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A Tale of Two Macro Tidal Estuaries: Differential Morphodynamic Response of the Intertidal Zone to Causeway Construction

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ABSTRACT

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This paper examines the spatial and temporal variability in the intertidal morphodynamic response of two macro tidal estuaries to tidal barrier construction. Contemporary bathymetric surveys of the Petitcodiac River and the Avon River in Canada were compared with historical surveys (1960s and 1860s). Both rivers underwent very rapid sedimentation during construction and rapid infilling downstream of the causeway during the first year after causeway completion. At both sites, there was an unexpected decrease on the order of 90% in intertidal cross sectional area within the first 1-2 km downstream of the causeway as extensive mudflats rapidly developed. Once sufficiently consolidated, these were quickly colonized by *Spartina alterniflora.* The response of the remainder of the intertidal zone in the two systems has differed significantly downstream of the area of initial sedimentation. In the Avon, no significant decreases in cross sectional area were recorded and seasonal cycles of changes in bed elevation exceed differences recorded between years. In the Petitcodiac however channel infilling continues up to 21 km downstream of the causeway. It is hypothesized that the response of the Avon system is mainly attributable to the connecting St. Croix River and associated hydrodynamics, as well as the position of the causeway within the broader estuary. A significant change in the calculated critical velocity in the Petitcodiac system before and after causeway construction implies that the actual physics of sediment erosion and deposition were altered. These results demonstrate the importance of considering the broader estuary when developing management guidelines.

ADDITIONAL INDEX WORDS: *Tidal Prism, Flocculation, Bay of Fundy, critical velocity*

INTRODUCTION

The construction of barriers across tidal rivers and estuaries has a long history of altering the sediment dynamics and ecosystem processes in the surrounding area. The degree of alteration to the system depends in part on structure design, surrounding geology, sediment characteristics, tidal range, and basin morphology. Tidal barriers can cause changes in sedimentation patterns within the estuary that may, over time, decrease the cross sectional area of the channels and the overall capacity of the system to distribute tidal waters. Rapid sedimentation and subsequent colonization by halophytic vegetation can be recorded downstream of the tidal barrier, (e.g. AMOS 1977; TURK et al., 1980; VAN PROOSDIJ and TOWNSEND, 2006). Restriction of flow within the system as a result of infill can increase the risk of flooding from both upstream (e.g. tide gate blocked by sediment) and downstream (e.g. storm surge) sources. This potential for flooding could be expected to increase with rising sea levels, placing infrastructure at risk. In most cases excessive siltation is reported in the years following closure of the estuary with extensive changes to the intertidal geomorphology (eg. WOLANSKI et al., 2001; BRAY et al., 1982; TONIS et al., 2002) altering hydrodynamics and decreasing the tidal prism (e.g. AMOS, 1977; OWEN and ODD, 1972). Over the last three decades there has been considerable interest in macro tidal estuarine processes and the impacts of tidal barriers on these ecosystems as well as a resurgence of interest in tidal power. Recent analysis suggests that the morphodynamic response of an estuary is geographically variable. Changes in the morphology of channels as a result of barrier construction must be interpreted with respect to natural changes that can also occur over similar timescales. This paper compares the differential response of two estuaries in the Upper Bay of Fundy to causeway development.

METHODS

The Bay of Fundy is a large macro tidal embayment situated on the east coast of Canada as an extension of the Gulf of Maine (Figure 1). It is characterized by a semi-diurnal tidal regime with a maximum tidal range of 16.3 m, high suspended sediment concentrations and ice. In 1948 the federal government set up the Maritime Marshland Rehabilitation Administration (MMRA) to rebuild and maintain dykelands in the Maritimes that had historically been built by early Acadian settlers. In 1966, the Provinces took over responsibility for dyke maintenance and a plan initiated to construct causeways across several rivers in an effort to decrease maintenance costs of upstream dykes and link adjacent communities. The Petitcodiac causeway located on the Petitcodiac River, at Moncton NB and the Windsor Causeway located on the Avon River at Windsor, NS are two examples

