Evaluation of the recent morphological evolution of the Gironde estuary through the use of some preliminary synthetic indicators

Aldo Sottolichio†, Vincent Hanquiez†, Helene Périnotto†, Laurie Sabouraud†, Olivier Weber†

†Universite Bordeaux 1,
EPOC Laboratory, UMR CNRS 5805,
avenue des Facultes,
33405 Talence - France
a.sottolichio@epoc.u-bordeaux1.fr

www.cerf-jcr.org

www.JCRonline.org

ABSTRACT

Sottolichio, A., Hanquiez, V., Périnotto, H., Sabouraud, L. and Weber, O., 2013. Evaluation of the recent morphological evolution of the Gironde estuary through the use of some preliminary synthetic indicators. *In:* Conley, D.C., Masselink, G., Russell, P.E. and O'Hare, T.J. (eds.), *Proceedings 12th International Coastal Symposium* (Plymouth, England), *Journal of Coastal Research*, Special Issue No. 65, pp. 1224-1229, ISSN 0749-0208.

Drastic evolution of the physical coastal environment are expected in the future under the effect of climate change. They make necessary to better understand the past morphology evolution, especially considering areas that are the habitat for some specific ecosystems. Moreover, because the context of the water framework directive (WFD), EU members need to generate indicators to evaluate the status of estuarine water masses. To satisfy these two obectives, the recent evolution of the Gironde estuary has been studied by the analysis of bathymetry with GIS. The Gironde is the largest estuary of western Europe, and one of the most turbid. In this study, the analysis extents from 1962 to 1994. Results show that the zone of maximum volume of deposited sediment has migrated continuously towards the upstream portion of the estuary, which is coherent with the decrease of summer river flow and the upstream shift of the turbidity maximum toward the riverine sections. In addition, zones with relative stable and unstable morphology were identified, showing rythmic distribution similarly to those previously recognized through the evolution over 160 years (1825-1984). This seems to be independent from the fluvial regime, but rather related to the interaction between tidal co-oscillations and estuarine morphology, which is not elucidated yet. Finally, some hydro-morpho-sediemntary (HMS) indicators useful to the WFD have been described : distribution of depths, changes on cross section areas, changes of intertidal areas. They are discussed to discriminate the "natural" and "anthropogenic" contribution to morphological changes observed.

ADDITIONAL INDEX WORDS: *bathymetry, DEM, sedimentary evolution, macrotidal estuary, long-term changes*

INTRODUCTION

Drastic changes of the physical coastal environment are expected in the future under the effect of climate change. They make necessary to better understand its morphology evolution, especially considering that these areas are the habitat for specific ecosystems. Understanding the past evolution of the systems is then an essential step to identify trends and achieve understanding of ecosystem trajectories. Estuaries are complex systems under constant evolution, where habitats are submitted to natural and anthropogenic pressures. Human interventions such as channel dredging, sand excavation, embakment and land reclamation cause significant changes in bathymetry, hydraulic regime and sediment transport patterns (Talke *et al.*, 2009; Juang *et al.*, 2011; Wang *et al.*, 2010).

Moreover, in the case of european estuaries, the context of the water framework directive (WFD) implies that a good ecological status must be achieved in 2020. This is conditioned by a good hydromorphological status. To evaluate this, EU members need to generate pratical indicators to describe and evaluate the status of water masses. Estuarine waters are part of the transitional waters that are needed to be evaluated. The indicators are still under development, in particular those concerning the hydro-morpho-sedimentary (HMS) functioning of large turbid estuaries. The recent French project LITEAU-BEEST (2008-2011) focused on the definition on primary synthetic indicators that can be useful to define the ecological status of an estuary (Le Hir *et al.*, 2011). This implies a good knowledge not only on the physical processes in estuaries, but also on the affinity of biological species with parameters of the estuary (Sottolichio *et al.*, 2011).

The main french estuaries (Seine, Loire and Gironde) are also the largest and present high levels of turbidity. In the Seine and the Loire estuaries, secular evolution was drastic because there have been intense civil engineering works during the XXth century (see for instance Lesourd *et al.*, 2001). The Gironde estuary, SW France, is the largest estuary of the west Atlantic coast, and also one of the most deeply investigated by numerous sedimentological studies in the past decades (Nichols and Biggs, 1985). Because engineering works were much less intense in the Gironde than in the Seine and in the Loire estuaries, it has been assumed that the Gironde estuary has experienced nonsignificant changes. However, and maybe for this reason, very few studies are available on the recent morphological evolution of the Gironde

DOI: 10.2112/SI65-207.1 received 07 December 2012; accepted 06 March 2013.

