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Morphological diversity and complex sediment recirculation on the ebb delta of a macrotidal inlet (Normandy, France): A multiple LiDAR dataset approach

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ABSTRACT

The shoreline in the vicinity of inlets can exhibit considerable variability in morphology in both space and time. Most studies on inlets and their adjacent shores have focused on the morphodynamics of sediment by-passing mechanisms generated by longshore transport. For the first time, the morphology, sedimentary features, sediment budgets and patterns of evolution of the shoreline and ebb delta in a macrotidal inlet system have been investigated using seven LiDAR topographic surveys in Normandy, France, over a period of 3.7 years from February 2009 to October 2012. The ebb delta shows strong development on the northern flank of the inlet, expressed by a large sand spit and two types of superimposed dynamic sandy features: eight long-crested and highly mobile transverse bars and a large swash bar. Sand transport from N–S on the updrift beach feeds the growth of the distal part of the spit. This sand supply is further augmented by the onshore movement of a large swash bar welding to the upper foreshore. However, the main topographic changes were induced by the northward migration of the transverse bars on the ebb platform. This is driven by strong northward-directed tidal currents parallel to the shore. The bars exhibit a more complex morphology and dynamics along the seaward margin of the ebb delta where their mobility is controlled by wave action. Topographic measurements suggest a clear sand recirculation pattern. In this morphodynamic model, sand coming from the updrift upper beach is transported southward and deposited at the distal end of the spit, where it serves to construct transverse bars close to the tidal inlet. Transverse bar migration ends in the wave-exposed northern margin of the ebb delta, where they are integrated into the shallow dissipative shoreface sand sink. This sink nourishes the southward longshore transport to feed growth of the large swash bar and southward spit elongation. This semi-circular recirculation cell model involves an inversion of sand movement close to the inlet and emphasizes the combined role of tidal currents and waves in the large-scale 3D ebb–delta sediment dynamics in this macrotidal setting, in contrast to the much more commonly reported alongshore sediment by-passing mode of microtidal inlets.

1. Introduction

Tidal inlets have been extensively studied in the coastal and estuarine sciences and in engineering because of their commercial, recreational and ecological values (Metha, 1996). These systems are generally highly dynamic and occur in a wide range of settings (FitzGerald, 1984; Fenster and Dolan, 1996; Elias and Hansen, 2013). Among issues of importance to the dynamics and management of these systems are sand transport pathways, sediment budgets and the consequent morphological evolution of both the tidal inlets and their adjacent beaches (e.g. Hayes et al., 1970; Hayes, 1980; FitzGerald, 1984; Kana et al., 1998; Balouin and Howa, 2002; de Swart and Zimmerman, 2009; Levoy et al., 2013). Sediment transport processes have generally been reported as strongly related to the combined action of tidal currents and the local wave climate. In general, investigations have focused on coasts downdrift of inlets where sediment by-passing mechanisms are of importance to coastal stability. Only a handful of studies have been devoted to coasts updrift of tidal inlets, where large morphological changes can, however, be observed. For instance, Fenster and Dolan (1996) found along the US mid-Atlantic coast that inlet effects dominated coastline change within 4.3 km of the inlet and influenced the coast up to 6.8 km on the updrift side in both wave- and tide-dominated environments. Investigating the updrift coasts of tidal inlets is also essential to a fuller understanding of the processes of sediment transport and morphological change close to inlets and in the elaboration of balanced and eventually sustainable management of inlets, and of successful sediment husbandry on shorelines in the vicinity of inlets.

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Ebb–tidal deltas (henceforth referred to as ebb deltas) are commonly a major feature of inlet systems, located on the seaward side and sometimes comprising a substantial amount of sediment (Hayes, 1980). The size, morphology, and configuration of an ebb–delta and its sedimentary features are controlled by the supply of sediment, by hydrodynamic forces and by the local geomorphic context in which these forms evolve (FitzGerald, 1996). Tidal inlets, ebb deltas and adjacent shorelines often exhibit large sedimentary features such as swash bars and swash platforms (FitzGerald, 1984; Robin et al., 2007), transverse bars (Niedoroda and Tanner, 1970; Gelfenbaum and Brooks, 2003; Levoy et al., 2013), and linear bars (Hayes, 1975, 1980; FitzGerald et al., 2000). The plan-view geometry and orientation of these constitutive sedimentary features are diverse, in response to the local hydrodynamic conditions and the successive forcing conditions. These features interact with, and alter the characteristics of the local wave- and tidally-driven current regimes, and these morphodynamic adjustments control, in turn, the stability of the adjacent coastline (Dyer and Huntley, 1999).

A number of conceptual models have been formulated to describe sediment transfers between inlets and adjacent beaches in micro- and mesotidal settings (e.g. Hayes, 1975, 1980; FitzGerald, 1996; Hicks and Hume, 1996; Elias et al., 2002; Elias and Hansen, 2013). However, these models may not be applicable to larger tidal settings (spring tidal range > 8 m), which differ in morphology and in hydrodynamic forcing regime. Interactions between large tide-induced water level fluctuations, commonly strong tidal currents, waves and wind-forced flows are expected to generate complex sediment circulation patterns and great diversity in tidal inlet morphology, ebb–delta development and sedimentary features, but these aspects still require further investigation, as Levoy et al. (2013) have noted. This complexity must also be expected in interactions between macrotidal ebb deltas and adjacent beaches.

