Revue Paralia, Volume 3 (2010) pp 6.17-6.31
Keywords: Intertidal mudflat, Hydrodynamics, Ridge-runnel bedforms (cross shore)

The use of altimetric data (Altus) in the characterization of hydrodynamic climates controlling hydrosedimentary processes of intertidal mudflat: the Vilaine estuary case (Brittany, France)

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Abstract:
Since the construction of the Arzal dam between 1965 and 1970, the Vilaine estuary is characterized by a strong silting up. Hydrodynamic climates could be identified as responsible for erosion or deposition at different spatio-temporal scales from bathymetrical, hydrological and altimetric (NKE-Altus) data. Each thickness of eroded or deposited sediment could be associated to a typical hydrodynamic climate. Furthermore, it was possible to show the effect of a ridge-runnel bedforms or a smooth surface on the dynamic of the intertidal mudflat.

Received 26 April 2009, accepted 1st September 2009, available online 20 December 2010.

Translated version not certified, published under the responsibility of the article authors.

How to cite the original paper:
GOUBERT E., FRENOD E., PEETERS P., THUILLIER P., VESTED H.J., BERNARD N. (2010). *Utilisation de données altimétriques (Altus) dans la caractérisation de climats hydrodynamiques contrôlant le fonctionnement hydrosédimentaire d'une vasière intertidale : cas de l'estuaire de la Vilaine (Bretagne, France).* Revue Paralia, Vol. 3, pp 6.1–6.15.
DOI:10.5150/revue-paralia.2010.006 (disponible en ligne – http://www.paralia.fr – available online)

1. Introduction

The dynamic of fine-grained sedimentation in estuarine domain is a recurrent problem for the users of estuaries.

In order to have a better management, numerous studies and numerical modellings were made to provide qualitative and quantitative knowledges on hydrosedimentological processes and solutions of development.

Some great estuaries, under fluvial control, were studied with multiproxy approach at different spatial and temporal scales to show the relative roles of the hydrodynamical, biological and morphological controlling factors: the Seine estuary, France (Seine-Ava project, DELOFFRE *et al.*, 2006; CUVILLIEZ *et al.*, 2009), the Marennes-Oléron Bay, France (BASSOULLET *et al.*, 2000), the Severn estuary, UK (KIRBY & KIRBY, 2008), the Humber estuary, UK (BLACK, 1998), comparison of different estuaries in northwest Europe (INTRMUD project, DYER *et al.*, 2000).

At the difference of the previous estuaries, the size of the Vilaine estuary is smaller and its water discharge is controlled by a dam (the Arzal dam). This dam blocks the salty waters during the rising tide. Another dam of this type was built in Mauritania, the dam of Diama (NUSCIA TAÏBI *et al.*, 2007). In the 1960s, the construction of the Arzal dam have induced an important infilling of the estuary, by modifying deeply the morphological features and the practices of the users (mussel farming, elvers, cockles, navigation). The major characteristic of the Vilaine estuary is that the sediment transport is from the bay to the internal estuary (GOUBERT, 1997).

The integrated management of the estuarine resources requires a detailed understanding of the hydrodynamical and sedimentological processes to propose planning scenarios suitable to the various constraints of the estuary. Thus, the hydrosedimentological modelling of the Vilaine estuary begun. This modelling is based on data specially acquired for this study and on available data.

This study deals with the characterization of the hydrosedimentological processes from the analysis of (1) twelve bathymetrical surveys and (2) the altimetrical monitoring (Altus©) of the northern intertidal mudflat completed with hydrodynamical parameters (tide height, significant wave height - Hs -, wind, turbidity, water discharge) from November 2007 to May 2008. The aim of this approach is the analysis of high-resolution altimetrical monitoring to define the contribution of each hydrodynamical event on the bed-level changes of intertidal mudflat to contribute to the hydrosedimentological modelling.

2. The Vilaine estuary and the Arzal dam

The Vilaine (figure 1) is 220 km long river which drains a 10000 km^2 catchment area. The Vilaine estuary opens onto the Vilaine Bay which is characterized by a maximum depth of 30 m and partially sheltered from swell by a line of islands from Quiberon to Le Croisic.

With an East-West aspect, the dynamic of the Vilaine estuary is controlled by the South-West swells, by the river discharge and by a mesotidal regime (neap tidal range = 2.5 m and spring tidal range = 5 m).

From the analysis of morphological features, the Vilaine estuary could be divided in three parts from East to West: the internal estuary with a meandriform channel, the intermediate estuary with a quasi linear channel and the external estuary with smooth shallow water depth indicated by the 2 m isobath. The limit between the intermediate and the external estuary is characterised by a muddy shallow bedform with amplitude of 10 to 40 cm. According to these morphological features, the Vilaine estuary is a transitional estuary between a wave-dominated and tidal-dominated system (DALRYMPLE and CHOI, 2007).

