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Assessing Future Coastline Change in the Vicinity of Tidal Inlets via Reduced Complexity Modelling

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ABSTRACT

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Coastline change in the vicinity of tidal inlets is mainly influenced by four processes; the Bruun effect, sea level rise driven basin infilling, variations in river discharge and fluvial sedimentation, which are driven by both climate change and anthropogenic activities. However, a coastline change model that accounts for all of the aforementioned processes under both climate change and anthropogenic influences has been lacking. The methodology presented here accounts for climate change and anthropogenic forcing in assessing potential future coastline change in the vicinity of two different types of tidal inlets. Application of this method indicates a coastline progradation of ~20 m at Kalutara inlet (Sri Lanka) and a coastline recession of ~30 m at Alsea estuary (USA) by 2100. Scrutinizing the relative contributions to these predicted coastline changes illustrates that anthropogenic influences could dictate fluvial sediment supply to coasts, underlining the significance of integrating both climate change and anthropogenic influences when assessing future coastline change along inlet-interrupted coastlines.

ADDITIONAL INDEX WORDS: coastline change, tidal-interrupted coasts, climate change, anthropogenic impacts

INTRODUCTION

Coasts and estuaries contain the worlds' most heavily populated terrestrial areas, providing habitat for about 60% of the global population (Kennish, 2003). This situation will exacerbate in future due to continued urbanization and population growth in coastal zones. Coasts and estuaries are also among the worlds' most dynamic and intricate natural systems, affected by a range of oceanic processes like sea level rise (Jennerjahn and Mitchell, 2013) and terrestrial processes such as fluvial sedimentation and runoff (Kettner *et al.*, 2009; Syvitski *et al.*, 2009). Anthropogenic factors such as large scale river flow diversion, damming and sand mining are also becoming very prominent aspects that affect these systems (Syvitski *et al.*, 2009). Despite the increasing recognition that both oceanic and terrestrial processes intrinsically contribute to the dynamic equilibrium of coasts and estuaries, most of the studies carried out to date are heavily biased towards fragmented scrutinization, resulting in an inadequate understanding of the long term evolution of Catchment-Estuary-Coastal (CEC) Systems (Ranasinghe *et al.*, 2013).

Foreshadowed population growth and climate change in the 21st century and beyond are almost certain to result in significant human perturbations, climate driven system changes and associated socio-economic impacts (Jennerjahn and Mitchell, 2013; Syvitski *et al.*, 2009). Thus, modelling methods that can

assess the long term (~100 years) physical responses of catchment-estuary-coastal systems to any substantial variation in anthropogenic and environmental forcing are a key requirement for effective coastal management and planning purposes.

Background and Aim

Owing to the inherent detachments between various disciplines such as hydrology, geography, geology, oceanography and coastal engineering, most of the studies to date have adopted fragmented approaches in assessing anthropogenic and environmental impacts on the long term evolution of catchment-estuarine-coastal systems, in which attention has only been given to one or two of the three main components of the systems (Green, 2013; Kettner *et al.*, 2009; Smith, 1988; Syvitski *et al.*, 2003). The Scale aggregated Model for Inlet - interrupted Coasts (SMIC) presented by Ranasinghe *et al.* (2013) is the only attempt to date that treats CEC systems in a holistic manner, while giving consideration to the description of physics governing each of the three components of the integrated systems.

SMIC was originally developed to assess climate change driven variations of coastlines adjacent to small bar-built mainland estuaries located in wave dominated, microtidal environments with little or no tidal flats, backwater marshes or ebb tidal deltas (Ranasinghe *et al.*, 2013). Although SMIC provides a solid foundation to probe into CEC systems in a holistic manner, restricted applicability and the simplified approach adopted in quantifying relevant terrestrial processes remains as its major drawbacks.

In view of the highly vulnerable coastlines adjacent to tidal

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inlets, their socio-economic significance and the paucity of suitable modelling techniques available to assess the holistic behaviour of CEC systems at macro time scales, a new reduced complexity modelling technique is currently being developed to assess probable future coastline changes at the vicinity of small tidal inlets (CEC-1), estuaries with low lying margins (CEC-2) and barrier island coasts (CEC-3) under the influences of climate change driven and anthropogenic forcing at 50–100 year time scales.