The present work focuses on morphological diversity across a macrotidal ebb delta where complex mechanisms of sediment transfer control the formation of non-rhythmic three-dimensional (3D) features, resulting in large morphological changes. Spatial and temporal changes in morphology in such environments are particularly visible manifestations of the dominant mechanisms of sediment transport (Morton et al., 1995). In this study, the morphological changes exhibited by sedimentary features associated with a large ebb delta are used as indicators of residual sediment transport. This is accomplished by characterizing, for the first time, the 3D morphology and sediment dynamics of the shoreline and ebb–delta deposits along the updrift side of a macrotidal inlet at a large spatial scale (>1 km) and over the medium term (3.7 years) using multi-temporal LiDAR datasets. The relative roles of externally forced and feedback-dominated responses are also addressed.

2. Regional and local settings

Regnéville inlet is a large tidal inlet on the west Cotentin coast of Normandy, France (Fig. 1A). This coast forms a sandy and relatively rectilinear embayment comprising the Channel Islands, and is segmented by several inlets, the largest of which is Regnéville. The Regnéville ebb delta is a large, asymmetrically shaped sand body covering an area of over 11 km^2 and skewed southwards in response to the net residual sediment drift direction on this coast. It is dissected by a main and large meandering channel in the center, and by numerous smaller channels located at the seaward margins (Figs. 2, 3B). During low spring tides, the exposed part of the delta extends up to 4 km offshore. One or two large sandy swash bars, often parallel to the coastline, and with a volume of about 25,000–30,000 m^3 each and a crest height of up to 2 m (Robin et al., 2009a), can be observed at any time on the northern part of the ebb delta (Fig. 2). The sandy beach updrift of the inlet can be up to 1 km wide at low tide, and typically exhibits a concave shape and a flat low-tidal zone (Levoy et al., 2001). Long-term profile monitoring has shown that the beach is stable or slightly accreting. It evolves in the vicinity of the inlet into a large and complex sandy spit, Agon spit, which exhibits southward-migrating distal curves (Robin et al., 2007) dominantly sourced by wave-induced longshore sand transport and secondarily by the onshore migration of wave-formed bars (Robin and Levoy, 2007). Robin et al. (2009b) reported that the onshore welding of each swash bar results in the formation of a new spit recurve over a decadal timescale. In addition, well-developed transverse bars perpendicular to the coastline are present on the updrift side of the ebb delta, as previously described by Levoy et al. (2013). However, they are not observed on the southern side of the delta, which is mainly characterized by flat topography (Fig. 3B) and a channel bar.

The tidal setting is semi-diurnal and macrotidal. The tidal wave propagates eastward from the Atlantic Ocean into the west Cotentin embayment and is reflected by the N–S oriented coast. The tidal range at Regnéville inlet is 11 m at mean spring tides and attains 14 m during exceptional spring tides. These tidal conditions generate a mean inlet tidal prism of 15×10^6 m^3 per tidal cycle and attaining 46×10^6 m^3 per tidal cycle during spring tides. The average freshwater discharge only corresponds to 0.2% of the mean spring tidal prism (10^5 m^3).

At the regional scale, the tidal circulation along the west coast of Cotentin between Granville and Barneville–Carteret (Fig. 1) is mainly characterized by a progressive tidal wave dominated by the M2 harmonic (Pingree and Griffiths, 1979). The tidal currents are parallel to the coast during most of the tidal cycle due to a strong longshore gradient in water level between the Cotentin embayment and the English Channel (Levoy et al., 2001). Offshore maximum velocities at Les Nattes (about 1 m s^{-1}) occur at about the high and low tide stages. The currents are directed northward around high tide and southward at low tide. At the study site close to the inlet, the northward-oriented tidal currents are observed over the central part of the ebb delta for 70% of the submergence period. During this time, the velocities are greater than 0.3 m s^{-1} between 2 h before high tide during the flood and 1 h 50 m after high tide during the ebb (Fig. 1C). Maximum velocities occur at high tide (about 0.7 m s^{-1}). At the beginning of the ebb tide, the northward-directed longshore tidal circulation induces a deflection of the ebb jet from the inlet towards the north. Neap tide currents are generally much weaker and also dominated by longshore flows.

The Cotentin coast is exposed to local wind waves (Levoy et al., 2001). Wave propagation is, however, complex because of the irregular shelf bathymetry and the presence of the Channel Islands and a large number of shoals and islets, which result in significant wave attenuation (Levoy et al., 2000). Wave modifications also occur over the numerous rock platforms and ebb deltas. Annual recorded offshore significant wave heights at Les Nattes are less than 1 m for 89% of the time and rarely exceed 2.7 m (Fig. 1B). Offshore wave heights also display seasonality, with significantly more energetic conditions in winter than in summer (Levoy, 1994). In response to the prevailing synoptic winds in this region, the dominant wave directions are from W to W–NW, and the peak periods range from 4 to 6 s. The local wave regime also comprises rare North Atlantic swells with periods ranging from 8 to 12 s. The west Cotentin embayment may be viewed as a large dissipative shoreface characterized by a marked decrease in wave heights from N to S and from W to E. Wave-generated sand transport is the dominant factor driving the southward growth of Agon Spit, leading to inlet diversion, but immediately S of the inlet, such wave-induced transport in the high-tidal zone is directed northward (counter-drift direction) as a result of refraction over the ebb delta platform (Levoy, 1994). This wave-induced bi-directional drift on either side of Regnéville inlet leads to sand convergence at the ebb delta platform.

3. Material and methods

An accurate depiction of 3D morphological variability in such a macrotidal setting is an essential pre-requisite for understanding the complex organization of the large sedimentary features associated with Regnéville inlet. However, deriving large-scale 3D changes to an appropriate level of resolution has had to await the advent of airborne topographic LiDAR (Light Detecting and Ranging) technology (Saye et al., 2005), currently, with photogrammetry, the only tools available