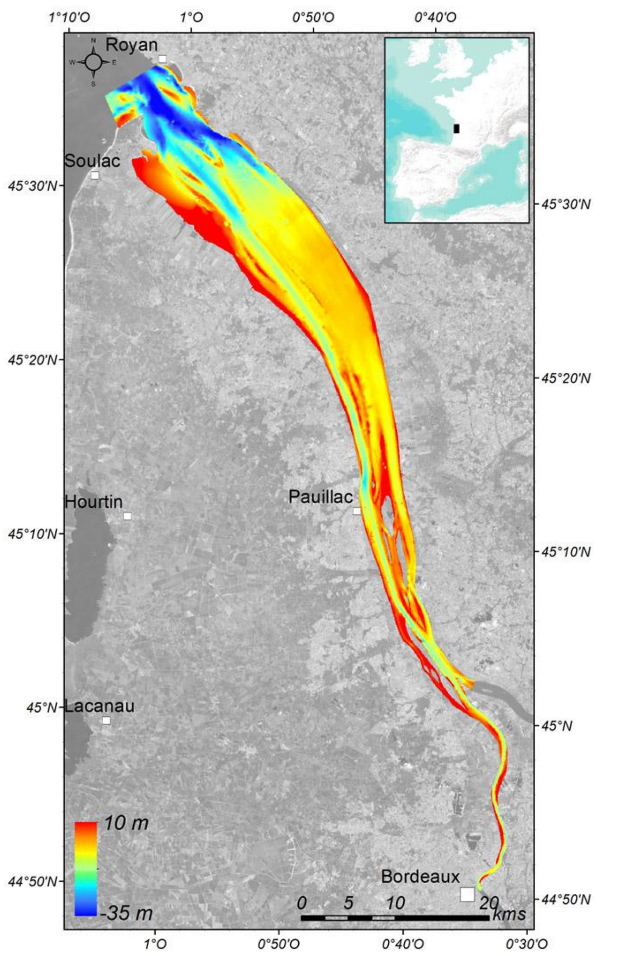

Figure 1. Location of the Gironde estuary and interpolated bathymetry for year 1994.

estuary. The last exhaustive review of the historical changes was published by Migniot (1971), who described in detail changes in channels and harbours, but with no direct correlation with forcings. Castaing (1989) investigated long term trends, but he focused in the secular evolution, and there is poor knowledge on later evolution covering recent decades. More recently, most of the reference studies have focused on fine sediment processes and turbidity maximum dynamics at tidal and seasonal scales (Allen *et al.*, 1980; Castaing and Allen, 1981; Sottolichio *et al.*, 2001 among others).

In this study we collected some available bathymetries to analyse changes at the scale of the last 50 years. Objectives are twofold; the first aim is to give a first overview and discuss on recent trends of the estuary. The second one is to describe some synthetic indicators that can be used to evaluate the HMS status in order to ensure a good ecological status of the estuary. This is a preliminary step before a detailed investigation on changes on physical settings in the Gironde estuary.

METHODS

General settings of the Gironde estuary

The Gironde estuary is formed by the junction of the Garonne and Dordogne rivers, in the south-western France of the Aquitaine coast (Figure 1). It forms a funnel-shape estuary, with a length of 75 km between the junction and the mouth, and a total surface of 635 km^2. A recent work from Billy *et al.* (2012) described the morphology as a tripartite zonation (Darlymple *et al.*, 1992), comprising from upstream to downstream: (1) a fluvially sourced bay-head delta that consists of estuarine meandering channels and tidal bars deposited in the estuary funnel (actually the riverine portion formed by the Garonne and Dordogne rivers), (2) a wide central basin filled with muddy sediments, centered at around Pauillac, and (3) an estuary mouth with a deeply scoured tidal inlet terminating landward and seaward in sandy flood and ebb deltas in front of Royan. In the estuary, tides are semi-diurnal; because of the variation of the tidal range, the estuary is macrotidal and hypersynchronous, with tidal amplitudes ranging from 1.3 to 5 m at Royan and from 3 to 6 m at Bordeaux (Figure 1). The tidal wave propagates up to 160 km from the estuary mouth and the tidal currents are characterized by a landward-increasing time–velocity asymmetry, which results in longer and weaker ebb currents and shorter and stronger floods currents (Allen *et al.*, 1980). One of the main consequences of tidal circulation is the existence of a highly concentrated turbidity maximum, which is a source of high siltation rate on the bottom (Allen *et al.*, 1980).