Improved quantification of the relevant terrestrial processes, applicability to a wider range of CEC systems and probabilistic estimations of modelled coastline change distinguish this new reduced complexity model from its predecessors. While this contribution presents the deterministic estimates of total coastline changes at CEC-1 (Kalutara inlet, Sri Lanka) and CEC-2 (Alsea estuary, Oregon, USA), future developments of this reduced complexity model will also focus on CEC-3 systems (barrier island coasts) and probabilistic estimations of coastline change at all three types of CEC systems as well.

METHODS

Total potential coastline change adjacent to tidal inlets can be computed as following (Ranasinghe *et al.*, 2013);

$$\Delta C_T = \Delta C_{BE} + \Delta C_{BI} + \Delta C_{BV} + \Delta C_{FS} \quad (1)$$

where; ΔC_T is the total potential coastline change (m), ΔC_{BE} is sea level rise driven landward movement of the coastline, ΔC_{BI} is the basin infilling due to sea level rise induced increase in accommodation space, ΔC_{BV} is the basin volume change due to climate change driven variation in river flow and ΔC_{FS} is the coastline change due to change in fluvial sediment supply.

Bruun Effect

Perhaps the most well-known mode of climate change driven coastline recession, Bruun (1978) describes the upward and landward movement of active cross-shore coastal profile. Resulting coastline recession (ΔC_{BE}) is given by;

$$\Delta C_{BE} = \frac{\Delta S}{\tan \beta} \quad (2)$$

where; ΔC_{BE} is the coastal recession (m), ΔS is sea level rise (m) and β is the slope of the active beach profile.

Basin Infilling due to Increased Accommodation Space

When the mean sea level is increased (ΔS), it will create an additional volume within the basin ($\Delta S \times A_b$; where, A_b is the basin surface area (m^2)), which is known as the accommodation space. This sediment demand creates an additional coastline recession (ΔC_{BI} (m)), which results in a landward shift of the active cross-shore coastal profile (*i.e.* coastal profile from the coastline to the depth of closure (h_{DOC} (m)) along a certain alongshore length (inlet-affected coastline length (L_{AC} (m))). This can be simplified to the following;

$$\Delta C_{BI} \times L_{AC} \times h_{DOC} = \Delta S \times A_b \quad (3)$$

Owing to the timescale differences in hydrodynamic forcing and the morphological responses associated, there is a time lag between the rate of sea level rise and basin infilling. This morphological response lag is accounted to be about 50% of the sediment volume demanded by the hydrodynamic forcing (Ranasinghe *et al.*, 2013).

Basin Volume Change due to Changes in River Flow

Changes in annual river flow (ΔQ_R (m^3)) result in altered basin volume. Following the quests to maintain its equilibrium cross-sectional velocity, an inlet-basin system would experience changes in its bed level to accommodate the relevant volume change. Thus, the resulting coastline change (ΔC_{BV} (m)) can be expressed as the following (Ranasinghe *et al.*, 2013).

$$\Delta C_{BV} \times L_{AC} \times h_{DOC} = \frac{\Delta Q_R \times V_B}{(P + Q_R)} \quad (4)$$

where, Q_R is the present river flow into the basin during ebb (m^3), ΔQ_R is the climate change driven variation in river flow during ebb (m^3), V_B is the present basin volume (m^3) and P is the mean ebb tidal prism (m^3).

Changes in Fluvial Sediment Supply

Climate change that may occur in future may result in rapid changes of fluvial sediment (ΔQ_S) supplied to coasts. This will increase/decrease the volume of sediment imported by inlet-basin system from its adjacent coast and thus alter the total coastline change. Changes in coastline due to the variations in fluvial sediment supply (ΔC_{FS} (m)) can be calculated as the following (Ranasinghe *et al.*, 2013).

$$\Delta C_{FS} \times L_{AC} \times h_{DOC} = \int_0^T \Delta Q_S(t) \cdot dt \quad (5)$$

where; T is the time period considered (in years).