In the 1960s, the construction of the Arzal dam allowed to reduce the floods of the swamps of Redon. The dam at 8 km of the mouth of the estuary blocks the salty and muddy waters during the rising tide.

The superficial sediments in the study area are fine-grained sediments, with a high silty/clay content (i.e. the <45 µm fine-grained content) from 10 to 99% according to the season (GOUBERT, 1997). The fine-grained sediments are resuspended by swell, storm-waves and wind-waves, and these suspended sediments are transported from the bay to the estuary or ejected from the estuary according to the tide (LCHF, 1960-1964).

The dam has led to the reduction of the oscillating volume and the speed of the tidal currents. Thus, the turbidity maximum zone have been displaced downstream from the internal estuary to the intermediate estuary, the value of the turbidity maximum have been reduced and the rate of decantation have been increased in the intermediate estuary (LCHF, 1960-1964; MAILLOCHEAU, 1980; MERCERON, 1985; GOUBERT, 1997; LATTEUX, 2005). LE BRIS and GLEMAREC (1996) have shown that in 1985 the maximum turbidity zone was from the dam to the Strado mudflat (intermediate estuary) according to the meio-macrofaunal distribution: the Strado mudflat being colonized by cockles (*Cerastoderma edule*). Recent data on the associated distribution of cockles and benthic foraminifera allow to precise that the maximum turbidity zone is located from the Strado mudflat up to the mouth.

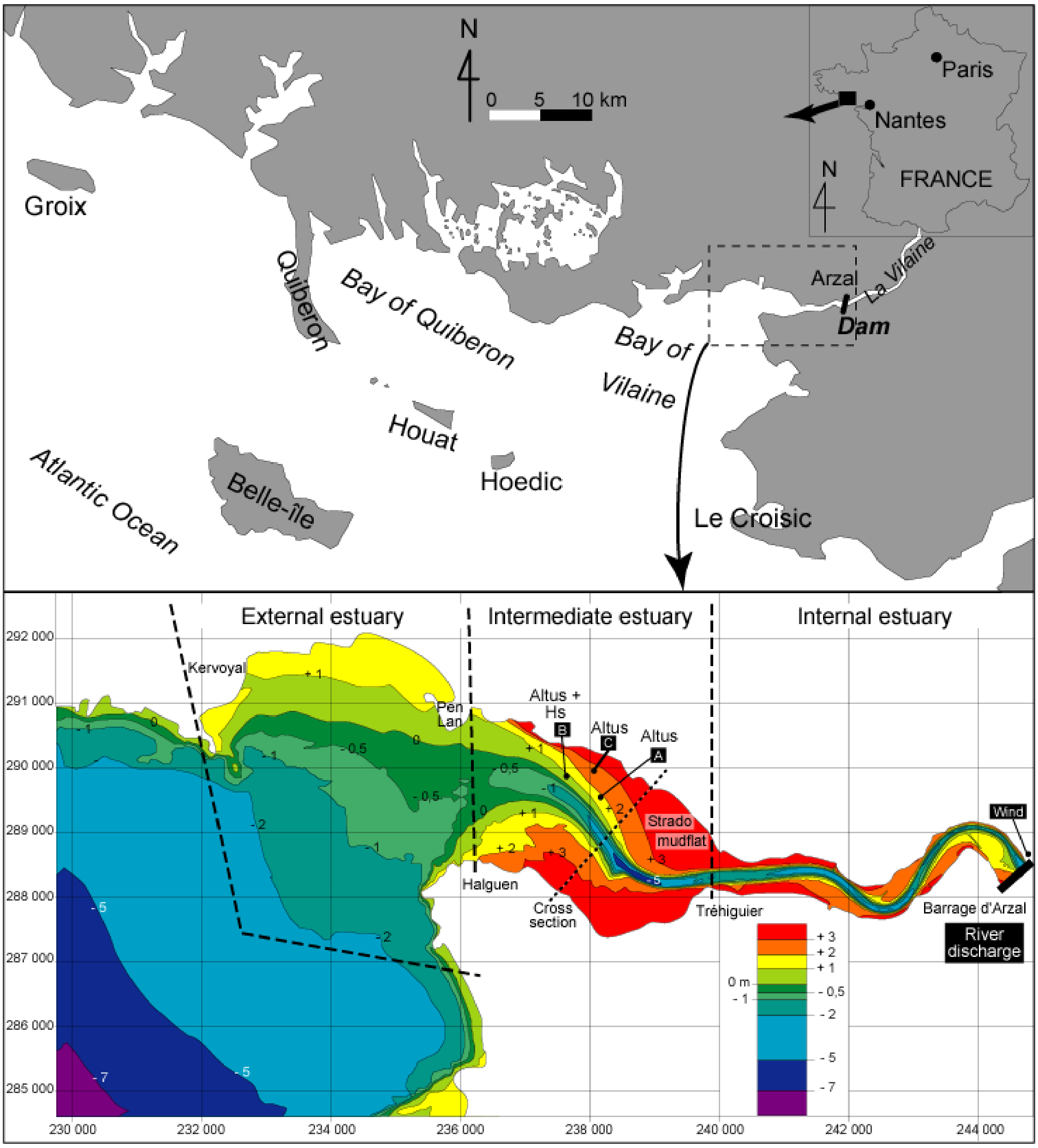

Figure 1. The Vilaine estuary: location, bathymetry of 2007 and position of the measuring stations.

