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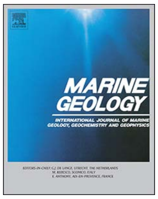

Assessing climate change impacts on the stability of small tidal inlets: Part 2 - Data rich environments

Trang Minh Duong[a,b], Roshanka Ranasinghe[a,b,c,*], Marcus Thatcher[d], Sarith Mahanama[e,f], Zheng Bing Wang[b], Pushpa Kumara Dissanayake[g], Mark Hemer[h], Arjen Luijendijk[b], Janaka Bamunawala[a], Dano Roelvink[a,b], Dirkjan Walstra[b]

[a] Department of Water Science and Engineering, UNESCO-IHE, PO Box 3015, 2601 DA Delft, The Netherlands
[b] Deltares, PO Box 177, 2600 MH Delft, The Netherlands
[c] Water Engineering and Management, Faculty of Engineering Technology, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands
[d] CSIRO Oceans & Atmosphere, Private Bag 1, Aspendale, VIC 3195, Australia
[e] Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, MD, USA
[f] Science Systems and Applications Inc, Lanham, MD, USA
[g] Environmental Physics group, Limnological Institute, University of Konstanz, 78464 Konstanz, Germany
[h] CSIRO Oceans & Atmosphere, GPO Box 1538, Hobart, TAS 7001, Australia

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ABSTRACT

Climate change (CC) is likely to affect the thousands of bar-built or barrier estuaries (here referred to as Small tidal inlets - STIs) around the world. Any such CC impacts on the stability of STIs, which governs the dynamics of STIs as well as that of the inlet-adjacent coastline, can result in significant socio-economic consequences due to the heavy human utilisation of these systems and their surrounds. This article demonstrates the application of a process based snap-shot modelling approach, using the coastal morphodynamic model *Delft3D*, to 3 case study sites representing the 3 main STI types; Permanently open, locationally stable inlets (Type 1), Permanently open, alongshore migrating inlets (Type 2) and Seasonally/Intermittently open, locationally stable inlets (Type 3). The 3 case study sites (Negombo lagoon – Type 1, Kalutara lagoon – Type 2, and Maha Oya river – Type 3) are all located along the southwest coast of Sri Lanka.

After successful hydrodynamic and morphodynamic model validation at the 3 case study sites, CC impact assessment are undertaken for a high end greenhouse gas emission scenario. Future CC modified wave and riverflow conditions are derived from a regional scale application of spectral wave models (WaveWatch III and SWAN) and catchment scale applications of a hydrologic model (CLSM) respectively, both of which are forced with IPCC Global Climate Model output dynamically downscaled to ~50 km resolution over the study area with the stretched grid Conformal Cubic Atmospheric Model CCAM. Results show that while all 3 case study STIs will experience significant CC driven variations in their level of stability, none of them will change Type by the year 2100. Specifically, the level of stability of the Type 1 inlet will decrease from ‘Good’ to ‘Fair to poor’ by 2100, while the level of (locational) stability of the Type 2 inlet will also decrease with a doubling of the annual migration distance. Conversely, the stability of the Type 3 inlet will increase, with the time till inlet closure increasing by ~75%. The main contributor to the overall CC effect on the stability of all 3 STIs is CC driven variations in wave conditions and resulting changes in longshore sediment transport; not Sea level rise as commonly believed.

1. Introduction

Bar-built or barrier estuaries (here referred to as Small tidal inlets - STIs) are one of the 3 main types of inlet-estuary/lagoon systems identified by Bruun and Gerritsen (1960). These systems are commonly found in wave dominated and microtidal environments; especially in tropical and sub-tropical regions of the world (e.g. India, Sri Lanka, Vietnam, Florida (USA), South America (Brazil), South Africa, and SW/SE Australia). STIs generally comprise narrow (< 500 m wide) inlet channels and shallow (average depth < 10 m) estuaries/lagoons with surface areas less than 50 km^2 (Duong et al., 2016).