The BQART Model

The empirical BQART model presented by Syvitski and Milliman (2007) is developed based on 488 globally distributed river basins. It estimates the annual sediment discharge to coast according to the following equation.

$$Q_s = \omega \times B \times Q^{0.31} \times A^{0.5} \times R \times T \quad (\text{for } T \geq 2^\circ\text{C}) \quad (6)$$

where; Q is the annual discharge from the catchment considered (km^3/yr), A is the catchment area (km^2), R is the relief of the catchment (km), T is the catchment wide mean annual temperature ($^\circ\text{C}$), and ω is 0.02 or 0.0006 for the sediment load (Q_s) expressed in kg/s or MT/yr, respectively.

The term 'B' is expressed as the following;

$$B = IL(1 - T_E)E_h \quad (7)$$

where; L is the average catchment lithology factor, T_E is the reservoir trapping efficiency ($0.1 \leq (1 - T_E) \leq 1$) and E_h is the anthropogenic factor (human influenced erosion factor) that depends upon socioeconomic condition, land use practices and population density of the catchment. In the BQART model, this E_h component is represented based on GNP (per capita) and population density. The suggested optimum range for E_h is $0.3 \leq E_h \leq 2.0$, but some studies have suggested this value to be high as 8.0 in extreme situations (Kettner *et al.*, 2005), allowing to accommodate high human disturbance potentials.

The term 'I' of the above equation (7) is the glacier erosion factor, expressed as the following;

$$I = 1 + (0.09A_g) \quad (8)$$

where A_g is the percentage of ice cover of the catchment area.

Global Human Footprint Index

The human footprint index presented by Wildlife Conservation Society-WCS & Center for International Earth Science Information Network-CIESIN-Columbia University, (2005) is an efficient estimate of the relative anthropogenic impact on natural environment, ranging from 1% to 100%. It is produced through an overlay of a number of global data layers that represent the location of various factors presumed to exert an influence on ecosystems such as human population distribution, urban areas, roads, navigable rivers, electrical power infrastructure, and various agricultural land uses. The data are regionally normalized to account for the interaction between human influences and natural environment (Sanderson *et al.*, 2002).

This high resolution spatial data set can be used (after rescaling appropriately) to represent the anthropogenic factor in BQART model (E_h), so that anthropogenic impacts on fluvial sediment supply is better represented. Human footprint indexes of the selected two sites are presented in Figure 1 and Figure 2.

Figure 1. HFPI for Kalu River Basin, Sri Lanka (CEC-1)

Figure 2. HFPI for Alsea River Basin, Oregon, USA (CEC-2)

Tidal Attenuation at Estuaries with Low Lying Margins

This category of CEC systems represent estuaries that contain salt marshes/tidal flats along their margins as well as those that contain banks with mild slopes. This type of estuarine environments are usually characterized by an almost flat back-barrier topographic profiles, covering a wide area. This unique hypsometry will result in significantly larger tidal prisms (P_T), driven by increased basin surface area (A_b) due to sea level rise.

$$P_T = A_b \times (2 \times a_b) \quad (9)$$

where; a_b is the tidal amplitude within the basin.

The volume of water flowing through the inlet during ebb (P) includes two components; (1) the volume of water flowing out of the estuary system due to tidal forcing alone, which is known as

ebb tidal prism (P_T) and (2) the volume of water supplied by the river flows (P_R). While sea level rise will increase the ebb tidal prism (as described above), climate change driven variations in terrestrial processes will also change the river flow component of tidal prism (P_R).

Increasing water levels and larger tidal inlets would reduce the frictional resistance in tidal propagation through the inlet, and hence will result in higher tidal elevations, increased tidal amplitudes and tidal prisms (Oliveira, 1970). According to the O'Brien relationship, an increase in tidal prism (P) will also enlarge the size of tidal inlet area (a) as well (O'Brien, 1969).

$$a = mP^n \quad (10)$$

where; m and n are correlation coefficients.

