitor soil, vegetation, water cover and coastal areas. Images are generally available every 5 days and images were filtered to select those with less than 10% cloud cover within the EO Browser (apps.sentinel-hub.com).

FIGURE 10: COPERNICUS SENTINEL-2 SATELLITE IMAGERY ILLUSTRATING OPEN GATES AND TIDAL EXCHANGE IN MAY 2020. ARROW INDICATES INTERTIDAL BAR.

The only period captured with less than 10% cloud cover between 2019-2020 where tidal waters are flowing upstream were May 3 and May 23, 2020 (Figure 10). Based on the bathymetric analysis, the intertidal bar indicated by the yellow arrow in Figure 10, has remained at the same elevation relative to datum since 1970. Using the measure tool within the EO Brower, the area of this deposited was estimated as 0.34 km^2. Sediment laden waters are visible upstream and deposition in lake Pisiquid is visible on May 23, 2020 which is supported by the profile changes recorded during the bathymetric analysis (Figure 6a,b). In addition, a plume of sediment is observed within the Lake on Oct. 10, 2020 when gates appear to be closed (as evidenced by low tide and exposed saltmarsh downstream of the causeway). This plume is observed further upstream on Oct 15, 2020 (Figure 11).

FIGURE 11: SEDIMENT PLUME IN LAKE PISIQUID ON OCT 10, 2020, AND FURTHER UPSTREAM OCT 15, 2020.

Based on the interpretation of satellite imagery from April to Dec 2021, with re-introduction of partial tidal flow, intertidal flats are clearly being established with one narrow main river thalweg at low tide (Figure 12). A false color composite of the Sentinel-2 imagery using near infrared, red and green bands can be used to assess plant density since plants reflect near infrared and green light while they absorb red. Therefore, areas in red indicate vegetation growth but not the type of vegetation. Figure 13 illustrates the sequence of colonization by vegetation from June to Nov 2021 on many of the flats. The persistent intertidal bar present since 1970 illustrated in Figure 10 remains unvegetated. A rough estimate of the surface area of exposed bar sediments ranged from 0.25 km^2 June 2, 2021, to 0.32 km^2 on Oct 10, 2021 (Figure 13). Elevation of the bar cannot be estimated for 2021 without a bathymetric survey. Based on sediment analysis from 2019, these sediments are classified as silty fine sand.