Bathymetry data and processing

Bathymetric charts used in this study come from the Bordeaux Harbour Authority (GPMB). From 1950 to 1973, bathymetric surveys covering the entire estuary were made almost regularly every year. Since 1974, surveys are made at irregular intervals, and entire covers are possible only by merging surveys of two or three consecutive years. In this study we used four bathymetric situations representative of four different periods over the last decades: 1962, 1970, 1980 and 1994. For the four periods we verified that the data cover the same area. The last available bathymetry (from year 2000) is not presented here because of uncertainties of the data. In this study, the region covered corresponds to zones (2) and (3) decribed by Billy *et al.* (2012). In the riverine portion, data are available only in a short sector of the Garonne comprised between Bordeaux and the confluence of Ambes (25 km length).

For each situation, the data has been taken from printed maps at the scale of 1/10 000, containing single depths and isobaths. Data were processed with ArcGIS10. To gain time, isobaths were digitised and indexed, and then converted in points with an equidistance of 50 m. The interpolation method used was the natural neighbor interpolation. Comparative tests performed with other frequently used methods such as krigging or Inverse Distance Weighted (IDW) showed that the natural neighbor is the only one that does not create any artefact or tendency between raw data (no artificial shoals or sills and no depression, contrary to other). The obtained morphology was considered as satisfactory because it was close to the natural estuarine morphology, made of channels and flats. A grid cell of 50 m was chosen considering the averaged distance between the digitised points. Interpolation values were compared with digitised points at the same geographic coordinates. Mean error was found to be equal to 0.6 cm, 0.8 cm, 1.6 cm and 1.1 cm for maps of 1962, 1970, 1980 and 1994 respectively, which is considered as satisfactory level of precision.

Finally, it has to be noted that since the Harbour Authority aims to ensure navigation, only channel areas were carefully surveyed There was sparse accurate measurements above the lowest water levels and near the banks; information of the intertidal areas were

