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Sediments and water fluxes in a muddy coastline: interplay between waves and tidal channel hydrodynamics

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ABSTRACT: Tidal channels are ubiquitous in muddy coastlines and play a critical role in the redistribution of sediments, thus dictating the general evolution of intertidal landforms. In muddy coastlines, the morphology of tidal channels and adjacent marshes strongly depends on the supply of fine sediments from the shelf and on the resuspension of sediments by wind waves. To investigate the processes that regulate sediment fluxes in muddy coastlines, we measured tidal velocity and sediment concentration in Little Constance Bayou, a tidal channel in the Rockefeller State Wildlife Refuge, Louisiana, USA. The tidal measurements were integrated with measurements of wave activity in the bay at the mouth of the channel, thus allowing the quantification of feedbacks between waves and sediment fluxes. Results indicate that the sediment concentration in the channel is directly related to the wave height in the adjacent bay during flood and high slack water, whereas the concentration during ebb depends on local channel velocity. Moreover, the sediment flux during ebb is of the same order of magnitude as the sediment flux during the previous flood, indicating that only a small fraction of transported sediments are stored in the marsh during a tidal cycle. Finally, very low tides, characterized by high ebb velocities, export large volumes of sediment to the ocean. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: Sediments fluxes; waves; tide; tidal channels; chenier plains, muddy coastline

Introduction

Muddy coastlines lack of barrier islands and sandy beaches that typically separate the ocean from terrestrial and intertidal landforms. As a result, salt marshes and chenier plains are the shoreline main morphological features, directly exchanging water and sediments with the ocean through a series of tidal channels. The morphology of chenier plains strongly depends on the supply of fine sediments from the shelf and on the resuspension of sediments by wind waves. In particular, fluxes of sediments in and out of tidal channels play a critical role in coastal evolution. In fact, channels provide sediments to the marsh surface, and thus determine whether the entire coastal area is able to keep pace with sea level rise (Kirwan and Murray, 2007; D'Alpaos *et al.*, 2007; Marani *et al.*, 2007). Similarly, in a marsh under erosion sediments are convoyed to the ocean from the interior of the marsh through tidal channels.

In intertidal environments it is common to assume a deposition rate that varies as a function of water depth (French, 1993; Morris *et al.*, 2002), this is particularly true for salt marshes, in which the inundation period, and therefore the time available for suspended sediments to settle, decreases with elevation when the marsh becomes emergent. Recent studies in the Netherlands have also shown that sediment concentration in the water column during marsh flooding is controlled by tidal inundation, and increases linearly with inundation height at high tide (Temmerman *et al.*, 2003). Other studies showed that, in some cases, sediment concentrations initially spike during high flood-dominated tidal currents then decrease to low concentrations with rising tide (Green and Coco, 2007). Empirical relationships between tidal elevation and sediment concentration have been used to model the long-term evolution of the entire marsh system (Kirwan and Murray, 2007). Other studies have used a constant concentration of sediments in the marsh channels to study the accretion of the marsh platform and the related feedbacks with marsh vegetation (D'Alpaos *et al.*, 2007) and the evolution of the channel cross-section in time (D'Alpaos *et al.*, 2006). However, all these studies do not directly address the link between sediment fluxes and the processes responsible for the resuspension and transport of sediments in the nearshore area. Recent research carried out by French *et al.* (2008) in a muddy estuary in the UK east coast linked sediment fluxes to meteorological forcing. Specifically, French *et al.* (2008) found that suspended sediment concentration varies intermittently as a function of meteorological surges and wind stress forcing, which generates waves and sediment resuspension.

A more process based approach is also deemed necessary for the characterization of the sediment export from the marsh interior to the ocean, since different mechanisms regulate the sediment concentration in tidal channels during ebb. For example, Mwamba and Torres (2002) stress the critical role of rainfall and, in particular, the detachment of sediment particles produced by raindrop impact on the erosion of the marsh platform and the related sediment flux to the ocean. More recently, Green and Coco (2007) also note the role rainfall has on increasing sediment loads and corresponding sediment exchange between mud flats and tidal channels. Goni and Gardner (2003) indicate that seepage flow from marsh banks during low tide can export significant volumes of both dissolved organic matter and sediment particles to the ocean.

The effect of wind waves on sediment substrate has been the focus of recent research projects in the nearshore area (Traykovski *et al.*, 2007; Kineke *et al.*, 2006; Sheremet *et al.*, 2005; Jaramillo *et al.*, 2009). All these studies indicate that waves are the chief mechanism for sediment resuspension in muddy environments. Wind waves have also been recognized as critical morphological agents for the evolution of tidal flats and intertidal landscapes in general (Fagherazzi *et al.*, 2006, 2007; Defina *et al.*, 2007).

In this article, we seek to link the processes responsible for sediment remobilization in tidal flats to the supply of sediments to adjacent marshes. In particular, through high resolution field measurements, we will determine the effects of tides and waves on the sediment fluxes in a tidal channel along a muddy coastline.

Study Site

We focus our study on Little Constance Bayou, a tidal channel in the Grand Chenier Plain, Louisiana, USA (Figure 1). The tidal channel is located within the Rockefeller National Wildlife Refuge, in one of the fastest eroding coastlines in the United States, with an average erosion rate higher than 10 m/yr between 1884 and 1994 (Byrnes *et al.*, 1995). The chenier plains in Louisiana are a system of shelly, elongated ridges perched on muddy sediments (Russell and Howe, 1935). Shell fragments are episodically deposited by waves at the coastline (white areas in Figure 1, right panel), but the entire system is mud-dominated. Erosion of muddy sediment is caused by wind waves propagating from offshore (Elgar and Raubenheimer, 2008) and lead to a uniform retreat of the coastline.

A series of artificial levees delimit the watershed of Little Constance Bayou, protecting both oil rigs and coastal settlements from moderate storm surges. The tide is diurnal with a maximum diurnal range of 60 cm at Calcasieu Pass (see Figure 1). The main offshore source of fine sediments is the Atchafalaya subaqueous delta (Draut *et al.*, 2005a), which terminates 10 km east of the study site, producing the accretion of the chenier plain east of Fresh Water Bayou (Draut *et al.*, 2005b; see Figure 1). On the contrary, the reduced amount of sediment input in our location leads to sediment starving conditions.

The regrading of the shoreline has considerably reduced the length of the tidal channel in the last 50 years (Figure 1), so that the bend at the channel mouth in Figure 1 is in reality a vestige of a channel meander. The channel is deeper and confined at the bend (section B–B, see Figure 2), but widens at the mouth (section A–A in Figures 1 and 2).