3. Materials and methods

3.1 Bathymetrical data from 1820 to 2007

Twelve bathymetrical surveys are available from 1820 to 2007. Data were acquired with tallowed lead then with 200 kHz and 33 kHz sounder. Numerical maps, cross-sections, isopac maps and sedimentary balances were made with MapInfo©/Vertical Mapper© (GOUBERT & MENIER, 2005) and with MIKE-DHI©.

3.2 Altimetrical monitoring (ALTUS) and further data

Three ALTUS altimeters (JESTIN *et al.,* 1998) were deployed from Nov. 7th, 2007 to May 7th, 2008 on the northern Strado mudflat (figure 1). The ALTUS altimeter is a 2 MHz echosounder with a transducer which measures the travel time between the mudflat surface and the instrument with an accuracy of ± 2 mm. The altimeter is coupled to a pressure sensor to monitor the water heights above the mudflat. Data were recorded every 2 min for the ALTUS A and C (figure 1). The ALTUS B was programmed to calculate the significant wave heights (one measure every 0.5 second during 4 min 40 sec then stop and renewal after 15 min). After a breakdown, this ALTUS C was removed on Dec. 30th, 2007, and deployed again on Jan. 24th, 2008. Each 2 or 3 weeks, a field survey was made to describe the mudflat surface and to collect the data. The three ALTUS were set out in a 500 metres side triangular shape. This can define an upstream/downstream gradient (ALTUS A, C and B) and a cross shore gradient (ALTUS B, A and C).

Different further data were measured at the Arzal dam and used to characterize the hydrodynamical climate (figure 1): hourly water discharge (m^3 s^{-1}), average speed and wind direction upon 10 min.

4. Results and interpretations

4.1 Bathymetrical changes from 1820 to 2007

The comparison of the 1820 and 1960 surveys (LATTEUX, 2005) shows an accretion of 1 to 4 metres, with the maximum of 4 metres in the Strado mudflat. Throughout the 1960 (figure 2) - 2003 period, the sedimentary balances indicate that 16 000 000 m^3 have filled the internal and intermediate estuary in 30 years (figures 3 and 5).

From the beginning 1990s according to the flood period (January 1995), the storms (December 1999 and December 2000) and the calm period (from 2001 to 2007), 1 to 2 millions m^3 of sediments were eroded or deposited respectively in the channel or on the mudflats.

In the case of the Strado mudflat, the maximum accretion is observed in the upstream area (figure 3) and along the channel (figure 4). Between the 1960 and 2003 surveys (figures 3, 4 and 5), the accretion along the channel is of 1 m in the downstream area and of 6 to 7 m in the upstream area. Between each survey from 1992 to 2007, the Strado mudflat shows either a stable bedform during erosional periods (floods or storms) or an accretion of 40 cm during calm periods (figure 5).

