Marine Pollution Bulletin xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Impact of sea-level rise on cross-shore sediment transport on fetch-limited barrier reef island beaches under modal and cyclonic conditions

T.E. Baldock *,[a], A. Golshani [a], A. Atkinson [a], T. Shimamoto [a], S. Wu [a], D.P. Callaghan [a], P.J. Mumby [b]

[a] *School of Civil Engineering, University of Queensland, St Lucia, Qld 4072, Australia*
[b] *Marine Spatial Ecology Lab, School of Biological Sciences, Goddard Building, The University of Queensland, St Lucia, Qld 4072, Australia*

ARTICLE INFO

Article history:
Received 6 March 2015
Revised 5 June 2015
Accepted 8 June 2015
Available online xxxx

Keywords:
Reef top wave dynamics
Sea level rise
Island beaches
Reef bathymetry
Sediment transport
Beach stability

ABSTRACT

A one-dimensional wave model is combined with an analytical sediment transport model to investigate the likely influence of sea-level rise on net cross-shore sediment transport on fetch-limited barrier reef and lagoon island beaches. The modelling considers if changes in the nearshore wave height and wave period in the lagoon induced by different water levels over the reef flat are likely to lead to net offshore or onshore movement of sediment. The results indicate that the effects of SLR on net sediment movement are highly variable and controlled by the bathymetry of the reef and lagoon. A significant range of reef-lagoon bathymetry, and notably shallow and narrow reefs, appears to lead hydrodynamic conditions and beaches that are likely to be stable or even accrete under SLR. Loss of reef structural complexity, particularly on the reef flat, increases the chance of sediment transport away from beaches and offshore.

1. Introduction

Barrier reef island beaches protect tropical island communities and ecosystems from wave impacts and coastal inundation, and also provide valuable habitat, breeding grounds and economic (tourism) benefits (Moberg and Folke, 1999). The potential impacts of climate change, including sea-level rise (SLR) and the mortality of coral during warm conditions (Hoegh-Guldberg and Bruno, 2010), may reduce the effectiveness of fringing and barrier reefs as protection for islands (Sheppard et al., 2005; Webb and Kench, 2010; Storlazzi et al., 2011). SLR creates deeper water over reefs and lagoons, potentially allowing larger waves, with possibly a different wave period to that of the locally generated wind waves, to reach the reef island shorelines. However, observations from a range of Pacific atolls indicate the many islands are stable or even increase in area under SLR (Webb and Kench, 2010). Thus, while this observation may not apply across the broad spectrum of reef types and climatic conditions, the beach face response to SLR is clearly complex and the vulnerability of reef-islands and atolls is therefore strongly dependent on their topography and lagoon characteristics (Woodroffe, 2008). While it is the net change in reef top depth that primarily controls the wave climate leeward of reefs, Buddemeier and Smith (1988) note that predicted rates of SLR are significantly greater than the maximum vertical accretion rates of coral reefs and therefore reefs are unlikely to keep up with SLR. Further, the time-scales of reef level adjustment to SLR are centennial to millennial, whereas beach morphology changes have a shorter more immediate timescale (Webb and Kench, 2010), including to sea level variations due to annual or decadal shifts in regional sea-level of order ±0.45 m driven by ENSO cycles (Church et al., 2006). On the reef itself, the wave dynamics are largely controlled by the morphology and physical roughness properties of the fore-reef and reef flat, and the morphology of the lagoon plays a minor role (Gourlay and Colleter, 2005). However, the nearshore conditions are also dependent on lagoon width (and to a lesser effect lagoon depth), since wind-wave forcing across the lagoon can change both wave height and wave period, and wave period is as important as wave height in the sediment transport model. Thus, while the reef flat width, depth and roughness determine the energy dissipation and are controlling parameters for the reef top wave dynamics (Sheppard et al., 2005; Madin and Connolly, 2006; Storlazzi et al., 2011), lagoon geomorphology, notably width, also matters, which increases the number of physical (and model) parameters that influence the beach face sediment transport.

---

* Corresponding author.
E-mail address: t.baldock@uq.edu.au (T.E. Baldock).

http://dx.doi.org/10.1016/j.marpolbul.2015.06.017

Please cite this article in press as: Baldock, T.E., et al. Impact of sea-level rise on cross-shore sediment transport on fetch-limited barrier reef island beaches under modal and cyclonic conditions. Mar. Pollut. Bull. (2015), http://dx.doi.org/10.1016/j.marpolbul.2015.06.017

Both long term and short term beach stability depend on the nearshore wave hydrodynamics and overall sediment supply from land (silicate beaches) or ocean (carbonate beaches). The latter can be influenced by carbonate production on the barrier reef itself (Woodroffe et al., 1999; Kench and Cowell, 2000), which is also subject to the influence of SLR and other climate induced changes. The ability to assess how SLR will impact on the nearshore wave climate that drives beach face sediment transport will improve the assessment and management of reefs and reef islands as coastal defences and useful habitat. The nearshore wave climate is strongly dependent on the reef-lagoon bathymetry, which modifies the off-reef wave height and wave period through wave breaking and further wind-wave growth in the lagoon. The reef top bathymetry also influences lagoon flushing, mixing processes and nutrient supply, and governs reef top hydrodynamics and wave forces on corals (Baldock et al., 2014a). Breakage of coral also leads to sediment supply, and is also likely influenced by SLR induced changes in water depth over barrier reefs (Baldock et al., 2014b). Therefore, the morphological response of reef-island beaches is strongly dependent on topography and geomorphic characteristics (Woodroffe, 2008).