Methods

We deployed a Sontek Acoustic Doppler Velocimeter (ADV) vertically mounted on a tripod in the bay in front of the channel mouth (see Figure 1) and measured wave climate every hour from December 17, 2007, at 3 p.m. to January 14, 2008, at 10 a.m. Each wave burst measured 2048 water elevations for 400 seconds at 5 Hz. The pressure data were used to compute wave statistics after removing high frequency components (more than 2 Hz). We extracted the significant wave height H_s (the average of the highest one-third of the waves) and the mean wave period T_{01} (first-order moment) from the wave spectrum.

Within the tidal channel, we deployed a Nortek Acoustic Doppler Current Meter (ADCP) and measured tidal elevation

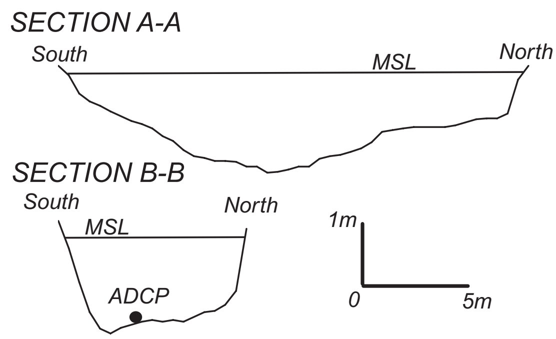

Figure 2. Channel cross-sections at the mouth and at the ADCP location (see Figure 1).

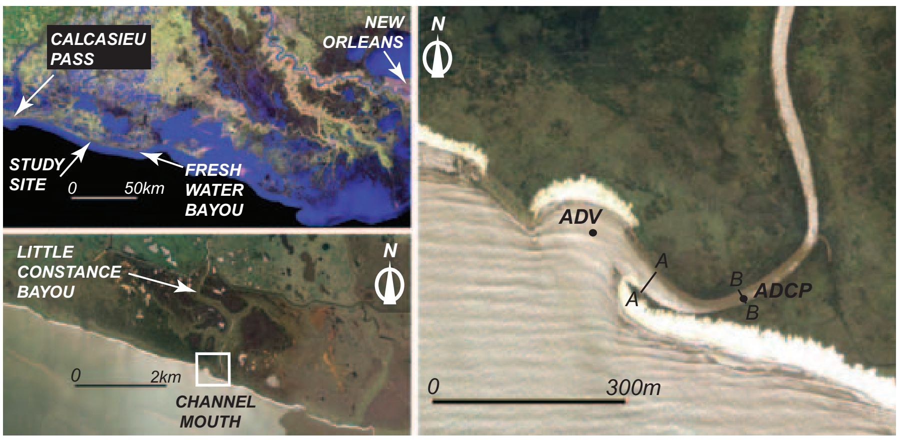

Figure 1. Location of the Little Constance Bayou in the Rockefeller National Wildlife Refuge, Louisiana, USA. This figure is available in colour online at www.interscience.wiley.com/journal/espl

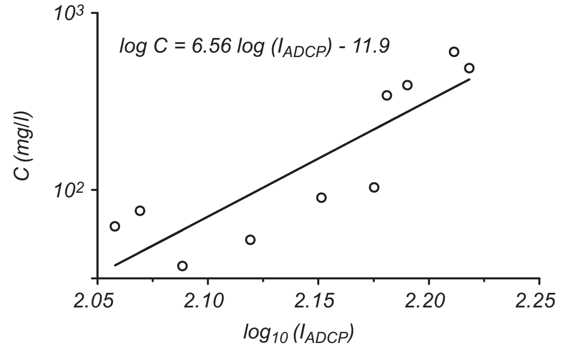

Figure 3. Calibration of the Nortek ADCP backscattering intensity with sediment concentration data collected in the field.

and water velocity (with 10 cm vertical bins) every hour during the same period as the ADV measurements.

Given the shallow depth of the channel we did not detect significant variations of velocity along the vertical (barotropic flow). Therefore, we used the sixth interval of the ADCP profiler, which measures the velocity between 0·3 and 0·4 m, for the determination of channel velocity. The horizontal velocity was rotated of 30° to be aligned perpendicularly to the channel axis. In the data shown herein a positive velocity denotes flood flow (water entering the marsh) whereas a negative velocity denotes ebb (water exiting the marsh).

Similarly, we use the amplitude of the ADCP acoustic signal between 0·3 and 0·4 m as a proxy for sediment concentration, assuming well mixed conditions. The amplitude was calibrated assuming a linear response of the instrument with sediment concentration (e.g. Voulgaris and Meyers, 2004). Ten water samples of one gallon were collected at the ADCP site under different conditions of sediment concentration. The water was filtered to extract suspended sediments. The filters were dried at 40 °C for two hours and then weighed to determine the total mass of suspended sediments. The sediment concentration was then correlated to the intensity of the backscatter signal with a log-log interpolation (Figure 3; see Voulgaris and Meyers, 2004). The tidal data were then compared to tidal and meteorological data at Calcasieu Pass, LA (NOAA station 8768094, see Figure 1).