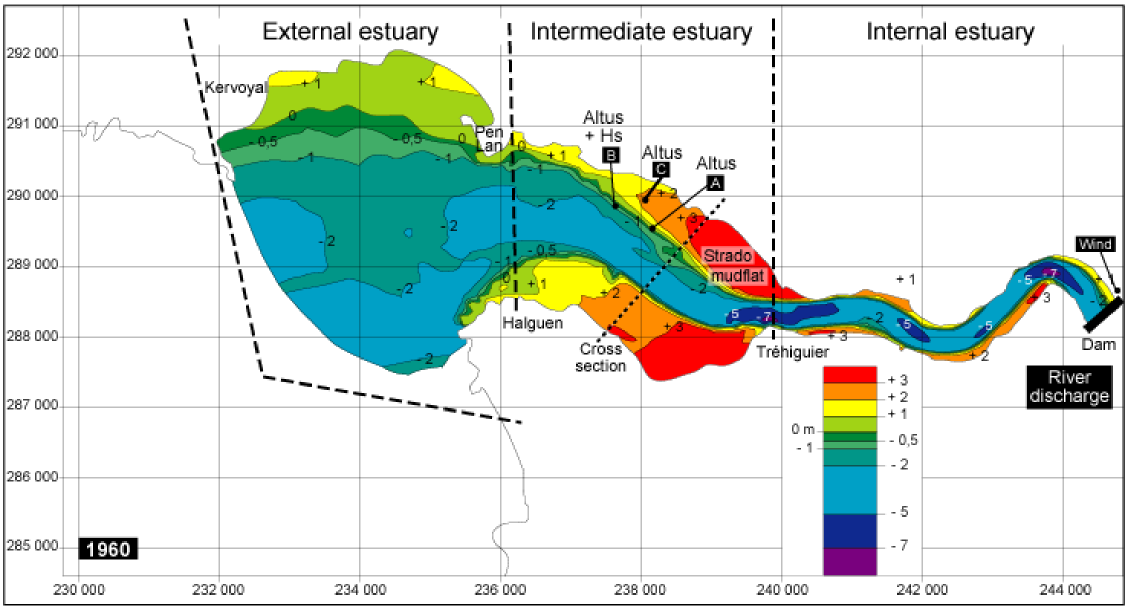

Figure 2. Bathymetrical map of 1960 (the vertical scale is the same as that of the map of 2007, figure 7).

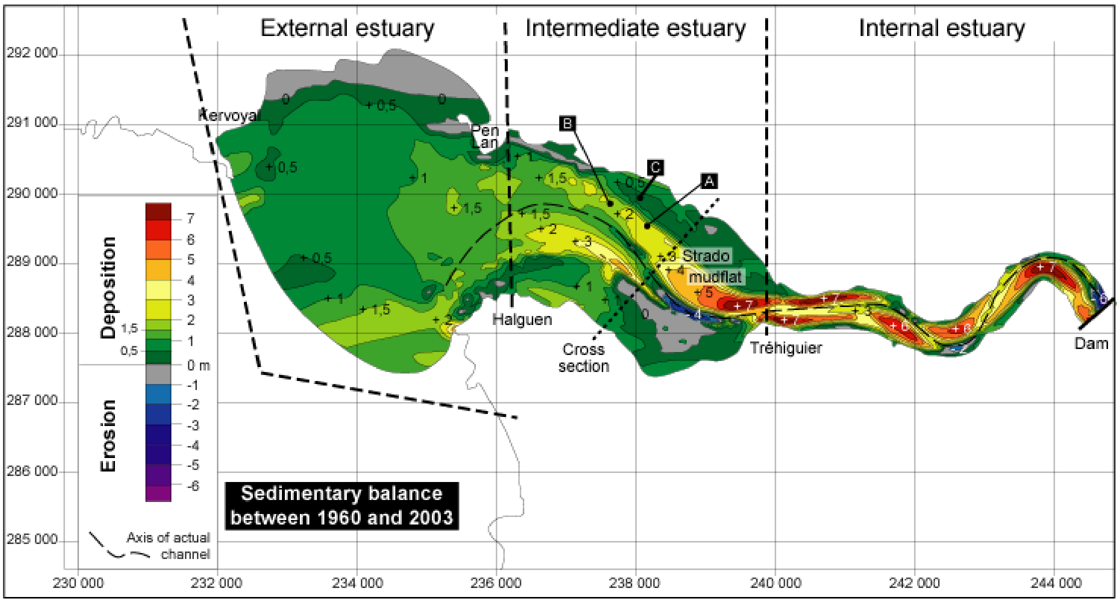

Figure 3. Sedimentary balance between 1960 and 2003.

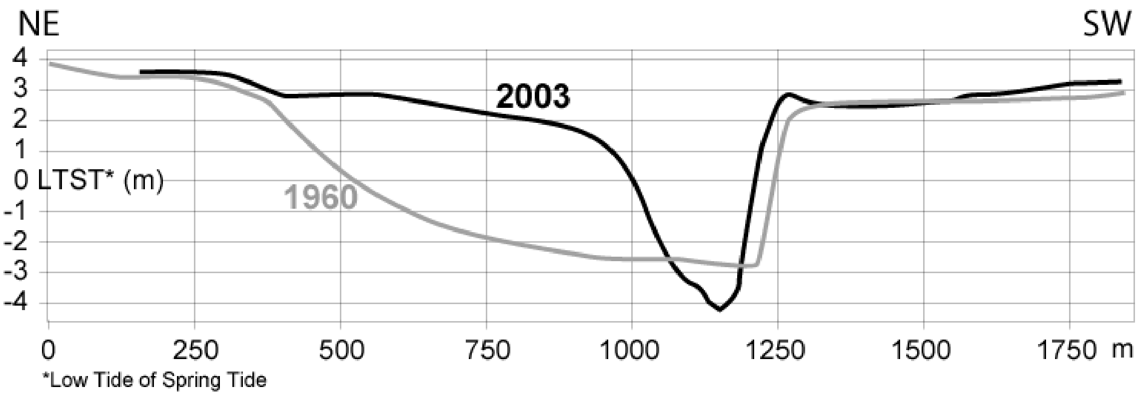

Figure 4. 1960 and 2003 cross-sections of the Strado mudflat (cross-sections located on figures 1 and 2).

