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TIDAL ASYMMETRY AND SUSPENDED-SEDIMENT TRANSPORT IN THE GIRONDE ESTUARY (FRANCE)

Kim Dan Nguyen[1], Ngoc Vinh Phan[2] and Sylvain Guillou[3]

Abstract: *A full 3-D numerical model is used for studying the estuarine circulation and the sediment transport in the Gironde estuary. The model is based on resolving the shallow-water equations by a finite differences method using the projection technique (Chorin, 1969). The turbulence is taken into account by the one-equation model K-L. The model was calibrated and verified using the data measured during two field surveys completed in 1974 and 1975. A study on the influence of tides and river discharges was done to understand the hydrodynamic structure and the main factors that can be responsible of changes of the estuarine circulation and the sediment transport.*

Key-words: *3-D Modelling, Gironde Estuary, Tidal Asymmetry, Sediment transport, Turbidity Maximum*

INTRODUCTION

In propagating into shallow-water of shelves and estuaries, tides generate higher-frequency overtides such as quatradiurnal (M4) and sextadiurnal (M6) lunar tides as well as several others. Overtide generation is caused by non-linearities due to bottom friction and continuity constraints. Overtides become important when the ratio of tidal amplitude to water depth is significant. The addition of the overtides to the M2 tidal current makes maximum ebb and flood closer to high or low water, and then distorts tidal currents from the M2 component to become asymmetric. Recent studies in estuaries have revealed significant influence of tidal asymmetry on estuarine circulation, on saline intrusion and on sediment transport.

Gironde, the French largest estuary is situated in the southwest of France (Fig 1). Its total drainage area is 8 10^4 km^2, i.e. 1/7 of the French territory. The Gironde is an estuary where the ocean tide is dominated by the semi-diurnal lunar tide (M2). The relatively restricted level of industrialisation and urban development in the southwest of France has left the Gironde as an almost undisturbed large estuary. It can be considered as a valuable quasi-natural model, with a strong system of turbidity due to the asymmetric tides (Jouanneau and Latouche, 1981). Allen (1972), by analysing the in situ observations, provided a synthetic description on salinity intrusion, estuarine circulation, and sediment transport in the Gironde Estuary. Although having addressed the tidal asymmetry characteristics of the Gironde estuary, Allen (1972) and Jouanneau & Latouche (1981) did not analyse how overtides would be generated and how the tidal asymmetry would affect the estuarine circulation and the saline intrusion there.

The aim of this paper, using a 3-D numerical model, is to investigate i) the spatial distribution of tidal distortion and asymmetry in the Gironde estuary, in harmonically analyzing tidal water levels and currents in the M2 component and M4 and M6 overtides; ii) the tidal-asymmetry effect to ebb-flood and neap-spring variation of estuarine circulation and sediment transport in the Gironde Estuary.

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MODEL DESCRIPTION

The governing equations for estuarine circulation and saline intrusion are Navier-Stokes ones using the Boussinesq approximation and the hydrostatic hypothesis, combined with transport equations for salinity and sediments. A *k-l*-type sub-model for turbulent closure is introduced in order to parameterise turbulent mixing. A σ-coordinates system for the vertical is used. The governing equations are then solved by Blumberg and Mellor's two-successive-mode technique (for details, see [3]). The water surface elevations are determined in the external mode by solving the 2-D Saint-Venant equations. Then, scalar variables including the velocity components and the suspended-sediment concentration will be determined in the internal mode using an explicit scheme.

SIMULATION OF THE GENERAL CIRCULATION IN THE GIRONDE ESTUARY

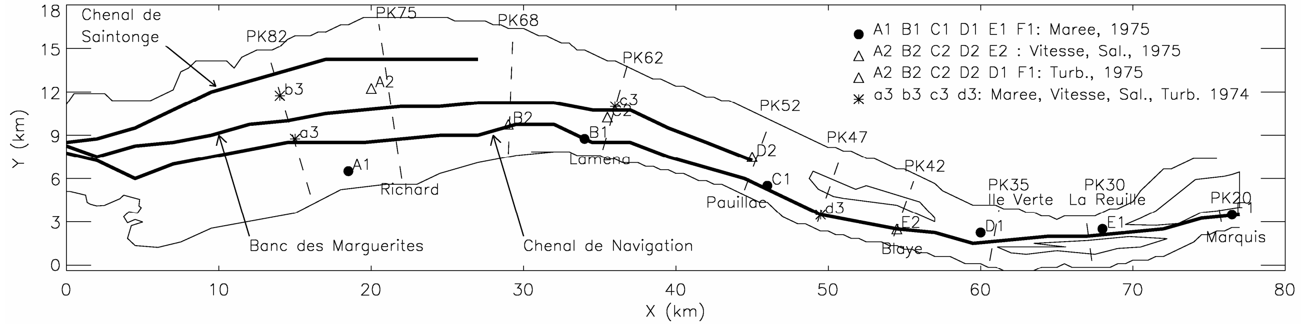

Fig 1. Location of the measurement stations in the field surveys in 1974 and 1975 (Estuarine part).