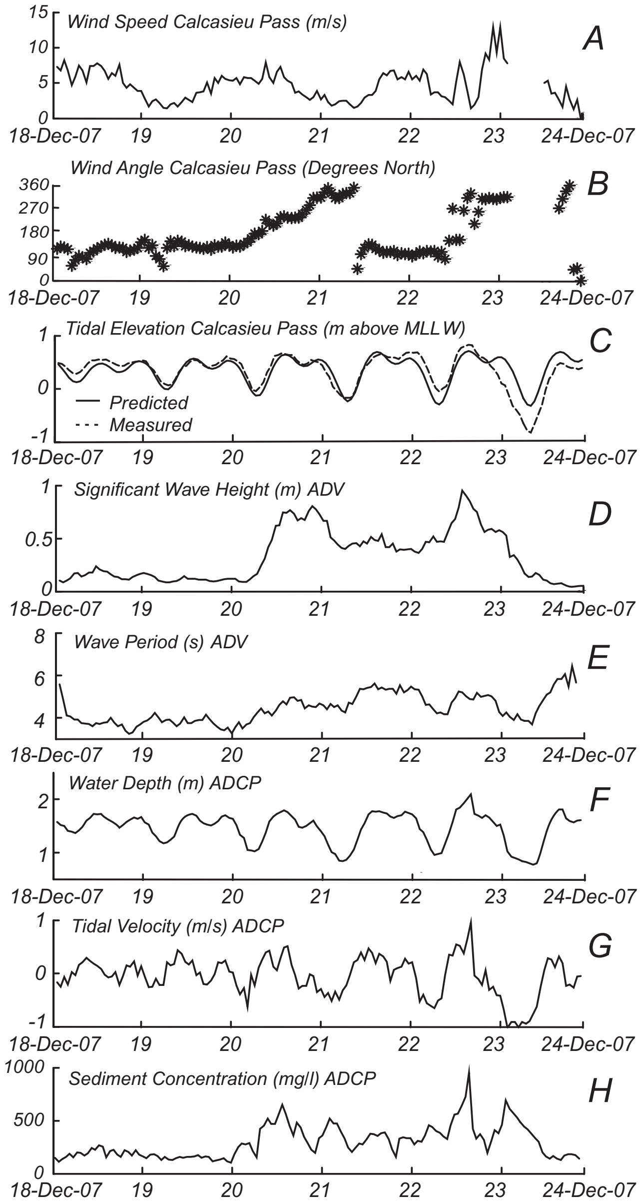

Figure 4. Measurement of hydrodynamic and sedimentological parameters at the tidal channel from December 18 to December 24, 2007: (A) wind speed; (B) wind direction; (C) measured and predicted tidal elevations at the NOAA station in Calcasieu Pass, LA; (D) significant wave height; (E) wave period at the channel mouth; (F) water depth; (G) tidal velocity; (H) sediment concentration in the tidal channel.

Results

The data collected were organized in an hourly time series. In Figure 4 we report an example of the data resolution from December 18 to December 24, 2007. A moderate storm hit the Louisiana coast from December 20 to December 24, producing two distinct wave events on December 20 and December 22, 2007, with significant wave height between 0·7 and 1 m. The first event occurred for wind directions from the south while the second was produced by winds blowing from the southwest perpendicular to the coastline. The wind in Calcasieu Pass was higher for the second event (Figure 4A), even though the lack of offshore data in front of Little Constance Bayou warrants a precise assessment of meteorological conditions at the study site. On December 22 a wind of 9 m/s coming from the northwest produced a moderate storm surge both at Calcasieu Pass (difference between predicted and measured tide in Figure 4C) and at our study site (Figure 4F). The storm surge increased water elevations in the channel (Figure 4F), tidal velocities (Figure 4G), and suspended sediment concentrations (Figure 4H).

Correlation between wind, waves and storm surges

The distribution of wind direction and intensity at Calcasieu Pass during the study period is reported in Figure 5(A). The most frequent wind direction is southeast followed by north, with only a very intense wind event from the northwest. In Figure 5(B) we plot the wave data collected in front of Little Constance Bayou along the wind directions measured at Calcasieu Pass (only significant wave height higher than 0·3 m is reported). As expected, the waves are produced by winds blowing from the ocean (from southeast in our study period), but not from winds blowing from the mainland (i.e. from north and northeast along this stretch of coastline). Wind speed and wave height are positively correlated for winds blowing from the southeast, south and southwest (Figure 5E), indicating that

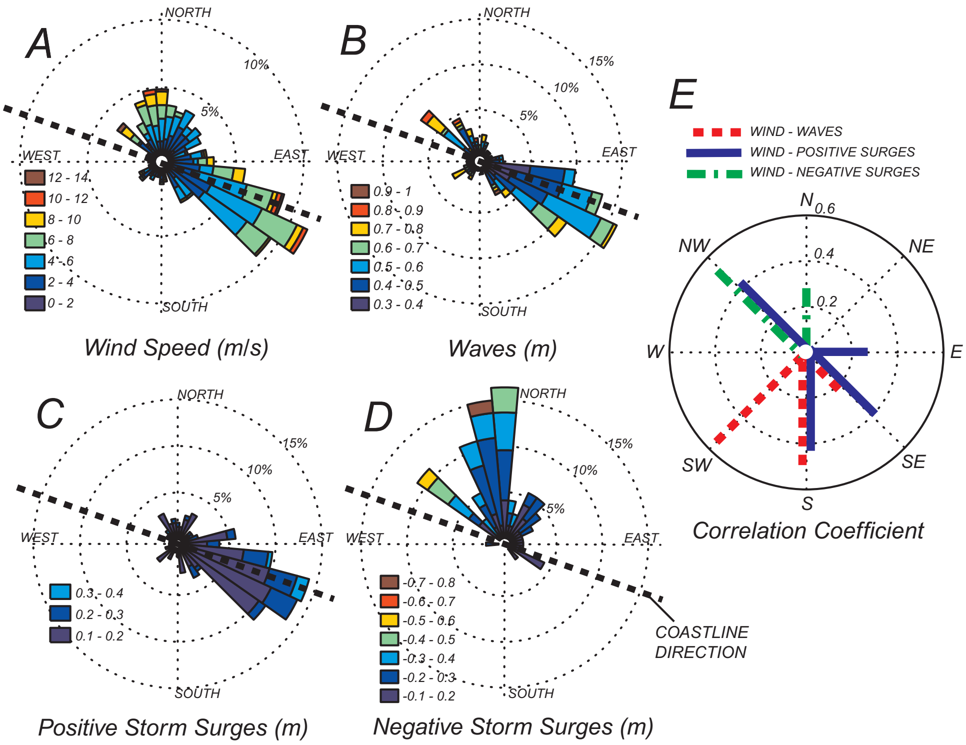

Figure 5. Wind, waves, and storm surges distribution from December 17, 2007, to January 14, 2008: (A) distribution of wind intensity and direction at Calcasieu Pass LA; (B) distribution of wave height in front of Little Constance Bayou as a function of wind direction measured at Calcasieu Pass; (C) distribution of positive storm surges (higher than predicted astronomic tide) at Calcasieu Pass as a function of wind direction; (D) distribution of negative storm surges (lower than predicted astronomic tide) at Calcasieu Pass as a function of wind direction; (E) correlation coefficients between wind speed and wave height, positive storm surges, and negative storm surges. The data are binned in eight wind directions, all correlations are significant with $p < 0{\cdot}05$. This figure is available in colour online at www.interscience.wiley.com/journal/espl