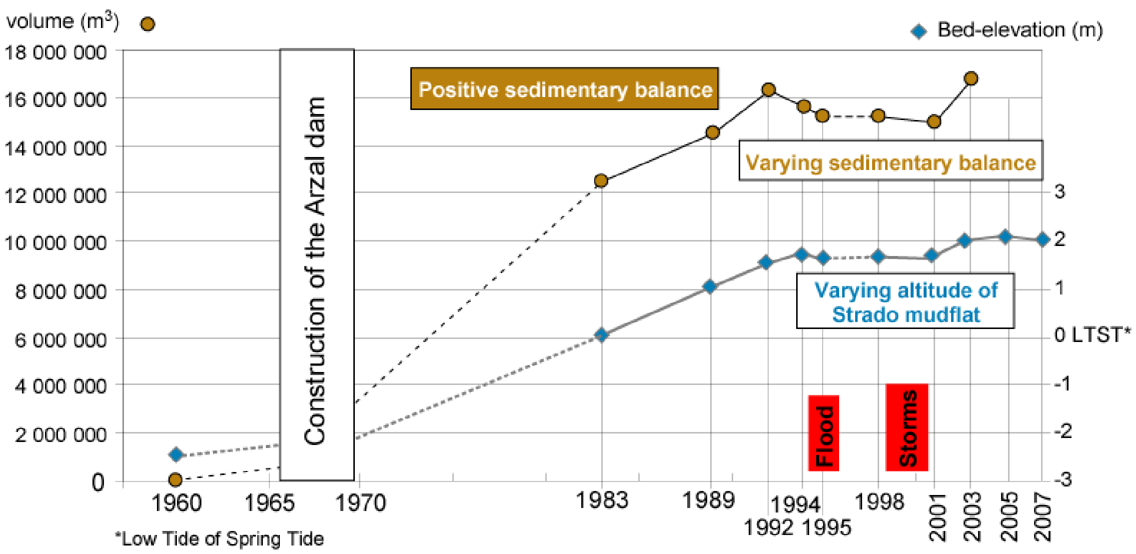

Figure 5. Changes of sedimentary balances for the internal and intermediate estuary (ERAMM-RIVAGES, 1995 and GOUBERT & MENIER, 2005) and changes of bed-elevation of the Strado mudflat.

The previous data acquired before the dam construction show that the Vilaine estuary was an active sedimentological environment with a sedimentation rate of 4 m in 140 years on the Strado mudflat. Since the dam construction, the Strado mudflat is characterized by a maximum accretion of 5 to 7 m in upstream in 40 years.

Since about 1990, the Vilaine estuary reached a balanced morphodynamic with erosion periods due to floods or storms. On the other hand, the Strado mudflat characterized by a variable accretion still shows an available space for sedimentation in the estuary. Thus, it is very important to quantify the morphological changes related to the hydrodynamical climate.

4.2 Evolution of the Strado intertidal mudflat from November 7th, 2007 to May 7th, 2008: bed-elevation, surface and hydrodynamical climates

After a relatively stable period (from November 8th to November 30th), the entire area is characterized by an intense erosional phase from December 1st to December 12th (figure 6a). This erosional phase is the result of three gusts of west wind (figure 6c), of 20 m s^{-1}, 18 m s^{-1} and 23 m s^{-1} successively which have induced Hs (figure 6b) of 40 cm, 30 cm and 50 cm, respectively. The proximal mudflat (ALTUS C) is the most affected with an erosion of 10 cm, when the two others ALTUS A and B, closer to the channel have only recorded an erosion of 6 cm.

After this first erosional period, the fragmentary data of the edge of channel (ALTUS B) show a trend to accretion with a deposit of about 20 cm until May 7th. Thus, during these 6 months, the edge of channel (ALTUS B) is characterized by accretion of 16 cm, with a maximum deposition of 24 cm from Dec. 11th, 2007 to April 15th, 2008.

After this first erosional period, the data of the two others ALTUS have changed in the same way or in the opposite way according to their geographical locations and to the hydrodynamical conditions. After Dec. 10th, a depositional phase begins by few days without changes, probably due to the important river discharges (figure 6d). Later on, the decantation of the suspended matter begins with the decreasing river discharges and the decrease of the tidal amplitude.

This decantation is interrupted at the end of December by two gusts of west and south wind leading to an erosional episode. The particularity of this episode is that the surface of the intertidal mudflat appeared with ridge and runnel system (RRS). This bedform is characterized by parallel and symmetric ridges and runnels, 30 to 50 cm wide and 10 to 20 cm deep and with an orientation perpendicular to the isobathic lines and separated from the network of the superficial run-off (GOULEAU *et al.*, 2000; WHITEHOUSE *et al.*, 2000; WILLIAMS *et al.*, 2008; CARLING *et al.*, 2009).

