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Short-term (≤2 yrs) estuarine mudflat and saltmarsh sedimentation: High-resolution data from ultrasonic altimetery, rod surface-elevation table, and filter traps

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ABSTRACT

Rates of short-term (up to 2 years) bed elevation change and sedimentation from mudflats to salt marshes were measured in a rapidly infilling macrotidal estuary using an original combination of three high-resolution techniques: an ultrasonic altimeter, the Rod Surface-Elevation Table (RSET) method, and filter traps. The Authie estuary is located on a straight, sand-rich coast and is undergoing rapid infill under the influence of flood-dominant tides reinforced by wave action. The estuarine sediment suite consists of both mud and sand derived from the sea, of sand derived from storm wave erosion of dunes lining the north bank of the estuary, and, to a much smaller extent, of mud from the river catchment. Bed elevation change and sedimentation rates show an expected increase with the duration of tidal flooding (hydroperiod) in both space and time. The estuarine bed sediment suite changes from sandy at the mouth to muddy within the low-energy inner estuary, where mudflats are rapidly accreting, paving the way for the formation of increasingly denser and mature salt marshes from the high-sedimentation pioneer zone to the upper marsh where annual sedimentation is very low. Recorded variability in rates of bed elevation change and sedimentation reflect the influence of estuarine macro-scale and local sediment transport and depositional processes in a macrotidal context dominated by high inputs of allochthonous sediments.

1. Introduction

The elevation of mudflat and salt marsh platforms within the intertidal frame determines tidal inundation frequency and duration, the latter also known as hydroperiod. These are, in turn, key parameters in spatial and temporal patterns of accretion in systems where the supply of sediment is essentially allochthonous. Generally, under conditions of adequate sediment supply, the lower the elevation of the platform, the greater is the accommodation space and the potential rate of vertical build-up of the platform. However, mudflats, and especially salt marsh platforms, are potentially subject to complex combinations of forcing agents and processes hinged on tidal range, topography, flow routing, and vegetation structure and density, such that sedimentation rates can be extremely variable (e.g., Allen, 2000; Davidson-Arnott et al., 2002; Temmerman et al., 2003; van Proosdij et al., 2006a,b). Additional variability may be caused by short- to medium-term sediment transport and supply processes. Such potential variability in real sedimentation rates calls for caution in extrapolating long-term patterns of mudflat and salt marsh sedimentation from short-term rates of accretion, especially in view of the susceptibility of such environments to flooding by sea-level rise. The results reported in this paper are part of a study undertaken with the aim of characterising the morphology and sediment dynamics of a small, temperate, macrotidal estuary that is undergoing rapid infill under the influence of both large-scale shoreface processes and flood-dominated tidal asymmetry associated with a long history of human modification. The paper focuses on patterns of short-term (up to 2 years) mudflat and salt marsh sedimentation using three complementary high-resolution methods. Specifically addressed is the commonly reported relationship between higher sedimentation rates and lower elevations due to longer flooding periods. The findings highlight temporal and spatial variability in monitored

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sedimentation rates, the reasons of which are discussed with reference to the main factors controlling sediment supply and deposition against a background of rapid estuarine infilling.

2. Study area

The Authie estuary (Fig. 1) forms the terminus of a relatively short (98 km-long), straight coastal river that drains a low-gradient Mesozoic limestone plateau catchment covering an area of 989 km^2. River discharge data show regular flow, characteristic of a small temperate catchment. The mean liquid discharge of the Authie over a 30-year (1963–1992) gauging period is 10.4 m^3 s^{-1}. Like the other estuaries on the French coast from the Somme River to the North Sea (Fig. 1A), the Authie is a sand-filled estuary, located along a major coastal sand transport pathway linking the eastern English Channel to the North Sea (Anthony, 2000, 2002; Anthony and Héquette, 2007). The shallow estuary mouth exhibits a massive sand platform (Fig. 1B) that confines the main channel towards the north bank, which is composed of a dune barrier that extends northwards up the coast. Dobroniak and Anthony (2002) showed from historical documents and maps that this sand platform has progressively extended northwards over the last three centuries, diverting part of the Authie channel towards the north bank and constraining it against the thick dune fields on this bank, where erosion has long been an acknowledged problem. This intertidal platform grades seaward into shallow linear coastal sand banks. Bare flats, salt marshes and polders occur in the inner estuary (Fig. 1). Catchment erosion provides exclusively fine-grained suspension load, but the bulk of the sediment supply to the Authie estuary is derived from the sea and from erosion of the aeolian dunes lining the north bank (Anthony and Dobroniak, 2000). The mud accumulating in the Authie estuary is mainly derived from suspension-sized sediments in a ROFI (Region of Freshwater Influence) linking the estuaries lining the French coast in the