strong winds from these directions produce high wave events at the shoreline. These results need to be accepted with caution since the distance between the NOAA station at Calcasieu Pass, where the wind data were collected, and Little Constance Bayou, where we measured the wave height, is large enough to affect the relationship between wind and waves. Of more interest is the connection between wind and storm surges. In Figure 5(C) we plot the positive difference between measured and predicted tidal elevations at Calcasieu Pass (water higher than 0·1 m the predicted astronomic elevation). All storm surges occur for winds blowing from the southeast, the only direction along which the wind was blowing on water during the studied period. Lack of wind events during this period from the south southwest and west unfortunately limits our analysis of storm surges. The storm surge is positively correlated to wind speed for east, southeast and south directions, but also for wind speed from the northwest, although fewer data points are available along this direction. As a result, strong winds from the south and southeast are responsible for storm surges at the coastline. Finally we also investigate the relationship between negative storm surges (measured water elevations lower than the astronomic prediction) and wind. Very low tides occur for winds blowing from the north and northwest, with departures from the tidal prediction up to –0·8 m (Figure 5D). A significant correlation exists between extreme low tides and winds blowing from the north and northwest (Figure 5E). Therefore when the wind comes from the mainland the tidal elevation is lower since the water is pushed by the wind shear stresses towards the ocean.

In general, when the wind blows from the southeast we have high waves and storm surges, whereas for winds from the north and northwest there are no waves and very low meteorological tides.

Of interest is also the storm of December 22–23, 2007, during which a wind of 10 m/s blowing from the southwest was followed by winds up to 15 m/s blowing from the northwest, thus producing a wave event superimposed to a storm surge during flood, followed by a very low meteorological tide during the following ebb (Figure 4). This event created the most favorable conditions for sediment resuspension both during flood and ebb in our study channel.

Controls on sediment concentration in tidal channels

To investigate the relationship between sediment concentration, tidal elevation, wave height, and flow velocity in the channel we divide the data in six different sets as a function of tidal elevation and flow velocity. The six sets roughly correspond to six different stages in the tidal cycle (Figure 6). For low velocities (less than 0·3 m/s) we have slack conditions and the water is either slowly entering in the channel or exiting from it. For high velocities (absolute value higher than 0·3 m/s) we have the two distinct events of flood and ebb. We also differentiate between high water (higher than Mean Sea Level, MSL) and low water events (lower than MSL). Since the velocity in the channel is never zero, instead of dividing the data in four sets (high slack water, low slack water, flood and ebb) we also separate slowly incoming flow during slack water from slowly exiting flow during slack water. For each stage, we run a correlation between sediment concentration in the channel and wave height, flow velocity, and tidal elevation. We report only correlation coefficients higher than 0·4 and all estimates are significant with $p < 0{\cdot}05$ (see Figure 6). Sediment concentration in the channel is highly correlated to wave

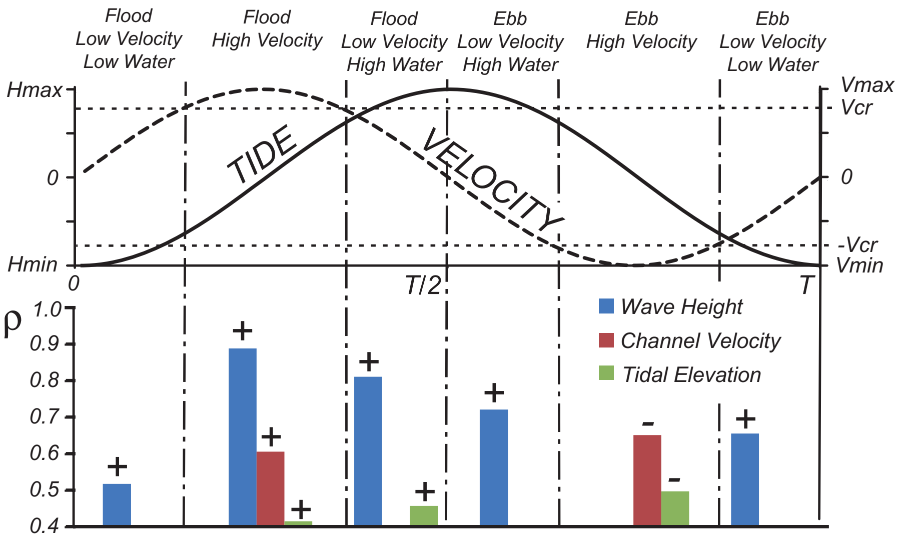

Figure 6. Correlations between sediment concentration in the channel, tidal elevation, flow velocity, and wave height in the bay. The data are grouped in six different tidal stages as a function of flow velocity and water elevation. This figure is available in colour online at www.interscience.wiley.com/journal/espl

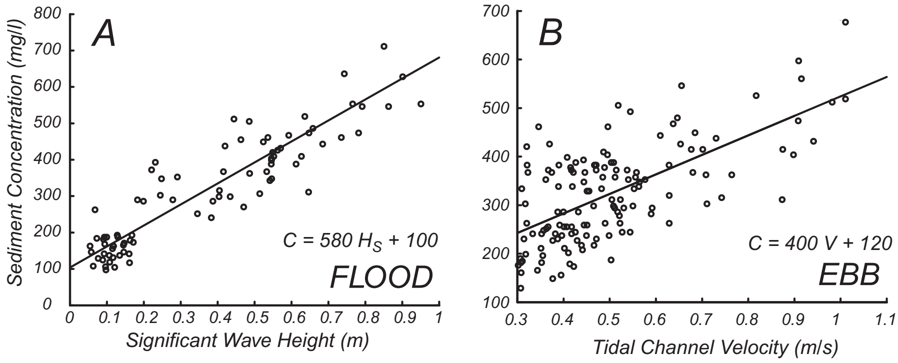

Figure 7. Relationship between sediment concentration and (A) significant wave height during flood and (B) tidal channel velocity during ebb.

height, particularly during flood events and during high slack water. It is easy to envision that sediment is first resuspended by waves near the channel mouth and then moved in the channel during flood. The transport of sediment continues during high slack water, although with a lower coefficient of correlation, and extends also to the first period of the ebb phase, probably because the combination of low velocities and proximity to energetic condition in the bay are still influencing the sediment concentration in the channel. During ebb, as expected, the sediment concentration is not influenced by wave climate, since the tidal flow is transporting sediments from the marsh interior to the ocean. During this stage there seems to be a relationship between sediment concentration and channel velocity, with high (negative) velocities promoting elevated bottom shear stresses that favor sediment remobilization in the channels and on the marsh surface. Similarly, even during flood there appears to be a positive correlation between flow velocity and sediment concentration, evidence of a combined effect of currents and waves in the resuspension of bottom sediments. We also detect a weak influence of water elevation on sediment concentration during the ebb phase, with high sediment concentration for low tidal elevation. This is probably due to sediment fluxes from the marsh banks during very low tide. In fact low tidal elevations in the channel create a hydraulic gradient between the marsh surface and the ocean that increases the seepage of sediment rich water from the channel banks.