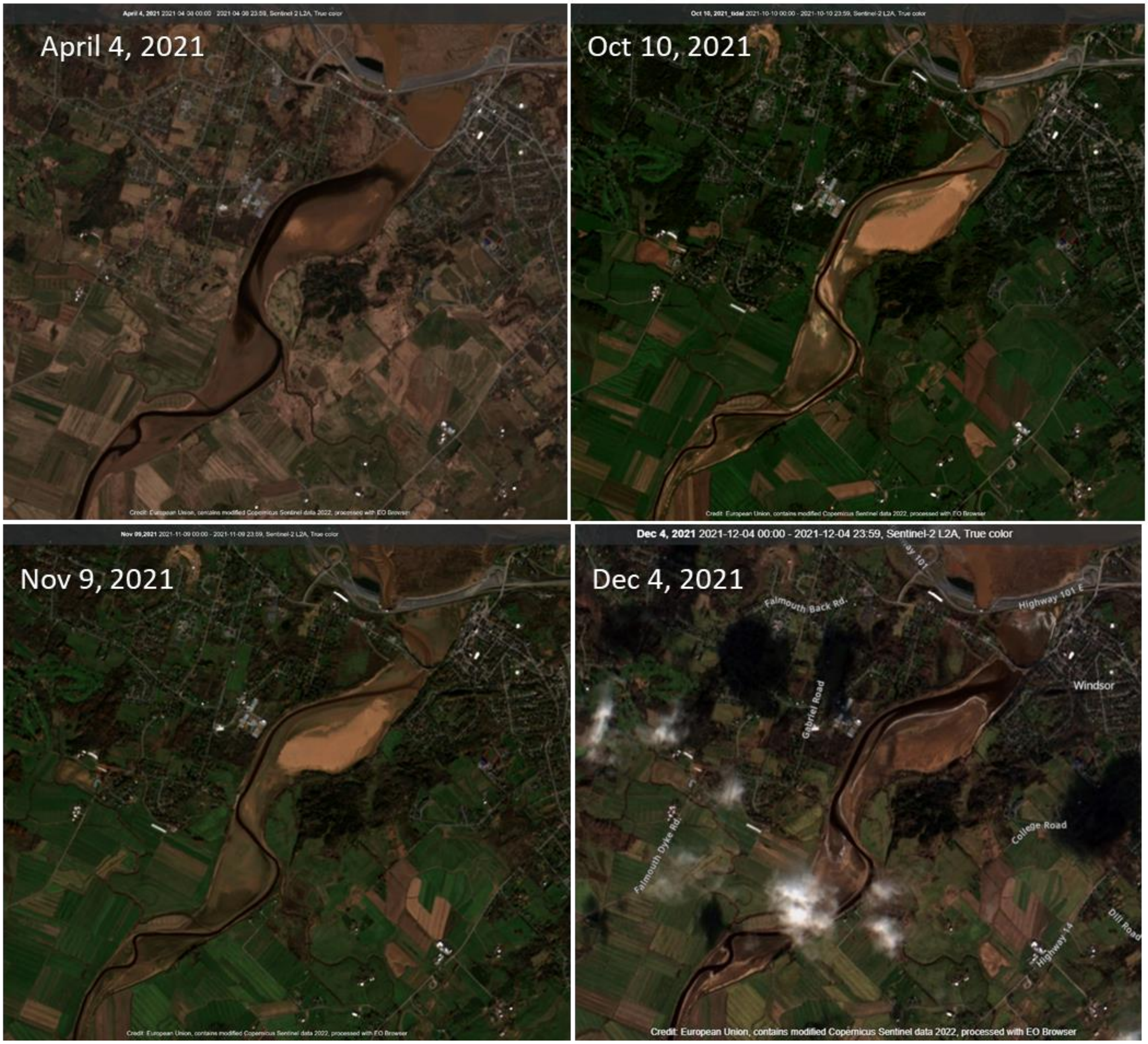

FIGURE 12: EVOLUTION OF TIDAL FLATS AND BEDFORM FEATURES UPSTREAM OF THE CAUSEWAY WITH GATES OPERATING ACCORDING TO MINISTERIAL MANDATE FOR FISH PASSAGE.