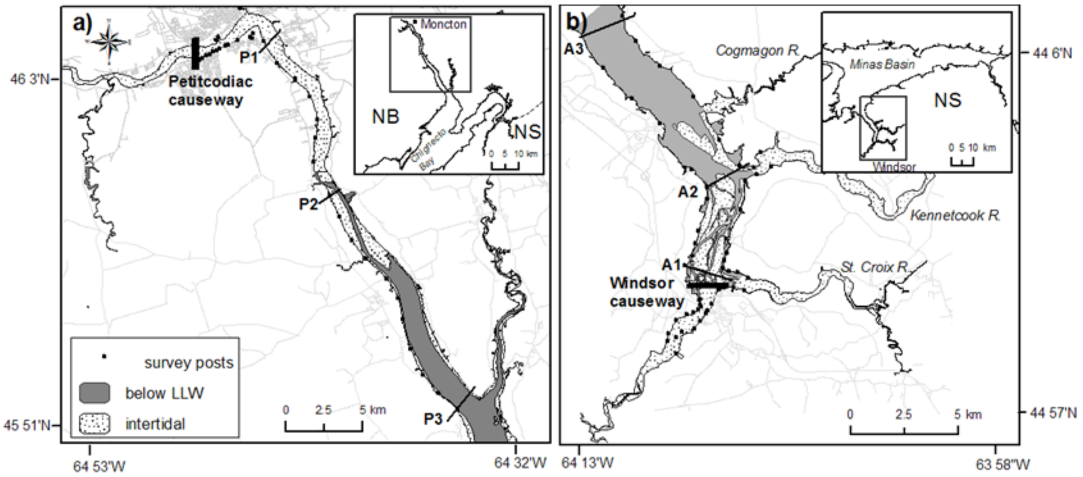

Figure 1: a) Location of the Petitcodiac causeway along the Petitcodiac River in the Upper Bay of Fundy within Shepody Bay; b) Location of the Windsor Causeway along the Avon River estuary within the Minas Basin

(Figure 1a,b). Both were constructed by dumping rock fill systematically across the river (Table 1). Gate structures controlling upstream flow were constructed outside of the main channel and later joined to the main channel to divert flow (Figure 2a) (VAN PROOSDIJ and BAKER, 2007). During construction and immediately following closure both systems experienced unexpected rapid sedimentation downstream of the causeway. The deposited sediment then underwent colonization by *Spartina alterniflora* further stabilizing the deposit (e.g. VAN PROOSDIJ and TOWNSEND, 2006; AMEC, 2005).

Changes in estuarine morphology over time were examined using all available bathymetric survey data, however this availability was limited. Full details are provided in VAN PROOSDIJ and BAKER (2007) and AMEC (2005). In both estuaries, echo sounding surveys were conducted seasonally along transects perpendicular to the main channel from the causeway downstream to the mouth of both estuaries. Where possible, these were located in areas previously surveyed by the MMRA pre and post construction. In total, 65 lines were surveyed in the Petitcodiac (AMEC, 2005) and 24 in the Avon System (VAN PROOSDIJ and BAKER, 2007) (Figure 1). The modern marsh surface was surveyed using differential GPS. Bathymetric charts from the Canadian Hydrographic Service (CHS) from the 1960s supplemented the downstream sections. Charts from the British Admiralty (1858 and 1861) were rectified against known geologic and topographic features and digitized. It should be noted that data were not available for all years at all locations, particularly in the upper portion of the estuary. All data were reduced to a common horizontal (NAD83 UTM Zone 20) and vertical datum (CGVD28) and three dimensional surfaces modelled in ArcGIS 9.3. Submerged bedrock shoals were used as an additional control. Various measures of hydraulic geometry were determined including channel depth, width and cross sectional area for each profile line. Both intertidal cross sectional area (A) and tidal prism (V) upstream of each section were calculated for HHWLT and HHWMT based on CHS tide stations at Joggins and Hantsport for the Petitcodiac and Avon River respectively. Intertidal cross sectional areas (between HHW and LLW) were calculated using a modified Trapezoid rule with a mean distance between points of 2 m and tidal prism calculated using an average end-area method (VAN PROOSDIJ and BAKER, 2007; AMEC, 2005). Channel stability in portions of the estuary where tidal flow dominates is characterized by similar velocities at all cross sections along the estuary (TOFFOLON and CROSATO, 2007). It is this critical velocity to which channel cross sectional area will respond. The stability of the channel was examined using critical