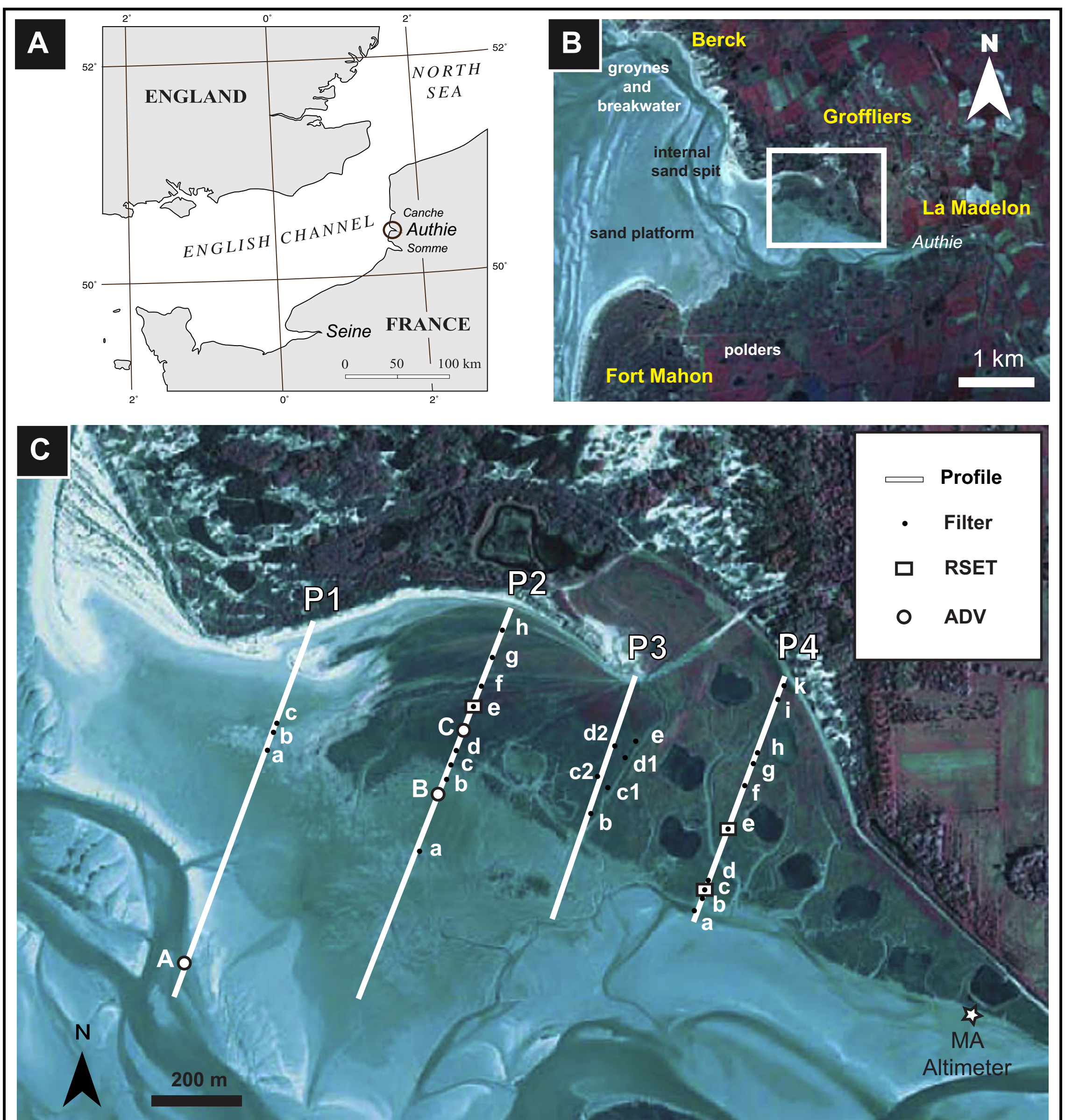

Fig. 1. The Authie estuary (A and B). Box in B shows the study site (C) and experimental setup along monitored transects (P1 to P4) on which were deployed filter stations and RSET measurement stations, and the deployment points of an ultrasonic altimeter (MA), and Acoustic Doppler Velocimeters (ADV).

eastern English Channel. This ROFI is governed by residual flow towards the North Sea (Sentchev and Korotenko, 2005), and is dominated by the Seine River (Fig. 1A), by far the largest of the river estuaries on this coast.

The Authie is a macrotidal estuary subject to semi-diurnal tides. The mean spring and mean neap tide ranges at the mouth of the estuary are respectively 8.54 m and 4.89 m. These ranges decrease to around 4 m and 1.8 m, respectively, 7 km up the estuary. The spring tidal influence reaches 16 km inland. The highest predicted tides at the mouth of the estuary, associated with the spring or autumn equinoxes, have a range of 9.99 m. Storms associated with low pressure zones in the western English Channel in winter can lead to rises of predicted water levels by over 1 m at the mouth of the estuary (Anthony and Dobroniak, 2000). Wave records from pressure sensors deployed near the mouth of the Authie show that the coast is affected by short, locally generated, dominantly westerly wind waves with periods of 3–8 s, and significant wave heights of 0.25–1.5 m, commonly exceeding 2 m during storms (Anthony et al., 2005). Because of the exposure, waves affect the north bank shoreline up to 3 km inland. A rapid wave height reduction occurs towards the inner estuary as the massive sand platform attached to the south bank dissipates energy. The mean currents at the mouth of the Authie are relatively strong with peak speeds of up to 1.5 m s^{-1} during spring tides (Anthony and Dobroniak, 2000).

3. Methods

The experimental site covers about 15 km^2 and consists of a wedge-shaped feature in plan view that narrows towards the inner estuary (Fig. 1). It comprises about 50% of bare flats and 50% of salt marshes. Historical data show that these salt marshes experienced a rather late but rapid progression over less than 50 years (Marion, 2007). A global topographic snapshot of the experimental site was obtained from a LiDAR survey carried out on July 13, 2006 at low tide using a Falcon II (TopoSys) system. The use of LiDAR is becoming increasingly popular in studies of mudflats and coastal marshes (e.g., Morris et al., 2005; Rosso et al., 2006; Proisy et al., 2009), especially because of the difficulty of accurately monitoring the elevation of the uneven substrates of these tidal flat environments, but also due sometimes to sheer inaccessibility (Anthony et al., 2008).

