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 km² 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 m³ 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 tidal prism of 15 × 10⁶ m³ per tidal cycle and attaining 46 × 10⁶ m³ per tidal cycle during spring tides. The average freshwater discharge only corresponds to 0.2% of the mean spring tidal prism (10⁷ m³).

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
to collect high resolution, instantaneous and accurate topographic data on a large spatial scale (Lane et al., 2003). One major advantage of LiDAR is that of specifically providing precise and high-density topographic point measurements, thus rendering it ideal for monitoring changes over large sandy macrotidal environments. Multi-temporal LiDAR datasets can enable high-resolution analysis of morphological changes, sediment transfers, and eventually, the calculation of sediment budgets.

3.1. Multi-temporal LiDAR dataset collection and DEM generation

A total of seven LiDAR topographic datasets of the study site, acquired using a Leica ASL60 over a 3.7-year period from February 2009 to October 2012 and at low tide during spring tides, were used to analyze morphological changes and to deduce, using a 3D approach, sediment budgets and transfers associated with coastal features north of the ebb delta. The technical details of the LiDAR system and survey conditions are presented in Levoy et al. (2013). LiDAR survey produces an irregular scanning pattern of clouds of point measurements (i.e. variable distance between measurements) due to the oscillatory mirror scanning system. The raw LiDAR data are thus composed of x, y and z values for each point measurement, with the x and y coordinates relative to the Lambert93 National Grid and the height z to m above IGN (French Ordnance Datum), corresponding to the mean sea level. A comparison of topographic changes over the intertidal area scanned between two different surveys is tricky because the horizontal coordinates of the points are not matched directly. Hence, clouds of points were used to derive a triangular irregular network (TIN) using Delaunay triangulation for each survey. This was then converted into a Digital Elevation Model (DEM) with 1 m-grid size in TerraSolid and imported into ArcGIS for analysis. The root mean square error (RMSE) for each DEM was less than 0.07 m. The landward margin of all the DEMs was located approximately 30 m inland of the HAT level position in survey 1. This was extracted using the approach of Stockdon et al. (2002) by locating the intersection of this HAT level on beach slopes derived from the LiDAR point measurements. Repeating this procedure at 5 m interval profiles generated points that were then connected to create a continuous shoreline (Fig. 2).

3.2. DEM of Difference (DoD) generation and geomorphic delineation

A DEM of Difference (DoD) between the DEMs in the first (S1 on 12th February 2009) and last (S7 on 15th October 2012) surveys was
produced by subtracting the elevations in each grid on a cell-by-cell basis in order to visualize the morphological changes over the 3.7-year period. As reported in the literature, considerations of uncertainty in DEM surface representation are crucial in the ability to identify and compare important changes in dynamic environments (e.g., Lane et al., 2003; Wheaton et al., 2010; Eamer and Walker, 2013). DEM error depends on survey point quality, sampling strategy, surface composition, topographic complexities and interpolation methods (e.g., Heritage et al., 2009). A commonly adopted procedure for managing DEM uncertainties involves specifying a minimum level of detection threshold (minLoD) to distinguish actual surface changes from inherent noise (Fuller et al., 2003). Previous studies (Brasington et al., 2003; Wheaton et al., 2010) have reported that individual errors in the DEM can be propagated into the DoD as:

\[
\delta u_{DoD} = \sqrt{(\delta z_{last})^2 + (\delta z_{first})^2}
\]

where \(\delta u_{DoD}\) is the propagated error in the DoD, and \(\delta z_{last}\) and \(\delta z_{first}\) are the individual errors in DEM\(_{last}\) and DEM\(_{first}\), respectively. The assumption of this method is that errors in each cell are random and independent.

In this study, the minLoD was based on the uncertainty threshold of the DEMs and its propagation into the generated DoD. Hence, the uncertainty threshold of the DEMs is 0.07 m, which leads to a propagating uncertainty of 0.1 m (DoD). This latter value was used to remove cells where elevation change values did not attain the precision of the computation procedure, thus making it possible to identify zones of significant morphological changes. Finally, relief maps generated from the S1 and S7 LiDAR surveys (Fig. 2) were used to delineate objectively the representative features along the study site. To assist in the interpretation process of the DoD\(_{S7-S1}\) map, a visual analysis was carried out of the morphological changes of the features. These changes were then used as indicators of pathways of sediment movement in the vicinity of the inlet, especially in the active zones of the ebb delta margins.