Table 1: Comparison of morphological and causeway characteristics within the Petitcodiac and Avon River estuaries

Estuary	Total distance from head of estuary (km)		Channel width at mouth (km)	Total watershed area of estuary *(km^2)	Total upstream area protected (Ha)	Total length of dyke upstream of causeway (km)	Timing of Construction		Gate Structure								
	Pre	Post					start	end	Length (m)	# gates	Size of gate (m)	Gate discharge area (m^2)	Design peak runoff $(m^{3} \cdot {}^{-1})$	Crest elevation (m O.D)	Depth of fill (m)	Bottom gate elevation (m)	Fishway
Petitcodiac	59.3	37.3	1.5	1424	1374	14	Feb 1966	Mar 1968	1158	5	6 x 9	279	934	10.1	12	-2	Y
Avon	24.1	16.0	2.3	1836	1307	26	Sept. 1968	July 1970	730	2	4.5 x 6	56	453	10.1	15	- 4	N

*includes watersheds of the St. Croix (742 km^2), Kennetcook (506 km^2) and Cogmogon (142 km^2). Watershed of Avon River = 447 km^2. Vertical datum (O.D.) = CGVD28. Both discharge structure types are concrete slab buttresses. Source: Maritime Marshland Rehabilitation Administration.

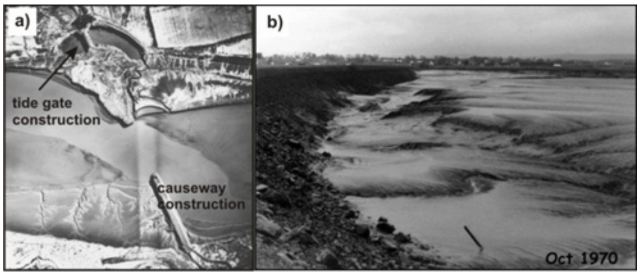

Figure 2: a) Rapid development of mudflat downstream of the Petitcodiac causeway in 1966, keeping pace with construction. Note dry land construction of tide gates; b) Rapid infilling of sediment adjacent to the Windsor causeway in Nov 1970.

velocity (U_c) as V/AT where T = time the tide flows through the cross section (Eq 1). T is assumed to be one half the tidal period for non-drying sections. No tidal assymetry is assumed. Note that U_c is simply the reciprocal of a, the parameter used by (BRAY et al 1982). In order to investigate the critical velocity associated with freshwater discharge, U_f was calculated as Q/A (Kestner, 1966) where Q = mean spring tidal discharge through the tide gates plus river discharge from any major adjoining rivers.

$$\left(\frac{12.42}{2pi}\right)\arccos\left(\frac{2Zd}{HHW-LLW}\right) \quad [1]$$

RESULTS AND ANALYSIS

The construction of the Petitcodiac and Windsor causeways immediately reduced the tidal prism upstream of the mouth of the estuary by between 5.6 and 6.3% respectively, shortening the channel of the Petitcodiac and Avon rivers by 63% and 69% respectively (Table 1). Both estuaries recorded significant decreases in cross sectional area (92% and 53% respectively) and decreases in bankfull channel width immediately downstream of the causeway (Figure 3a,d). A layer of sediment 6 m deep accumulated downstream of the Windsor causeway and similar deposits were recorded on the Petitcodiac. These surfaces are now fully vegetated by *Spartina alterniflora* and are approaching the limit of HHWLT in the Petitcodiac and HHWMT in the Avon. Statistically significant (95% confidence level) differences in cross sectional area were recorded 4.5 km downstream of the causeway in the Avon system however beyond 2.4 km most were associated with increases in area (Figure 3e-f) or coupled with marked shifts in the position of the main thalweg. In the Petitcodiac system, a 54% decrease in cross sectional area was recorded 21 km downstream and 18% at the mouth with a 3-5 m increase in bed elevation (Figure 3b-c). The downstream grade of the channel remained relatively constant (0.03-0.02 %) from 1861 to 2002. In the Avon River however, the grade decreased (from 0.11 to 0.04%) from 1858 to 1969 in the section between the St.Croix and the Kennetcook rivers and decreased to 0.02% by 2005. Downstream of the Kennetcook, the grade increased from 0.08 to 0.18% between 1858 and 2005.