A plot of sediment concentration in the channel as a function of significant wave height during flood indicates that the relationship between the two quantities is linear, with higher waves increasing sediment concentration (Figure 7A). Similarly, the relationship between sediment concentration during ebb and tidal channel velocity appears to be linear as well, but with a larger data spread (Figure 7B).

We also put forward the hypotheses that sediment concentration during ebb is related to (i) the concentration of sediment that entered the channel during the previous flood; (ii) the hydrodynamic conditions during the previous flood. The first hypothesis, which can be defined as the continuity hypothesis, simply states that if water with high sediment concentration enters the marsh during flood, a fraction of the same suspended sediments will likely exit during the subsequent ebb, since not all sediments will be deposited within the marsh.

The validity of the continuity hypothesis depends on the relative value of the settling velocity with respect to water velocity, which dictates the residence time of the sediments in the system. In a muddy environment the settling velocity of fine particles is low, so that sediments do not have enough time to deposit on the marsh in a tidal cycle.

A comparison between sediment concentration during ebb and sediment concentration during the previous flood (evaluated at the maximum flood velocity) shows that the two quantities are correlated (Figure 8). Sediment concentration during ebb is also correlated to the maximum wave height during the previous 24 hours, which is the mechanism initially responsible for sediment resuspension. Furthermore the correlation increases if we only consider the wave height at the maximum flood velocity, indicating that the synchronous occurring of both high sediment resuspension in the bay and high flood fluxes in the channel determines the amount of sediments entering in the marsh and then exiting during the subsequent ebb. It is also important to stress the limit of this analysis. The fact that sediment concentrations are correlated to all these quantities might not prove causality, since all these quantities could be cross correlated just because they all depend on the same external driver, with no direct causal relation between them.

The second hypothesis, which can be called the energetic hypothesis, states that the sediment concentration in the channel during ebb is also influenced by the velocity of the flow entering and exiting the marsh, since higher velocities give rise to large shear stresses that remobilize sediments in the channels and, possibly, on the marsh surface. Furthermore, we can explore whether the sediment concentration during ebb is directly linked to the total volume of water that enters the marsh in the previous tidal cycle, or is instead a function of the speed at which the water is moved within the marsh boundaries. In the first case we should expect a correlation with the peak water elevation during the previous flooding event, whereas in the second case we should find a correlation with the flood velocity during the previous tide. Our data suggest that both mechanisms are present (Figure 8), with a higher correlation between sediment concentration during flood and the maximum flood velocity within the previous 24 hours. This suggests that not only the total tidal prism is regulating sediment resuspension during ebb, but also the rate at which the water enters (and subsequently exits) the marsh area.

Sediment and water fluxes

An estimate of water discharge can be computed by multiplying the cross-sectional area of the channel at each tidal elevation by velocity. Similarly, the sediment flux is simply obtained by multiplying discharge by sediment concentration. Both estimates assume that the values of velocity and sediment concentration at 30 cm from the bed are representative of average flow conditions. Results show that a high flux of sediments enters the marsh during the storm surge of December 22 (Figure 9D), much higher than the relative increase in discharge (Figure 9C). Two low tide events exported sediments to the ocean (December 28 and January 1). Spring tides between January 4 and January 12 increased the exchange of water between the ocean and the marsh (Figure 9C), and the

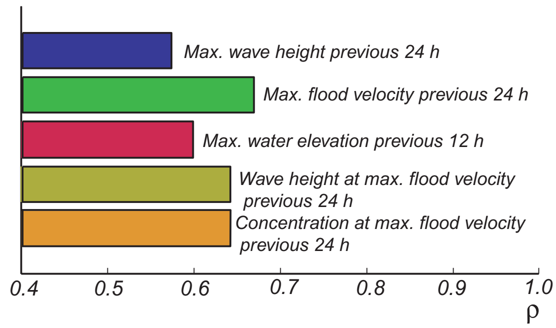

Figure 8. Correlation coefficient ρ between sediment concentration during ebb and (i) maximum wave height in the previous 24 hours; (ii) maximum flood velocity in the previous 24 hours; (iii) maximum water elevation in the previous tidal cycle (e.g. previous 12 hours); (iv) wave height at the instant with maximum flood velocity in the previous 24 hours; (v) sediment concentration at the instant with maximum flood velocity in the previous 24 hours. This figure is available in colour online at www.interscience.wiley.com/journal/espl