The field methodology comprised reconnaissance and mapping of salt marshes, and monitoring of elevation change and sedimentation rates at short (1–2 yr) timescales. The variations were monitored along four topographic transects (Fig. 1C) referenced to benchmarks of the French ordnance datum (IGN69) and surveyed using a LEICA TC 600 laser station. A total of 35 sediment samples were collected along the stations set up on these four transects and grain-size parameters were determined using a Malvern Mastersizer 2000 with a range of 0.02–2000 μm. Current measurements were carried out over one semi-diurnal tidal cycle at three points (one in the Authie channel on transect P1, and two on transect P2, Fig. 1C) using Nortek Acoustic Doppler Velocimeters (ADV).

There is a large variety of techniques presently available to carry out fine-scale measurements of elevation change and net sediment accumulation rates in estuarine, mudflat and salt marsh systems (Thomas and Ridd, 2004; Marion et al., 2005). This study has had recourse to a combination of three high-resolution methods, the choice and deployment strategies of which have been determined by logistical, security and accessibility criteria. To measure bed-level changes in the mudflat, an ALTUS NKE ultrasonic altimeter with a precision of ±2 mm, was deployed near La Madelon (MA, Fig. 1C), considered a 'safe' mudflat spot upstream of the main salt marsh area that is highly frequented by wild fowl hunters. A similar altimeter deployed earlier between transects P3 and P4 was destroyed by vandals barely two days after it started operating. The ALTUS altimeter has been used successfully to monitor bed accretion in mudflat environments (e.g., Deloffre et al., 2006; Gratiot et al., 2007). The altimeter was deployed from 01/12/2002 to 28/11/2004. The principle of the altimeter is to measure the time taken between the emission by the transducer of a 2 MHz wave and the reception by the same transducer of the echo sent back by the target (i.e. the sediment surface). The time measurements can then be transformed easily into distance via prior calibration of coordinates. The low-energy consumption of the altimeter allows for deployments of several months, enabling monitoring of seasonal trends in sedimentation. An instantaneous measurement was effected by the sensor once every 5 min over the 2-year survey. A pressure sensor coupled to the altimeter enabled simultaneous measurements of water level variations. Once the tidal signal is removed from the transducer signal, the system provides changes in mud surface elevations due to high-frequency sediment deposition.

A Rod Surface-Elevation Table (RSET) was used to quantify marsh elevation change from September 2005 to October 2006 at three stations: P2e, P4c and P4e (Fig. 1C). The RSET is a non-intrusive method for precisely measuring elevation changes over long periods (Cahoon et al., 2002). It provides a constant reference plane in space from which the distance to the sediment surface can be measured by means of pins lowered on this surface. Under field conditions, confidence intervals for the measured heights of an individual pin range from ±1.3 mm to 4.3 mm in a salt marsh (Cahoon et al., 2002). The results presented here are the average of the 72 measurement points in each station, covering a 1 m^2 surface. These results also provide snapshots of the microtopography.

Sediment supply was evaluated with the help of a filter trap method (Jigorel, 1996) at a total of 27 stations set up on the four transects (Fig. 1C). Filter traps are an inexpensive survey method that offers deployment possibilities in large batches, thus enabling a better appreciation of the spatial variability of tidal platform sedimentation. The filter technique chosen consists of a PVC rack comprising a paper and a fibreglass filter clipped to the marsh surface. Only the paper filter is previously weighted and removed for further analysis. The fibreglass filter is part of the trap drainage system. The racks and fibreglass filters were deployed over 26 neap–neap tidal cycles from 06/11/2004 to 24/11/2005, and the paper filters collected for weighing and replaced every two weeks. The collected filters were dried at 60 °C for 48 h to obtain the total weight of deposition. The results were aggregated for each filter over the one-year period of deployment, in g cm^{-2} relative to the filter collecting surface (75.43 cm^2), and the total per station expressed in kg m^{-2}.

In order to assess the relationship between elevation and sedimentation rates at the micro-scale level of the filter stations from the mudflats to the salt marshes, the predicted hydroperiod per semi-lunar tidal cycle was estimated for each filter station from the tidal levels and from the elevation data, and then cumulated for the one-year survey in each station. Because of a low inundation period (less than 13 h a year or 30 min over a semi-lunar cycle), several stations hardly trapped any sediment and were discarded from the comparative analyses.

The vegetation cover was characterized using a phytosociologic method based on the Braun-Blanquet (1964) index which recognises abundance/dominance criteria. This index expresses the ratio of the surface occupied by each plant species to the total surface occupied by all the vegetation in the survey area. A floristically homogeneous surface is defined by an area where the list of species does not vary independently of the more or less aggregative distribution of the individual.

4. Results

4.1. Elevation, marsh vegetation, and hydroperiod

A typical cross-shore distribution of the tidal platform zones and the vegetation belts in the Authie estuary is depicted in Fig. 2A. The cross-shore distribution of these zones as a function of topography, tidal flooding, and hydroperiod on the transects on which were deployed the RSET and filter sedimentation stations is shown in Fig. 2B. The vegetation cover shows a progressive increase from the upper mudflat area (as distinct from the lower, muddy sand flat), which includes a pre-pioneer zone (vegetation cover $<5\%$) and a pioneer zone *sensu stricto* ($5\% <$ vegetation cover $< 25\%$), to the salt marshes proper. The pioneer, and low- to mid-marsh zones range from mean high water neaps (MHWN) to mean high water springs (MHWS) and represent the most frequently flooded zones (flooded by ca. 90% of all tides). High marshes occur at elevations between 4 and 5 m IGN69, which corresponds to elevations between MHWS and exceptional high water springs (EHWS) (flooded by ca. 10% of all tides). Low marshes are dominated by *Spartina anglica* or *Salicornia sp*., whereas mixed assemblages of *Aster tripolium*, *Puccinellia maritima*, *Triglochin maritima*, *Halimione portulacoides* and *Suaeda maritima* occupy the mid- to high marshes. *Spartina anglica* and *Salicornia sp*. are exclusive macrophytes within the pioneer zone but the former forms a monospecific belt at the edge of the salt marsh. The transects exhibit marked topographic variability amidst relatively convex shapes (Fig. 2B). They also highlight the increasing elevation of the mid- to high marsh zone towards the inner estuary from P2 to P4. The predicted cumulative hydroperiods for vegetated transects P2 to P4 over the one-year filter station survey ranged from 170 to 1290 h, with decreasing values on each transect from salt marsh to mudflat (Fig. 2B). The variations in these values reflect the uneven topography of the transects.