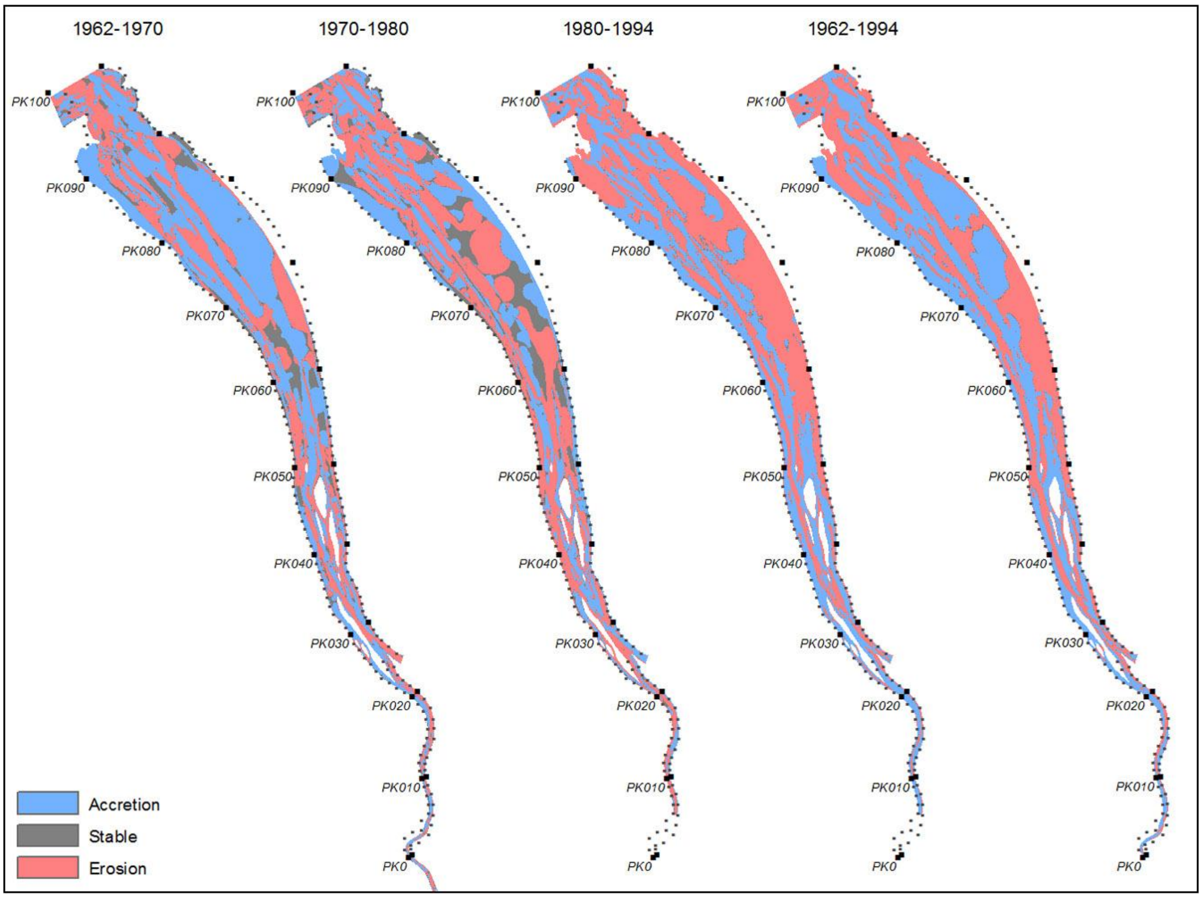

Figure 2. Sediment budget in the Gironde estuary for the three time intervals considered: 1962-1970, 1970-1980, 1980-1994, and global budget 1962-1994. PKs are reference points in km downstream from Bordeaux (PK 0).

therefore more limited. The horizontal intertidal surface was estimated by a simple interpolation between the 0 isobath and the coastline. These results are presented and commented in the next section.

RESULTS

Bathymetry and morphology changes

Figure 1 shows an example of interpolated bathymetry obtained for year 1994. In the estuary, the deepest areas are in the navigation channel, which extends near the left bank from Bordeaux to Soulac, with averaged maximum depth of 8m. At the mouth, depth increases significantly to more than 20 m, and a secondary channel appears near the right bank. Wide shoals develop in the eastern part, lower estuary. In general, intertidal areas are reduced, with the exception of the lower estuary, left bank. Comparison of bathymetries obtained for the four considered periods give a total budget which is illustrated in figure 2. For more clarity, the budget is showed only in terms of accretion and erosion. It can be seen that the lower estuary in general experiences accretion between 1962 and 1970, but shows erosional patterns in the later periods. The whole period 1962-1994 shows residual erosion of the shoals of the lower estuary and of the navigation channel. Evaluation of trends by sections every km (data not shown) revealed that the maximum accretion rate shifted progressively upstream estuary. For the period 1962-1970 maximum accretion is near PK 70; for the period 1970-1980 it is located at PK 54 and for the period 1980-1994 it is situated at PK 30. As a global sedimentary budget, it has been found that the period 1962-1970 experienced gain of about 40 km^3 of sediment, showing net siltation. The period 1970-1980 shows an inverse trend, with a total loss of about 17 km^3 of sediment, leading to global erosion. The final period of 1980-1994 has a similar trend, with a net loss of 60 km^3. This corresponds to an average erosion of 12 cm in the estuary.

Preliminary synthetic indicators

Here we present two preliminary indicators proposed by the LITEAU-BEEST project. The first is the distribution of surfaces by classes of depth, which can be easily obtained from the interpolated digital elevation models (DEM). The interest of this indicator is that it can readely indicate if the estuary is in global deepening or siltation. Figure 3 shows that the dominant depth in the Gironde estuary is the value comprised between -4 and -2 m (centered at -3 m). The peak value occupies a surface of 80 km^2. A secondary mode is found at the depths around 0 (very shallow depths and intertidal zones), which represent an area of 40 to 50 km^2. The comparison of the four considered periods shows that changes are weak and difficult to identify clearly. However, looking to the values of the extreme years (1962 and 1994) allows to see that, in the overall period, the surfaces of depths comprised between -5 and -3 m and between -1 to 1 m have decreased, while the surface of depth centered at -7 m increased. In other terms, the estuary seems to have experienced slight deepening (increasing of

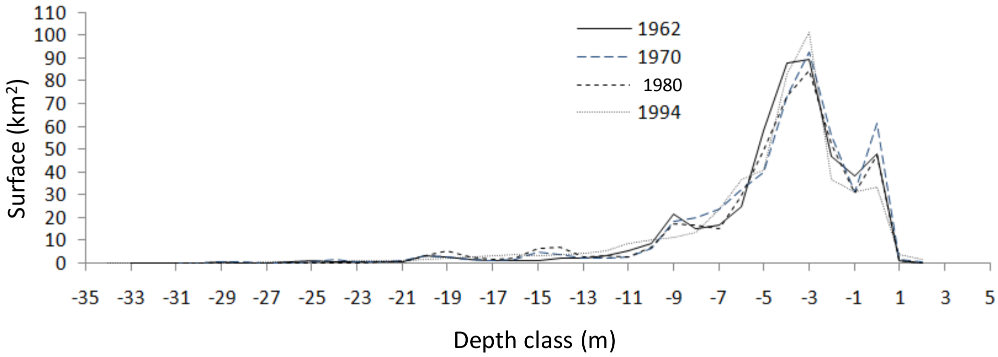

Figure 3. Distribution of surface per class of depths in the Gironde estuary, derived from interpolated bathymetries of 1962, 1970, 1980 and 1994.

