8th INTERNATIONAL CONFERENCE ON COASTAL AND PORT ENGINEERING IN DEVELOPING COUNTRIES

COPEDEC 2012, IIT Madras, Chennai, INDIA.
20-24 Feb. 2012

CLIMATE CHANGE IMPACTS ON THE STABILITY OF SMALL TIDAL INLETS: A numerical modelling study using the Realistic Analogue approach

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Abstract: Tidal inlets are of great societal importance as they are often associated with ports and harbours, industry, tourism, recreation and prime waterfront real estate. Their behaviour is governed by the delicate balance of oceanic processes (tides, waves and mean sea level), and fluvial/estuarine processes (riverflow and heat fluxes), all of which can be significantly affected by climate change (CC) processes. This study investigates the potential range of CC impacts on the stability (closed/open state and locational stability) via the application of a sophisticated process based morphodynamic model (Delft3D) to strategically selected schematised inlet morphologies and forcing conditions.

Keywords: *Climate change; Tidal inlet, Sea Level Rise, Delft3D.*

INTRODUCTION

Tidal inlets are also among the most morphologically dynamic regions in the coastal zone (Kjerfve, 1994; Nicholls et al., 2007; Stive et al, 2009). These dynamic systems are also of great societal importance as they are often associated with ports and harbours, industry, tourism, recreation and prime waterfront real estate. The complex feedbacks between system forcing and response in inlet/lagoon systems result in ongoing spatial and temporal variations in system characteristics which are of great scientific interest and continue to be the focus of numerous scientific studies (Bruun, 1978; Aubrey and Weishar, 1988; Prandle, 1992, Ranasinghe et al., 1999; Lam, 2009; Dissanayake et al., 2009; Tung, 2011).

Tidal inlet behaviour is governed by the delicate balance of oceanic processes such as tides, waves and mean sea level (MSL), and fluvial/estuarine processes such as riverflow and heat fluxes. Alarmingly, all of these processes can be significantly affected by climate change (CC) processes, which may result in severe negative physical impacts such as erosion of open coast beaches adjacent to the inlet and/or estuary margin shorelines, permanent or frequent inundation of low lying areas on estuary margins, eutrophication, and toxic algal blooms etc. Furthermore, CC driven changes in forcing may affect the stability of the inlet itself. For example, a permanently open, locationally stable inlet may evolve into an alongshore migrating, intermittently closing inlet; or, a seasonally closing, locationally stable inlet may evolve into a permanently open, alongshore migrating inlet. Such changes in inlet condition are highly likely to affect navigability and estuary/lagoon water quality. Consequently, these impacts are also likely to result in significant socio-economic, environmental and ecological losses.

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Although a very few recent studies have investigated CC impacts on large tidal inlet/basin systems (e.g. Wadden Sea - Dissanayake et al. (2009)), the exact nature and magnitude of CC impacts on the more commonly found small tidal inlet/estuary systems remains practically un-investigated to date. Furthermore, whether currently available predictive tools are capable of simulating CC impacts on these systems also remains unknown. These knowledge gaps are a serious threat to effective adaptation to climate change in small tidal inlet environments. The present study aims to take an initial step towards addressing these knowledge gaps.

For the purposes of this study, small tidal inlets (STIs) are defined as those with inlet channels that are less than 500m wide, and are connected to relatively shallow (average depth < 10m) estuaries/lagoons with surface areas less than 50 km^2. Such inlets are common in tropical and sub-tropical regions (e.g. India, Sri Lanka, Vietnam, Florida (USA)), South America (Brazil), South Africa, and SW/SE Australia.

Inlet stability:

The stability of a tidal inlet can also be considered in light of its capacity for sediment bypassing which is the transport of sediment from the updrift to the downdrift margin of the tidal inlet. Bruun and Gerritsen (1960) presented the ratio P/M_{tot} as an indicator of overall inlet stability, where: M_{tot} = total annual littoral drift (m^3/year) and P= tidal prism (m^3/tidal cycle).