Keulegan (1951) provides an analytical solution to calculate tidal attenuation at inlets. This involves the determination of the coefficient of repletion (K) through a set of lookup tables for a given set of parameters; oceanic tidal amplitude (H), basin surface area (A_b), and hydraulic radius (r), area (a), length (L) and bed roughness (n) of the inlet channel as shown in the following equation (11).

$$\frac{A_b K \sqrt{H}}{a} \times 10^{-4} = f(n, r, L) \quad (11)$$

Keulegan (1951) also provides another lookup table to determine the resulting tidal attenuation to compute the tidal amplitude (a_b) within the basin.

$$\frac{a_b}{H} = \sin \tau \quad (12)$$

where; $\sin \tau$ is also given in lookup tables as a function of the coefficient of repletion (K).

In the reduced complexity model developed for CEC-2, these processes are seamlessly integrated to determine the resulting tidal attenuation and hence the equilibrium total tidal prism (P), which is to be used as an input to determine coastline change in the vicinity of the inlet (Figure 3).

Figure 3. Computation of Tidal Attenuation at CEC-2 systems

MODEL APPLICATION AND RESULTS

The above modelling technique was applied at selected study sites to estimate potential changes in coastlines due to climate change and anthropogenic impacts by 2100. Model input parameters for the study sites were obtained from published literature and/or using standard calculation methods (Table 1). Anthropogenic factor (E_h) is represented via HFPI data, obtained from Wildlife Conservation Society-WCS & Center for International Earth Science Information Network-CIESIN-Columbia University (2005). Those values [1, 100] were linearly rescaled, so that the rescaled HFPI values [0.3, 2.0] would comply

with BQART model and encapsulate the E_h range suggested by Syvitski and Milliman (2007). Mean climate projections for temperature, rainfall, and river flow values reported for the RCP 8.5 scenario of the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013) were adopted (Table 2) in all calculations. Other system variations introduced as model input parameters by 2100 are presented in Table 3.

Table 1. *Model input parameters (present condition)*

Parameter	CEC-1	CEC-2
Discharge (Q in km ³ /yr)	3.782	1.430
Temperature (T in °C)	26.0	11.3
Tidal prism (P in m ³)	6.2 x 10 ⁶	9 x 10 ⁶
Basin surface area (A_b in m ²)	1.75 x 10 ⁶	9.1 x 10 ⁶
Basin volume (V_b in m ³)	5.25 x 10 ⁶	20 x 10 ⁶
Catchment area (A in km ²)	2,778	1,225
Catchment relief (R in km)	2.25	1.25
Lithology factor (L)	0.5	1.0
Anthropogenic factor (E_h)	0.93	0.67
Beach profile slope (tan β)	0.02	0.02
Depth of closure (h_{doc} in m)	15	15
Inlet-affected coastline length (L_{AC} in m)	7,500	7,000
River Sand mining (m ³ /yr)	634,590	-

Although there are no major reservoirs built within the catchments of both the systems considered, river sand mining is a major concern for the Kalu River Basin (CEC-1). According to the Geological Survey and Mines Bureau of Sri Lanka, registered sand extraction volume of the Kalu River can be considered as 423,060 m³/yr. However, it is well known that there are many unauthorised/unmonitored sand mining activities carried out along the lower reaches of the Kalu River. In order to account for this sediment loss, annual sand extraction from the CEC-1 was set to be 1.5 times the recorded value. This value for year 2100 is considered to be 25% larger than the value adopted for present conditions (Table 3).

Table 2. *Model input parameters (year 2100)*

Parameter	CEC-1	CEC-2
Sea level rise (ΔS in m)	0.63	0.63
Temperature increment (ΔT in °C)	3.7	3.7
Change in runoff (ΔQ in mm/day)	+0.25	-0.05

Table 3. *Changes included in model parameters for year 2100*

Parameter	CEC-1	CEC-2
Tidal prism (P in m ³)	6.2 x 10 ⁶	2.5 x 10 ⁷
Change in basin surface area (%)	-	+4
Change in anthropogenic factor (%)	+20	+20
Change in river sand mining (%)	+25	-

Projected coastline changes at Kalutara inlet, Sri Lanka (CEC-1) and Alsea estuary, USA (CEC-2) by 2100 are presented in Table 4 and Figure 4. Different temperature and human impact scenarios were considered to assess their relative importance in predicted coastline changes. Those values adopted, together with the resulting changes in coastline are presented in Table 5. Positive and negative values in Table 4 and Table 5 correspond to coastline recession and progradation, respectively.