depths corresponding to the navigation channel), with a simultaneous loss of moderate and shallow depths.

A second indicator proposed in the LITEAU-BEEST project is the surface of the intertidal zones. From the point of view of the ecological status, changes on the horizontal extent are as relevant as changes on depths and volumes, because the surface area can be directly linked to the space available for the development of benthic communities. As explained in the Methdods section, to obtain the horizontal intertidal surface, a simple interpolation was done between the 0 isobath and the coastline. The calculated areas are considered by longitudinal portion of the estuary (Figure 4). The total area is much larger than that considered in Figure 3. As expected, the largest intertidal areas are in the lower estuary, at the level of the widest sections (between km 70 and 90), where they represent an area comprised between 15 and 25 km^2. Upstream, intertidal areas are very narrow, with a relative increase between km 40 and 50 because of the presence of many islands and sandbanks in this zone (Billy *et al.*, 2012). Time variations of intertidal areas are weak and do not seem to show significant trend. Between 1962 and 1970 some longitudinal sections experience increase (PKs 0 to 10, 20 to 30, 30 to 40, 70 to 80 and 90 to 100) while others show a decrease of intertidal areas (PKs 10 to 20, 40 to 50, 50 to 60, 80 to 90). From 1970 to 1994, an increase is observed in all the sections, except for sections 60 to 70 and 90 to 100 which remain unchanged. Considering the whole period 1962-1994, the zones corresponding to km 40 to 50 and 80 to 90 show apparent slight loss in the surface area, while the others show a increase of the surface. The most significant gain of the total period is observed between km 70 and 80.

DISCUSSION

Causes of the observed changes

At this stage of the study, observations are still qualitative. However, the trends suggested by the bathymetry are coherent with the natural evolution observed in the Gironde through other investigations. Several recent studies (David *et al.*, 2005; Etcheber *et al.*, 2011) have reported a long term change in the fluvial regime. A major phenomenon is the longer duration of the dry season, with subsequent effects on salinity intrusion and turbidity maximum. Recent turbidity monitoring compared with some historical data (Sottolichio *et al.*, 2011b) showed turbidity has increased significantly in the last years, with more frequent presence of the turbidity maximum in the tidal rivers than in the past during the summer period. If we consider the time interval of this study (Figure 5), averaged river discharges decreased regularly; during the period 1962-1970 the average river discharge was about 1100 $m^3.s^{-1}$, from 1970 to 1980, the average decreased to 900 $m^3.s^{-1}$, and between 1980 and 1994 the averaged decreased to 600 $m^3.s^{-1}$. The last interval corresponds to the years with severe dry periods (1989 and 1990). As a result, salinity front and turbidity maximum have progressively shifted upstream, inducing more sedimentation in the tidal rivers. The sediment budget confirms the trend: the accretion period (1962-1970) was followed by an erosion period, which intensifies from 1980 to 1994. A

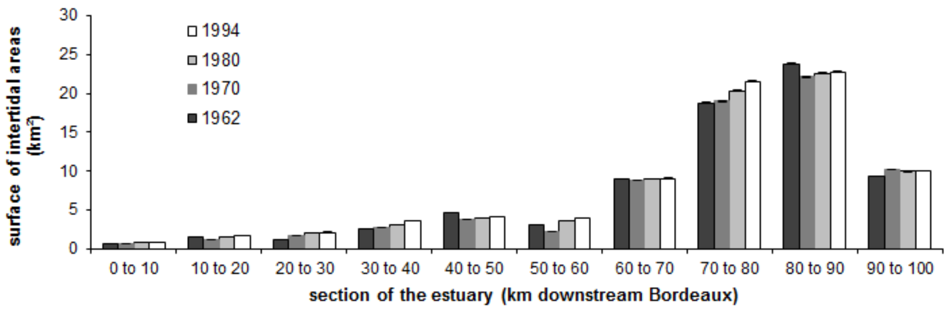

Figure 4. Distribution of lateral intertidal areas per longitudinal segment of 10 km in the Gironde estuary, derived from interpolated bathymetries of 1962, 1970, 1980 and 1994.

plausible explanation is that the accretion occurred in the tidal portion of the Garonne and Dordogne rivers. This hypothesis cannot be verified because the lack of recent bathymetric data in the rivers.

