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The effect of wind waves on spring-neap variations in sediment transport in two meso-tidal estuarine basins with contrasting fetch

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ABSTRACT

Higher-energy episodic wind-waves can substantially modify estuarine morphology over short timescales which are superimposed on lower-energy but long-term tidal asymmetry effects. Theoretically, wind waves and tidal currents change the morphology through their combined influence on the asymmetry between bed shear stress, τ_{max}, on the flood and ebb tide, although the relative contribution of such wind-wave events in shaping the long-term morphological evolution in real estuaries is not well known. If the rising tide reaches sufficiently high water depths, τ_{max} decreases as water depth increases because of the depth attenuation of wave orbital velocities. However, this effect is opposed by the increase in τ_{max} associated with the longer fetch occurring at high tide, which allows the generation of larger waves. Additionally, these effects are superimposed on the spring-neap variations in current associated with changes to tidal range. By comparing two mesotidal basins in the same dendritic estuary, one with a large fetch aligned with the prevailing wind direction and one with only a small fetch, we show that for a sufficiently large fetch even the small and frequently occurring wind events are able to create waves that are capable of changing the morphology ('morphologically significant'). Conversely, in the basin with reduced fetch, these waves are generated less frequently and therefore are of reduced morphological significance. Here, we find that although tidal current should be stronger during spring tides and alter morphology more, on average the reduced fetch and increased water depth during spring tides mean that the basin-averaged intertidal τ_{max} is similar during both spring and neap tides. Moreover, in the presence of wind waves, the duration of slack water is reduced during neap tides relative to spring tides, resulting in a reduced chance for accretion during neap tides. Finally, τ_{max} is lower in the subtidal channels during neaps than springs but of a similar magnitude over the intertidal areas, and so sediment is more likely to be advected from the intertidal regions during neap tides rather than springs. This spring-neap cycle in sediment transport potential is in sharp contrast to that found previously in microtidal wave-dominated environments, where spring tides are expected to enhance erosion.

1. Introduction

Tides are often considered to be the morphologically significant hydrodynamic process operating within estuaries, controlling the transport and distribution of sediment through tidal asymmetry (Friedrichs and Aubrey, 1988; Friedrichs, 2011). Tidal asymmetry operates through a non-linear feedback process in that the tidal currents are modified by the morphology to change the relative dominancy of the ebb and flood tide. This in turn results in more sediment being transported by the ebb (or flood) tide, which consequently means the morphology accretes sediment (or erodes) — the morphological effect of which is to change the ebb-flood dominance, completing the feedback cycle. Sediment fluxes over a tidal cycle can be controlled by three forms of imbalance between processes exporting or importing sediment (tidal asymmetry) (reviewed in Hunt et al., 2015). First, a difference in the duration of either the ebb or flood part of the tidal cycle can create a greater or more sustained maximum velocity and consequently a larger volume of sediment being transported into (flood dominant) or out of (ebb dominant) an estuary. Secondly, changes to the duration of slack water at high or low tide can affect the amount of fine sediment deposition over the intertidal (high water slack) and subtidal (low water slack) of an estuary. Finally, spatial variations in bed shear stress (τ) can result in a gradient of fine suspended sediment and advection either towards subtidal areas ($\tau_{intertidal} > \tau_{subtidal}$) or towards intertidal areas ($\tau_{subtidal} > \tau_{intertidal}$). All of these tidal asymmetry mechanisms can result in disproportionate erosion or deposition over the intertidal areas relative to the subtidal areas. This variation in sedimentation rates changes the morphology and distorts the progression of high water relative to low water thereby causing further tidal asymmetries. This feedback

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mechanism is hypothesised to allow estuarine morphology to reach a semi-stable intermediate state between the extremes of unstable flood and ebb dominant states.

Evidence shows that locally-generated wind waves can also exert a significant control on estuarine morphology (Fagherazzi et al., 2007; Mariotti and Fagherazzi, 2013a; Hunt et al., 2015; Zhou et al., 2015). Waves are able to directly modify the underlying tidal asymmetry by firstly reducing slack water duration and secondly increasing $\tau_{intertidal}$ relative to $\tau_{subtidal}$ (where the bed shear stress includes both the effect of tides and waves). Analytical and numerical models have shown that the profile of a wave-dominated intertidal flat will be concave (Friedrichs and Aubrey, 1996; Waeles et al., 2004; Bearman et al., 2010; Zhou et al., 2015) whereas a tide-dominated flat will be convex (Friedrichs and Aubrey, 1996; Roberts et al., 2000; Waeles et al., 2004) and there is some empirical evidence within the South San Francisco Bay to support this theory (Bearman et al., 2010). Previous research has used the concept of a “morphologically significant wind speed” to describe the meteorological conditions required to generate waves of sufficient magnitude and occurrence to change estuarine morphology (Fagherazzi and Wiberg, 2009; Hunt et al., 2016). Although strong winds during storms can produce larger waves than are generated during calmer periods, these energetic events occur less frequently. In comparison, although smaller wave events may suspend smaller amounts of sediment over intertidal flats, these smaller events occur frequently and therefore may have a greater impact over a longer time period (Leonardi et al., 2016). Overall, the degree of wave influence has been shown to be highly dependent on estuarine depth, shape and infilling and the orientation of the basin's fetch relative to the prevailing wind direction (Fagherazzi and Wiberg, 2009; Hunt et al., 2015, 2016).