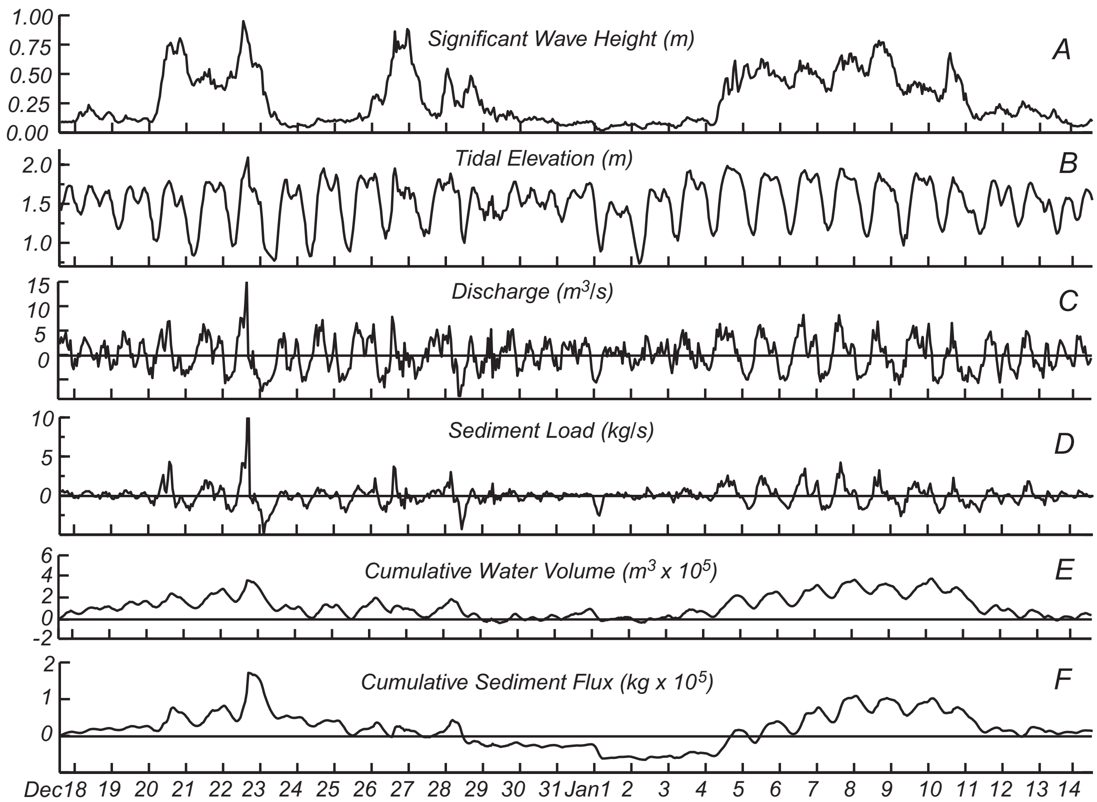

Figure 9. Time series of (A) wave height at the channel mouth, (B) tidal elevation in the channel, (C) channel discharge, (D) sediment load in the channel for the entire study period, (E) cumulative water volume and (F) cumulative sediment mass that entered the marsh.

corresponding sediment fluxes are enhanced by the presence of waves at the channel mouth (Figures 9A and 9D), whereas during periods of fair weather (e.g. December 29–January 4) the sediment fluxes are reduced. It is also important to note that the wave height seems to be modulated by the tide (Figures 9A and 9B for the period from January 5 to January 11), with lower waves during low tide. This is probably due to higher wave dissipation at the bottom when the water depth is low (Fagherazzi *et al.*, 2007). To determine the long-term effect on the marsh sediment budget, we compute the cumulative volume of water and mass of sediments that enters the channel (the integral in time of discharge and sediment flux, respectively). These results are only qualitative in nature, since residual fluxes are often of the same order of magnitude as the measurement errors associated with larger gross tidal transports (French *et al.*, 2008). In fact, the cumulative water volume stored in the marsh is not the same for a given water level (Figure 9E), thus violating water conservation. The difference can probably be ascribed to the fact that the system is not completely closed (the channel eventually connects to two shallow lakes and back to the ocean) or to approximations in the measurement of velocities. Interestingly, it appears that during wave conditions more water enters the system than expected, and is then stored in the lakes upstream or returned to the ocean through a different pathway (Figure 9E). Of more significance is the accumulation of sediment in time within the marsh. The storm surge of December 22 transported an estimated 130 tons of sediments in the marsh through the channel, but the same amount was then exported to the ocean in the subsequent ebb phase (Figure 9F). In fact the cumulative sediment flux in Figure 9(F) is identical before and after the storm surge of December 22, indicating that the net accumulation of sediments in the marsh as a result of the surge is negligible.

Instead, exceptionally low tides during fair weather and absence of waves produced a net loss of sediments to the ocean that was not recovered in subsequent tidal cycles (16 tons on December 28 and 32 tons on January 1). A series of spring tidal cycles during wave events (January 4–January 10) produced a net accumulation of sediment in the chenier plain that roughly balanced the loss during fair weather conditions. Part of this net accumulation is due to the higher estimated discharges, and should not be accounted for. In fact Figure 9(E) indicates that during this period the cumulative water volume increased in time, so that not all the water entering the marsh is then returned during the following ebb (although this result might be affected by errors in estimating cumulative water and sediment balances). Since the sediment flux is the product of water discharge and sediment concentration, a net water flux also produces a net sediment flux (more water with sediments is stored in the marsh).

Regardless of this effect, the cumulative sediment mass grew faster than the cumulative water volume. This means that water with high sediment concentration entered during flood and water with relatively low sediment concentration exited during ebb, thus producing, qualitatively, a net accumulation of sediments. It is important to note that despite the inherent errors in the measurement of residual water and sediment budgets, as pointed out also by French *et al.* (2008), the net water accumulation in the marsh at the end of the studied period was only 5% of the gross tidal fluxes. Therefore our methodology does conserve water mass in the long term with an estimated error of only 5% of the total volume of water mobilized by the tide. During the same period the net accumulation of sediments in the marsh was only 3% of the total sediment fluxes, demonstrating that the system is close to morphological equilibrium, and that only residual sediment budgets can lead to long-term accretion.

Storm surge of December 22

A detailed analysis of the December 22 storm surge reveals that at our study site and at the Calcasieu Pass both wind and waves setup increased the water elevation of several centimeters (13 cm at the Calcasieu Pass and 23 cm in our channel; the tidal measurements at the Cacasieu Pass were referenced to the average sea level at our site calculated during the entire deployment period, see Figure 10A). The maximum storm surge at 3 p.m. is delayed three hours with respect to the highest waves measured in the bay (at 1 p.m., Figure 10B). This notwithstanding, the peak in sediment concentration in the channel is reached when the flood velocity also peaks (Figures 10C and 10D). Presumably, higher velocities in the channel favor resuspension and hinder deposition, thus increasing sediment concentration. Moreover, it might take some time to resuspend sediment in the coastal area and then move it into the channel, so that we would expect the highest concentrations to occur at some time after the beginning of a wind event. During the slack water period after the storm surge, the sediment concentration decreases in the channel due to lower tidal velocities and lower waves in the bay. The following ebb was particularly intense, with an ebb velocity