4. Results

4.1. Overall geomorphic description of the study site

A geomorphic assessment was initially undertaken in order to further characterize the morphology at the reach scale and to gain insight into the morphodynamic influence of the inlet on the coast (Fig. 2). The identified features are shown in Fig. 2. Although the beach morphology is relatively simple, two isolated, single and asymmetric shore-oblique bars (OB in Fig. 2) are present throughout the surveys above the mean low water neap level (MLWN), corresponding to a height of around \(-1.81\) m IGN. Further south near the distal tip of Agon spit, the dominant feature is a 450 m long swash bar lying parallel to the coastline and oriented 300°–120°. Fig. 2 also shows eight long-crested transverse
bars, oriented obliquely from 130° to 158° to the shore. Levoy et al. (2013) have described in detail the characteristics of these bars. In February 2009 (S1), the bars were located mainly in the lower part of the foreshore between 1.5 m and −3 m IGN and were attached to the mid-tidal zone around mean sea level (MSL), corresponding to 0.84 m IGN. In October 2012 (S7), the bar field stretched c. 2.8 km along the coast from N to S and 1.5 km in a cross-shore direction. Field observations also confirmed the development of small asymmetrical swash bars close to the inlet, as depicted in Fig. 2. The bars were incorporated into a transverse bar up to 520 m long in S7 at the seaward entrance of the inlet. Levoy et al. (2013) showed that inception of these transverse bars occurs in this area.

4.2. Geomorphic changes between surveys S1 and S7

DoDs S7–S1, based on a minLoD as shown in Fig. 3, allows for the identification of a signal of actual topographic changes, with light gray showing erosion and black accretion, thereby enabling visualization of the residual sediment dynamics along the entire study site over the 3.7-year period. To assist in the process of interpretation, the DoDs S7–S1 was further classified into geomorphic zones using the detection of uncertainty threshold. The observations indicate that erosion and deposition tend to occur in spatially coherent patterns with regard to the morphological characteristics of the study site previously described in Section 4.1. Spatially, significant changes (i.e. ≥0.1 m) account for 47%

Fig. 3. Map of the DoDs S7–S1 using a minLoD threshold of 0.1 m (A), and aerial photograph from S7 showing superimposition of the delineated zones with the features of 12th February 2009 (S1) and 15th October 2012 (S7) (B). The dashed contours show the delineated zones. Solid line corresponds to the positions of the MLWN tidal level.
and 66% of the surface areas above the MLWN level respectively in the northern (zone 1) and southern (zones 2 to 6) sectors of the study site respectively. The seaward margin of significant morphological change in the N sector is up to 590 m offshore from the MLWN level, whereas it matches well with this level in the S where a substantial part of the ebb delta is covered by the surveys. In this part of the study site, the MLWN contour of the ebb delta extends from 1.5 to 4.5 km seaward and displays high spatial complexity.

Zone 1 corresponds to the updrift beach. Significant morphological changes in this zone are located above MSL, and the zone is characterized by continuous net accretion of the upper beach, whereas negative morphological changes dominate the mid-tidal beach. DoD_{S7-S1} also highlights some interesting local small-scale variations reflecting the directions of sediment transport. Firstly, a distinct pattern of erosion and deposition of an isolated and oblique bar oriented NE is present in surveys S1 and S7 (Fig. 2), suggesting SE migration of the bar. Secondly, an abrupt decrease in the width of the mid-tidal beach and marked beach retreat observed S of the boat ramp in the middle section of this zone are classical indicators of residual sand movements. These results imply a relatively simple functioning of zone 1 over the study period, typical of an open-coast beach subject to cross-shore sediment transport, but also to appreciable longshore transport. No sediment movement below MSL was detected from the data, but this is related to the technical limitation of airborne LiDAR data. In contrast, the adjacent beach in the N of this zone, a narrow alongshore swathe of significant shoreline erosion extending about 0.8 km, and immediately followed by a sector of accretion exceeding 6.5 m between S1 and S7 at the tip of the spit. This zone ends in the elongated transverse bar mentioned above in Section 4.1, close to the inlet. Morphological analysis of the features was also carried out using an objective delineation based on the relief maps in S1 and S7. This analysis reveals intra-morphological variability within the ebb delta from the N to the S. Zone 3 is characterized by small elongated bars oriented NE. Zone 4 shows well-developed transverse bars. Zone 5 exhibits small, active and heterogeneous features that are probably the precursors of the transverse bars, and zone 6 comprises large shallow accumulations of sand without a clearly defined morphology. Within the ebb delta, the transverse bar field is characterized by an alongshore pattern of alternating sequences of erosion and deposition from the S to the N. This spatio-temporal pattern suggests N migration of the transverse bars, as observed by Levoy et al. (2013).