No significant decreases in tidal prism were measured in the Avon river pre and post causeway construction. The calculated critical velocities remained relatively constant (0.22 to 0.57 $m \cdot s^{-1}$) with highest velocities near the mouth of the estuary (Figure 4). The only exception was within 0.5 km downstream of the causeway where U increased by 0.25 $m \cdot s^{-1}$ in the narrower channel. Pre-causeway conditions in the Petitcodiac appeared to have higher values of U_c ranging from 0.51 (P1) to 1.70 $m \cdot s^{-1}$ at P3. Post construction this decreased to between 0.35 and 0.72 $m \cdot s^{-1}$. U_f values (max 1.48 $m \cdot s^{-1}$) equalled or exceeded the U_c values in both estuaries post construction for the first one km downstream of the causeway. Excluding the volume of tidal flow directly lost as a consequence of shortening the estuary, the tidal prism of the Petitcodiac system decreased by 38% over a 140 year period, accumulating approximately 161 million m^3 of sediment within the estuary.

DISCUSSION

The overall equilibrium state of an estuary results from the balance of sedimentological, hydrological and biological forces controlling shear stress within the channel. If some boundary condition is changed (e.g. tidal barrier constructed), then the system will adjust to a new state of equilibrium (e.g. KESTNER, 1966; BRAY et al., 1982; WOLANSKI et al. 2001; TONIS et al., 2002). A decrease in cross sectional area within the tidal portion will in turn decrease the tidal discharge, decreasing velocity and the transport capacity of the tidal waters, causing sedimentation. If this occurs, an equilibrium form will develop, which is an expression of the dynamic equilibrium between erosional and depositional processes. The time to reach this new equilibrium can vary from 10 to 100 years (e.g. TONIS et al., 2002; KRAGTWIJK et al., 2004). Both estuaries demonstrated significant decreases in cross sectional area immediately downstream of their respective causeways due to excess sedimentation. This supports previous research in the Avon (e.g. AMOS, 1977; TURK et al., 1980), Petitcodiac (BRAY et al., 1982) and elsewhere (e.g. SHI et al., 1995). However the response of the system downstream of the initial 1.5 km differs markedly between the two systems and does not support the findings of AMOS (1977) which suggested that the Avon system was still prograding. Changes reported by AMOS (1977) fall within the range of natural seasonal variability and can also be explained by the migration of an intertidal bar. Bed elevations may vary by as much as 6 m (Petitcodiac) (2 m in Avon) seasonally (VAN PROOSDIJ and BAKER, 2007; AMEC, 2005). Therefore minor changes in cross sectional area (<8%) in the section between the St. Croix and Kennetcook rivers in the Avon system fall within the bounds of natural variability. The formation of intertidal bars is balanced by lateral erosion of the marsh bank as the main thalweg shifts within the main channel (e.g. ALLEN, 1996; SHI et al., 1995). These intertidal bars will also concentrate the flow when the water level is slightly lower than the tops of the intertidal sediment bodies with velocities ranging from 0.5 to 1.7 $m \cdot s^{-1}$ measured by LAMBIASE (1980). One of the significant differences between the Petitcodiac and Avon estuaries is the presence of additional rivers contributing to the overall discharge of the Avon. Combined, these rivers account for 76% of the watershed area. These rivers have likely played a key role in moderating the impacts of the causeway construction by both preventing the massive build up of sediment and the decreased hydraulic capacity recorded in the Petitcodiac River. In turn, the increased fluvial discharge has assisted in maintaining the relatively sandy base of the channel (SWIFT et al., 1967; LAMBIASE, 1980). In the Petitcodiac, no major fluvial inputs are present until the Memramcook River, which is also dammed, more than 30 km downstream of the causeway. The two systems also differ in terms of modern substrate composition and suspended sediment concentrations. In general in the Avon, mean grain sizes fall within the medium sand range at the mouth, fining to very fine sand and coarse silt near the causeway (PELLETIER and MCMULLEN, 1972; YEO and RISK, 1981; LAMBIASE, 1980). Suspended sediment concentrations recorded on the mudflats in the early 1980s ranged from 26 to 94 $mg \cdot l^{-1}$ (AMOS and MOSHER,