According to the value of P/M_{tot}, the stability of an inlet is rated as good, fair, or poor as shown in Table 1.

Table 1: Bruun and Gerritsen's (1960) classification of Inlet stability

P/M_{tot}	Inlet stability classification
> 150	**Good** – *predominantly tidal flow by-passers;* *entrance with little or no ocean bar outside gorge and good flushing*
100 – 150	**Fair** – *mix of bar-by-passing and flow-by-passing;* *entrance has low ocean bars, navigation problems usually minor*
50 – 100	**Fair to poor** – *inlet is typically bar-by-passing and unstable;* *entrance with wider and higher ocean bars, increasing navigation problems*
< 50	**Poor** – *inlet becomes unstable with non-permanent overflow channels;* *entrance with wide and shallow ocean bars, navigation difficult*

Inlet stability can be further classified into two broad types: Cross-sectional stability and locational stabilty. The above classification by Bruun and Gerritsen (1960) does not differentiate between these two categories, but describes inlet stability in an overall sense.

Cross sectional stability of Tidal inlets:

The inlet dimensions of a cross-sectionally stable inlet will remain more or less constant over time. These inlets may or may not stay fixed in one location. The study of cross sectional stability of tidal inlets was pioneered by the early works of O'Brien (1931), Escoffier (1940). O'Brien (1931), through his purely empirical work found that inlet cross-sectional area could be related to the tidal prism and the average inlet current velocity over a tidal cycle. The general form of the relationship is given as:

$$A_c = a . P^n$$

where, A_c: cross sectional area of inlet gorge (m^2), P: spring tidal prism (m^3), a and n: empirical coefficients. For many coasts the value of n is found to be of the order 1 (Jarrett, 1976; Van de Kreeke, 1990).

Escoffier (1940) introduced a hydraulic stability curve, commonly referred to as the *Escoffier diagram*, in which maximum flow velocity is plotted against cross sectional flow area (Figure 1). According to this diagram, an inlet which has a cross sectional area larger than a critical flow area is termed hydraulically stable. Any change in a hydraulically stable inlet that brings its cross-sectional area out of its equilibrium size will result in a change in inlet velocity that forces the inlet to return to its equilibrium value via deposition or scour. On the other hand, an inlet is hydraulically unstable if its cross sectional area is smaller than the critical flow area value. Since any initial change in flow area is accentuated under this condition, the hydraulically unstable inlet will either continuously scour until the equilibrium flow area is attained, or continuously shoal until the inlet closes.

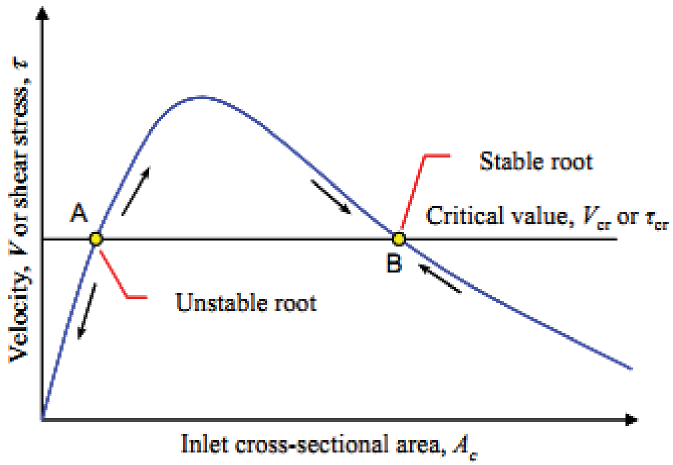

Figure 1. The Escoffier curve (after Escoffier, 1940)

An example of a cross-sectionally unstable (but locationally stable) inlet is shown in Figure 2. Note that, the inlet location of a cross-sectionally stable inlet may or may not fixed over time**.**

Figure 2. Cross-sectionally unstable inlet of the Russian River, California, USA (from Behrens, 2008)

Locational stability of Tidal inlets:
Locationally unstable inlets are those that migrate alongshore. The cross-sectional area of these inlets may or may not remain constant in time. Alongshore migration of inlets is a common feature along many coasts around the world where wave-induced longshore sediment transport is dominant in one direction. Figure 3 shows an example of a locationally and cross-sectionally unstable inlet.