Computational condition

The computed domain covers the estuarine part and two rivers: the Garonne and the Dordogne. The estuarine part extends from the mouth to the confluent point at the Bec d'Ambes. The river part prolongs from the Bec d'Ambes to "La Reole" in the Garonne and to 10 km upstream Pessac in the Dordogne. The longitudinal length of the computed domain is then nearly 160 km. As the tidal upper-limit is observed at about 150 km upstream the mouth, river discharges are imposed as the boundary conditions at the upstream limits. The computed domain is discretised by a mesh of 360 x 68 x 20 in the x, y and z directions respectively. The mesh is regular in the horizontal directions with spacing of 500m x 250m. In the vertical direction, a stretch arrangement is used to get a mesh refinement in proximity of the bottom. The computing time step is 30 sec, which corresponds to a maximum Courant number. C_t =2.4. No wind is considered. The Coriolis parameter is fixed at f=1.17 10^{-4}, which corresponds to a latitude of 45°. The friction stress on the bottom is calculated using the Chezy's formula with Chezy's coefficients varying from 50 to 80 $m^{-1/2}s^{-1}$. The coefficients for the turbulence closure sub-model are taken as follows: C_v=0.425, C_μ=0.022, γ_s=0.1 and γ_c=0.5.

At the seaward open boundary, the observed tidal water levels are imposed for every time. In ebb tide, no additional condition is necessary. However in flood tide, the velocity and the salinity must be given at every boundary point. Therefore, the radiation method proposed by Orlanski (1976), improved by Blumberg and Kantha (1985) is used to determine the velocity component normal to the seaward open boundary. The salinity is given by a sinusoidal function, whose the maximum values are observed in the Gironde mouth. At the upstream open boundaries, the discharge of the Garonne and Dordogne rivers, and a salinity of 0.01ppt corresponding to the salinity of the fresh water are specified. Moreover, a radiation condition is also used to determine the water levels at every point at these boundaries. At the wall boundaries, the non-slip condition is imposed. The initial conditions for the simulations were obtained with a long simulation of 120 hours.

Calibration and verification

Until now, there only exist two field surveys, which could be used for calibrating and verifying tide-propagation, saline-intrusion and sediment-transport models in the Gironde Estuary: the one was performed in situ from 19th to 25th May 1975 and the other from 19th to 22nd May 1974. Fig 1 gives the location and the nature of measuring punctual stations of these surveys. The model is therefore calibrated with the measurements performed in May 1975 at six water-level stations and five velocity and salinity stations, which were regularly spaced along the estuary. This corresponds to an average-tide period. The model is then verified by the measurements obtained at four other stations, where the water level, velocity and salinity were measured during the field survey in May 1974. For this period, the tide is spring. A river discharge of 700 $m^3.s^{-1}$ that corresponds to a yearly-average discharge in the Gironde estuary is imposed at the upstream boundaries for both calibration and verification.

A quantitative comparison between the computed and measured values by harmonic analysis using a least-square technique for the M2 tide and the M4 and M6 overtides was then done. Table 1 represents the harmonic-analysis results. It is noticed that for the M2 tide, the difference in amplitude between computed and measured values is very small: no-difference for Marquis and La Reuille stations, and 8 cm of maximum difference was observed at Richard, Lamena and Pauillac. The gap in phase, averaged for all stations, was about 2 degrees (equivalent to 4 minutes approximately) with a maximum value of 8 degrees (16 minutes) was observed at Marquis and Lamena. Additionally, Table 1 shows that for a mean M2-tide, whose the water-level amplitude normally varies from 220 cm to 260 cm, the contribution of the M6 is more important than that of the M4: Indeed, the water-level amplitude generated by the M6 is estimated about by 60-70 cm whereas that is only 10-20 cm for the M4. Once again, Table 1 quantitatively shows that there is no difference between computed and measured amplitudes of the M6 at Marquis. However, it varies from 3 cm to 10 cm elsewhere.

Table 1: Comparison between the computed and measured values of water levels in the M2 and the overtides M4 and M6 for the calibration step.