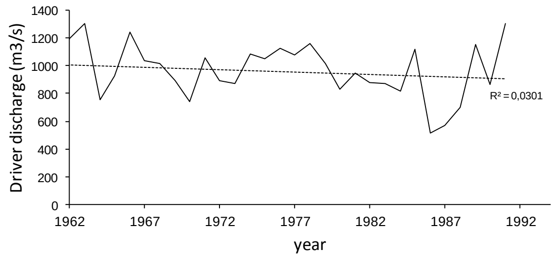

Figure 5. River flow in the Gironde (Garonne+Dordogne rivers) Annual mean between 1962 and 1994

Despite weak changes in the general morphology, changes in section and intertidal areas show good coherence too. In Figure 6, changes in estuarine water volume between 1962 and 1994 are compared with the rate of change of intertidal areas for the same period. Different portions of the estuary are considered. In general there is a good correlation between the two variables. This indicates that relative deepening of the channel corresponds to local extension of intertidal areas, which is a dynamic response to maintain the morphological equilibrium of the estuary. It is interesting to note that the rate does not depend on the estuarine section, as maximum rate change occurs in section 30-40, i.e. upper estuary, close to the junction Garonne-Dordogne. Minimum changes occur in the Garonne portion (section 10-20) and near the

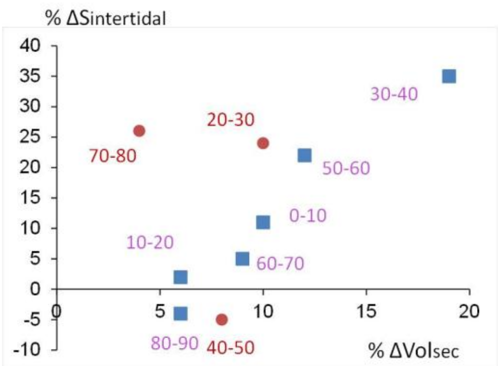

Figure 6. Change rate of estuarine section as a function of change rate of horizontal surface of intertidal areas, considered by longitudinal portions of 10 km along the estuary.

mouth (section 80-90) where the change in intertidal areas is negative. Most of the estuarine sections follow a similar "normal" response. However, some other areas seem to respond differently. In Figure 6, three sections are represented by red circles: PK 20-30, 40-50 and 70-80. They actually correspond to the estuarine sections where channel dredging or sediment pilling are the more frequent. It can bee seen that only section 70-80 seems to differ from the general trend. In this area, the intertidal surface increased at abnormal rate compared to other sections, as observed in figure 4. It is suggested that in this area, the expected morphodynamic equilibrium can be locally disturbed by anthropogenic activity. However in the present state of our study, such interpretation needs to be confirmed by deeper analysis.

Correlation between decadal and secular changes

The bathymetries shown in this study are the first evidence of changes in morphology at the scale of the estuary for the last decades. A recent study localised around estuarine bars in the upper estuary (Billy *et al.*, 2012) also demonstrated the long term control of the tide and the river flow on such sedimentary bodies. Our study is based on four situations covering 32 years, therefore it is not possible to investigate any effect at higher frequency. One of the useful primary indicators than can be easily described is the change on estuarine cross sections. Figure 7 shows the relative change for the whole period 1962-1994. It can be observed that there is a periodic response along the estuary, with areas experiencing high rates of change (PK 15, 30, 60 and 90) while some others exhibit low rates (PK 20, 45, 70, 100), suggesting stability. A previous investigation conducted in the Gironde estuary showed similar patterns. Results from Castaing (1989) are included in the Figure 7 for comparison. That previous study concerned a very different period (1825-1984), but the result is surprisingly close to our study. Periodic oscillations of rate of change are also visible, in general at the same locations than given by the recent period. In addition, rates of change are in general higher, but this can be explained by the longer time interval considered. There is an exception on km 30-40, where the rate of change 1825-1984 and 1962-1994 are very close. Castaing (1989) proposed the hypothesis that the observed long term changes in the Gironde could be due to a tidal co-oscillation, generated by a stationnary wave favoured by a low level of damping of the tide during its propagation, and by dimensions of the estuary that promote oscillations. Castaing (1989) calculated nodes and antinodes of this co-oscillation, which are indicated in Figure 7. The maximum co-oscillation levels correspond to the zones where the rate of change of estuarine section is maximum, while minimum co-oscillation zones are located at minimum levels of change on section. Then it is suggested by Castaing that tidal co-oscillation causes instabilities by the local hydrodynamics, probably characterized by higher vertical velocities that cause higher erosion or deposition fluxes than elsewhere.