At the end of this erosional episode, the ALTUS A was above a runnel and the ALTUS C above a ridge. From January 2008, a succession of gusts of south to west wind leads to an overall erosion of the mudflat, with an erosion/deposition alternation of fluid mud in the runnels (ALTUS A) and a slight erosion of the top of the ridges (ALTUS C). In the same time, the edge of channel (ALTUS A) which is not reached by RRS has recorded a deposit of fluid mud of 6 cm. This period (January 2008) characterized by sustained west winds and by high river discharges ends with a double gust of west wind at the beginning of February leading to an erosional episode. The ridge and runnel system RRS disappears during this erosional period and it is replaced by a plane surface. Afterwards, the winds have shifted to the east and the suspended matters settle down on all the studied area at the beginning of February during a spring-neap tide cycle. From February 28th to March 9th, the RRS appears again but at a superior altitude than the RRS of December. This RRS is erased by the storm of March 10th, 2008 (west wind of 25 m s^{-1}) which has eroded the mudflat of 6 to 8 cm. Finally, from March 13th

to April 2nd, the same hydrodynamical conditions that in January: series of gusts of northwest to southwest winds with a medium speed. The altitude of the mudflat decreases with a cyclic succession of erosion (2 to 3 cm) during gusts and accretion (1 to 2 cm) of fluid mud during calm days. This episode occurs on a plane mudflat (ALTUS A and C record similar changes) unlike January with a RRS (ALTUS A and C record opposite changes).
From April 3rd to 29th, all three ALTUS show a trend to deposit interrupted by two erosional phases due to two moderate gusts of west wind.
April is characterized by less numerous and less strong gusts of west wind than in March. Thus, the length of gusts of east wind progressively increases. This change of hydrodynamical climate induces a slight trend to accretion. This depositional trend is interrupted by a gust of west wind of 14 to 16 m s^{-1} from April 28th to 30th. All three ALTUS have recorded an erosion of 4 to 7 cm.
The erosional periods highlighted in grey on figure 6 are associated to storms and gusts of west winds. The length and intensity of the erosional periods seem to be increased when the west winds occur during a wet event with strong river discharges. At the opposite, when the gusts occur with no strong discharge, the length and intensity of erosional events are weak (i.e. the gusts of March 16th and 22th).

5. Discussion

The altimetrical survey by ALTUS systems and the description of the intertidal mudflat surface allow to quantify deposits and erosion during a windy winter period: storms and gusts with speed superior to 10 m s^{-1} have occurred 6.3% of time compared with 2.7% for an average winter. The relationships between wind, significant wave height and the sedimentary dynamic have been identified.
For each gust of west wind with speed superior to 10 m s^{-1} whatever the other hydrodynamical conditions, the Hs are superior to 20 cm and lead to an erosion event. The scale of this erosion depends on the wind speed, the tide, the river discharge and the bedform of the intertidal mudflat (figure 7). In the case of neap-spring tide cycle, the suspended matter will slowly settle or will be transported outside the mudflat. If the river flow is high, the suspended matter will be transported outside of the estuary.
At the opposite, during east winds or slow west wind, the Hs are low (Hs<20 cm) and the trend is to accretion of the entire intertidal mudflat (figure 7).
In both cases, the length and the intensity of erosional/depositional event are controled by the tide and the river regime. A periode from a neap tide to a spring tide or high river regim leads to an increasing of erosional rate. At the opposite a periode from a spring tide to a neap tide or low river regime leads to a low rate of erosion (figure 7).