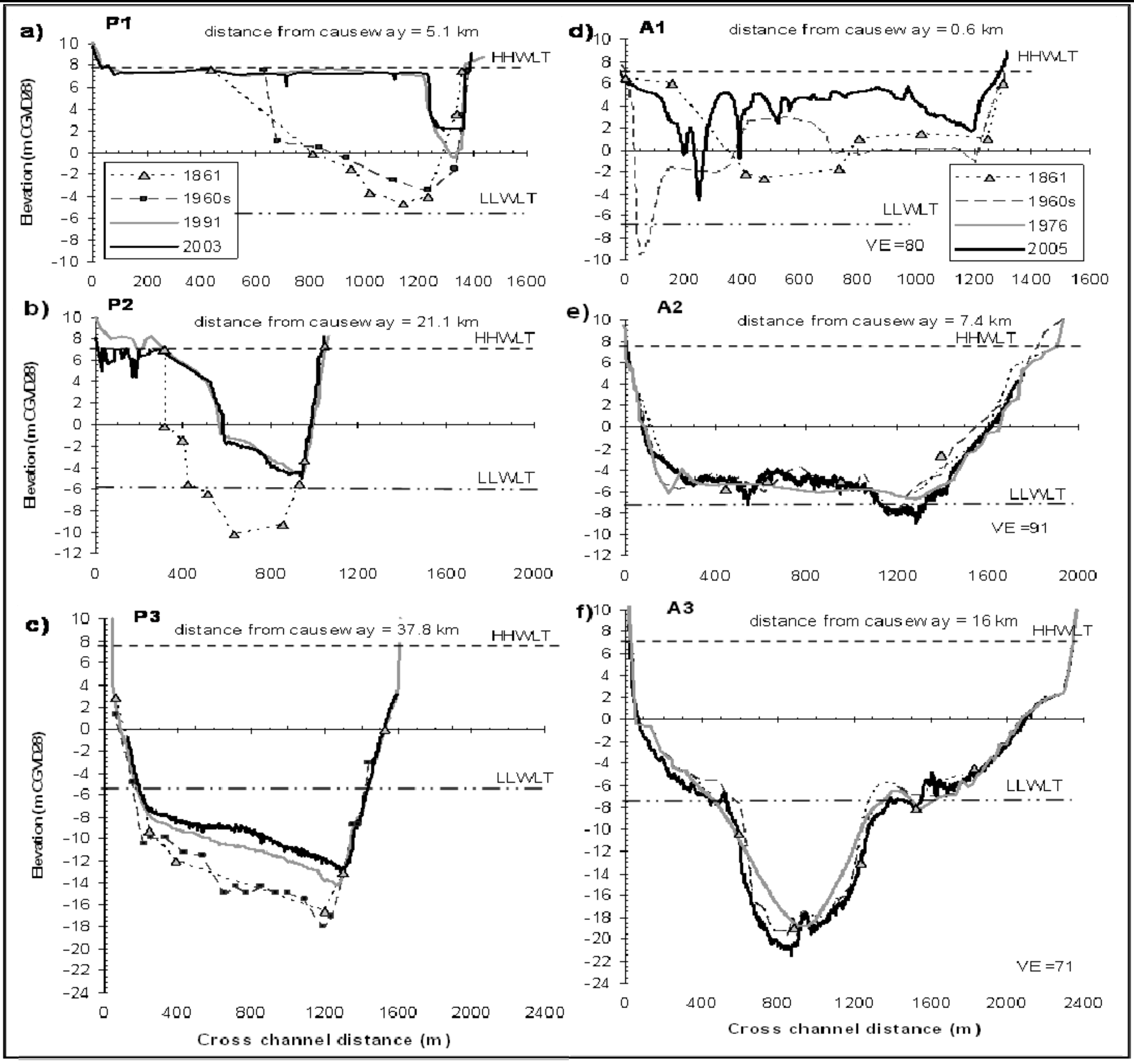

Figure 3. Variation in tidal channel cross sections on the Petitcodiac (a-c) and Avon (d-f) rivers since the 1860s. Elevations are in meters relative to the Canadian Geodetic Vertical Datum CGVD28. HHWLT=higher high water large tides, LLWLT=lower low water large tides.

1985) and data collected in 2002 from the main tide gate channel ranged from 100 – 1700 mg·l^{-1} (DABORN et al., 2003). Much

higher values of SSC were recorded (up to 30,000 mg·l^{-1}) in the Petitcodiac (CURAN et al., 2004). In a highly turbid system such as the Petitcodiac, an increase in sedimentation due to reduced cross sectional area can then in turn induce high rates of flocculation (MILLIGAN et al., 2007). AMEC (2005) recorded increases in SSC from 38 mg·l^{-1} to 2,835 mg·l^{-1} within a 2 hour period when the gates were closed. This sets up a feedback loop where higher concentrations in turn lead to the formation of fluid mud and associated density stabilization, trapping sediment near the bed which further reduces the cross sectional area (ORTON and KINEKE, 2001). Although flocculation likely does occur in the tide gate channel of the Avon river, when sediment is re-suspended during high fresh water discharge periods, the material only has a short distance to travel (< 1 km) before it enters the main river channel at the confluence with the St. Croix river and is quickly mixed. As a result a feedback loop is not initiated and fluid mud does not form. In the Petitcodiac, the closest major river is 37 km downstream of the causeway. In addition, the fact that

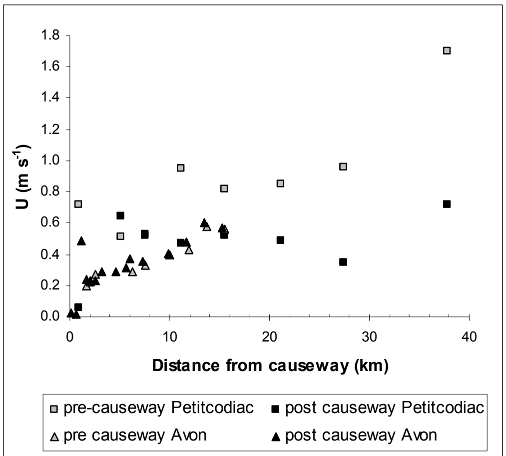

Figure 4. Variation in critical tidal velocity pre and post construction at HHWLT.