4.3. Areal and volumetric distributions of elevation changes within the zones

For each delineated zone, data were extracted from the DoD_{S7-S1} as elevation change distributions (ECDs cf. Wheaton et al., 2010), with histograms showing the total of both area and volume experiencing a given magnitude of elevation change in bin size classes of 0.1 m. The ECD analysis makes it possible to assess the representativeness of sediment mobility in each zone, and to depict the different morphosedimentary stages of the features (i.e. formation, migration, destruction or redistribution). The areal ECDs (left-hand side of Fig. 4) show a normal distribution with a single peak roughly centered around an elevation change of 0 m for all the zones with the exception of zone 2. Spatially, the uncertainty threshold ranges from 9% in zone 2 to 42% in zone 5. However, the volumetric ECDs (right-hand side of Fig. 4), reflecting the area multiplied by the magnitude of elevation change, display different distributions for the six zones with an uncertainty threshold of 0.1 m from 0.4% (zone 2) to 12% (zone 5).

The volumetric ECD plot for the N part of the study area (zone 1) shows an asymmetric distribution with two high peaks. The higher peak concerns a low negative magnitude of elevation changes (−0.2 m) because these are being multiplied by small elevation changes (Fig. 4Aii). In contrast, the second peak is centered on a positive, slightly higher elevation change (0.9 m) and wider range than the negative peak. The zone also underwent negative changes of mainly low magnitude although a spread-out ridge of high magnitude is observed ranging from −1 to −2 m. These latter characteristics appear to be plausible signatures of erosion. Overall, the plot indicates volumetric equilibrium with a very slight dominance of deposition.

The areal ECD plot for zone 2 follows a normal distribution centered on a mean elevation change of 0.4 m (Fig. 4Bi). In terms of surface area, 61% of the tidal zone experienced accretion. The volumetric ECD confirms this accretion with values ranging from 0.3 m to 3.1 m characterized by a maximum elevation difference of 0.5 m, and also by the presence of a long positive ridge of high-magnitude changes, indicating that some areas experienced significant accretion of up to 6.7 m (Fig. 4Bii). The volumetric distribution is also very spiked, containing at least four peaks concentrated on high-magnitude elevation changes. This complexity appears to be a morphological signature of the main features in this zone (large swash bar, transverse bar, distal tip of spit, Fig. 2). Further volumetric measurements were undertaken on the large swash bar, which underwent substantial accretion of up to 188,760 m³ between S1 and S7, whereas the downdrift coastline was strongly eroded to the tune of 156,000 m³. These results indicate that the swash bar is directly supplied by sediments from the N–S longshore transport, but also possibly by onshore sand reworking as shown by the negative trend in elevation just seaward of this bar (Fig. 3). Downdrift and shoreward of this sand-sequestering swash bar, under-nourishment occurs, resulting in significant shoreline erosion. The volumetric change of the S part of this zone, characterized also by the transverse bar near the inlet and by deposition at the tip of Agon spit, indicates net accretion through capture of up to 80% of the eroded sediments. The remaining 20% is probably trapped by the nearby inlet channel.

The volumetric ECDs for zones 3, 4 and 5 are relatively similar with a simple distribution characterized by two high symmetrical peaks of low-magnitude elevation changes centered on −0.1 m and 0.1 m (Fig. 4Cii, Dii, Eii). The distribution blends more smoothly into high-magnitude changes within a relatively restricted elevation range of between −1 m and 0.9 m in zone 3, and −1.5 m and 1.7 m in zone 4. The ECD distributions for the three zones imply a balance between erosion and deposition, which is confirmed by the low net volumetric changes measured. This might further indicate conservation of the transverse bars as they migrate. In zone 6, the highest peak is positively centered on 0.2 m and nearly three times greater than the negative peak (Fig. 4Fii). The long and low negative tail ranging from −0.8 m to −2 m indicates that some areas experienced erosion, but this zone is nevertheless dominated by deposition.