This paper investigates the effects of SLR on the nearshore lagoonal wave climate and the subsequent likely impact on beach face sediment transport landward of fetch-limited barrier reefs using a 3rd generation wind-wave model and a wide suite of idealised 1-D reef-lagoon bathymetry. Here, we focus on cross-shore sediment transport processes because these are most sensitive to SLR and govern the profile evolution in the classical SLR beach response model of Bruun (1962) and later refinements (Dean, 1991; Cowell et al., 1992). Investigating the impact of longshore transport processes requires a 3-D model and the range of possible bathymetry is almost infinite, and beyond the scope of the present study. 3D model results in complex environments are promising (e.g. Vitousek et al., 2007; Saunders et al., 2014), but computation time would be excessive for the modelling approach adopted here. Gourlay (1988) and Kench and Brander (2006) provide a comprehensive review of the mechanisms leading to plan form rotation and longer term seasonal changes on reef-islands.

We consider how the present net sediment transport may change as water depths change over reefs, and identify which reef-lagoonal bathymetries cause the greatest changes for these fetch-limited wave conditions. We follow the approach and use the same model as two recent studies that considered the changes to reef top hydrodynamics and wave forces for this same suite of idealised bathymetry and a Great Barrier Lagoon (Australia) wave climate (Baldock et al., 2014a,b). Further model results are reported here, notably the influence of SLR on the nearshore lagoonal wave climate. These results are used to drive a conceptual model for net sediment transport (Baldock et al., 2011), derived from the seminal beach response model of Wright et al. (1985). The net sediment transport model proposed by Baldock et al. (2011) is based on both small and large scale physical models, and is further verified here, and the behaviour is broadly consistent with the equilibrium shoreline response models of Miller and Dean (2004) and Yates et al. (2009). The paper is organized as follows. Section 2 presents a brief overview of the hydrodynamic model, together with the off-reef wave climate chosen for the model input. The sediment transport model is also presented and verified, together with how it is applied in the current context. Results are given in Section 3, commencing with a summary of the changes in nearshore wave climate under SLR, followed by the changes in net cross-shore sediment transport. The implications of the results for barrier reef island stability and conservation of habitat are discussed in Section 4. Final conclusions follow in Section 5.

2. Methodology

2.1. Wave model

The SWAN (Delft University of Technology) third-generation wave model was adopted for the modelling, including recent model improvements (van der Westhuysen, 2010) relevant for simulating waves in lagoons. A full description of the model parameters and environmental conditions is given in Baldock et al. (2014a,b). The SWAN model has been used for prediction of waves over coral reefs in a range of locations (see Hoeke et al., 2011 and Storlazzi et al., 2011 for examples), and extensively tested for wave propagation in a wide variety of coastal environments (Ris et al., 1999). A suite of idealized bathymetry representing typical cross-section of barrier reefs was generated for the modelling, each which includes a sloping fore-reef, a horizontal reef flat, a sloping back-reef, a deeper lagoon, and the shoreface (Fig. 1). The range of the bathymetric parameters (reef flat depth and width, lagoon width and depth, and surface roughness, representing coral cover and dead carbonate) was selected based on typical values for reefs in the GBR and worldwide. The fore-reef and back-reef have a slope of 1:2 (26°), the beach has a slope of 1:10 (6°), and the water depth on the outer fore-reef is 50 m. The choice of beach slope is discussed further below. A range of values for the width (50–1200 m) and depth (0.5–3 m) of the reef flat and the width (50–2000 m) and depth (5–20 m) of the lagoon were combined to create 540 different reef profiles. In addition, the roughness of the reef flat was varied between rough and smooth for each profile, resulting in a total of 1080 different reef bathymetries (Table 1). Sheppard et al. (2005) recommended friction factors (f_w) of 0.1 and 0.2 for smooth reef and rough healthy coral reefs, respectively, based on the measurements performed by Nelson (1996). The impact of loss of rugosity can then be assessed for otherwise

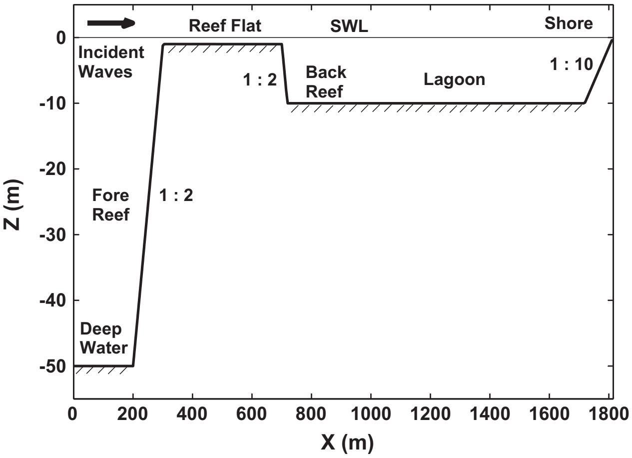

Fig. 1. Definition sketch of idealised reef bathymetry adopted in the model.

Table 1
Bathymetric parameters.

Parameter	Number of cases	Values
Surface roughness (Nikuradse, m)	2	0.04 (smooth), 0.1(rough)
Reef flat depth (m)	6	0.5, 1, 1.5, 2, 2.5, 3
Reef flat width (m)	6	50, 100, 200, 400, 800, 1200
Lagoon depth (m)	3	5, 10, 20
Lagoon width (m)	5	50, 200, 400, 1000, 2000

Please cite this article in press as: Baldock, T.E., et al. Impact of sea-level rise on cross-shore sediment transport on fetch-limited barrier reef island beaches under modal and cyclonic conditions. Mar. Pollut. Bull. (2015), http://dx.doi.org/10.1016/j.marpolbul.2015.06.017