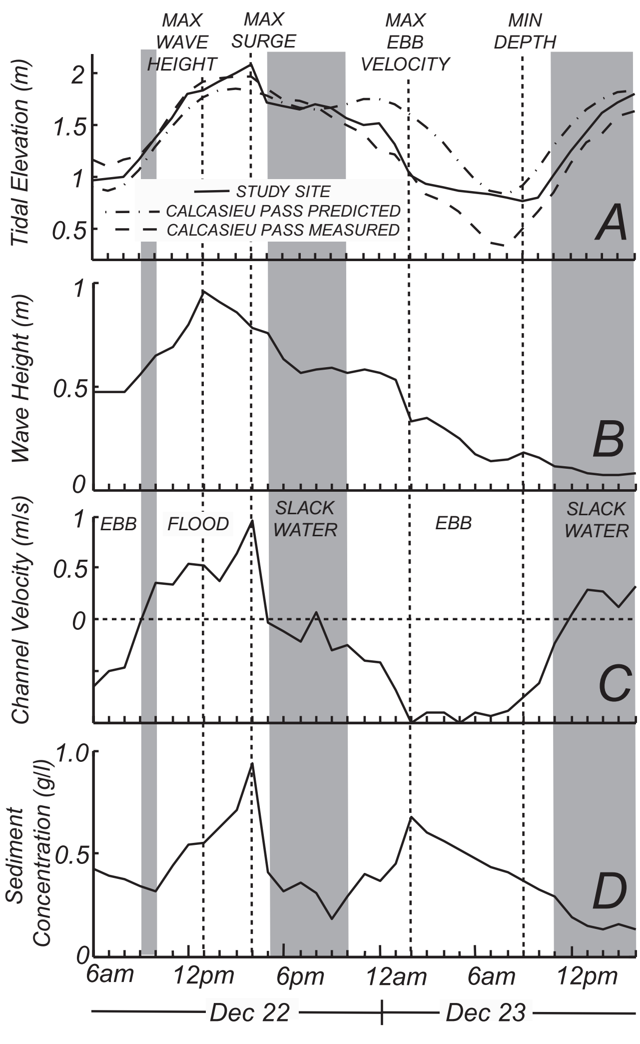

Figure 10. Detail of the December 22, 2007, storm surge: (A) tidal elevation in the channel compared to the predicted and measured tidal elevations at the Calcasieu Pass; (B) significant wave height in the bay; (C) channel velocity; (D) sediment concentration in the channel. The gray intervals denote slack water (channel velocity less than 0·3 m/s)

around 1 m/s lasting for five hours. Sediment concentration increased with ebb velocity, reaching a peak when the ebb velocity was maximum (at 2 a.m. on December 23). The higher tidal velocities probably favored sediment remobilization in the channel, and a large fraction of the sediment transported in the marsh during flood was thus returned to the ocean. After the maximum ebb velocity was attained, the sediment concentration decreased almost linearly, even though the ebb velocity remained constant at around 1 m/s. We interpret this behavior as a slow depletion of available sediment in the channel, so that most of the material is transported out of the system in the first stages of the ebb, whereas during the last stages there is not much left to be remobilized despite high tidal velocities. The sediment concentration decreased as soon as the velocity dropped in the channel after 8 a.m. on December 23. Interestingly, the water elevation during ebb in the channel did not drop as much as at the Calcasieu Pass, although the water elevations during the storm surge were similar (Figure 10A). In the six hours from 2 a.m. to 8 a.m. the velocity in the channel was close to 1 m/s and the water depth just slightly decreased. We put forward the hypothesis that during very low ebbs there is always a higher water level in the channel compared to the ocean, and that this difference is due to the draining water collected from the marsh that refills the channel. Under these conditions the gradient in water elevation dominates the temporal variations in water level, so that the tidal channel resembles a river draining the chenier plain. To test this hypothesis, we utilize a uniform flow equation to explore whether the channel velocity and the water difference between channel and bay are comparable to the tidal channel hydraulic characteristics. The Manning equation reads:

$$v = \frac{1}{n} R_H^{2/3} S^{1/2} \tag{1}$$

where n is the Manning coefficient, which we assume equal to 0·025 s/m$^{1/3}$ (typical value for earth channels with vegetation), a hydraulic radius R_H of 0·65 m from channel geometry (Figure 1). We also adopt a bottom slope S of 0·0015, assuming that the maximum difference in water level between the channel cross-section and the water level in the bay, equal to 0·47 m (Figure 9), is gradually achieved along a length scale of 300 m, comparable to the distance between the channel cross-section and the bay (see Figure 1). With these parameters we compute a channel velocity of 1·16 m/s, which is of the same order of magnitude as the measured velocity in the channel (Figure 9). Therefore, during very low tides the channel discharge is determined by friction and channel geometry, and not by tidal oscillations, thus justifying the departure from the tidal elevation in Figure 9(A). The gravity regime continues until the increasing tide produces a backwater effect in the channel, from this moment the water depth in the channel follows the tidal oscillation. Channel geometry and bottom friction limit the channel velocity during the gravity phase; as a result, during the entire period of measurements the ebb velocity never exceeded 1 m/s. It is important to note that Equation 1 is valid only for uniform flow, and cannot account for temporal variations in water surface and velocity. Therefore it can be applied only during slack water, and it cannot model the rise of the tide during flood.

The high sediment concentrations during ebb subsequent to the storm surge indicate that a large fraction of the sediments carried by the storm surge is not deposited within the marsh, but is instead released to the ocean, as already shown in Figure 8(F). Our detailed analysis also indicates that the largest sediment export to the ocean is reached as soon as the channel velocity peaks, and then dwindles in the late stages of the ebb phase. Our results clearly show that during ebb sediment concentration in the channel is affected by high tidal velocities, which in turn remobilize material and maintain it in suspension.

Low tides of January 1 and 2

On January 1 at 2 a.m. and January 2 at 5 a.m. two meteorological low tides decreased the channel depth of 0·35 m and 0·45 m with respect to the predicted tidal elevation at the Calcasieu Pass (Figure 11A). Both low tides were caused by sustained wind conditions (around 10 m/s) blowing from the north, with wave heights less than 0·1 m in the bay (Figure 8A). The first low tide followed a moderate storm surge so that the marsh had a larger volume of water (i.e. tidal prism) to be delivered to the ocean during ebb. Consequently, the ebb velocity was relatively high (0·67 m/s) peaking two hours before the minimum elevation (Figure 11B). The high velocities in the channel remobilized marsh sediments, increasing the sediment concentration in the channel (Figure 11C). The high velocities combined with resuspension produced a net export of material to the ocean (see Figure 8F). Since wind waves were negligible during the tidal cycle, a limited amount of sediment entered the channel during flood, and the sediment export during ebb was determined by the remobilization of sediments previously stored in the marsh.