		M2		***M4***		***M6***	
		Amplitude (cm)	Phase (deg)	Amplitude (cm)	Phase (deg)	Amplitude (cm)	Phase (deg)
RICHARD	Computed	222.39	21.3	15.76	64.14	55.54	174.85
	Measured	228.37	23.53	16.11	61.84	63.53	178.05
	Difference	-5.98	-2.23	-0.35	2.30	-7.99	-3.20
LAMENA	Computed	246.44	11.65	11.29	66.72	61.47	161.41
	Measured	254.68	14.07	11.58	71.67	71.58	169.34
	Difference	-8.24	-2.42	-0.29	-4.95	-10.11	-7.93
PAUILLAC	Computed	256.89	3.02	5.05	9.34	63.8	150.16
	Measured	264.73	5.40	2.85	41.67	73.24	158.28
	Difference	-7.84	-2.38	2.2	-32.33	-9.44	-8.12
ILE VERTE	Computed	253.19	11.61	14.45	25.44	62.83	132.78
	Measured	259.72	9.77	10.62	32.93	70.47	139.47
	Difference	-6.53	1.84	3.83	-7.49	-7.64	-6.69
LA REUILLE	Computed	255.4	15.36	14.96	22.54	64.18	129.53
	Measured	255.33	7.38	7.72	77.19	67.45	157.71
	Difference	0.07	7.98	7.24	-54.65	-3.27	-28.18
MARQUIS	Computed	235.58	27.15	18.92	23.56	60.8	114.98
	Measured	233.41	21.26	11.33	53.03	60.85	135.45
	Difference	2.17	5.89	7.59	-29.47	-0.05	-20.47

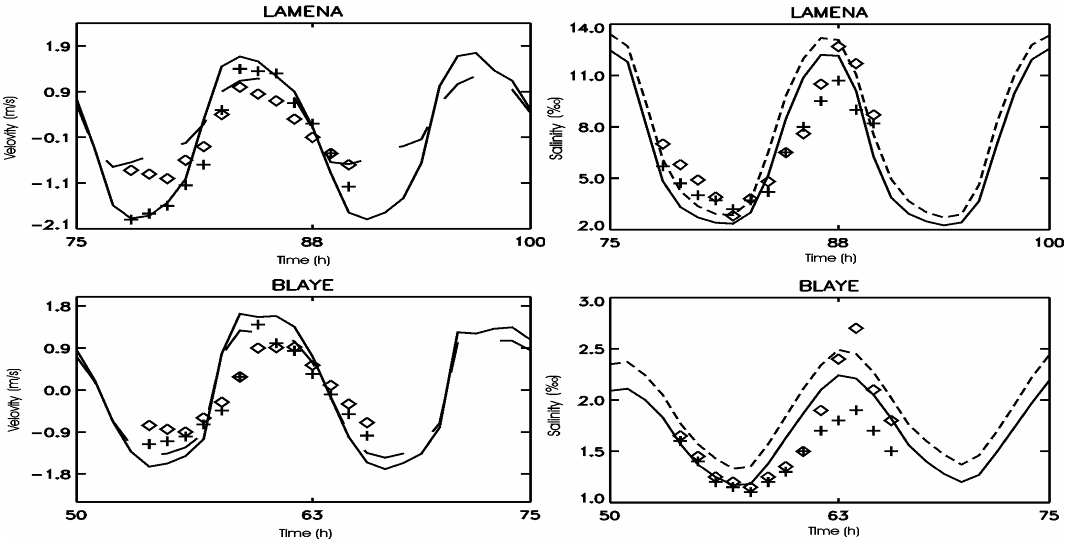

Fig 2. Comparison between observed and calculated velocity (left) and salinity (right) (average discharge ≈700m3s-1) for calibration (— computational results at the surface ; +++ Measurements at the surface ; ---- computational results at the bottom ; ◊ Measurements at the bottom).

Fig2 presents the comparison between calculated and observed longitudinal velocity and salinity for the calibration step at Lamena and Blaye. These stations represent the largest difference between values calculated and observed at all stations. The maximum distance is about 0.35 m.s^{-1} for a surface velocity of 1.60 m.s^{-1} at Blaye. The location of the Blaye station, which is situated between small islands near the Gironde confluent point (Fig 1), explains this disagreement. Indeed, facing this complex geometry of the computed domain, the small islands have been grouped and represented by an only big one in the computing mesh. This meshing could more and less modify the current field there. Except for the Blaye station, calculated velocity and salinity are in a reasonable agreement with the measured values.