Figure 3. Navarro Inlet, USA (*photos courtesy of D.Behrens*)**.**

METHODS

STI behaviour will vary depending on three main phenomena: tidal prism, nearshore sediment transport (cross-shore and longshore), and riverflow. For each combination of these 3 phenomena an STI is likely to have some type of dynamic equilibrium as far as inlet stability is concerned (i.e. inlet dimensions, shape, closed/open/migration state will be unique for each combination of these 3 phenomena over the long term). However, globally, many variations of tidal prism, nearshore sediment transport (cross-shore and longshore), and riverflow are possible even within the constraints inherent in the definition of an STI given above. Assuming just 3 different values for each of the above 3 phenomena will result in 27 cases. Therefore, if the range of CC impacts for these 27 scenarios were to be investigated via process based modelling for field sites, a state-of-the art coastal morphodynamic models (such as Delft3D, Mike21) will have to be applied to 27 locations from around the world that satisfy the 27 phenomenological conditions. In most practical situations, time and budgetary constraints will not allow such an exhaustive modelling study. Therefore, in this study, a series of strategic idealised cases are simulated using the state of the art morphodynamic model Delft3D (see Lesser et al., 2004 for a model description).

The schematised inlet/forcing conditions were developed such that the following main inlet morphodynamic characteristics are represented:

1. *Permanently open, locationally stable inlet*
2. *Permanently open, alongshore migrating inlet*
3. *Seasonally/Intermittently closed, locationally stable inlet*
4. *Seasonally/Intermittently closed, alongshore migrating inlet*

The initial bathymetry for all of schematised cases consist of a rectangular estuary/lagoon of constant depth connected to the ocean via a straight, constant depth channel. The inlet and lagoon/estuary dimensions were chosen such that the schematised system loosely represents a real-life system in each of the above four system categories. Type 1 is represented by Negombo lagoon, Sri Lanka; Type 2 by Currumbin river, Australia; Type 3 by Maho Oya river, Sri Lanka, and Type 4 by Navarro inlet, USA. In all cases the bathymetry of the ocean side consisted of shore parallel depth contours such that a Dean's equilibrium profile (with appropriate D50 depending on the associated field site) is followed up to 20m depth. Figure 4 below shows the schematised STI bathymetries that were used in this study.