The spatial elevation pattern of the mudflat and marshes is shown as a LiDAR digital model (Fig. 3A) from which the tidal levels associated with the marsh zones have been extracted (Fig. 3B). The clear surfaces on the digital model correspond to areas of sparse vegetation cover typical of the pioneer zone (see also Fig. 1C). The platform is limited to the north by the aeolian dune shoreline which shows up in dark red in the LiDAR image with elevations of up to 24 m, and southwards by the main estuarine channel which is characterized by meander bars and numerous 3D hydraulic dunes generated by large current speeds (point A, Fig. 3C). Current speeds and directions within the estuary are strongly influenced by tidal dissipation and by the estuarine morphology (Anthony and Dobroniak, 2000), and weaken considerably in the inner estuary from the Authie channel (point A) to the mudflat (point B) and the peripheral mid-marsh zone (point C) along the north bank of the estuary (Fig. 3C).

Platform elevation increases, as shown by the transects, from the Authie channel towards the dune-bound shore, and inland towards the inner estuary. The LiDAR image also highlights a series of successive vegetated sand spits attached to the dune shoreline (Fig. 3A). They record successive positions of the shoreward translation of sand bodies along this part of the north bank shoreline prior to the full establishment of the salt marshes that show up in green. This juxtaposition attests to the rather late expansion of salt marshes in this part of the estuary. The LiDAR image also shows several circular depressions dug out in the marshes by hunters of wild fowl.

4.2. Sediments and bedforms

At the estuary mouth, the platform is characterized by very fine to fine ($D_{50} = 0.07$–0.3 mm), well-sorted sand with a symmetrical distribution. The sediment becomes finer, less well-sorted, and highly asymmetrical towards the finer particles with distance into the inner estuary, where the sand flats progressively evolve into mudflats and salt marshes (Fig. 4). This inner estuary-ward variability in grain-size properties is especially apparent in the lower mudflats, notably with enrichment in coarse silt and fine sand as a function of the proximity of the main channel. The salt marshes and mudflats exhibit mud contents varying from 76 to more than 90% and high calcium carbonate contents comprised between 34 and 43%. Medium to coarse silts constitute the major fraction of total sediment with values from 42.5 to 90%. The clay fraction does not exceed 4.5% and is comprised of smectite (30–36%), illite (32–39%), kaolinite (19–24%) and chlorite (9–14%). The lower sand flat areas are characterized by ripples sometimes superimposed on 2D to 3D dunes. The bedforms become less pronounced towards the muddy inner estuary. Large tides can also result in the trapping of temporary mud patches on the sand flats, and in the deposition of coarser sediment on mudflats and marshes, although this is in no way comparable to the cheniers associated with certain tidal flat environments (e.g., Anthony, 1989; Neal et al., 2003; Quaresma et al., 2007), and formed by (storm) wave impingement on the marshes.

4.3. Elevation change and sedimentation rates

The results on elevation change and sedimentation rates yielded by the three methods are depicted in Fig. 5. The bed-level change and the corresponding water levels recorded by the altimeter and the attached pressure sensor deployed over the mudflat at La Madelon are shown in Fig. 5A. The elevation change attains 26 cm of fine sand and mud over the two-year survey. However, much of this accretion occurred in the first 13 months of the deployment following which there was a clear slow-down and relative stability in the last few months before the instrument was removed.

The RSET data for the stations within the salt marsh (Fig. 5B) show a positive cumulative elevation change in all three stations over the study period. The maximum rate attained 1 cm in station P4c, the least elevated of the three stations, in March, 2006, after six months of implantation, but two other noteworthy aspects are those of the cumulative change in June and then October 2006, and the net change at the end of October 2006. The cumulative change shows relative uniformity, while the net accretion reported in October 2006, after 13 months of implantation, was in the 0.71–0.75 cm range for the three stations. These values are quite similar despite the variability of both the vegetation cover and the elevation (Fig. 5B), and of the cumulative hydroperiod (Fig. 2B). The results show a gradual elevation change over mid-marsh stations P2e and P4e, with the greatest accretion at the former station between November 2005 and March 2006. The low marsh P4c station shows erosion of about 0.3 cm between March and June 2006. Overall, the RSET data also highlight significant spatial micro-topographic variability of the substrate. These data show that at comparable elevations, *Halimione portulacoides* is associated with larger elevation variations than *Puccinellia maritima* (Fig. 5B).

The annual sedimentation rates obtained with the filter traps ranged from 1.8 to 80.7 kg m^{-2} (Fig. 5C). Only stations that trapped sediment are shown (18 out of the initial 27). The three traps set up on P1 were removed following one neap–neap tidal cycle because of the propensity for this transect to be affected by wind-blown sand at low tide. Sedimentation over the one-year survey was negligible in the high-marsh stations (P2g-h, P4g-k). The highest sedimentation rates (>50 kg m^{-2} in one year) occurred in the pioneer zone (P2a, P4a). The values decrease from this zone to the mid-marshes, which evince the lowest sedimentation rates, albeit with variability, as in the case of P3 stations (Fig. 5C).