The influence of waves on estuarine morphology has generally been studied in microtidal environments where tidal processes are weak in comparison to wave processes. The presence of waves explains the characteristic bi-modal distribution of depths and distribution of saltmarshes within these environments (Fagherazzi et al., 2007) and even small waves have the ability to affect sediment transport (Green, 2011). Within mesotidal estuaries, the conditions are more complex (Green et al., 1997; Hunt et al., 2015, 2016). The tides are proportionally stronger, rarely symmetrical and are capable of transporting considerable volumes of sediment. The larger tidal ranges encountered in mesotidal estuaries also cause substantial variations in fetch and therefore wave size throughout a tidal cycle (Green et al., 1997).

In a ‘tide-only’ case, it might be expected that more sediment would be mobilised during the higher energy spring tides than during neap tides and therefore spring tides would be more morphologically significant (Rinaldo et al., 1999; Fagherazzi et al., 2007). However, the presence of waves modifies these processes substantially. Wave orbital velocities are attenuated with water depth and conceptual models suggest that the variability in water levels within a mesotidal environment can result in a marked contrast in patterns of erosion and deposition between spring and neap tidal events (Hunt et al., 2016). Therefore, greater erosion might be expected during a wave event coinciding with a neap tide where orbital velocities over the intertidal are greater and tidal currents in the channel are weak and therefore $\tau_{intertidal} > \tau_{subtidal}$. Conversely during a wave event coinciding with a spring tide, erosion is less likely because the orbital velocities are weakened over intertidal areas due to deeper water and the subtidal currents are greater and therefore $\tau_{subtidal} > \tau_{intertidal}$ (Hunt et al., 2016). This switch between erosion and accretion during neap and spring tides has not been described elsewhere and is in direct contrast to previous studies in wave-dominated microtidal estuaries which found more erosion during springs relative to neaps (Fagherazzi et al., 2007). Here, we use field data and numerical modelling to investigate both the spring-neap modulation and the interplay between waves and tidal asymmetry within a mesotidal system to determine whether morphodynamic changes are more likely to occur during spring or neap cycles.

2. Study area and numerical modelling

To test how the distribution and magnitude of τ varies in response to changes in wind waves caused by the wind climate, a calibrated numerical model of an estuary with two basins with differing fetch was forced with a range of wind and tidal events. The chosen wind events were based on historic wind data and the orientation of the estuary relative to the wind. This aim of this approach is to understand the probability of occurrence of morphologically significant events, and to determine what type of event (regular versus stronger wind events (‘wind events’)) is most important in controlling morphological development. The scenarios were designed to incorporate both the most severe (in terms of wave generation) and the most common wind directions.

2.1. Case study area

Raglan Harbour is a dendritic flooded river valley situated on the west coast of New Zealand (Fig. 1a); tidal ranges are macrotidal during springs and mesotidal during neaps. The tidal prism is 46×10^6 m^3 during springs and 29×10^6 m^3 during neaps (Heath, 1976), both larger than the mean freshwater input to the estuary (18 m^3/s, Heath, 1976). Evidence from sediment distribution (Sherwood and Nelson, 1979), sediment cores (Swales et al., 2005), sediment plates (Hunt et al., 2016) and hydrodynamic measurements (Hunt et al., 2016) has demonstrated the existence of two contrasting morphological environments: the northern (Waingaro) arm and the southern (Waitetuna) arm, and that this distinction is entirely related to the degree of wave exposure rather than differing tidal processes. Within the northerly arm (Fig. 1b) the longest fetch is orientated with the prevailing winds from the southwest (and therefore waves are frequently generated in this part of the harbour), whereas the southern arm (Fig. 1b) is sheltered from the prevailing winds and consequently wave generation in this part of the estuary is rare (Hunt et al., 2016). The distribution of sediments in the northern arm shows coarser sediment grain size over intertidal areas and finer sediments within the subtidal channel, and within the southern arm the sediment gradient is reversed (Sherwood and Nelson, 1979). This gradient in sediment size could be related to the dominance of either wave or tidal processes with the northern arm experiencing greater hydrodynamic energy at high water (largest fetch and slack water) and the southern arm experiencing greater hydrodynamic energy during the time when flows are restricted to the main channel (smallest fetch and peak tidal velocity). Cores and sediment plates show that the wave-dominated northern arm has experienced almost no contemporary sedimentation for at least the last 150 years, whereas the southern arm has experienced sedimentation rates ranging from 0.35 mm/yr prior to human settlement increasing to 1.1 mm/yr since 1890 (following catchment deforestation), further increasing to 2.5 mm/yr since the early 1990s (Swales et al., 2005; Bentley et al., 2014) and ~3.4 mm/yr between 2003 and 2011 (Swales et al., 2005).

2.2. Field data and numerical model

The hydrodynamics within the case study area were modelled using the Delft3D open source numerical model (Lesser et al., 2004). Tidal processes were modelled using the hydrodynamic module and the wind waves were modelled using SWAN (Simulating WAves Nearshore). Intertidal elevations were measured using LiDAR (recorded by Waikato Regional Council in 2010) and the subtidal depths were measured during a series of bathymetric surveys (single beam collected in 2008 and 2009, multibeam collected in 2014) and navigation charts (LINZ chart NZ4421). The model was run in 2D mode and a rectangular grid with a resolution of 50 m was used. Tides in the model were forced using tidal constituents along the western seaward boundary from the Manu Bay tide gauge (⊗, Fig. 1b) and the waves and wind-driven currents were forced using time-series of wind speeds and directions