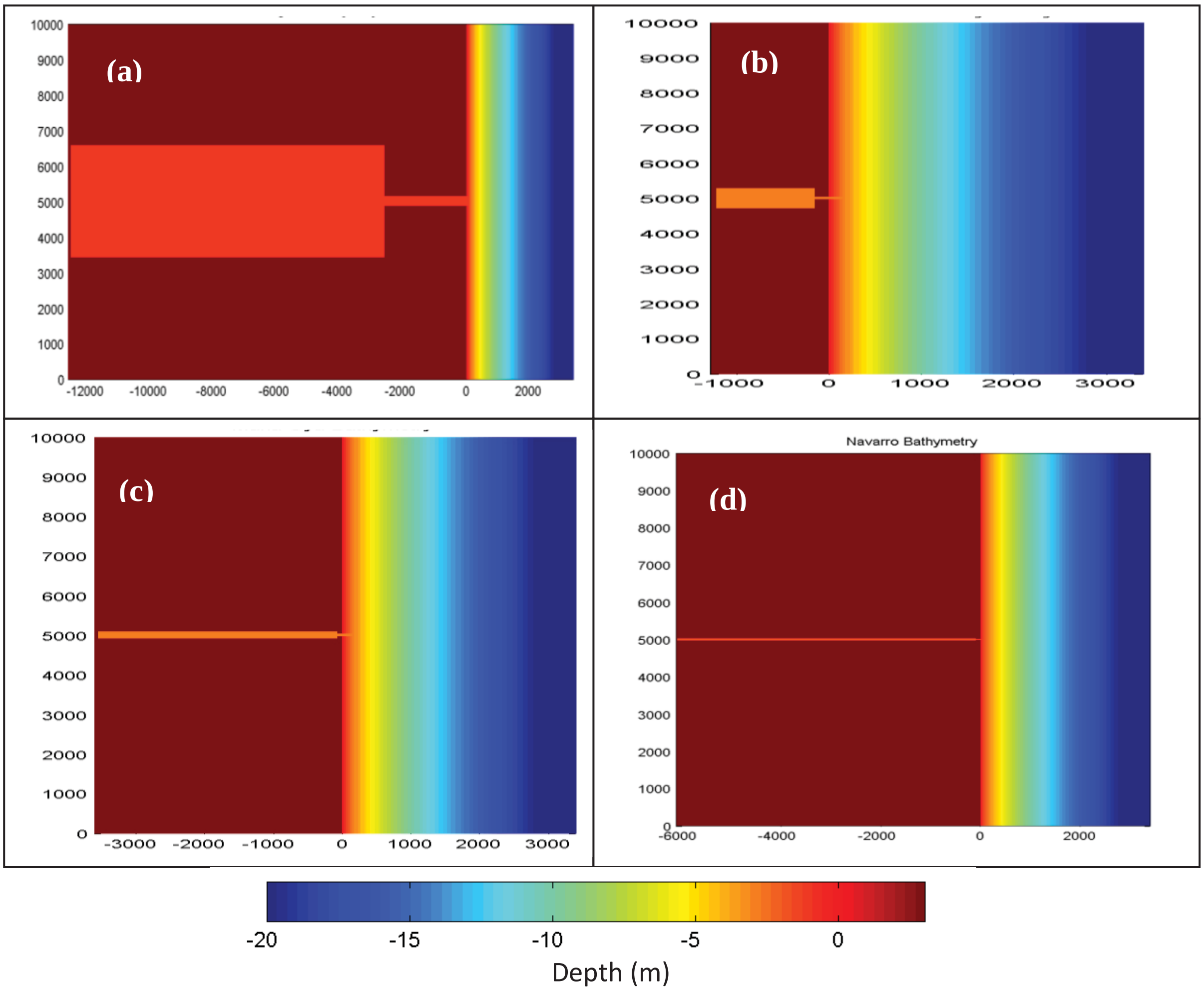

Figure 4. Schematised bathymetries representing; (a) Negombo lagoon, Sri Lanka (Type 1), (b) Currumbin river, Australia (Type 2), (c) Maha Oya river, Sri Lanka (Type 3), and (d) Navarro river, USA (Type 4).

For each inlet type a series of Delft3D simulations were undertaken following the Realistic analogue modelling philosophy (Dissanayake et al., 2011). In each case, a long morphological establishment simulation, starting with the schematised bathymetry, was undertaken with only tidal forcing to develop a morphology that was more or less in equilibrium with the ambient tidal forcing in the representative case study area. The establishment simulations were continued until the average rate of daily morphological change was sufficiently small and time invariant to assume morphodynamic equilibrium. Figure 5 illustrates the establishment simulation for a Type 3 system (represented by Maha Oya river, Sri Lanka).