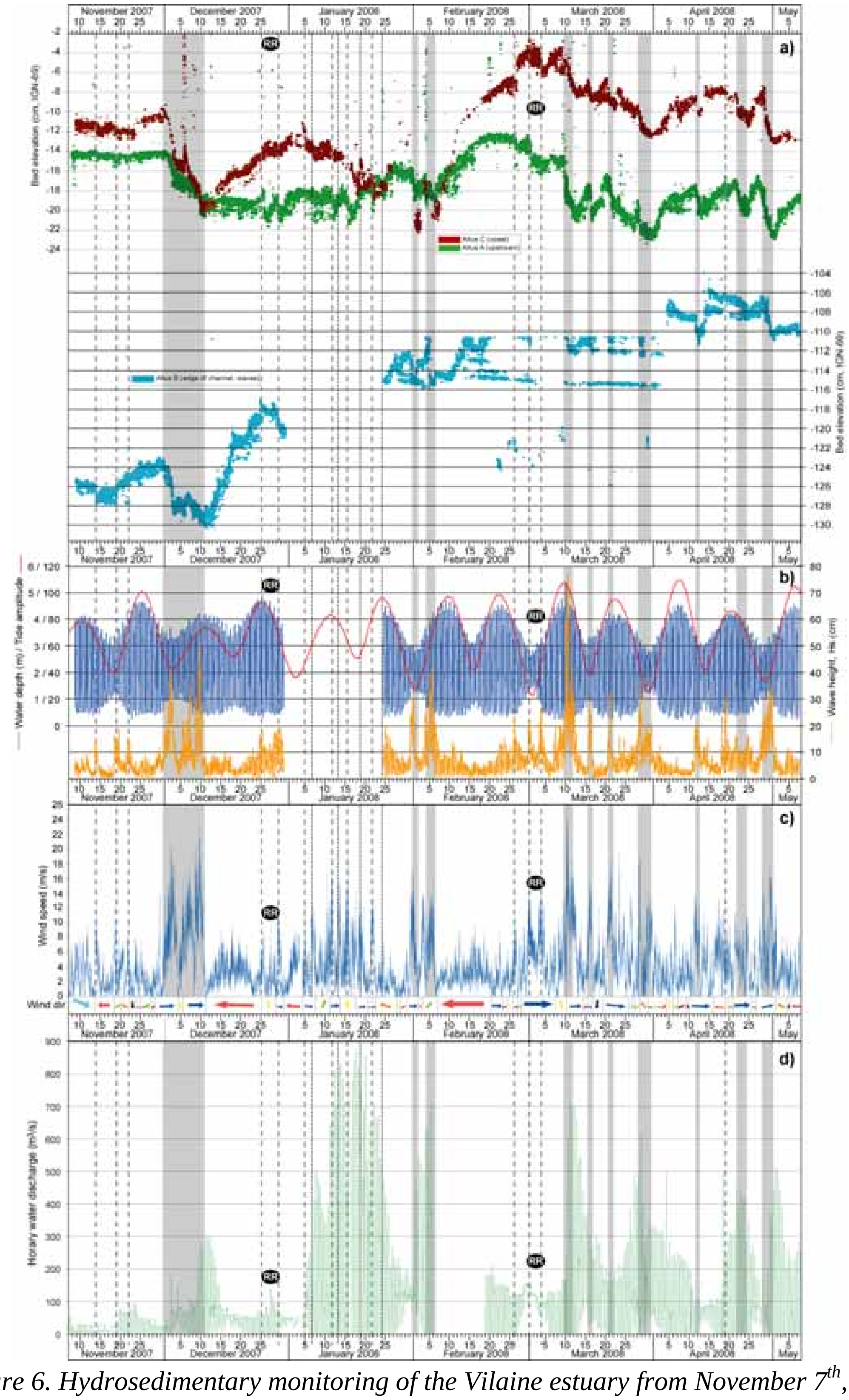

Figure 6. Hydrosedimentary monitoring of the Vilaine estuary from November 7th, 2007 to May 7th, 2008. (grey background: erosional phase; RR: ridges and runnels).

Moreover, the new appearance of the mudflat is different according to the previous state: smooth surface or ridge-runnels bedforms (figure 7). Thus, the same hydrodynamic conditions can lead to a different appearance according to the morphological past of the mudflat.
The major control of the wind is observed in the case of estuaries with the same geographical scale than the Vilaine estuary (the Têt estuary, SW Gulf of Lions, France, GUILLÉN *et al.* 2006), when in others estuaries, river regimes or tidal currents are dominant (The Authie and Seine estuaries, France, DELOFFRE *et al.*, 2007).
During the studied period, the intertidal mudflat of the Vilaine estuary have been eroded of 6 to 11 cm during the first strom (December) and of 4 to 6 cm during the second strom of March.

