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MIXING AND DISPERSION IN TIDAL BORES: A REVIEW

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Abstract : When a river mouth has a flat converging shape and when the tidal range exceeds 6 to 9 m, the river may experience a tidal bore. A tidal bore is basically a positive surge propagating upstream as the tidal flow turns to rising. The occurrence of a bore has a significant impact on estuarine systems. Bed erosion and scour take place beneath the bore front while suspended matters may be carried upwards in the following wave motion. Analogies between hydraulic jumps and positive surges suggest that the mixing coefficients are much greater than in estuary flows. Tidal bores impact also significantly on eco-systems. The existence of tidal bores relies upon a fragile hydrodynamic balance, which may be easily disturbed by changes in boundary conditions and freshwater inflows.

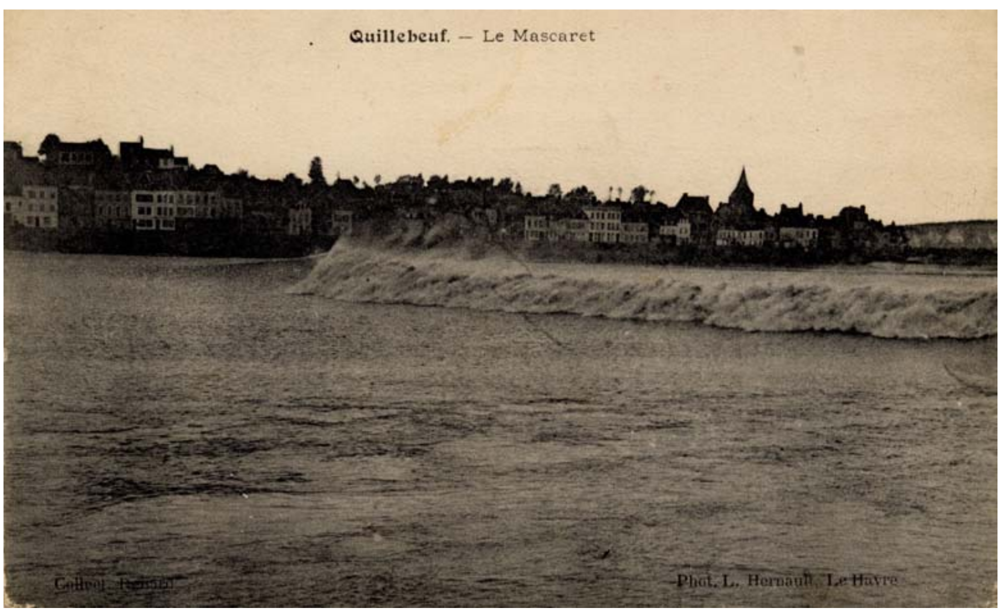
Keywords : tidal bore, mixing and dispersion, sediment process, ecology, review.

INTRODUCTION

When a river mouth has a flat, converging shape and when the tidal range exceeds 6 to 9 m, the river may experience a tidal bore (Fig. 1). A tidal bore is basically a series of waves propagating upstream as the tidal flow turns to rising. It is a positive surge. As the surge progresses inland, the river flow is reversed behind it (e.g. LYNCH 1982, CHANSON 2001). The best historically documented tidal bores are probably those of the Seine river (France) and Qiantang river (China). The *mascaret* of the Seine river was documented first during the 7th and 9th centuries AD, and in writings from the 11th to 16th centuries (MALANDAIN 1988). It was locally known as "la Barre". The Qiantang river bore, also called Hangzhou bore, was early mentioned during the 7th and 2nd centuries BC, and it was described in 8th century writings. The bore was then known as "The Old Faithful" because it kept time better than clocks. A tidal bore on the Indus river might have wiped out the fleet of Alexander the Great (MALANDAIN 1988, JONES 2003). Another famous tidal bore is the "pororoca" of the Amazon river observed by PINZON and LA CONDAMINE in the 16th and 18th centuries respectively. The Hoogly (or Hooghly) bore on the Gange was documented in 19th century shipping reports. Smaller tidal bores occur on the Severn river near Gloucester, England, on the Garonne and Dordogne rivers, France, at Turnagain Arm and Knik Arm, Cook Inlet (Alaska), in the Bay of Fundy (at Petitcodiac and Truro), on the Styx and Daly rivers (Australia), and at Batang Lupar (Malaysia) (Fig. 1).
In this paper, the impact of tidal bores on estuarine systems is reviewed. A particular emphasis is placed on the role of bores on mixing and dispersion. The results bring new evidences on its ecological significance.