The theory of the tidal co-oscillation needs to be carefully verified and deeply investigated before to be considered as an effective forcing for long term sedimentation. However, the coincidence between the comparison of bathymetries over 160 years and over 32 years is rather remarkable. The fact that there is a recovery period between 1962 and 1984 could be a factor that explains the similarity in budget trends. If the most significant changes occurred during this specific period, then it would be logical that the rates of change in both studies vary in the same way. This needs also to be verified by looking to other interval periods, which will be possible depending on available data.

CONCLUSION

The Gironde estuary is the largest estuary of western Europe, one of the most turbid and also one of the less altered by extensive engineering works. In this study, the analysis of general bathymetry extents from 1962 to 1994. Results show that the zone of the maximum volume of deposited sediment has migrated continuously towards the upstream portion of the estuary. The positive/accretion bugdet in the period 1962-1970 evolved to a negative/erosion budget in the period 1970-1994, which is coherent with the decrease of summer river flow and the upstream shift of the turbidity maximum zone to the riverine sections in the Garonne and Dordogne. The equilibrium between changes in

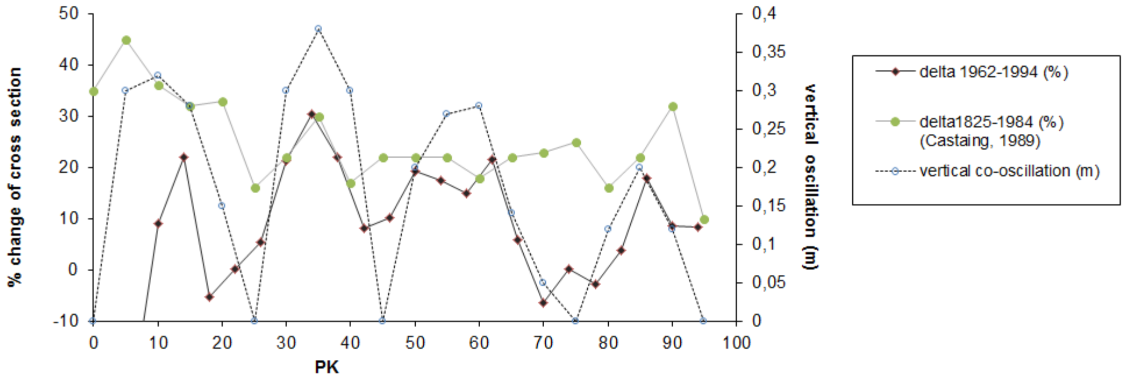

Figure 7. Comparison of change in estuarine section between 1962 and 1994 (this study), with the change between 1825 and 1984 (Castaing 1989) and the theoretical vertical tidal co-oscillation calculated by Castaing (1989). PKs are km downstream Bordeaux

estuarine cross sections and surface of intertidal areas suggests that anthropogenic actions have no direct effect on morphology changes. In addition to depth changes due to the fluvial control, stable and unstable zones can be identified along the estuary, apparently similarly to those already recognized through a previous study on the evolution over 160 years (1825-1984). This seems to be independent from the fluvial regime, but rather related to interactions between the tide and the general morphology, which are not elucidated yet. Finally, some HMS indicators useful to the WFD have been described: distribution of depths, changes on cross section areas, changes intertidal areas. Their determination from a DEM is simple, and their interpretation in terms of changes of the habitat could be very useful for managers and estuarine ecologists. Further analysis of changes on morphology will include changes on the tidal wave, its asymmetry and its propagation in the estuary and in the upstream sections.

ACKNOWLEDGEMENTS

The authors thank J. Mas and A. Fort (Bordeaux Harbour Authority GPMB) who provided bathymetric data, and P. Le Hir (Ifremer) and R. Lafite (Univ. of Rouen) for fruitful discussions. The working group of the French LITEAU-BEEST project, funded by ONEMA is also acknowledged.

LITERATURE CITED

Allen, G.P., Salomon, J.C., Bassoullet, P., Du Penhoat, Y., and De Grandpre, C., 1980. Effects of tides on mixing and suspended sediment transport in macrotidal estuaries. *Sedimentary Geology*, 26, 69–90.