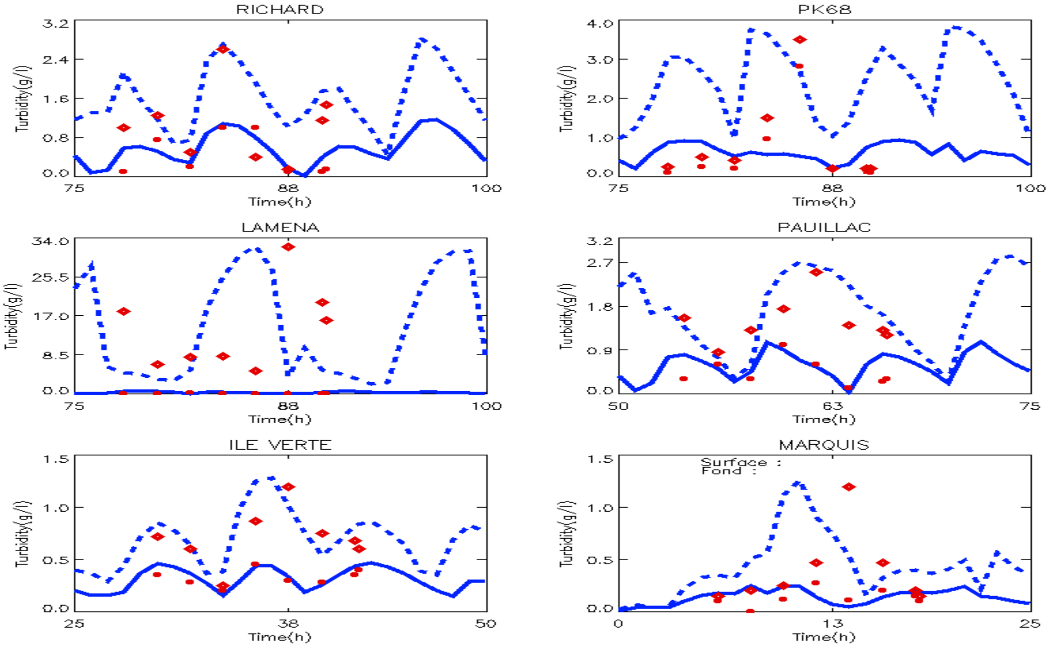

Fig 3. Comparison between calculated and observed TSM for calibration step (River discharge of 700m3s-1).

Concerning the Total Suspended Matter (TSM) concentration, it is necessary to underline that the TSM concentration values measured in situ reveal some incertitude. Therefore, in general it is not able to get a so good agreement between numerical and measured values of TSM concentration as the cases for velocity and salinity. However, the comparison shows that calculated and observed TSM concentration are in the same magnitude order on the surface and on the bottom for both calibration and verification (Fig 3).

Tidal asymmetry

Strong tidal asymmetry in the Gironde Estuary has been observed and also predicted by the present numerical model. Table 1 shows for a mean tide, a gradual increase of the M2 elevation amplitude from the estuary mouth over a distance of nearly 45 kms to reach a maximal value of 256.89 cm at Pauillac. Phase lag of M2 along this distance is about 36 min. Upstream Pauillac, caused by the topographical complex with the presence of islands and sand banks, the variation of tidal-elevation amplitudes in the longitudinal is more complicated. Neither increase nor decrease of the tidal-elevation amplitude is clearly observed there. Indeed, the tidal-elevation amplitude keeps a value nearly constant of about 255 cm from Pauillac to La Reuille and then decreases into 235 cm at Marquis. The same phenomenon is observed for spring and neap M2 tides (table 1). Inversely, the M4 tidal-elevation amplitude decreases from 15.76 cm at the mouth to a minimum value of 5.05 cm at Pauillac and then increases up to 18.92 cm at Marquis.