STIs can be classified into 3 main categories based on their general

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[*] Corresponding author at: Department of Water Science and Engineering, UNESCO-IHE, PO Box 3015, 2601 DA Delft, The Netherlands.
E-mail addresses: T.Duong@un-ihe.org (T.M. Duong), R.Ranasinghe@un-ihe.org (R. Ranasinghe).

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morphodynamic behaviour as:

- Permanently open, locationally stable inlets (Type 1)
- Permanently open, alongshore migrating inlets (Type 2)
- Seasonally/Intermittently open, locationally stable inlets (Type 3).

The Type of the STI reflects the stability of the inlet (i.e. open, close, migrating) which governs the dynamics of the adjacent coastline and of the estuary/lagoon connected to the inlet, and is therefore a key diagnostic in assessing potential CC impacts on STIs. The term “inlet stability”, in general usage, may refer to locational stability or channel cross-sectional stability. Locationally stable inlets are those that stay fixed in one location, but may stay open (i.e. locationally and cross-sectionally stable inlets - Type 1) or close intermittently/seasonally (i.e. locationally stable but cross-sectionally unstable inlets - Type 3). Cross-sectionally stable inlets are those in which the inlet dimensions will remain mostly constant over time. However, cross-sectionally stable inlets may also migrate alongshore (i.e. cross-sectionally stable but locationally unstable - Type 2) (Duong et al., 2016).

The stability of STIs (or the inlet condition) is governed by two main phenomena: the flow through the inlet (tidal prism and riverflow) and nearshore sediment transport in the vicinity of the inlet. Thus, inlet stability is a function of the balance between terrestrial (e.g. riverflow) and oceanic forcing (e.g. mean sea level, waves) (Ranasinghe et al., 2013). All of these system forcings are expected to be affected by climate change (CC) (Duong et al., 2016; Ranasinghe, 2016). IPCC (2013) projections indicate a global mean sea level rise (SLR) of 0.26–0.82 m by 2081–2100 (relative to 1986–2005) with the most pessimistic RCP 8.5 scenario projecting an SLR of 0.52 m to 0.98 m by 2081–2100. Where future riverflows are concerned, IPCC (2013) projections for the RCP 8.5 scenario indicate increases/decreases of up to 30% in annual runoff in many parts of the world by the end of the 21st century relative to the present. Hemer et al. (2013) presented wave projections which indicate that annual mean wave heights will decrease in around 25% of the global ocean, while an increase is projected for about 7.1% of the global ocean. Furthermore, Hemer et al. (2013) projected clockwise and anti-clockwise rotations in wave direction for about 40% of the global ocean. Thus, the stability of thousands of STIs around the world that are governed by these forcings are likely to be impacted by CC in the 21st century, potentially resulting in serious socio-economic consequences owing to the wide range of economic activities (e.g. tourist hotels and tourism associated recreational activities, inland fisheries, harbouring of sea going fishing vessels) that STIs and surrounding areas often support.

Recognising the difficulty associated with investigating CC impacts on the stability of STIs via a straightforward application (i.e. a single 100 yearlong morphodynamic simulation) of presently available process based coastal morphodynamic models (e.g. *Delft3D*, *CMS*, *Mike21*, *Xbeach*) (see for e.g. Nienhuis et al., 2016; Dodet et al., 2013;), Duong et al. (2016) proposed two different ‘snap-shot’ process based modelling approaches to investigate this phenomenon in data poor and data rich environments (see Figs. 10–12 in Duong et al., 2016). The main differences between the two approaches are: (a) the data poor approach uses schematised system bathymetry while the data rich approach requires good measured system bathymetry for model initialisation; (b) the data poor approach uses freely available coarse resolution (∼100–200 km) global scale projections of future CC modified system forcing (i.e. waves, riverflows and sea level rise) while the data rich approach requires site specific projections of future system forcing obtained from high resolution regional scale hydrologic and wave models forced with dynamically downscaled Global climate model (GCM) output; and (c) coastal impact models are only qualitatively validated in the data poor approach, while both quantitative and qualitative model validation are required in the data rich approach.