Billy, J., Chaumillon, E., Féniès, H., Poirier, C., 2012. Tidal and fluvial controls on the morphological evolution of a lobate estuarine tidal bar: The Plassac Tidal Bar in the Gironde Estuary (France). *Geomorphology*, 169-170, 86-97.

Castaing, P., Allen, G.P., 1981. Mechanisms controlling seaward escape of suspended sediment from the Gironde: a macrotidal estuary in France, *Marine Geology*, 40, 101–118.

Castaing, P. 1989. Co-oscillating tide controls long-term sedimentation in the Gironde Estuary, France. *Marine Geology*, 89 (1-2): 1-9.

Dalrymple, R.W., Zaitlin, B.A., Boyd, R., 1992. Estuarine facies models: conceptual basis and stratigraphic implications. *Journal of Sedimentary Petrology* 62 (6), 1130–1146.

David V., Sautour B., Chardy P., Leconte M., 2005. Long term survey of the zooplanktonic variability in a turbid estuary :Gironde estuary (France), *Estuarine, Coastal and Shelf Science*, 64, 171-184.

Etcheber H., Schmidt S., Sottolichio A., Maneux E., Chabaux G., Escalier J.M., Wennekes H., Derriennic H., Schmeltz M., Quemener L., Repecaud M., Woerther P., Castaing P., 2011. Monitoring water quality in estuarine environments: Lessons from the MAGEST monitoring programme in the Gironde fluvial-estuarine system, *Hydrology and Earth System Sciences*, 15, 831-840.

Jiang, C., Li, J., de Swart, H.E., 2012. Effects of navigational works on morphological changes in the bar area of the Yangtze Estuary. *Geomorphology*, 139–140: 205–219.

Le Hir, P., Sottolichio, A., Foussard, V. 2011. Computation of Hydro-Morpho-Sedimentary indicators of good ecological status in estuaries, from mathematical process-based models. *Internatonal Symposium "Estuarine and Lagoon Ecosystem Trajectories" (ELET)*. ECSA-Cemagref, Bordeaux, 25-28 oct. 2011.

Lesourd, S., Lesueur, P., Brun-Cottan, J.C., Auffret, J.P., Poupinet, N., Laignel, B., 2001. Morphosedimentary evolution of the macrotidal Seine estuary subjected to human impact. *Estuaries and Coasts* 24(6): 940-949.

Migniot, C., 1971. L'évolution de la Gironde au cours des temps. Bulletin de l'Inst. de Geol. du Bassin d'Aquitaine., 11: 221-279

Nichols, M.M., Biggs, R.B., 1985. Estuaries. *In:* DAVIES Jr., R.A. (Ed.) *Coastal sedimentary environments*. New York, USA, Springer-Verlag, pp. 77-186.

Sottolichio, A., Le Hir, P. and Castaing, P., 2001. Modeling mechanisms for the turbidity maximum stability in the Gironde estuary, France. *In:* W.H. McAnally, A.J. Mehta (Eds.), *Coastal and Estuarine Fine Sediment Processes*, Elsevier, Amsterdam, 373-386.

Sottolichio, A., Foussard, V., Le Hir, P., Lafite, R., Lesourd, S., Bachelet, G., Barillé, A.L., Bruchon, F., Delattre, M., Devreker, D., Fattal, P., Langlois, E., Lepage, M., Thiebot, J., Vinchon, C., Ximénès, M.C., 2011. Hydro-morpho-sedimentary (HMS) patterns in large turbid estuaries: determination of indicators of the good ecological status, based on links between habitats and species. *International Symposium "Estuarine and Lagoon Ecosystem Trajectories" (ELET)*. ECSA-Cemagref, Bordeaux, 25-28 oct. 2011.

Sottolichio A., Castaing P., Etcheber H., Maneux E., Schmeltz M., Schmidt S., 2011. Observations of suspended sediment dynamics in a highly turid macrotidal estuary, derived from continuous monitoring, *Journal of Coastal Research*, Sp. Issue 64, vol 2, 1579-1583.

Talke, S.A., de Swart, H.E., Schuttelaars, H.M., 2009. Feedback between residual circulations and sediment distribution in highly turbid estuaries: an analytical model. *Continental Shelf Research* 29, 119–135.

Wang, Y., Shen, J., He, Q., 2010. A numerical model study of the transport timescale and change of estuarine circulation due to waterway constructions in the Changjiang Estuary, China. *Journal of Marine Systems* 82, 154–170.