4.4. Mobility of sedimentary features

To further investigate the sediment dynamics, topographic profiles (Fig. 5) were extracted perpendicular to the representative features of the delineated zones for each survey (see Fig. 2 for profile locations). Profiles P3, P4, P6 and P7 are located at the seaward margin of the ebb delta where complex changes have been described in the previous sections. The monitoring of these profiles may also throw light on how specific features within zones 3 to 6 respond to hydrodynamic forcing and also relate to the dynamics of the ebb delta. Observations of bar positions and of morphology inform on the direction of bar migration, which is, in turn, a good indicator of the direction of sediment transport (Gelfenstein and Brooks, 2003).

In zone 1, profiles P1 and P2 are typical of sandy macrotidal beaches with a concave shape and flat low tidal zone (e.g. Clarke et al., 1984; Masselink and Short, 1993; Levoy et al., 2000, 2001; Reichmüth and Anthony, 2007). Profiles were relatively stable over the 3.7-year period with a balanced sand budget, as previously mentioned, between the accreting high-tide beach and the eroding mid-tide beach. Profile P8 illustrates the large shore-parallel and asymmetric swash bar in zone 2...
Fig. 4. Comparison of areal (ⅰ: left-hand column) and volumetric (ⅱ: right-hand column) DoDS1–S7 distributions for: A) zone 1; B) zone 2; C) zone 3; D) zone 4; E) zone 5; and F) zone 6. Estimates of significant sediment volume changes, excluding those that fell with the threshold values between −0.1 m and −0.1 m. Note the different axis scales. Areas and volumes of significant changes (minLoD of 0.1 m) are reported.
Initially 235 m wide and with a crest elevation of about 2.6 m IGN in February 2009 (S1), the bar grew to attain a crest height above 4.7 m IGN, and had gained another 90 m in width by October 2012 (S7). In the meantime, it migrated landward over about 110 m, whereas progressive retreat affected the high-tide beach. The movements of the crests of the transverse bars that dominate in zones 3 and 4 are depicted in Fig. 5C–G. Fig. 5E shows, for zone 4, a large and high bar in the N part of the profile, stable in position over much of the study period, but which migrated slightly northward and became lower over the last two surveys. In contrast, the bar to the S was smaller and migrated progressively northward at a rate of around 2.5 m month$^{-1}$. The same bars in P6 profile were smaller and often presented two rounded crests during the study period. North of these bars, in zone 3, profile P3 was characterized by a main bar that moved northward by about 105 m between S1 and S5, corresponding to a mean rate of 2.4 m month$^{-1}$. This bar further migrated N before finally disappearing, apparently integrated into the shoreface sand sink, as Levoy et al. (2013) have suggested as accounting for bar disappearance in the N confines of the study area. Fig. 5D indicates, however, a southward displacement of the same bar at its seaward margin, an illustration of some of the complexity of movement shown by these features. In zone 5, profile P7 oriented west–east crosses several distinct features identified as small asymmetric swash bars. A residual onshore migration of the bar is observed, but no clear pattern of mobility is depicted on either side of this bar where the...
small swash bars were often observed in the field during the study period. These results therefore demonstrate high spatial variability in the presence, the morphology and the mobility of the bars, depending on their position. This further illustrates the complex 3D behavior of the sediment stock on the updip side of this macrotidal ebb delta.

5. Discussion

This study has used seven LiDAR datasets obtained over a period of 3.7 years in order to illustrate the dynamics of shoreline change in the vicinity of a macrotidal ebb delta. The analysis has illustrated the robustness of LiDAR data, especially at this relatively high temporal density of acquisition (one survey c. every 6 months), in revealing complex morphological behavior and sediment movements at a large spatial scale and in a setting with a large tidal range. Furthermore, the use of a DEM of Difference (DoD) between the DEMs and of a minimum level of detection threshold (minLoD) to distinguish actual surface changes from inherent noise has enabled high-resolution depiction of the morphological changes over the 3.7-year period. The following discussion will successively examine the pertinence of the acquired data in terms of the generation, dynamics and sediment circulation of the major features characterizing the macrotidal ebb delta of Regnéville inlet, followed by a consideration of potential inlet sediment by-passing as a template for comparing this macrotidal setting with microtidal inlet systems.