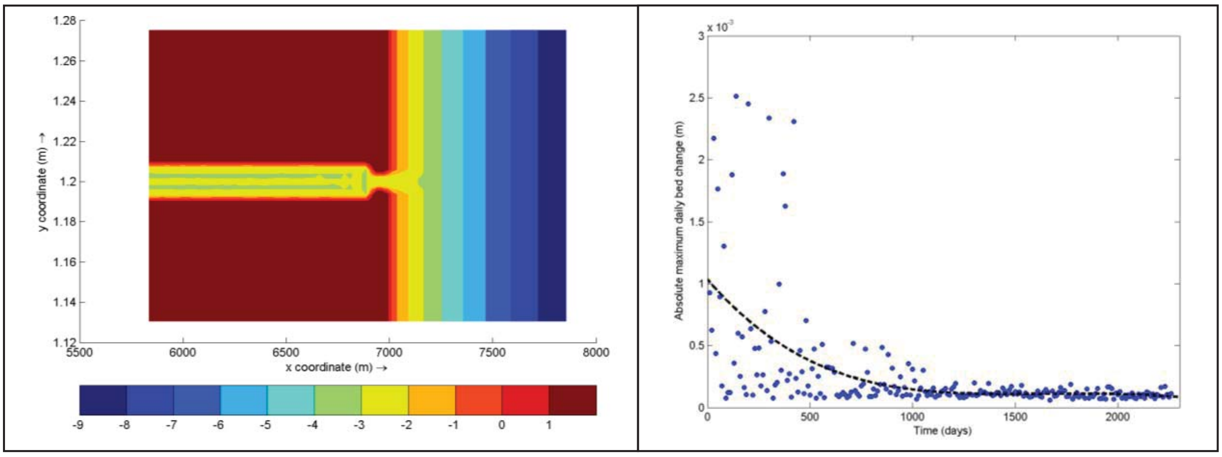

Figure 5. Establishment simulation for a Type 3 system: simulated morphology at the end of the 4 year (1500 days) establishment simulation (left) (colorbar indicates depth (m)), and the rate of daily bed level change during the simulation showing equilibrium conditions after about 4 years.

A present condition simulation (i.e. benchmark simulation) was then undertaken using the established morphology (i.e. the morphology produced at the end of the above described establishment simulation) as the start bathymetry. The model was forced with schematised tidal and wave forcing representing the conditions at the relevant case study area. For each system type two sets of forcing conditions were used: favourable (i.e. promoting inlet stability) and unfavourable (i.e. promoting unstable inlet conditions), to ensure that the adopted modelling approach could reproduce both stable and unstable inlet conditions with qualitative accuracy. The length of each simulation varied depending on observed behavior at the relevant case study sites. For example, for the Type 1 system represented by the permanently open Negombo lagoon, Sri Lanka, both the favourable and unfavourable forcing simulations were continued for 1 year to gain confidence that the adopted modelling approach will reproduce the observed highly stable system behaviour under both types of forcing conditions over an extended period of 1 year (although unfavourable forcing conditions at Negombo lagoon only last for a maximum of about 3 months during the NE monsoon when riverflows are very low). In contrast, the locationally stable, but cross-sectionally unstable Maho Oya river (on which the Type 3 system is based on) closes during the NE monsoon (usually occurring over the 3 month period from December to February), while it is generally open during the rest of the year (unless riverflow decreases significantly). Therefore, the Type 3 simulation with favourable forcing was continued for 9 months, while the Type 3 simulation with unfavourable forcing was continued only for 3 months. Due to space limitations, however, only the unfavourable forcing scenario of no riverflow is discussed hereon.

Following the benchmark simulations, a series of CC perturbed simulations (CC set) representing potential future changes in mean sea level (i.e. SLR) and wave characteristics were undertaken for each system category. The CC scenarios considered were:

i. SLR of 1m
ii. Wave height increase/decrease of 50%
iii. Wave angle increase/decrease (relative to shore normal) of 15^0

iv. Combination of (ii) and (iii)
v. Combination of (i), (ii), and (iii)

Each CC set simulation was continued for the same duration as the corresponding benchmark simulation length. In the SLR scenarios, the basin infilling due to the SLR induced accommodation space effect was taken into account by increasing the established morphology lagoon bed levels by 50% of the SLR value (Ranasinghe et al., 2011) before the CC set simulations commenced. The predicted morphological changes for the above CC scenarios for the Type 3 system are shown in Figure 6.