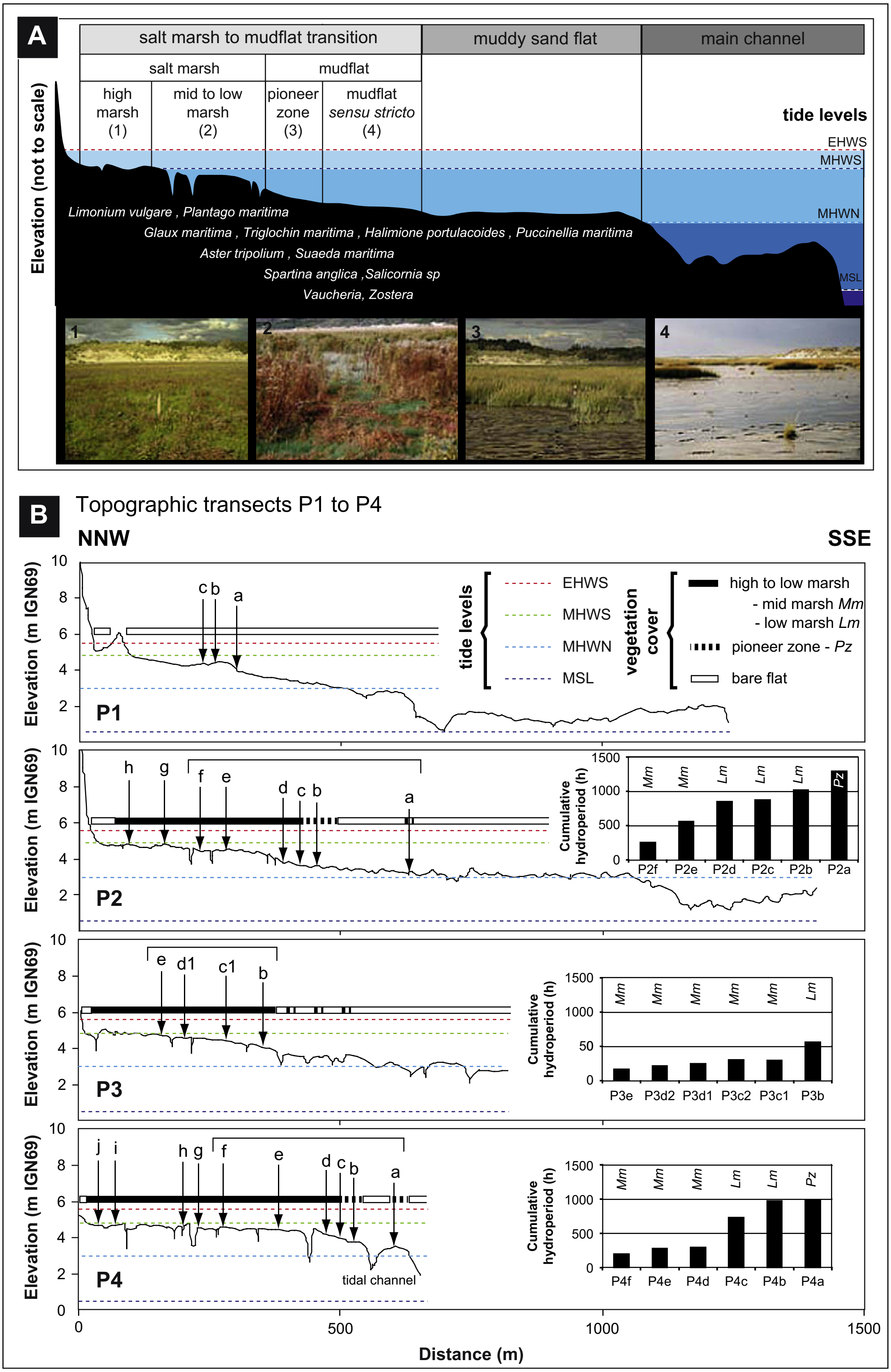

Fig. 2. Schematic cross-shore zonation (A) and topographic transects (surveyed in September, 2004) of the salt marshes and mudflats with deployed filter and RSET stations along the north bank of the Authie estuary (B). Horizontal accolades delimit stations retained for analysis. EHWS = Exceptional high water springs; MHWS = Mean high water springs; MHWN = Mean high water neaps. MSL = Mean sea level. Shown on the right are the cumulative hydroperiod values expressed as the total number of hours of tidal flooding at each retained filter station over the one-year survey.