5.1. Geomorphic processes and morphology and behavior of the ebb–delta features

The ebb delta of Regnéville inlet is characterized by two main types of superimposed dynamic sandy features: transverse and swash bars. Specifically, the bar field is characterized by eight long-crested transverse bars and a by large orthogonal swash bar (Fig. 2). In addition to these features, several small swash bars also occur, migrating towards the transverse bar close to the inlet. Previous studies have reported the existence of subtidal bar fields composed of both transverse and shore-parallel bars in microtidal settings (e.g. Caballiera et al., 2002; Garnier et al., 2006). The mechanisms proposed to explain their development and evolution are generally based on surf processes and self-organization under conditions of significant wave action (e.g. Ribas et al., 2011, 2012). This does not seem to be the case for the Regnéville ebb–delta bars where the observations presented in this study favor a morphodynamic interpretation based on adjustments between sediment availability, hydrodynamic factors, and inlet size determined by accretion.

The complex features on the north shore of Regnéville inlet are absent S of the inlet, thus indicating the primacy of a large-scale N–S coupled sediment circulation and hydrodynamic system. The general patterns that have emerged from the morphological changes demonstrate a clear transition between the beach in the N part of the study site (zone 1), its southward prolongation as zone 2 comprising features impinging on the ebb delta (Agon spit and the large swash bar), and the ebb delta proper (zones 3 to 6). Over the 3.7-year study period, the volumetric trend showed slight positive accretion in zone 1 (Fig. 4Aii), whereas the ebb delta, represented by zones 3 to 6, experienced a sand gain of up to 78,000 m³ over a surface of 2.2 km² (Fig. 4Cii, Dii, Eii, Fii). This corresponds to an annual net input exceeding 21,000 m³. However, the surface area of the active zone of the ebb delta seems to have been relatively stable in time, thus confirming significant vertical accretion. The main process of sediment sourcing of the ebb delta and zone 2 is the southward wave-driven longshore transport in the high-tidal zone along the beach. The accretion of the large swash bar located close to the high-tidal zone in zone 2 enables an estimation of wave-induced longshore sediment transport of about 51,000 m³ year⁻¹. This rate is slightly higher than a previous estimate of 40,000 m³ year⁻¹ obtained using a numerical approach (Levoy, 1994). However, the growth of this swash bar also appears to have been sourced by onshore sand reworking by wave action seaward of this bar, where a sector of significant sand deficit probably marks the shoreward migration of this feature. Over the study period, zone 2 experienced significant accretion of approximately 142,000 m³, and was characterized by very large elevation changes with a maximum of 6.5 m in the downdrift sector of the spit and a minimum of −0.20 m just N of the newly formed transverse bar (Figs. 3, 4Bii). The main sediment sink in the Regnéville ebb delta thus appears to be the large platform, corresponding to zone 2, at the tip of the spit. From this platform, sand reworked by flood jets during rising tides is transported through to the flood delta. The reverse process prevails during ebb tides, when sand is re-injected back to the platform, probably onto the newly formed transverse bar near the inlet. This sand exchange process does not therefore appear to be a source of net loss for the ebb delta platform, although there has not been a sediment budget study of the flood delta. Regnéville inlet is, however, a highly infilled inlet. The upper part of the ebb delta is clearly a dynamic zone of both sediment transport and abundant storage related to wave processes that are dominant in the high-tidal zone. Significant sediment storage is also observed close to the inlet, but here the morphodynamic processes are likely to reside in interactions between the tidal inlet ebb jet and the flood discharge of the inlet. In contrast, morphological changes are less marked away from the inlet northward in the high-tidal zone and towards the lower SW part of the ebb delta. Over the study period, relative morphological stability occurred in this part of the ebb delta. This sector is composed of very fine sands, whereas the large bars impinging on it are dominated by fine to medium sands (Levoy et al., 2013). The mobility of these two sediment populations is potentially different, and therefore the ebb delta might not be contributing directly to the sediment budget of the bars. What is still unclear at this stage is whether the tidal channel, which is disproportionately small relative to the ebb delta, plays an active role in ebb delta bar dynamics. Since the development and evolution of tidal channels are controlled by factors on timescales of decades (de Swart and Zimmerman, 2009), longer timeseries of LiDAR data and detailed field hydrodynamic and modeling studies will be necessary to elucidate the role of the channel.