The meteorological low tide persisted even during the subsequent tidal cycle, resulting in a second exceptional low water on January 2. However, this time the volume of water accumulated in the marsh during the previous flood was much less (the maximum tidal elevation on January 2 was 25 cm

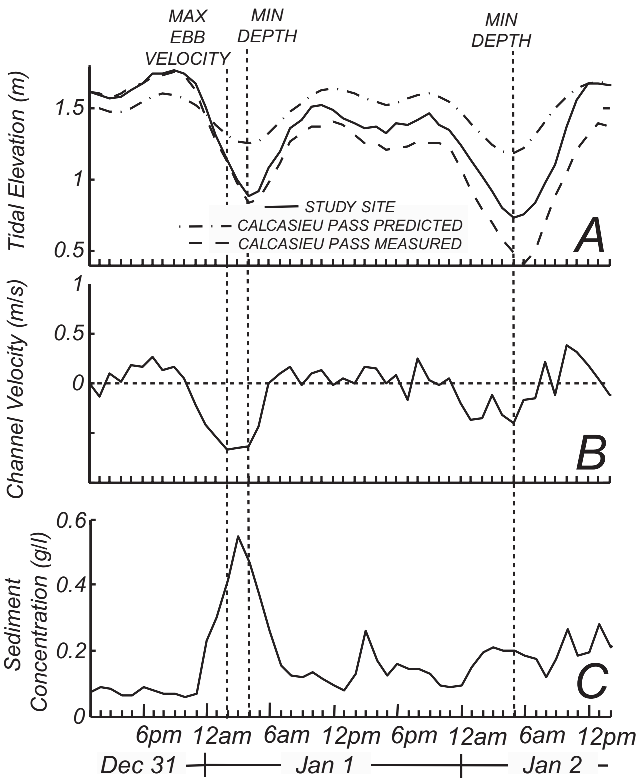

Figure 11. Detail of the January 1 and January 2, 2007, meteorological low tides: (A) tidal elevation in the channel compared to the predicted and measured tidal elevations at the Calcasieu Pass; (B) channel velocity; (C) sediment concentration in the channel.

less than January 1); therefore the reduced tidal prism did not give rise to high velocities in the channel. From a sediment budget viewpoint the second low tide, although being much lower than the first, had a limited effect (Figure 8F). Once again our data highlight the role of ebb velocities in sediment remobilization in a muddy coastline.

An important observation arises from the integration of the meteorological and sediment concentration data. Strong winds blowing from the south and southeast generate high waves and storm surges, and thus a large flux of sediments to the marsh during flood. However, the surge is often followed by an ebb phase with very high flow velocities, when the extra volume of water stored in the marsh is restituted to the ocean. Hence most of the sediments accumulated during the surge are remobilized during the following ebb, producing a limited net effect. On the contrary, strong winds from the mainland (from the north and northwest) trigger very low tides but not wave events at the shoreline. As a consequence, the net export of sediments facilitated by high ebb velocities is not compensated by an import of sediments during the flood phase, since calm conditions at the shoreline do not favor sediment resuspension. Extreme low tides therefore seem favoring a net sediment loss through channel fluxes. Finally, moderate winds from the ocean can produce wave events that are decoupled from storm surges, thus avoiding fast ebb flows and sediment export during ebb. These events seem more favorable for sediment retention and marsh accretion.

The three possible metereological conditions observed during the study are summarized in Figure 12. Moderate storms that do not trigger storm surges seem to be the most effective mechanism for sediment import to the marsh, whereas very low tides without waves lead to sediment export. It is important to note that this discussion is valid for the chenier plain studied herein, in which the marsh platform is very high in the tidal range and flooded only during spring tides.

Conclusions

The following conclusions can be derived from our measurements in a muddy coastline:

(1) Sediment fluxes in a tidal channel during flood are determined by wave climate. During storms, waves resuspend sediment in the nearshore area. These sediments are then funneled in marsh channels by the tide. Sediment concentration in the channel is linearly proportional to significant wave heights in the ocean.
(2) The rate at which water flows in the channel during flood is an important control on sediment concentration, but not as critical as the presence of waves in the nearshore zone.
(3) During ebb, the total sediment remobilization on the marsh is directly related to the tidal velocity in the channel, so that outgoing sediment fluxes increase for high tidal velocities. We found a linear relationship between sediment concentration in the channel and ebb velocity.
(4) Sediment concentration in the channel during ebb is also related to the amount of sediment entering the marsh during the previous flood, indicating that only a fraction of suspended sediment has time to settle in the marsh in a tidal cycle, whereas the remnant stays in suspension and exits during ebb.
(5) Storm surges carry large volumes of sediment to the marsh, but most of the material is returned to the ocean during the subsequent tidal cycle.
(6) On the contrary, long periods of waves, even of mild intensity and not necessary linked to storm surges, produce a net accumulation of sediments in the marsh.
(7) Meteorological low tides during fair weather conditions result in large ebb velocities which export sediments to the ocean. This sediment is not replaced in subsequent tidal cycles, giving rise to a net negative budget for the system.
(8) During very low tides the water elevation in the channel is higher than the water in the bay, since water is still exiting from the marsh. This gradient in water elevation regulates the velocity of the water in the channel, which is then gravity driven rather than tidally driven. Water discharge is thus determined by channel geometry and bottom friction, like in terrestrial streams.

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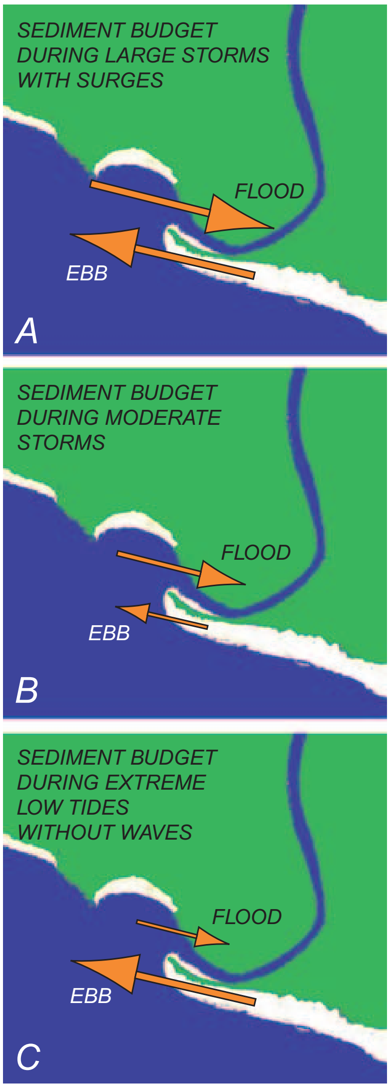

Figure 12. Sediment fluxes under different metereological conditions: (A) during large storms triggering storm surges large volumes of sediments enter the channel but then exit during ebb tide; (B) moderate storms with waves yield to net sediment input to the salt marsh (the volume of sediments entering during flood is much larger than the volume of sediments exiting during ebb); (C) extreme low tides occurring when the wind blows from the mainland lead to sediment export during ebb that is not compensated by sediment input during the subsequent flood. This figure is available in colour online at www.interscience.wiley.com/journal/espl

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