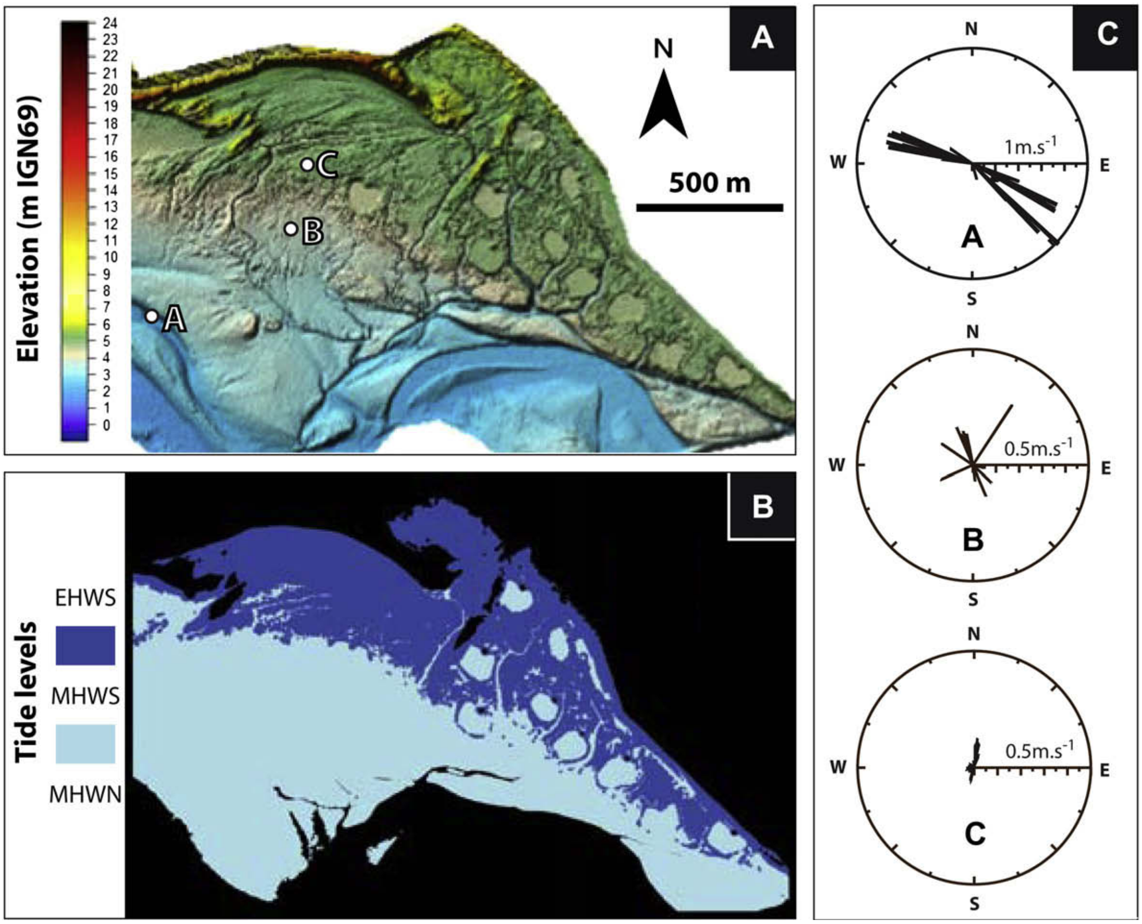

Fig. 3. Extract of a LiDAR image and elevation of the experimental site (A), spatial distribution of tidal elevation zonation (B), and summary flow speed data obtained on May, 7, 2004, at points A, B, and C (C).

5. Discussion

The north bank of the Authie estuary, a small, rapidly infilling macrotidal estuary, offers an opportunity for observing fine-scale relationships between the macro-scale morphology and estuarine forcing agents, and local-scale patterns of sedimentation. The elevation changes and sedimentation rates shown by the three methods deployed in the Authie estuary confirm the active accretion of this estuary, and pave the way for the future rapid expansion of salt marshes over the tidal platform, as Anthony and Dobroniak (2000) envisaged from cartographic and historical records. There is a tendency for accretion rates to increase with depth to the substrate, as shown by the data from both the altimeter (Fig. 5A) and the filter stations (Fig. 5C). The pattern of sedimentation in the altimeter data reflect the lunar neap–neap tidal cycle. The outliers in the data probably reflect floating vegetation, litter, and passing wild fowl feeding on the mudflat. The very rapid sedimentation, expressed by peaks between March and April 2003 (Fig. 5A), reflects the influence of a combination of increased sediment supply by winter storms and equinoctial tides, materialised by the recorded high water levels, at a time when a longer hydroperiod favoured sedimentation. This effect is not replicated by the equinoctial tides of 2004 probably because of a lower propensity for net sedimentation due to a shorter hydroperiod following substrate

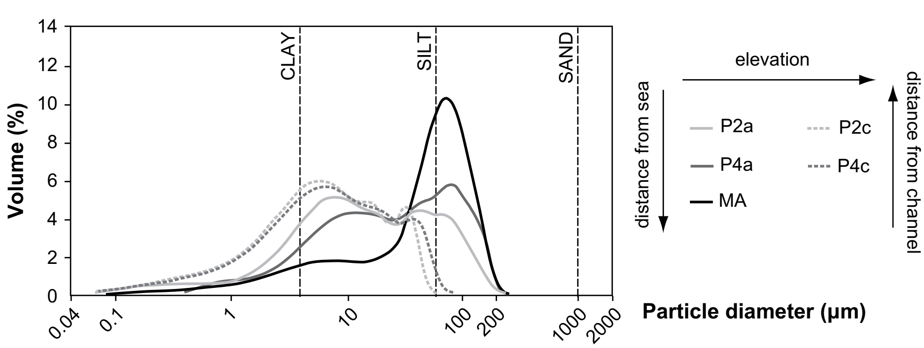

Fig. 4. Selected stations showing grain-size variations and gradients in September, 2004.