This study has reported a 3.7-year monitoring of bar morphology that included both periods of active change and relative stability. The main hydrodynamic factors affecting ebb delta bars are tidal and wave-induced currents (Hayes, 1975). Tidal currents often prevail in the center of the ebb delta and in the nearby inlet, whereas waves are more efficient in higher-elevation areas (Powell et al., 2006). The sand circulation pattern in the center of the ebb delta of Regnéville inlet is driven by the strong shore-parallel tidal currents from SE to NW, a direction that runs counter to the wave-generated longshore transport. However, at low tide, breaking waves on the W and NW margins of the ebb delta also contribute, especially during stormy conditions, to the sediment transport. The topographic profiles in Fig. 5 show that the transverse bars (PS) in the center of the ebb delta underwent accelerated migration between the S5 and S7 surveys with a rate of up to 2 m month⁻¹ higher than in the course of the previous survey intervals. This acceleration is also observed for other features over the ebb delta. Levoy et al. (2013) reported that bar migration rates in winter are generally higher than in summer, because of enhanced wave re-suspension of sand during storm conditions. This acceleration trend is also illustrated by the migration of the large swash bar and by concomitant retreat of the upper beach in the northern part of the study site, both of which are responses to winter increase in wave energy levels.

The large swash bar has been shown to be a wave-formed feature (Robin et al., 2009a) nourished by the N–S longshore transport, which is remarkably clear in surveys S6 and S7. As this bar migrates upwards towards the high-tidal level, the longshore sediment transport is disrupted, causing accretion updip and erosion downdrift of the bar. Wave-induced onshore sediment transport in the mid-tidal zone is also highlighted by reworking seaward of the swash bar. This results in additional sourcing of this bar and in the concomitant sand deficit adjacent to this bar, as well as in the presence of the small asymmetrical...
sandy swash bars in zone 5, which are distinct from this larger ebb delta swash bar. These smaller onshore migrating swash bars become progressively coalescent with the transverse bar close to the inlet. Levoy et al. (2013) reported that the bar migration rate is relatively low in the vicinity of the tidal inlet, probably in response to an alongshore gradient in the strength of tidal currents over the complex shallow ebb delta platform. The well-developed transverse bars, in volumetric equilibrium, cover an area of up to 1.06 km² in the middle of the ebb delta, migrating northward under the command of the strong spring tidal currents, leaving a shore-transverse signature of accretion and erosion (Fig. 3). Fig. 5 shows that the migration rate of the bars in the center of the ebb delta (P5) is higher than on the seaward margin (P6) where these features are more rounded and lower in amplitude. The displacement of the bar sections located offshore (P3) and farthest from the inlet (P4) is likely to depend on varying exposures to wave energy. Similarly, in the NW, seaward part of the ebb delta, which corresponds to the most wave-exposed sector, wave action might explain the progressive disappearance of the transverse bars as they are recycled into the nearshore sand sink. These complex patterns thus suggest morphosedimentary adjustments to the joint action of tidal, especially inlet jet, currents, and wave-induced currents.
5.2. 3D sediment recirculation

Fig. 6 shows a schematic sediment mobility model synthesizing the dominant forcing factors on the Regnéville ebb delta and the shoreline N of the delta. The macrotidal beach (zone 1) is a relatively simple system dominated by wind and wave-driven processes that are dominantly cross-shore, and with secondary longshore processes in the high-tidal zone. As suggested by its volumetric equilibrium, this zone is a pathway for southward longshore sediment transport. Drift is perturbed by the large ebb delta swash bar in zone 2, which causes undernourishment of the beach shoreward and downdrift, resulting in the 800 m erosion swath of the high-tidal zone along Agon spit. This eroded sand ends up in the ebb delta at the distal end of the spit, which serves as a depocentre that releases sand for the formation of transverse bars close to the tidal inlet. A secondary sand source for these transverse bars may be the small wave-formed swash bars observed in zone 5. Once the bars form, they migrate away from the inlet zone northward within a spring-tide controlled bar conveyor belt (zone 4). The transverse bars progressively disappear in time but rather abruptly in space in the northern margin of the ebb delta (zone 3), which is the most wave-exposed sector of the study site. The large dissipative embayment into which these features are finally integrated has been reported to act as a source of sand for the development of aeolian foredune fields on the west Cotentin coast (Anthony, 2004). We suggest here that sand transported in the high-tidal zone of the beach, including inputs from seasonal storm wave reworking of these foredunes, nourishes the southward longshore transport that contributes to source the inlet. This yields a cyclic sand circulation pattern on this part of the Normandy coast. Regnéville inlet is thus nourished in sand that circulates from NW to SE in the high-tidal zone. In contrast the sediment circulation on the ebb delta, which also corresponds to that of transverse bar migration, is opposite, from SE to NW.