Table 4. *Model results*

	Coastline change (m) by 2100	
	CEC-1	CEC-2
Bruun effect (ΔC_{BE})	32	32
Basin infilling (ΔC_{BI})	5	28
Basin volume change (ΔC_{BV})	-1	~0
Fluvial sediment change (ΔC_{FS})	-55	-34
Total (ΔC_T)	-19	26

Figure 4. Predicted coastline change by 2100 at Kalutara inlet (CEC-1; left) and Alsea estuary (CEC-2; right)

Table 5. *Predicted coastline changes by 2100 under different temperature and anthropogenic forcing scenarios considered*

	CEC-1		CEC-2	
	ΔC_{FS} (m)	ΔC_T (m)	ΔC_{FS} (m)	ΔC_T (m)
B = 1	-42	-6	-28	32
$\Delta E_h = +10\%$	-19	17	-26	34
$\Delta T = 4.8\text{ °C}$	-72	-36	-41	19
$\Delta T = 2.6\text{ °C}$	-39	-4	-27	33

DISCUSSION

Model applications indicate 58 m of coastline progradation at Kalutara inlet, Sri Lanka (CEC-1) and 29 m of coastal recession at Alsea estuary, Oregon, USA (CEC-2) by year 2100. These results indicate that the coastline change due to variations in fluvial sediment supply is pivotal in determining total coastline change at inlet-interrupted coasts.

Setting B = 1 nullify possible human and geological impacts on total sediment yield from the catchments and hence result in

over-predicting total coastline change at both the systems. On the other hand, assuming a smaller increment in anthropogenic impacts by year 2100 (*i.e.* 10% increment of E_h) results in less volume of sand supplied to the coasts. This reduction results in significantly reduced coastal progradation at CEC-1 and increased shoreline recession at CEC-2 considered in this study.

The two different temperature increments considered in Table 5 are related to the IPCC predicted temperature increment range for RCP 8.5 scenario. Resulting coastline changes clearly illustrate that temperature is a vital component in determining coastline change due to fluvial sediment supply and hence the total shoreline changes at inlet-affected coasts.

Analysis of modelled results also indicate that the percentage change in river sand extraction volume considered for year 2100 is crucial in predicting the total coastline change. If this increment is considered to be 10% of the present value, resulting coastline progradation at the Kalutara inlet would change from 19 m to 62 m. On the other hand, under the assumption of no change in river sand extraction by year 2100, coastline change would increase by 72 m, resulting in a total 91 m of coastline progradation along the inlet-affected coast. However, considering the contemporary and future developments planned within this study area (Kalutara River Basin), a 25% volumetric increment of annual river sand extraction by year 2100 is not an unrealistic consideration.

Scrutinization of the modelled results at Alsea estuary (CEC-2) revealed that the tidal attenuation at its inlet would cease to exist by 2100. This is primarily governed by the projected sharp change in the rate of sea level rise by the end of the 21st century.

CONCLUSIONS

As part of a long term study that is currently being undertaken on holistic assessment of catchment-estuary-coastal system behaviour at macro time scales, a modelling technique that incorporates the main climate change driven and anthropogenic impacts to compute coastline changes in the vicinity of different types of tidal inlets is proposed. This technique was applied to Kalu River Basin, Sri Lanka (CEC-1) and Alsea estuary, Oregon, USA (CEC-2) as case studies.

Analysis of model results indicate that temperature, catchment characteristics and human impacts are crucial in determining total shoreline change, which have been routinely neglected in previous studies on coastline change at inlet-interrupted coastlines. Therefore, in general, coastline prediction techniques that do not comprise these phenomena are likely to underpredict future fluvial sediment supply to estuaries and coasts and subsequently overpredict (underpredict) total coastline recession (progradation).

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