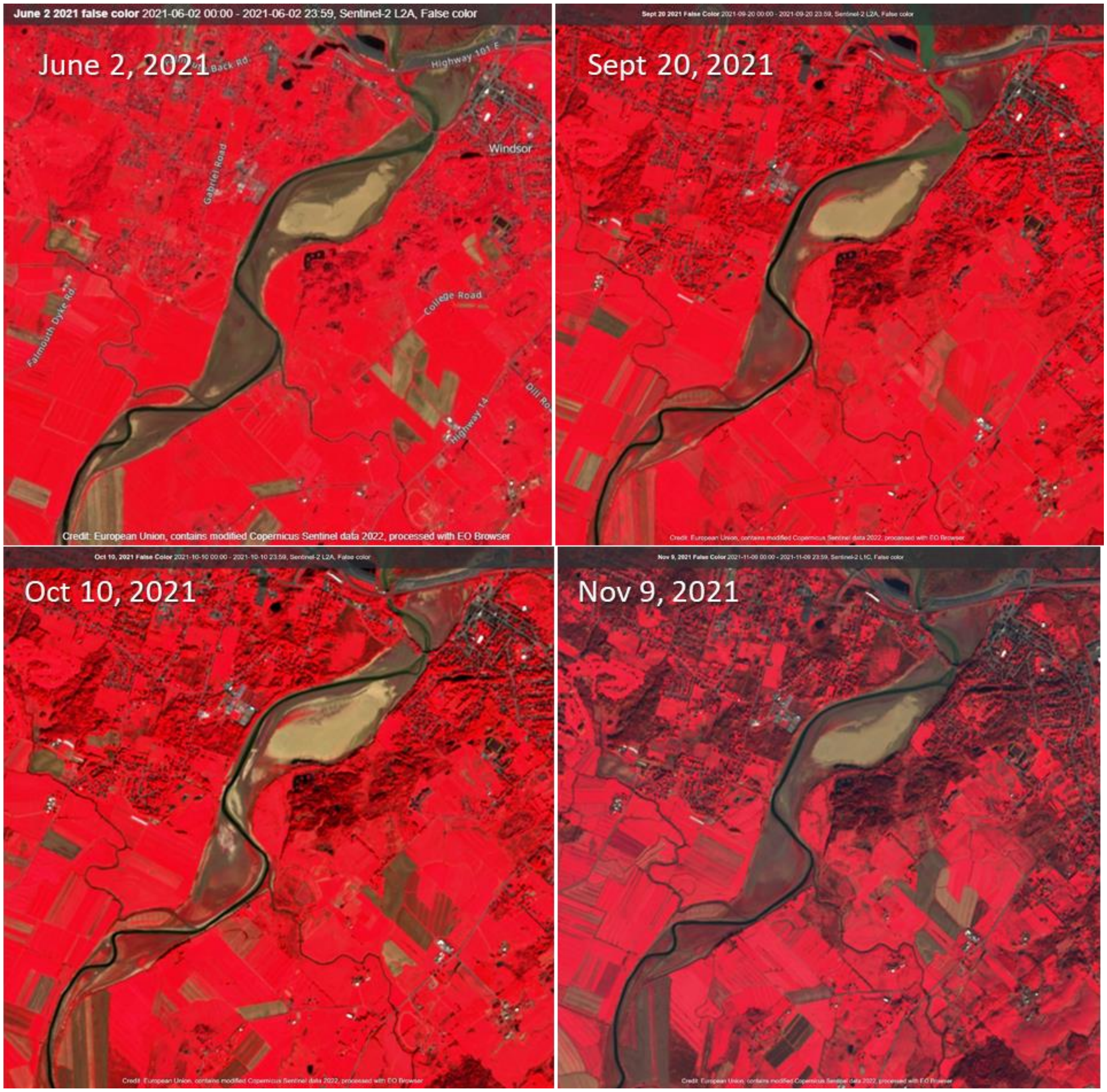

FIGURE 13: COPERNICUS SENTINEL-2 SATELITE IMAGERY DISPLAYED AS FALSE COLOR BANDS 8,4,3 ILLUSTRATING VEGETATION GROWTH ON INTERTIDAL FLATS UPSTREAM OF CAUSEWAY FROM JUNE 2, 2021 TO NOV 9, 2021

Discussion and Conclusions

The most significant changes to the Avon River were recorded between 1970 and 2005/2007 after the causeway was completed. The river infilled in most areas, however, the greatest changes were recorded along transects within the first 1.3 km upstream of the structure. Between Line G and furthest Line S.5 7.5 km upstream, the main river channel narrows and the bed elevation of the thalweg increases between 0.5 to 1 m (Figure 7, Figure 8). However, the elevation of the large sandy bars relative to datum remained relatively constant from 1970 to 2020 and are clearly visible in satellite imagery. Limited introduction of tidal flow upstream in May 2020 allowed sediments to be deposited upstream as anticipated (van Proosdij et al., 2020). Based on the comparison of transect profiles between 2019 and 2020, the impact of re-introduction of tides was limited to line B and C, 450 m upstream of the causeway with most sedimentation concentrated within Pisiquid Lake.