RESULTS

The result of the present condition simulation (3 month simulation, following the worst case conditions at Maha oya river) is shown in Fig 6a. Following the actual situation at Maha Oya, the model correctly predicts the gradual downdrift movement (waves are incident 10^0 North of the shore normal in the figure) of the inlet channel due to the growth of a spit on the updrift side of the channel, and the closure of the inlet after 3 months of being subjected to forcing that is typical during the NW monsoon in Sri Lanka (signoficant wave height = 1m, wave angle to shore normal = 10^0). Therefore, this benchmark simulation provides qualitative validation of the model's ability to reproduce the observed behaviour at Type 3 systems. A 50% increase in significant wave height (to 1.5m) does not appear to change inlet behaviour significantly (Fig. 6b). The main differences (relative the present condition) that can be expected under this forcing scenario are that the updrift spit growth is slightly enhanced, while the ebb shoal is deflected slightly downdrift. The inlet closure still occurs after 3 months as in the benchmark simulation. A 15^0 increase in the wave angle (wave height = 1m) results in a significant enhancement of the updrift spit (resulting in a curved spit) and a slight downdrift migration of the inlet (~ 50m) before it closes (Fig. 6c). The ebb shoal is less prominent while some erosion of the downdrift shoreline is also shown under this scenario. When both the wave height and angle are increased, the inlet migrates downdrift by upto 100m before closing (Fig. 6d). The closure in this case occurs after about 2.5 months. The ebb shoal development is minimal under this scenario. Under a SLR of 1m (no change in wave conditions), the inlet remains fixed in place (no migration) and it does not close within 3 months (Fig. 6e) (or 6 months - not shown). Indeed under this scenario, the inlet appears to be more stable compared to the present condition. Under this scenario, The ebb shoal is more prominent while the expected shoreline erosion also occurs. When the effects of SLR and increases in wave height and direction are combined, the inlet migrates downdrift by upto 200m and closes within 2 months. Thus under this scenario it appears that a locationally stable, cross-sectionally unstable inlet (Type 3 system) may transform into a locationally and cross-sectionally unstable inlet (Type 4 system).

CONCLUSIONS

A process based coastal morphodynamic model (Delft3D) is used with schematised morphology and forcing representing real inlet/lagoon systems to investigate potential climate change impacts at small tidal inlets (STIs). Four different types of inlets with varying locational and cross-sectional stability conditions were investigated. The system types investigated were: Permanently open, locationally stable inlet (Type 1); Permanently open, alongshore migrating inlet (Type 2); Seasonally/Intermittently closed, locationally stable inlet (Type 3); and Seasonally/Intermittently closed, longshore migrating inlet (Type 4).

Results show that a climate change driven increase in mean sea level or wave height alone is unlikely to have a negative impact on inlet stability in any of the four STI types under unfavourable forcing conditions. However, a significant change in the wave direction may result in a deterioration of inlet stability, especially in Type 3 and Type 4 systems under unfavourable forcing conditions. The integrated effect of climate change driven increase in mean sea level, wave height and wave angle may result in a Type 2 system turning into a Type 3 system and a Type 3 system turning into Type 4 system. The impact of climate change on STI behaviour under favourable forcing conditions is currently being investigated.