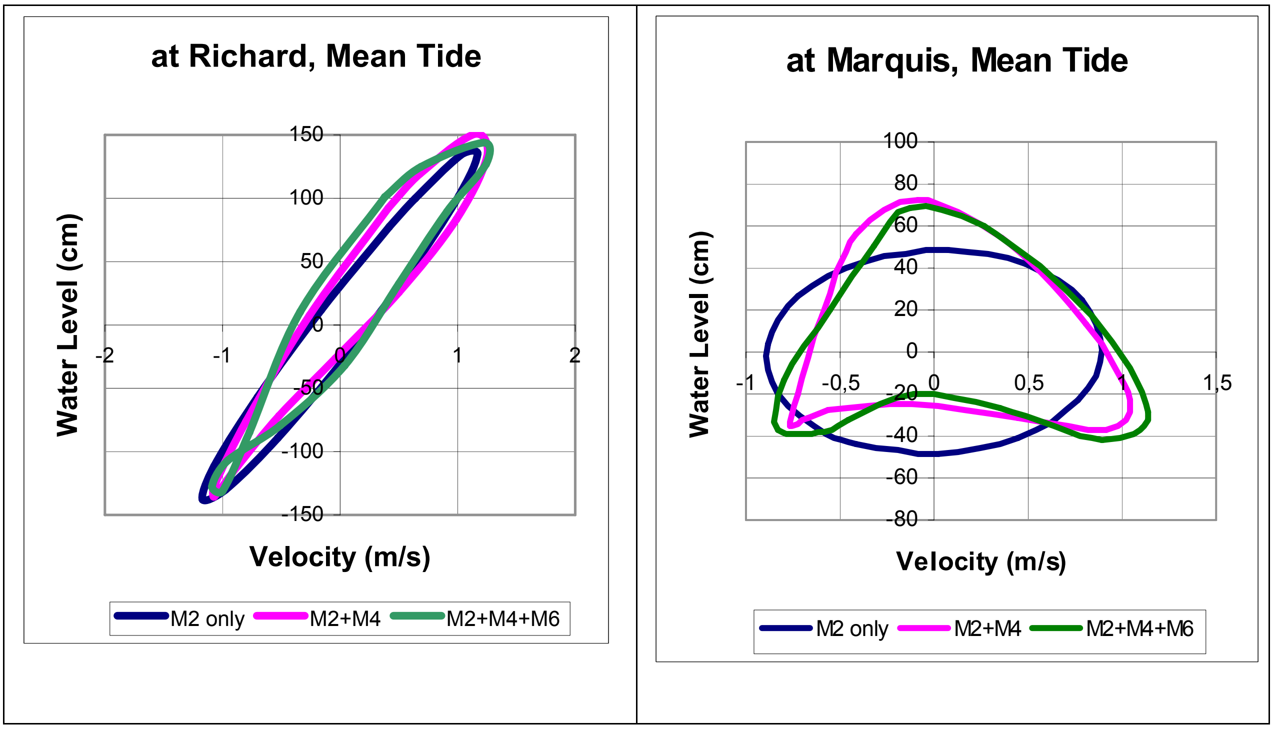

Fig 4 – The Stage-Velocity diagrams at the mid-depth at Richard (18 kms from the mouth); Pauillac (46 kms) and Marquis (78 kms) for a mean tide.

As suggested by Blanton et al (2002), the stage-velocity diagrams are used to describe how overtides M4 and M6 distort the tidal propagation and engender the tidal asymmetry in the Gironde Estuary. Fig 4 plots the stage-velocity diagram at the mid-depth for a mean tide at Richard (station A1 in Fig 1), and Marquis (station F1), which are located at 18 km and 78 km from the mouth, respectively (see Fig 1). The stage-velocity ellipses turn in counter-clockwise as one proceeds further into the estuary. Consequently the lag between the WLS and LW (or HWS and HW) clearly decreases landward from Richard to Marquis (Fig 4). At Richard, the comparison between M2 ellipse with M2+M4 and M2+M4+M6 ellipses shows that the addition of M4 and M4+M6 to M2 somewhat increases maximum flood current and decreases maximum ebb current. This makes the tide very slightly flood-dominant there. At Marquis, the addition of M4+M6 to M2 totally transforms the shape of the stage-velocity diagram. During a tidal cycle, there exist three levels of LW. The one is slightly higher than two others. LWS nearly coincides with this higher LW. Also HWS and HW almost appear at the same time.

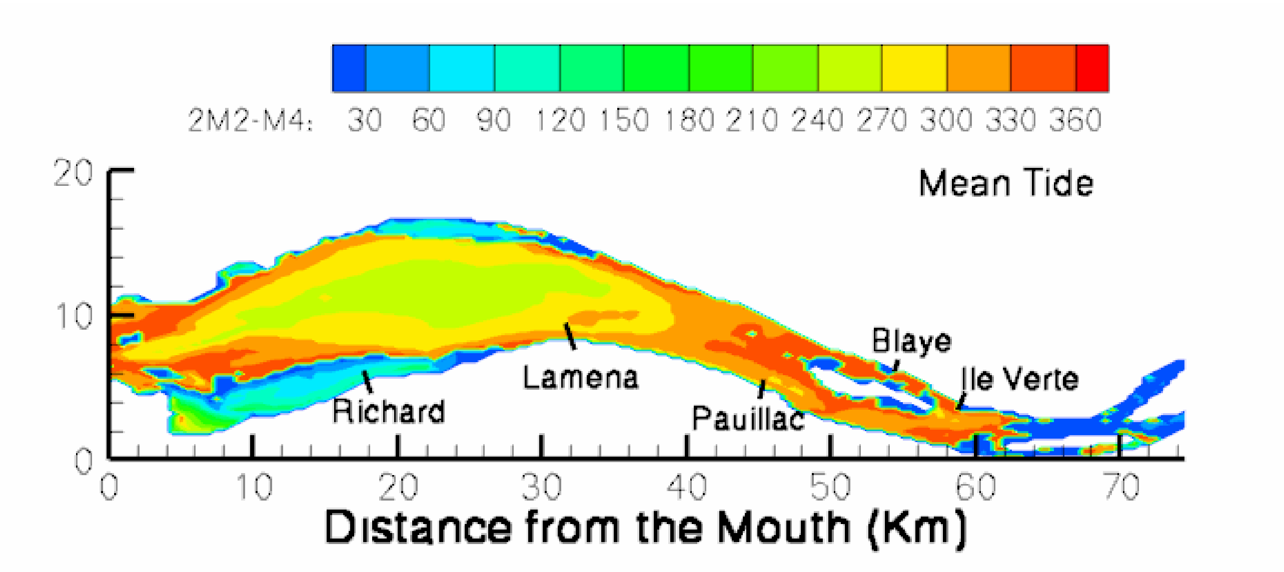

Fig 5- Map of the (2M2-M4) isovalue contours of the phase difference between M2 and M4 for a mean tide.