Fig. 1 - Examples of tidal bores
(A) Tidal bore on the Daly river, Northern Territory (Aus.) (Courtesy of Gary & Rhonda HIGGINS)

(B) Tidal bore of the Seine river at Quilleboeuf (Fra.) at end of 19th century or early 20th century - Photograph by I. Hernault (Le Havre) (Courtesy of J.J. MALANDAIN)



Basic theory

Although a bore may be analysed using a quasi-steady flow analogy, its inception and development is commonly predicted using the method of characteristics and Saint-Venant equations. During the flood tide, the tailwater level increases with time, and the forward characteristics converge and eventually intersect at a point where the water depth has two values at the same time: i.e., the abrupt front of the tidal bore.

After formation of the bore, the flow properties immediately upstream and downstream of the front must satisfy the continuity and momentum principles (e.g. HENDERSON 1966, CHANSON 1999). The shape of the bore is a function of the surge Froude number. For Froude numbers between 1 and 1.3 to 1.5, the bore exhibits an undular profile (Fig. 1A). For larger Froude numbers, the surge has a breaking front (Fig. 1B). In the latter, significant energy dissipation takes place in the roller, while the rate of energy dissipation is negligible in undular bores (CHANSON 2001).

IMPACT ON MIXING AND DISPERSION

Tidal bores induce strong turbulent mixing in the estuary and river mouth. The effect may be felt along considerable distances. With appropriate boundary conditions, a tidal bore may travel far upstream : e.g., the tidal bore on the Pungue river (Mozambique) is still about 0.7 m high about 50 km upstream of the mouth and it may reach 80 km inland. Mixing and dispersion in a tidal bore affected estuary are not comparable to well-mixed estuary processes. Instead the effects of the tidal bore must be accounted for and the bore may become the predominant mixing process.

The effect on sediment transport was studied at Petitcodiac and Shubenacadie rivers (Can.), in the Sée and Sélune rivers (Fra.), Ord river (Aus.), Turnagain Arm inlet (Alaska) and on the Hangzhou bay (Chin.) (e.g. TESSIER and TERWINDT 1994, BARTSCH-WINKLER et al. 1985, WOLANSKI et al. 2001, CHEN et al. 1990). The arrival of the bore front is associated with intense bed shear and scour. Behind sediment material is advected upwards by large scale turbulent structures evidenced in Figure 2. Sediment suspension behind the bore is sustained by strong long-lasting wave motion. At the Dee river (UK), Dr E. JONES observed more than 230 waves, also called whelps or *éteules*. MURPHY's (1983) photograph showed more than 30 well-formed undulations behind the Amazon *pororoca*. At the Dordogne river (Fra.), the writer observed an intense wave motion lasting more than 20 minutes after the bore passage (CHANSON 2001).

Fig. 2 - Advection of bed material to the surface (bottom right of photograph) immediately downstream of an undular tidal bore - Dordogne river (Fra.), 27 Sept. 2000 around 5:00 pm - Looking from behind the advancing bore front

FIELD OBSERVATIONS

Field measurements in tidal bores are scarce. KJERFVE and FERREIRA (1993) and WOLANSKI et al. (2001) reported observations of sediment mixing immediately behind bores in the Rio Mearim (Bra.) and Ord river (Aus.) respectively. BARTSCH-WINKLER and LYNCH (1988) dropped bags of dye in the Turnagain Arm bore.

RULIFSON and TULL (1999) discussed the longitudinal dispersion of fish eggs in tidal bore affected rivers in the Bay of Fundy (Can.). KJERFVE and FERREIRA (1993) presented quantitative measurements of salinity and temperature changes behind a bore. Their data highlighted a sharp jump in water properties about 18 minutes after the bore passage at two locations, while a rapid change in salinity was observed 42 minutes after the bore passage at a more upstream location.

Two fascinating experiments were conducted by M. PARTIOT in the Seine river mouth (in BAZIN 1865, pp. 640-641). The experiments highlighted different flow patterns next to the surface and at deeper depths. On 13 Sept 1855, in front of the Chapel Barre-y-Va (downstream of Caudebec-en-Caux), two floats were introduced in the river flow (a) at the surface and (b) next to the bottom (3.3 m beneath the surface). When the undular bore arrived, the surface float (a) continued to flow downstream for 130 sec. after the bore passage and flowed upstream afterwards, while the bottom float (b) flowed downstream only 90 sec. after the bore passage. On 25 Sept 1855, in front of Vallon de Caudebecquet, three floats were introduced (a) at the surface, (b) 1.5 m beneath the surface and (c) next to the bottom, all in the middle of the river. At the undular surge arrival, the float (a) started to run upstream 145 sec. after the bore passage, while the floats (b) and (c) flowed upstream 60 sec. after the bore passing.