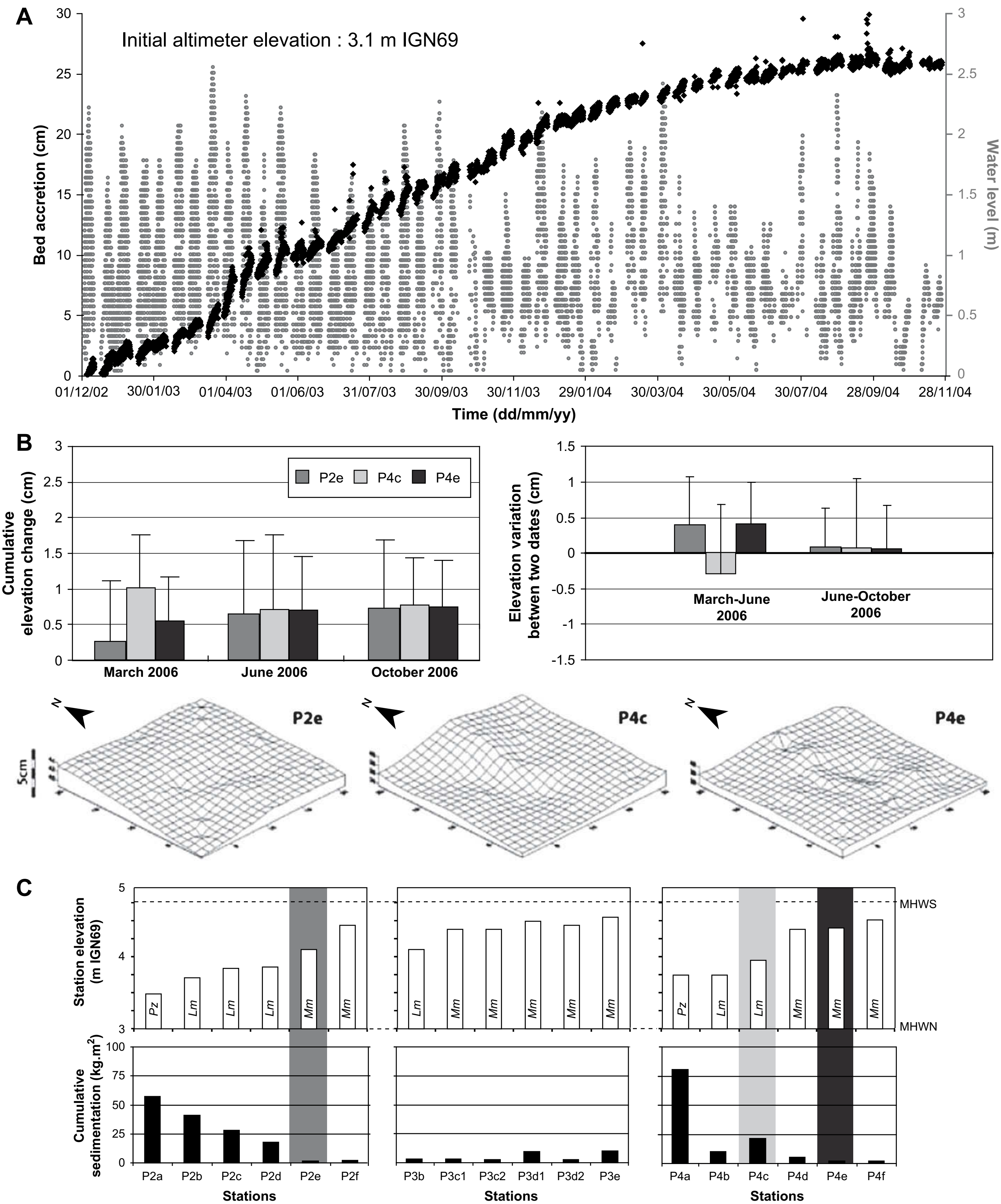

Fig. 5. Summary of the results on bed-level change/sedimentation obtained using the altimeter (A), the RSET stations with T-bars showing standard deviation (B), and filter stations (C). Pz = pioneer zone; Lm = low marsh; Mm = mid-marsh. Also shown in B are digital elevation models of RSET changes between September 2005 and October 2006. Salt marsh vegetation: P2e – *Puccinellia maritima*, P4c – *Spartina anglica*, P4e – *Halimione portulacoides*.

accretion. The high-sedimentation rates on the mudflat shown by the altimeter measurements diminish progressively over time (Fig. 5A) as substrate elevation increases and tidal inundation decreases. The net accretion rate may also have diminished as a result of increasing sediment compaction over time.

The point data from the altimeter are replicated spatially by the filter station data from the pioneer to the mid-marsh zone (Fig. 5C). The high rates of net sediment accumulation at the pioneer zone stations P2a (3.5 m IGN 69) and P4a (3.75 m IGN 69) express, to a large degree, the high bed accretion rates recorded at the lower-elevation (3.1 m IGN 69) altimeter station. The RSET data for the three stations within the salt marsh (Fig. 5B) provide a control on net elevation changes within the vegetated platform. Although the net accretion rate at all three stations is significant over the 13-month deployment, exceeding 0.5 cm, in reality, this accretion expresses net sedimentation rates based on the filter method that are much weaker compared to those of most of the lower-elevation stations (Fig. 5C). The decrease in accretion with increasing elevation is a classic pattern in tidal flat environments, and is at the basis of models of long-term marsh development, especially with reference to sea level (e.g., Morris et al., 2002; Temmerman et al., 2004; French, 2006; Kirwan and Murray, 2008).

Although there is a tendency for sedimentation to increase with flooding depth, the statistical trend yielded by the more spatially representative data sets from the filter stations shows only a moderate relationship ($R^2 = 0.58$) when all the 18 retained stations are considered (Fig. 6). The relationship between these two parameters improves considerably ($R^2 = 0.84$) when the lowest P4 stations (4a–c) are removed from the analysis. These stations appear to be influenced by a nearby active tidal creek (Fig. 2B). The pattern evinced by the filter stations for the mid-marsh zone is in agreement with that of the RSET data which also show relatively homogeneous rates of net salt marsh accretion, notwithstanding differences in hydroperiod and plant cover between the low marsh (P4c) and mid-marsh stations (P2e, P4e). The RSET data also show that the low marsh station in proximity to the afore-mentioned tidal creek is more susceptible to elevation change (i.e., accretion and erosion) over time than the other two, more elevated and less frequently flooded stations. Accretion between September, 2005 and March, 2006 was followed by erosion between March and June, 2006, probably in response to channel dynamics under the possible influence of large equinoctial tides.