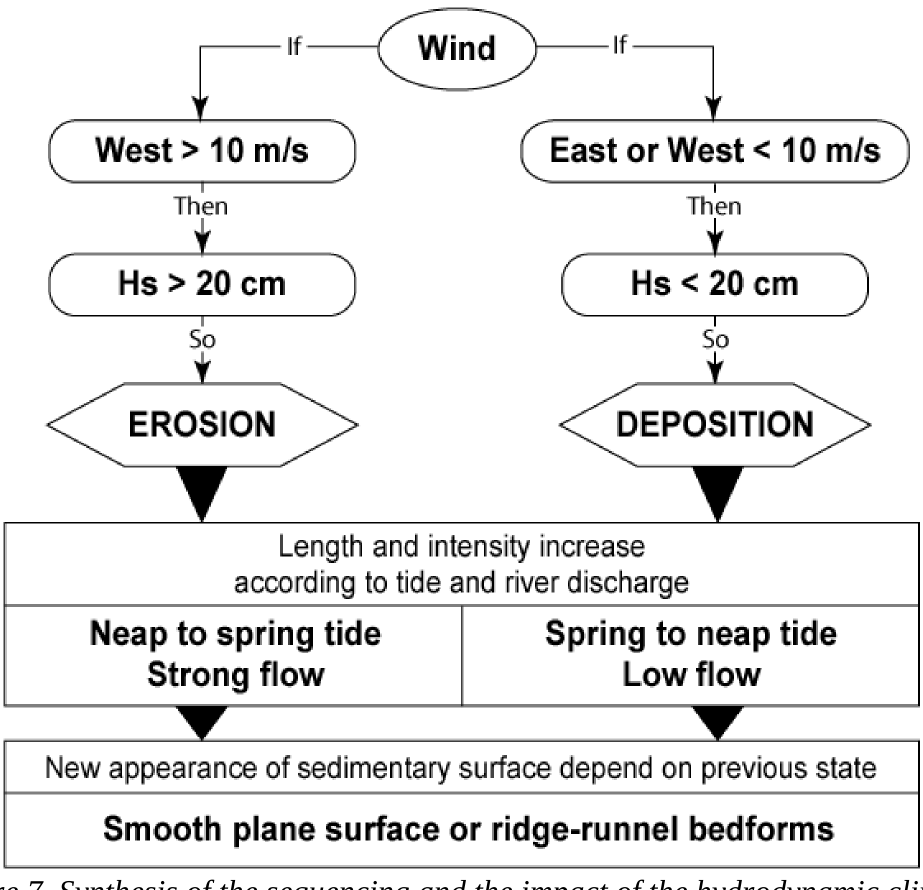

Figure 7. Synthesis of the sequencing and the impact of the hydrodynamic climates onthe altitude of the intertidal mudflats in the estuary of the Vilaine.

The sedimentation rates have reached 26 cm in 4 months for the ALTUS B and 16 cm in one month (February) for the ALTUS C. These rates are superior to those observed in Marennes-Oléron Bay, France (BASSOULLET *et al.*, 2000). On the other hand, the

Vilaine and the Seine estuaries (DELOFFRE *et al.*, 2006) have a similar sedimentation rate even though the Seine estuary is characterized by specifical features: the high silt/sand content, the large dimensions and the high hydrodynamic conditions.
The ridge and runnel system (RRS) seems to be an important sedimentological factor to understand the morphodynamic of the intertidal mudflat of the Vilaine estuary. This RRS appears and disappears according to the erosion and the altitude of the mudflat. Thus, the RRS can appear from a smoothh surface during high hydrodynamic conditions (late December 2007 and early March 2008). Or, similar hydrodynamic conditions can remove the RRS (early February 2008 and late March 2008).
According to previous studies (GOULEAU *et al*., 2000; WHITEHOUSE *et al*., 2000; WILLIAMS *et al.*, 2008 ; CARLING *et al.*, 2009), the RRS is well-considered as an important factor in the dynamic of intertidal mudflats, but no successive appearance/disappearance phases have been observed. In the case of the Vilaine estuary, an erosional or depositional period is able to induce a reactivation or a creation of RRS.
The study of the bathymetrical data of the Vilaine estuary show that the sedimentological processes have led to a morphodynamic equilibrium. In the detail, the study of the northern mudflat show that sedimentation space is available. Thus, the aggradation of the northern mudflat leads to progradation of the Strado mudflat to the channel. In the mouth, the channel width and depth could still reduce and increase the difficulties for navigation.

6. Conclusion

The construction of the Arzal dam by blocking the rise of salty water into the estuary of the Vilaine, which sedimentary dynamic was already very active locally, has accentuated the rate of estuary infilling until the early 1990’s. Since, the trend still seems to be infilling, but with a lower rate.
Altimetry data acquired on the northern intertidal mudflat (Strado) and hydrological data allowed to highlight the factors controlling sedimentation. Conjunctions of hydrodynamic conditions could be associated with erosion/deposition phases, providing information to calibrate and validate the hydrosedimentary numerical model of the Vilaine in the case of hydrodynamic specific scenarios (conjunctions of wind/Hs/flow/tide, smooth intertidal mudflat, ridges and runnels system, fluid mud layer). The morphosedimentary dynamic of the Vilaine Estuary is therefore strongly controlled by the wind. The control by the flow seems to be either the increasing of the effect of wind and associated Hs (erosion or deposition), or the slowing or stopping of the settling of suspended matters. Currently available data do not say whether the effect of flow may oppose the effect of wind.
This first study with altimetry data during the six winter months can be supplemented by an analysis of data at high temporal resolution to better understand the sequence of events: wind, Hs, behavior the surface of the mudflat during erosion, according to the

flow and the tide. The focus could be on the chronology of a erosional phase, according to the opening of the dam and the flows generated. This analysis could be useful to the managers of the Arzal dam to better take into account the consequences of the opening of the dam on the hydromorphodynamic of the Vilaine estuary.

Acknowlegements

This work was supported by a convention between the "Institution d'Aménagement de la Vilaine", the "Danish Hydraulic Institut" and the université de Bretagne Sud. We thank Herve Jestin, Philippe Bassoullet and Pierre Le Hir for their valuable advice on Altus and for the availability of these devices.

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