Friedrichs & Aubrey (1988) show that if 90° < ($2M2_{phase}$ -$M4_{phase}$) < 270°, the tide is flood-dominant, and otherwise it is ebb-dominant. $M2_{phase}$ and $M4_{phase}$ are the tidal-current phase of M2 and M4 respectively. Fig 5 plots a map of the ($2M2_{phase}$ -$M4_{phase}$) iso-value contours for a mean tide. Clearly, the big part of the estuary is ebb-dominant. Only the zones near riverbanks and that on the Marguerites bank, where the water is shallow, are flood-dominant. As a consequence, on and around the Marguerites bank there might exist residual re-circulation cells.

Saline Intrusion and Residual Circulation

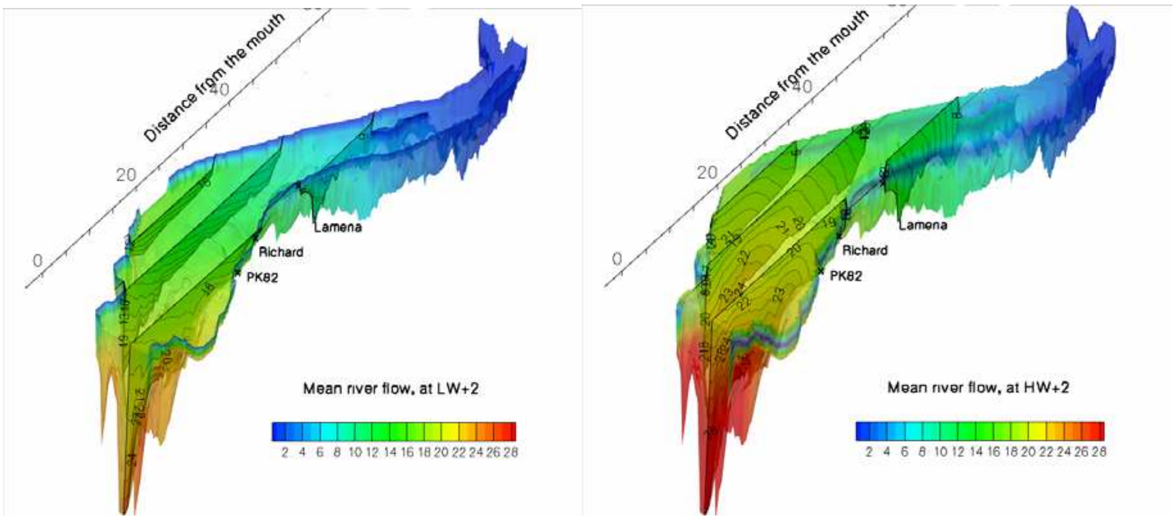

Fig 6. Salinity fields in 3-D (discharge ≈700m3s-1, meaning tide): at LW+2, in ebb (left) and at HW+2, in flood (right)

As water outflows have tendency to be deflected to their right, from PK80 to the mouth, salinity near the right shore is always lower than that near the left one. Also the numerical results (Fig 4) show that the difference between the salinity near the right and left shores is more important in the ebb tide (approximately 4 g.l^{-1} on the surface) than that in flood (nearly 1 g.l^{-1} - 2 g.l^{-1} on the surface). On the other hand, in the upper estuary (from PK35 to PK50), the transversal distribution of the salinity is strongly influenced by river discharges and by currents mainly flowing in the Navigation channel. In this zone, the salinity near the left shore is lower than that near the right one.

The vertical gradient of salinity in ebb tide is more important than that in flood tide. In flood tide, at 30 km upstream from the mouth, the vertical gradient of salinity is practically nil while it is still important (0.50 g.l^{-1}.m^{-1}) at 50 km from the mouth in ebb tide. It shows once again that, large magnitudes of TKE play in favour of vertical mixing in flood tides. Indeed, in this period the vertical mixing is stronger than that in ebb one.

In general, the stratification and the horizontal gradient of salinity in the estuary increase with river discharges and decrease with tidal amplitude. The effects of tides and river discharges will be discussed more in detail in the next section.