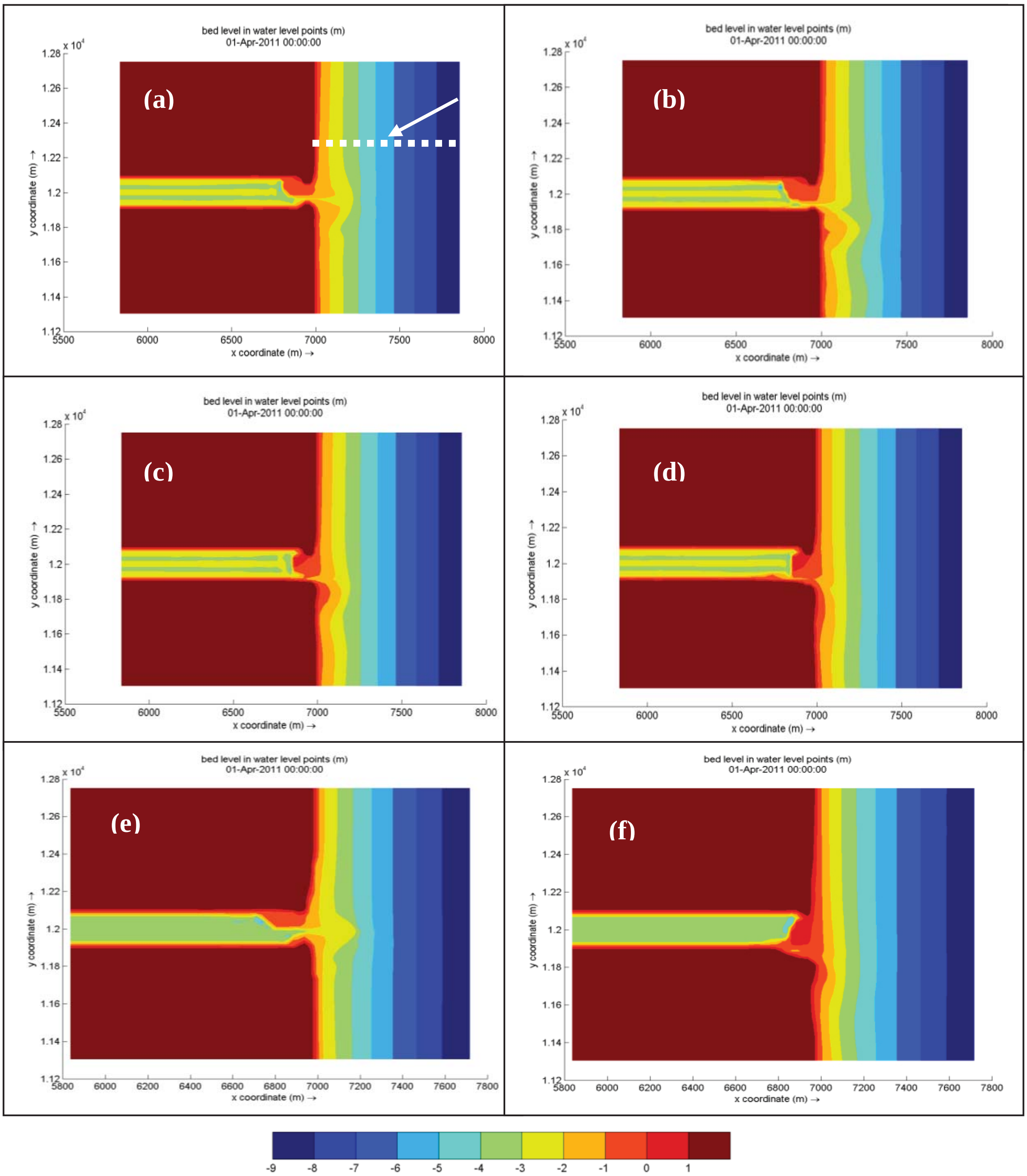

Figure 6. Model predicted morphological changes for a Type 3 system with unfavourable forcing over a 3 month duration for: (a) present forcing conditions (arrow indicates wave direction, dashed white line indicates shore normal), (b) CC driven 50% increase in significant wave height (from 1m to 1.5m), (c) CC driven 15^0 increase in wave angle to the shore normal, (d) combination of (b) and (c), (e) sea level rise of 1m, and (f) combination of (b), (c) and (e). (colorbar indicates depth (m))

ACKNOWLEDGEMENTS

This study is funded via a UNESCO-IHE/DGIS UPARF CatII project (CC-SIOTI). The first author's attendance at COPEDEC VIII was supported by a PIANC-COPEDEC travel fellowship.