At the short timescale (1–2 years) represented by these data, the relationship between elevation within the tidal frame and sedimentation is modulated by local hydrodynamic or morphodynamic controls, hinged on position within the estuary, on tidal cycle variations, and on proximity to pathways of incoming sediment, but also by plant cover. These variations are inherent, over the longer timescale (>2 years), in the uneven topography of the transects along which the sedimentation rates were monitored (Fig. 2). The morphology of transect P1 basically reflects feeding of the tidal platform by sand derived from the mouth of the estuary, essentially under the episodic influence of residual storm wave energy that is considerably dissipated over the estuary-mouth sand platform, and of exceptional tides. This outer zone is subject to relatively strong tidal currents that are modulated by the neap-spring tidal range, and that lead to rapid changes in the morphology and bedforms of the main Authie channel (Anthony and Dobroniak, 2000). This zone of rapid estuarine morphological change extends up to the main internal sand spit (Fig. 1), which shelters the mudflats and salt marshes of the north bank from wave action. Beyond this energetic zone, from profiles P2 to P4, and up to MA, the tidal currents on the mudflat (point B) and salt marsh (point C) become much weaker (Fig. 3C). Muddy sedimentation has prevailed in this inner part of the estuary, with silt brought in suspension progressively becoming the dominant facies towards MA (Fig. 4). In this inner part of the estuary, sedimentation over the tidal platform is essentially controlled by variations in local water depth and by the possibilities of local reworking by tidal currents, tidal creeks, and the mobile main estuarine channel. Channel activity may lead to either enhanced sedimentation in peripheral areas or may be a potential source of sediment remobilisation. The main estuarine channel is characterized by much stronger current speeds (point A, Fig. 3C), and constitutes a southward limit for salt marsh expansion. As the estuary widens seaward (Fig. 1B), the proportion of sand increases considerably (Fig. 4), and the rugged muddy bed is replaced by sandy bedform development (Fig. 2B) which imparts marked topographic variability to the channel-ward part of profile P2. The overall large-scale profile configurations are relatively convex, a configuration typical of accreting tidal flat profiles (Kirby, 2002; Mehta, 2002).

The afore-mentioned macro-scale constraints of estuarine morphology and channel dynamics are likely to impart spatial variability in mudflat and salt marsh sedimentation rates. Plants also exert a strong influence on the hydrodynamics, and, consequently, modulate suspended sediment concentrations and the deposition rate through the effects of bed shear stress and turbulence of flow within the canopy (e.g., Allen, 2000; Leonard and Croft, 2006; Neumeier and Amos, 2006; Neumeier, 2007). The dissipative effect of vegetation on flow is illustrated by the significant drop in mean current speeds in the salt marsh (point C, Fig. 3C). There are, however, numerous imponderables, such as patchiness in

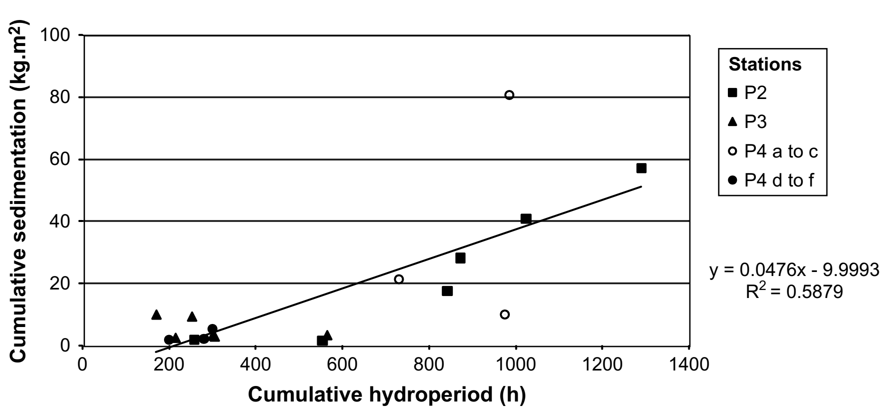

Fig. 6. Correlation between cumulative sedimentation at filter trap stations and cumulative hydroperiod. The coefficient of determination is considerably improved when outlier P4 stations are excluded from the analysis.

vegetation cover (Bouma et al., 2007), flow routing (Allen, 2000; Temmerman et al., 2005a,b), the flexibility of the vegetation (Stephan and Gutknecht, 2002; Järvelä, 2005), and floc dynamics (Graham and Manning, 2007) that still render elusive a full comprehension of these effects (Le Hir et al., 2007). Variations in net sedimentation due to differences in canopy-flow interactions may be masked where overall sediment supply is adequate. In the Authie estuary, the local wave and tidal conditions, the morphology of the estuary and of the tidal platform, and the available sediment supply constitute macro-scale controls that are determinant in local sedimentation rates. While elevation constitutes a major control on potential accretion over salt marshes, short- to medium-term rates in sedimentation can show significant spatial and temporal variability, as shown by this, and a number of recent case studies (e.g., Temmerman et al., 2005b; van Proosdij et al., 2006a,b). This variability in sedimentation also has implications for the determination of spatial and temporal patterns of sedimentation in salt marshes, which require caution when deduced from point sampling stations, still the only way of obtaining continuous *in situ* high-resolution data. However, high-resolution field studies coupled with innovative spatial modelling techniques should enable more representative characterisation (e.g., Temmerman et al., 2005b).

6. Conclusion

The overall context of a significant allochthonous sediment supply controlled by hydrodynamic variables seems to be the key feature of sedimentation patterns in a mudflat and salt marsh platform in the Authie estuary, a rapidly infilling macrotidal estuary on the English Channel coast. The data collected in this study have highlighted some of the local relationships between elevation, hydroperiod, sedimentation, and the presence of salt marshes. The results show that although there is a tendency for higher sedimentation rates at lower elevations on the tidal platform, due essentially to longer flooding periods, sedimentation rates may vary at similar elevations, while being relatively homogeneous in marsh areas with variable canopy cover.

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