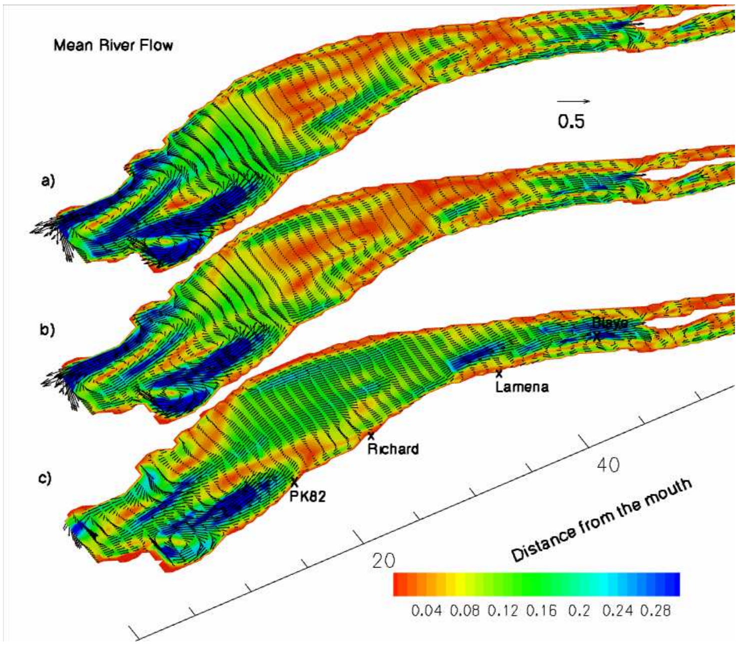

Fig 7. Residual Circulation on surface (a); Mid-depth (b) and bottom (c)

Fig 7 shows the residual circulation computed in mean tide and mean river discharge. Clearly there exist several eddies engendered by the presence of the sand banks (Marguerites, Talais, Richard, St. Estèphe and Trompeloup). On the surface, the residual currents flow seaward while on the bottom they are upstream ward. This is explained by the fact that on the bottom, there exist important horizontal upstream-ward gradients of salinity, which make the bottom residual currents stronger than that on the surface (Fig 7). The numerical results obtained with the different conditions of tides and river discharges allow us to get some following remarks: i) the residual-current pattern on the surface is nearly the same in flood and in the dry season with only the difference on the intensity; ii) in both flood and dry seasons, the surface residual currents flow seaward first following the Navigation channel and then deflecting into the Saintonge channel. This deflection is caused by the Coriolis effect; and iii) the presence of the sand banks of Talais and of Marguerites, generates a large eddy near the mouth;

SIMULATION OF THE TURBIDITY MAXIMUM TRANSPORT:

Hydrodynamic effects:

The evolution of bottom shear stresses versus erosion and deposit rates, which are presented in Fig 8, provide the information that where and when the erosion or/and deposition take place in the Navigation channel. The numerical results allow us to reveal the main remarks as follows:

Generally, calculated erosion and deposit rates are about 1.0 N.m^{-2} and 0.4 N.m^{-2}, respectively, apart from the lower estuary part near the estuary mouth (PK80-PK100), they are successively 2.5 N.m^{-2} and 0.1 N.m^{-2};

Except for the slack flood tide (HW+1 to HW+2), the calculated bottom shear stresses are often important over the area between PK40 and PK60 with a maximum that is greater than 5.0 N.m^{-2} at LW+4 in tide flood and at HW+4 in tide ebb. However, this maximum value in the flood period is more important than that in ebb. Therefore, almost time the erosion occurs in this area and the turbidity maximum will be developed there for both the flood and ebb period.

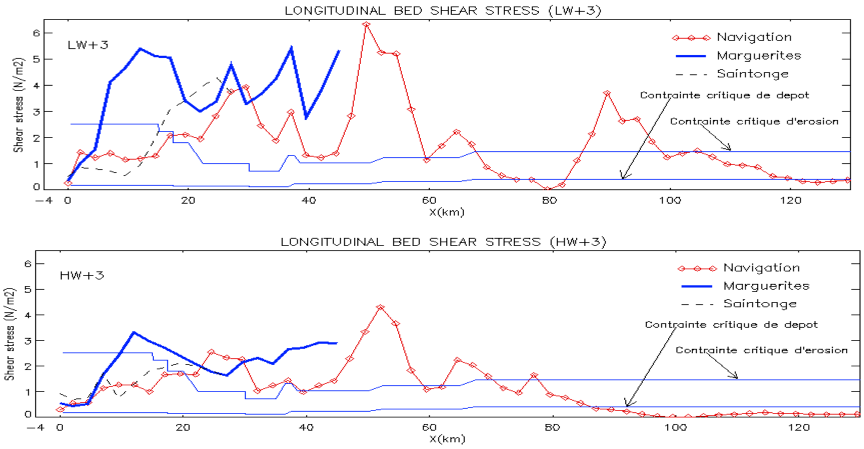

Fig 8. Variation of the bottom shear stress versus the deposit and erosion rates at LW+3 and HW+3.

Additionally, in the flood period, from LW+1 to LW+5, another area (PK10 to PK30) with strong bottom shear stresses appears and develops. In this area, the bottom shear stresses can reach a maximum value of 3 $N.m^{-2}$ versus the erosion rate is 1 $N.m^{-2}$. Thus, the erosion takes place and the second turbidity maximum is developed there, just downstream Bordeaux.

In the lower part near the estuary mouth (PK80-PK100) and the area upstream Bordeaux, the bottom shear stresses are always smaller than the erosion rate and even than the deposit rate. Therefore, there is not erosion there.