critical tidal velocities for the Petitcodiac are quite different pre and post causeway indicates that the processes of erosion and deposition have changed in some manner, perhaps due to changes in flocculation and non-linear fluid mud processes.

Although both estuaries were shortened by the same relative amount, the position of the causeway within the fully drying or non-drying segments varies between the two systems. In the Avon, the causeway was placed within the drying section whereas in the Petitcodiac it was placed within the estuarine section. Given the low 1858/1960 slope of the Petitcodiac, this may have potentially contributed to increased settling in the upper reaches.

CONCLUSIONS

The research presented here demonstrates that even within a small geographical area, the morphodynamic response of individual estuaries can vary significantly. This response is linked to the overall morphology of the estuary, sediment composition and suspended sediment concentration and potentially the position of the causeway within the larger estuary. It also suggests that in estuaries with a low channel gradient dominated by high concentrations of fine grained sediment where fluid mud might form, a feedback loop may develop which further enhances sedimentation. If an estuary such as the Avon is able to maintain tidal velocities that suppress that development and maintain a sandy substrate, then infilling may be reduced. Additional research is needed to examine the role of changing sea levels and decreased accommodation space associated with dyking. Environmental impact assessments and coastal management strategies need to account for changes within the broader estuary and for site specific differences, and not assume that all tidal barriers exert the same influence in every location.

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