The overall sediment mobility suggests a 3D semi-circular pattern (Fig. 6). The recirculation model emphasizes the role of tidal currents in transverse bar dynamics in the center of the ebb delta, whereas wave action most likely controls sand mobility on the seaward margins and shoreline north of the ebb delta and organization into transverse bars and swash bars. Although this medium-term study only deals with the sediment dynamics occurring N of Regnéville inlet, the semi-circular sand circulation pattern and the relative stability of the active zone of the ebb delta would tend to suggest that inlet by-passing does not occur. A number of studies have stated that sediment by-passing is the most characteristic process in inlet systems, whereby sediment transported by littoral drift by-passes the inlet by going across the ebb delta and then onwards along the coast (e.g. Hayes, 1975; FitzGerald, 1984, 1996). Sediment by-passing has been thus a widely accepted model, but a few investigations have also reported sediment recirculation on ebb deltas in micro- and mesotidal settings (e.g. Sha, 1990; Smith and FitzGerald, 1994; Elias et al., 2006; Son et al., 2011). The present study observes, for the first time, this mechanism on a macrotidal ebb delta. Even though zone 6 evinces no clear features indicative of residual sand transport, our observations suggest that it is not a by-pass zone. Further investigations will be necessary to elucidate sand movements related to the meandering of the main tidal channel.

Regnéville inlet appears to be the only macrotidal inlet of several inlets on the W Cotentin coast that does not seem to undergo clear by-passing. This may be related to the sheer size of the ebb delta, which has undergone significant accretion. This large dissipative ebb delta currently acts as a sediment storage and recirculation zone, attracting sand both from the N (dominant longshore transport direction) and an apparently much more limited supply from the S from tidal currents and refracted waves. Longer time series of LiDAR datasets will be needed to determine the modern net long-term sediment budget of the Regnéville inlet.

6. Conclusions

This study has investigated, for the first time, the 3D sediment dynamics at the updrift side of a macrotidal inlet using seven multi-temporal LiDAR datasets covering 3.7 years. The analyses conducted from these datasets highlight the utility of LiDAR as a source of information for high-resolution coastal morphological and sediment budget determinations, especially for large, sandy coastal systems in macrotidal settings where complex sediment mobility patterns are likely under the joint action of waves and tides. A large sand spit and two types of superimposed dynamic features occur over the ebb delta platform: eight long-crested transverse bars and a large orthogonal swash bar. The mobility of these main sedimentary features on the ebb delta, depicted in the topographic surveys, shows a complex 3D circulation of sands. Sand transport on and in the vicinity of the Regnéville ebb tidal delta follows a semi-circular pattern involving constant recycling driven by tidal currents and waves. The cycle begins with the genesis of the transverse bar close to the inlet, followed by northward bar migration under the influence of the strong shore-parallel tidal currents that prevail during a large part of the tidal cycle. The bars end up being recycled into the shallow shoreface. Sand mobilized from the shoreface contributes to the formation of beaches and aeolian foredunes that are seasonally eroded, releasing sand that is transported southward along the high-tidal beach zone by wave-generated longshore transport. This transport contributes to the growth of a spit as well as to the formation of the transverse bars, thus completing the cycle. Clearly, in this large tidal range setting, the mechanisms of transverse bar development and evolution are different from those invoked for bars in microtidal settings. Here, a key element of the specific morphodynamic behavior is the strong longshore tidal current, oriented northward over the ebb delta platform during much of the tidal cycle. By-passing is a commonly reported process across wave-dominated microtidal ebb deltas. In the studied macrotidal environment, the sediment pattern deduced from the 3.7 year LiDAR datasets and the relative stability of the active zone of the upper ebb delta do not support an inlet sediment by-passing mode at this stage, although the influence of tidal channels on sand transport is still unknown. This aspect, and the longer-term net sediment budget of the ebb delta and its vicinity, will require longer LiDAR time series and more detailed field hydrodynamic studies.

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