TURBULENT MIXING IN HYDRAULIC JUMPS AND BORES

Diffusion coefficient estimates in rivers and estuaries were developed for gradually-varied flows and uniform equilibrium flows. They do not apply to rapidly varied flow conditions: e.g., hydraulic jumps, tidal bores. Hydraulic jumps are known indeed for their strong mixing properties (HENDERSON 1966, CHANSON 1999). Experimental observations of mixing coefficients in hydraulic jumps and bores are summarised in Table 1. In laboratory hydraulic jumps, the vertical diffusion coefficient of entrained air bubbles was about:

$$\frac{\varepsilon_V}{V_1 * d_1} \approx 4.5\text{ E-2} \qquad 5.0 < Fr_1 < 8.5$$

in the turbulent shear flows, where d_1 is the upstream water depth, V_1 is the upstream flow velocity and $Fr_1 = V_1/\sqrt{g*d_1}$ (CHANSON and BRATTBERG 2000). In another series of experiments with dye and salt injection at the jump toe, complete vertical and transverse mixing was rapid implying a transverse mixing coefficient estimate:

$$\frac{\varepsilon_t}{V_1 * d_1} \approx 0.14 \qquad 5.9 < Fr_1 < 7.7$$

In the Ord river, transverse sediment diffusivity ε_t was estimated to be about 0.71 m^2/s. For comparison, measured transverse diffusivities were about 0.014 to 0.02 m^2/s in the Severn river that has a similar water depth and possibly smaller width (ELLIOTT et al.'s work, in LEWIS 1997).

Overall the results (Table 1) emphasise strong mixing coefficients that are consistent with field measurements in the Ord river and visual field observations elsewhere.

Table 1 - Experimental observations of vertical and lateral mixing in hydraulic jumps and bores

Experimental data	Fr_1	d_1 (m)	$\frac{\varepsilon_v}{V_1 * d_1}$ (1)	$\frac{\varepsilon_t}{V_1 * d_1}$ (1)	Remarks
(1)	(2)	(3)	(4)	(5)	(6)
CHANSON and BRATTBERG (2000)					W = 0.25 m. Air bubble entrainment at jump toe.
	5.01	0.0158	1.5E-2	--	
	5.67	0.0158	6.2E-2	--	
	6.05	0.017	6.1E-2	--	
	6.32	0.014	5.0E-2	--	
	8.03	0.0158	5.2E-2	--	
	8.11	0.0158	3.0E-2	--	
	8.48	0.014	4.5E-2	--	
BHARGAVA and OJHA (1990)					W = 0.3 m. Dye and salt injection at jump toe on centreline.
	7.30	0.0070	--	0.222	
	7.40	0.0072	--	0.227	
	6.37	0.0091	--	0.212	
	7.62	0.0109	--	0.123	
	8.11	0.0119	--	0.110	
	6.14	0.0150	--	0.105	
	5.90	0.0167	--	0.102	
	6.94	0.0162	--	0.083	
	6.42	0.0180	--	0.081	
WOLANSKI et al. (2001)	1.2 to 1.3	--	--	ε_t = 0.71 m^2/s	Undular tidal bore of the Ord river (East branch) on 31 Aug. 1999. W = 390 m (at mean still water level).

Notes : (1) data re-analysis by the writer; d_1, V_1, Fr_1 : upstream water depth, velocity & Froude number

DISCUSSION

ECOLOGICAL IMPACT OF TIDAL BORES

The impact of tidal bores on the ecology is acknowledged. In the Amazon river, piranhas eat matter in suspension after the passage of the bore (COUSTEAU and RICHARDS 1984). At Turnagain Arm inlet, bald eagles and eagles were seen fishing behind the bore, while beluga whales were observed playing in the bore as it formed near the mouth of the arm (BARTSCH-WINKLER and LYNCH 1988, MOLCHAN-DOUTHIT 1998). In the same estuary, a moose tried unsuccessfully to outrun the bore; he was caught and disappeared (MOLCHAN and DOUTHIT 1998).

In the Severn river, the bore impacted on sturgeons in the past and on elvers (young eels) today (WITTS 1999, JONES 2003). In the Bay of Fundy, RIFSON and TULL (1999) studied the impact of bores on striped bass spawning.