Formation and displacement of the Turbidity maximum

The results show that two peaks of turbidity maximum are formed during one tidal cycle because tidal currents twice reach their maximal values, triggering the re-suspension of sediments, one during the tide flood and the other during the tide ebb. As the tidal currents are asymmetric with a predominance of the tide ebb, the erosion is more important in the tide ebb than in the tide flood. This tendency is proved by the observations (Allen, 1972). Generally, the turbidity maximum begins to be formed at about one hour after slack tides when tidal currents are strong enough: The first peak is formed in tide flood at LW+1 and fully extended at LW+4, while the second begins at HW+2 and reaches its maximum at HW+4 in tide ebb.

During the tide ebb, the turbidity maximum is developed with a lack value of TSM concentration that reaches 2 $g.l^{-1}$ maximum at the water depth of 4–6 m from the bottom for 2 hours, from HW+3 to HW+4. The going-out of suspended matters seaward can occur during this period. During the tide flood, the water level arises and the turbidity maximum is developed over all the water depth (Fig 9) with its upstream limit moving upstream ward. On the water surface, the TSM concentration is nearly 0.5 $g.l^{-1}$ while near the bottom in the turbidity maximum core, which extends from PK65 to PK55, this value can be greater than 10 $g.l^{-1}$. In the navigation channel, two turbidity maximums are observed: the first one is situated around LAMENA and the second one extends from PK15 to PK5 (near Bordeaux). The longitudinal size of the first turbidity maximum varies from 20 km at LW+2 to 40 km at HW+2.

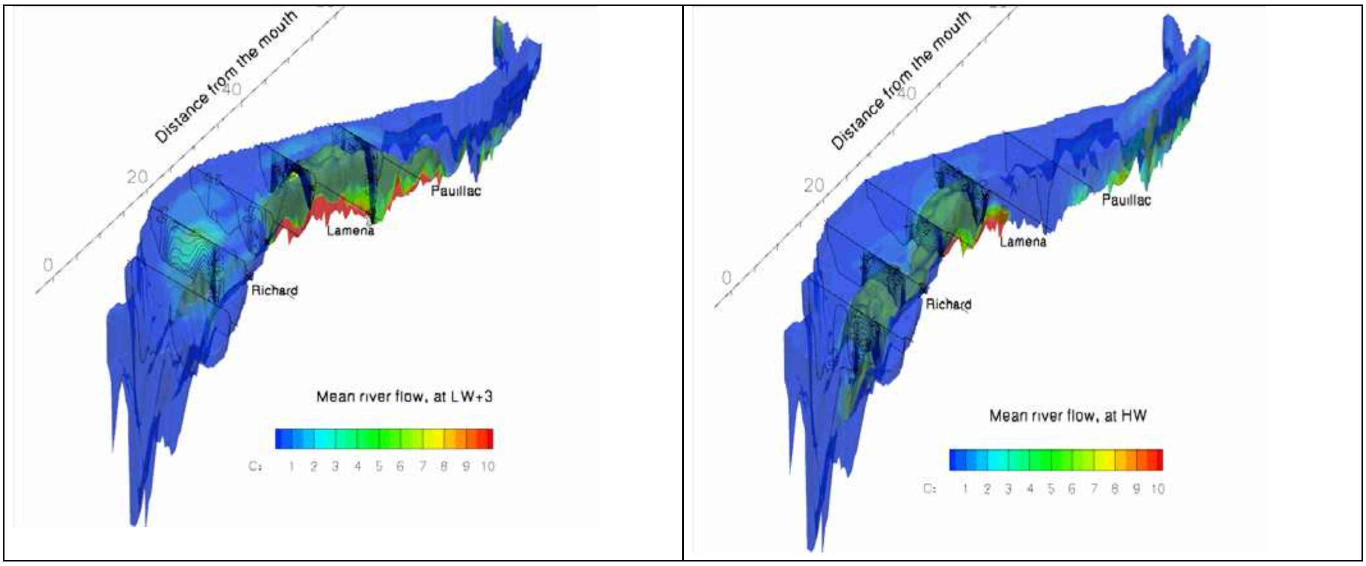

Fig 9. Maximum Turbidity predicted by the model at LW+3 and at HW+3 (mean tide and mean river discharge).

CONCLUSIONS

This paper presented a study on the residual circulation and the sediment transport in the Gironde estuary using a fully 3-D numerical model. The present model was calibrated and verified by the measurements made during two field surveys in 1974 and 1975. The numerical results obtained from the model are in fair agreement with the observed data for both calibration and verification cases. Also, a schematic diagram of residual circulation was established. It is in conformity with the synthetic analyse of Allen (1972). The present model was then used for studying the influence of tides and river discharges on the estuarine circulations and sediment transport. The study cases, which are a combination between neap and spring tides, dry and flood discharges (300 and 3000 $m^2.s^{-1}$ respectively), are realised. The numerical results show that tidal propagation, residual currents and sediment transport are deeply modified with tides and river discharges. Spring tides make the asymmetry between flood and ebb periods as well as sediment transport stronger. The discharge increasing doesn't affect patterns but modifies intensities of residual currents.

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