Duong et al. (2017) demonstrates the application of the ‘data poor’ approach to 3 case study sites representative of the 3 main STI types. This article demonstrates the application of the ‘data rich’ approach at the same 3 case study sites to derive site-specific projections of CC impacts, and through a comparison of results obtained using the ‘data rich’ and ‘data poor’ approaches, suggests a basic guideline on when to use which approach.

2. Study areas

The 3 case study sites selected for this study are: Negombo lagoon (Type 1), Kalutara lagoon (Type 2) and Maha Oya river (Type 3), all of which are located along the SW coast of Sri Lanka. For CC impact studies, a study area may be considered to be ‘data rich’ when wave, wind and riverflow data (ideally exceeding 10 years to encapsulate inter-annual variability); downscaled future CC modified wave and riverflow data, and bathymetries of the study area are available. All these data are available for the 3 case study sites.

Located in the Indian Ocean Southeast of India (Fig. 1), Sri Lanka experiences a tropical monsoon climate with 2 monsoon seasons: the Northeast (NE) monsoon (November–February) and the Southwest (SW) monsoon (May–September). October to December is the wettest period with about one third of the total annual rainfall occurring during this time (Zubair and Chandimala, 2006). The coastal environment of Sri Lanka is micro-tidal (mean tidal range ∼0.5 m) and wave dominated (average offshore significant wave height ∼1.1 m). The SW coast of Sri Lanka, where the 3 case study sites are located, experiences the most energetic wave conditions during the SW monsoon with offshore significant wave heights of 1–2 m incident from the SW-W octant. Almost all the beaches around the country are sandy with grain diameters (D_{50}) of 0.2–0.45 mm. Detailed descriptions of the 3 case study sites are provided in Duong et al. (2017) and are therefore not repeated here. For the sake of completeness however study area locations, case study sites and main system characteristics are shown in Figs. 1, 2 and Table 1 respectively. The system characteristics listed in Table 1 were obtained from a range of sources including scientific articles, technical reports, post-graduate theses, field visits and local experts. Information on Negombo lagoon was mostly obtained from Chandramohan and Nayak (1990) and University of Moratuwa (2003); on Kalutara lagoon from Perera (1993) and GTZ (1994); and on Maha Oya from GTZ (1994). Fluvial sediment transport into the 3 systems is expected to be practically zero due to impoundments at upstream dams (personal communication, Sri Lanka Coast conservation department).

3. Methodology

As proposed by Duong et al. (2016) for data rich environments, a modified version of the ensemble modelling framework proposed by Ranasinghe (2016) (Fig. 3) was adopted in this study. Ranasinghe's (2016) modelling framework proposes the sequential application of GCM projections, Regional Climate Models (RCMs), Regional wave/hydrodynamic/catchment models, local wave models, and coastal impact models to obtain a number of different projections of the coastal CC impact of interest.

In Step 5 of the above framework (see Fig. 3), it is necessary to use a coastal impact model that is appropriate for investigating the CC impact of interest. In this study, which focusses on CC impacts on the stability of STIs, the coastal area morphodynamic model *Delft3D* was extensively used (in 2DH mode). The *Delft3D* model is described in detail by Lesser et al. (2004) and hence only a very brief description is provided here. The basic model structure is shown in Fig. 4. The model comprises a short wave driver (SWAN), a 2DH flow module, a sediment transport model (van Rijn, 1993), and a bed level update scheme that communicate with each other during a simulation. To accelerate morphodynamic computations, *Delft3D* adopts the MORFAC approach (Roelvink, 2006; Ranasinghe et al., 2011) which takes into account that time scales associated with bed level changes are generally much greater than those associated with hydrodynamic forcing. The MORFAC approach essentially multiplies the bed levels computed after each hydrodynamic time step by a time varying or constant factor (MORFAC) which results in fast morphodynamic computations.