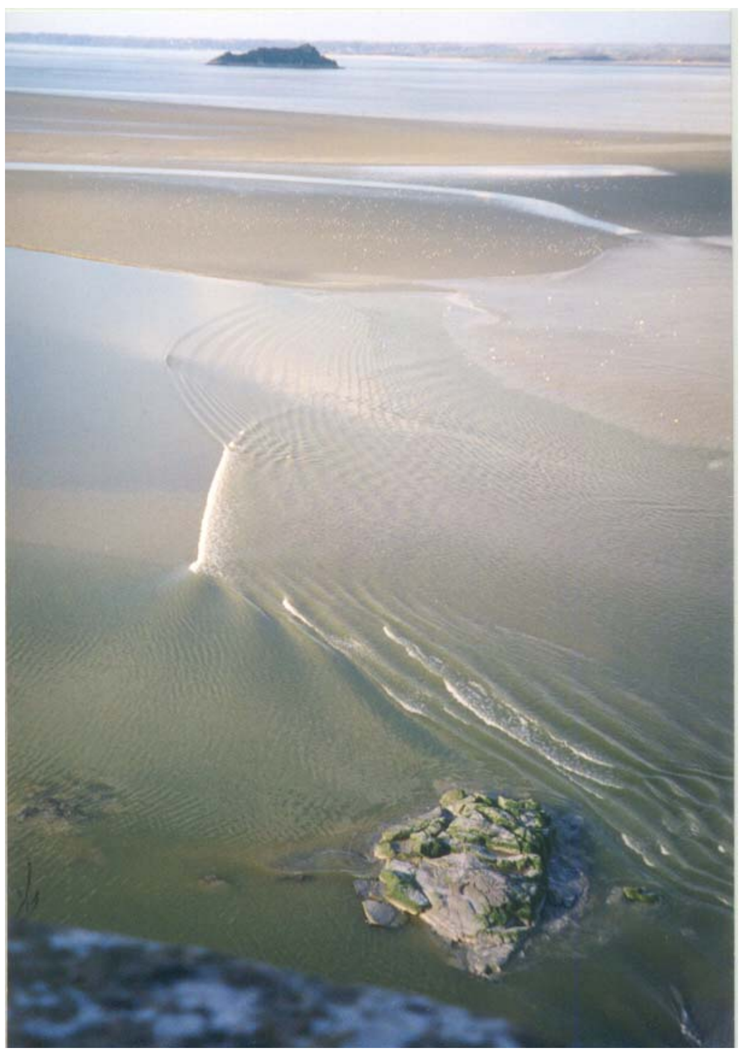
A FRAGILE BALANCE !

A tidal bore is a very fragile process. The bore development is closely linked with the tidal range and river mouth shape. Once formed, the bore existence relies upon the exact momentum balance between the initial and new flow conditions. A small change in boundary conditions and river flow may affect adversely the bore existence.

Dredging and river training yielded the disappearance of several tidal bores : the *mascaret* of the Seine river (Fra.) no longer exists, the Colorado river bore (Mex.) is drastically smaller. Although the fluvial traffic gained in safety in each case, the ecology of the estuarine zones were adversely affected. The tidal bores of the Couesnon (Fra.) and Petitcodiac (Ca.) rivers almost disappeared after construction of an upstream barrage (Fig. 3). Natural events may also affect a tidal bore. During the 1964 Alaska earthquake (magnitude 8.5), the inlet bed at Turnagain and Knik Arms subsided by 2.4 m. Since smaller bores have been observed. Also at Turnagain and Knik Arm inlets, strong and winds (opposing the flood tide) were seen to strengthen the bore.

On the other side, the construction of the Ord river dam (Aus.) induced siltation of the river mouth and appearance of a bore (WOLANSKI et al. 2001). The bore disappeared since following large flood flows in 2000 and 2001 which scoured the river bed.

Fig. 3 - Small tidal bore in the Couesnon river (Fra.), viewed from the Mont-Saint-Michel on 19 March 1996 (Courtesy of Dr Pedro LOMONACO) - Bore direction from right to left



SUMMARY AND CONCLUSION

The occurrence of tidal bores has a significant impact on river mouths and estuarine systems. Bed erosion and scour take place beneath the bore front while suspended matters are carried upwards in the ensuing wave motion. The process contributes to significant sediment transport with deposition in upstream intertidal areas. Basically tidal bores induce strong mixing and dispersion in the river mouth. Classical mixing theories do not account for such type of discontinuities. Analogies with hydraulic jumps and positive surges suggest that both vertical and transverse mixing coefficients are much greater than the estuary flow diffusivities (in absence of bore).

Tidal bores impact significantly on eco-systems. Few studies documented the effects, but these are difficult because of the limited number of bore occurrence each year at one site. Further the existence of tidal bores is based upon a fragile hydrodynamic balance, which may be easily disturbed by changes in boundary conditions and freshwater inflow. Man-made interventions led to the disappearance of several bores, with often adverse impacts onto the eco-system.

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