In March 2021 the Federal Department of Fisheries and Oceans issued a ministerial order requiring the aboiteau gates to be fully opened on the ebb tide and for a minimum of 10 minutes on the flood tide which was renewed throughout the year. Under the new gate management regime, water levels upstream of the causeway now fluctuate significantly, depending particularly upon how long the gates are open on the flood tide and the amount of tidal water that is allowed to enter the upstream system. The operation of the gates in this manner is intended to allow for the improvement of fish passage. It has also resulted in the restoration of limited tidal influence to the upstream of the causeway portion of the river. Comparison of intertidal flats and position of the main thalweg between May 2020 and Oct 2021 from sentinel satellite imagery does not indicate the formation of new flats, however, the elevation of the flats are likely rising in response to sedimentation with every tide. The upstream extent of this impact is currently unknown without field observations. The grain size composition will likely also be changing and there is evidence of colonization by halophytic vegetation and algae as seen on satellite imagery. The approximately 0.32 km^2 section of intertidal bar that remains unvegetated has the potential to be a source of airborne sediment when fully dry, however, updated grain size analyses are required to determine aeolian transport thresholds (e.g., strength of wind required to entrain sediment). Cohesive sediments such as silts, if regularly flooded by tides, are unlikely to be a source of concern, particularly as these become increasingly colonized by vegetation. Continued tidal exchange upstream will facilitate the development of tidal wetland habitat upstream of the causeway. Continued monitoring of upstream conditions including salinity, water levels, grain size, suspended sediment concentrations and vegetation establishment is recommended.

References

Gerwing, T.G., Hamilton, D.J., Barbeau, M.A., Haralmpides, K., & Yamazaki, G. (2016). Short-term response of a downstream marine system to the partial opening of a tidal –river causeway. Estuaries and Coasts, 40(3): 717-725. DOI: 10.1007/s12237-016-0173-2.

Gerwing, T.G., Davies, M.M., Clements, J., Flores, A., Thomson, H.M., Nelson, K.R., Kushneryk, K., Brouard-John, E., Harvey, B., & Plate, E. (2020). Do you want to breach an embankment? Synthesis of the literature and practical considerations for breaching of tidally influenced causeways and dikes. Estuarine, Coastal and Shelf Science, 245. DOI**:** 10.1016/j.ecss.2020.107024.

Graham,J; Bowron, T.M; van Proosdij, D.; Baker, G and K. Eillis. (2018). *Avon River Aboiteau and Causeway Upgrades: Pre-construction monitoring of the Avon River Estuary.* Final report submitted to NS Department of Transportation and Infrastructure renewal, 70 p.

Natural Resources Canada. (2020). Height Reference System Modernization version 2.0

van Proosdij, D; Bambrick, J. and G. Baker. (2006). Spatial and Temporal Variations in the Intertidal Geomorphology of the Avon River Estuary. Final report prepared for the Nova Scotia Department of Transportation 82 pp.

van Proosdij, D., and Baker, G. (2007). Intertidal Morphodynamics of the Avon River Estuary. Final report prepared for the Nova Scotia Department of Transportation 186 pp.

van Proosdij, D., Milligan, T., Bugden, G., and Butler, C. (2009). A Tale of Two Macro Tidal Estuaries: Differential Morphodynamic Response of the Intertidal Zone to Causeway Construction. Journal of Coastal Research SI 56: 772-776. ISBN 0749-0258.

van Proosdij, D. and Bowron, T. (2017). Contemporary Morphodynamics of the Avon River Estuary: Implications for Twinning the Windsor Causeway. Submitted to the NS Department of Transportation and Infrastructure Renewal, 39pp.

van Proosdij, D.; Baker, G.; Poirier, E.; Aykol, R. and S. Lewis. (2020). Sediment Dynamics of the Avon Tide Gate Channel: Implications for Modelling and Aboiteau Design. Final report prepared for CBCL Ltd Consulting Engineers, sub-contract 170146.00 78p.