REFERENCES

Bruun, P. 1962. Sea-level rise as a cause of shore erosion, Journal of Waterways Harbors Division, 88: 117-130.

Aubrey, D. G. and Weishar, L., (Editors), 1988. Hydrodynamics and sediment dynamics of tidal inlets. Lecture Notes on Coastal and Estuarine Studies, 29. Springer-Verlag, New York.

Behrens, D. C., 2008. Inlet Closure and Morphological Behavior in a Northern California Estuary: The Case of the Russian River. MSc thesis, University of California, Davis.

Bruun, P. and Gerritsen, F., 1960. Stability of Coastal Inlets. North-Holland Publishing Co., Amsterdam.

Dissanayake, D. M. P. K., Ranasinghe, R., and Roelvink, J. A., 2009. Effect of sea level rise on tidal inlet evolution, Journal of Coastal Research, SI 56, Vol 2, 942-946.

Dissanayake, D. M. P. K., Ranasinghe, R., and Roelvink, J. A., 2011. The morphological response of large tidal inlet/basin systems to relative sea level rise, Climatic Change (in press).

Escoffier, F. F., 1940. The stability of tidal inlets. Shore and Beach, 8:111–114.

Kjerfve, B., 1994. Coastal Lagoon Processes. In: Kjerfve, B., (Editor), Coastal Lagoon Processes. Elsevier Science Publishers, Amsterdam, pp. 1-8.

Lam, N. T., 2009. Hydrodynamics and morphodynamics of a seasonally forced tidal inlet system. Ph.D. Thesis, Delft University of Technology.

Lesser, G. R., Roelvink, J. A., van Kester, J. A. T. M. and Stelling, G. S., 2004 . Development and validation of a three-dimensional morphological model. Coastal Engineering, 51 (8-9): 883-915, Elsevier Science Publishers B.V.

Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. Hay, R.F. McLean, S. Ragoonaden and C.D. Woodroffe, 2007: Coastal systems and low-lying areas. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 315-356.

O'Brien, M. P., 1931. Estuary Tidal Prisms Related to Entrance Areas. Civil Engineering, 1(8): 738-739.

Prandle, D., 1992. Dynamics and Exchanges in Estuaries and the Coastal Zone. American Geophysical Union, Washington.

Ranasinghe, R., Pattiaratchi, C. and Masselink, G., 1999. A morphodynamic model to simulate the seasonal closure of tidal inlets. Coastal Engineering, 37(1):1–36, Elsevier Science Publishers B.V.

R. Ranasinghe, J. Bosboom, S. Uhlenbrook, D. Roelvink, H. Ngo and M. J. F. Stive. 2011. A scale aggregated model to estimate climate change driven coastline change along inlet interrupted coasts. Proceedings of Coastal Sediments 2011, Miami, FL, USA, pp. 286-298

Stive, M. J. F., van de Kreeke, J., Lam, N. T., Tung, T. T. and Ranasinghe, R., 2009. Empirical relationships between tidal inlet cross section and tidal prism: A review. Proceedings of Coastal Dynamics 2009, World Scientific (CD Rom).

Tung, T. T., 2011. Morphodynamics of Seasonally closed coastal inlets at the central coast of Vietnam. Ph.D. Thesis, Delft University of Technology.

Jarrett, J. T., 1976. Tidal Prism – Inlet Area Relationships. Technical Report GITI No.3, CERC, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Van de Kreeke, J., 1990b. Stability analysis of a two-inlet bay system. Coastal Engineering, 14(6): 481-497.