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Estuarine, Coastal and Shelf Science 60 (2004) 629–636
ESTUARINE COASTAL AND SHELF SCIENCE
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Undular tidal bore dynamics in the Daly Estuary, Northern Australia

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Received 2 January 2004; accepted 10 March 2004

Abstract

Measurements in the macro-tidal Daly Estuary show that the presence of an undular tidal bore contributed negligibly to the dissipation of tidal energy. No recirculation bubble was observed between a trough and the following wave crest in the lee waves following the undular bore. This differs to stationary undular bores in laboratory experiments at larger Froude numbers where a recirculation bubble exists. Secondary motions and the turbulence generated by the undular bore had no measurable influence on the sediment transport. This situation contrasts with the intense sediment resuspension observed in breaking tidal bores. The tidally averaged sediment budget in the Daly Estuary was controlled by the asymmetry of tidal currents. The undular bore may widen the river by breaking along the banks that it undercuts, leading to bank slippage. A patch of river-wide macro-turbulence of 3-min duration occurred about 20 min after the passage of the bore during accelerating tidal currents.

Keywords: tidal bore; recirculating flow; sediment transport; tide-velocity asymmetry; turbulence

1. Introduction

A tidal bore is a positive surge that may form at flood tide in shallow estuaries with a large tidal range (Bazin, 1865; Tricker, 1965; Lynch, 1982; Chanson, 1999, 2001; Simpson et al., 2004-this issue). There are two types of tidal bores, an undular bore and a breaking bore (Chanson, 1999). Energy is released as turbulent kinetic energy in a breaking bore and this turbulence resuspends sediment (Wolanski et al., 2001; Simpson et al., 2004-this issue). In an undular bore (Fig. 1a), there is an upward velocity flux between each trough and following crest, as observed in laboratory experiments and predicted by ideal fluid flow calculations (Chanson, 2001). In a steady undular jump, a recirculation bubble is observed beneath the first crest. Chanson proposed that such flow motion could carry sediment upward and contribute to sediment transport with deposition in upstream intertidal areas. No field data exist to quantify undular tidal bore dynamics in estuaries where the bore is propagating up the estuary instead of being stationary as in a laboratory flume. To obtain such field data, we conducted a field experiment in the Daly Estuary (Fig. 2). This estuary is shallow, with numerous sand and mud banks emerging at low tide particularly in the lower 30 km. The estuary is 100 km long and is macro-tidal with a peak spring tidal range of about 6 m at the mouth (Chappell, 1993; Royal Australian Navy Tide Tables). An undular bore was present. Vertical currents during the passage of the bore showed no spike or features different to those during the rest of the tidal cycle. This observation suggests that there was no recirculation bubble. Further supporting evidence for this is that no instantaneous resuspension of sediments was observed under the bore. A patch of river-wide macro-turbulence of 3-min duration occurred about 20 min after the passage of the bore. Tidally driven sediment resuspension processes dominated. The undular bore appeared to have little influence on the sediment budget.

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doi:10.1016/j.ecss.2004.03.001

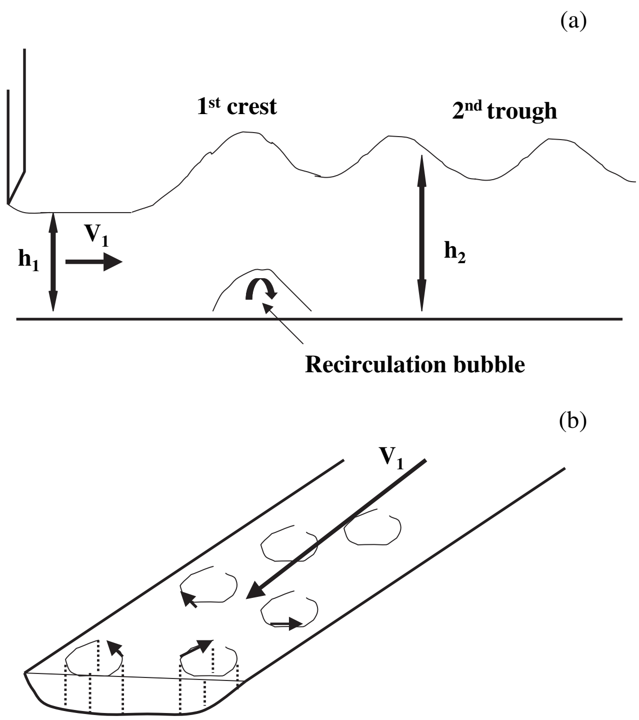

Fig. 1. (a) Sketch of a steady undular hydraulic jump in a laboratory flume. (b) Sketch of the 3-min-duration patch of macro-turbulence that occurred 20 min after the passage of the undular bore in the Daly Estuary.

2. Methods

To measure the tidal bore speed, we deployed two bottom-mounted Rigo and Aqualab Diver water level recorders at sites A and B on September 9, 2002 (see Fig. 2 for a location map). These gauges recorded data at 2-s intervals. The speed of the bore was also measured by a GPS while following the tidal bore with a small boat.

To measure the internal water and sediment dynamics in an undular bore at spring tide, on July 1, 2003, we deployed for one tidal cycle two 1.2-m-high aluminum frames at site C. At this section the estuary is straight, about 120 m wide, with steep banks, the depth was 1.5 m at low tide on the east side and increasing linearly to about 4 m on the west side (Fig. 2). The frames contained a Nortek Aquadopp ADCP and nephelometers (Table 1). The ADCP bin size was 1 m. This mooring also contained an upward looking RDI ADCP. Twenty meters downstream we deployed a 3rd mooring as a tripod containing an InterOcean model S4 current meter. We repeated this experiment on August 2, 2003, with one mooring. These instruments collected data at a sampling interval of 0.5 or 1 s. (see Table 1).

Also at site C we deployed for 28 days a tripod containing an InterOcean model S4 current meter and a nephelometer, these instruments collected data every 15 min.

A SeaBird SBE 39 CTD with an Analite nephelometer was used to measure vertical profiles of salinity, temperature and suspended sediment concentration (SSC) at stations.

Microphotographs of suspended matter were obtained using the technique of Ayukai and Wolanski (1997).

River gauging data were provided by the Department of Infrastructure, Planning, and Environment (DIPE).

3. Results

The freshwater discharge was about 30 $m^3 s^{-1}$. The resulting mean velocity at site C was about 0.07 $m s^{-1}$ at low tide and 0.01 $m s^{-1}$ at high tide. By comparison the peak tidal velocity was about 0.7 $m s^{-1}$ at 0.5 m off the bottom.

The estuary was well-mixed in salinity and temperature. The salinity was 0 at station A and 2 (psu) at station B at low tide. The estuary was continuously stratified in suspended sediment concentration (SSC), with no lutocline. The SSC stratification was the smallest (not shown) during peak tidal currents. In the river SSC was about 0.005 $kg m^{-3}$. A turbidity maximum was observed near the salinity intrusion limit, the peak SSC was about 5 $kg m^{-3}$.

The microphotographs revealed (not shown) that the suspended matter was flocculated mud, the flocs were small (diameter less than 50 microns) and no marine snow was observed.

An undular bore was observed. The water was smooth upstream of the bore (Fig. 3a) and in the leading wave. A series of waves occurred downstream of the bore, mainly traveling along-channel. There were also waves traveling across the channel, particularly near river bends (Fig. 3b). The bore broke only along the banks (Fig. 3c) as a plunging breaker.

On September 9, 2002, the tidal bore propagated from stations B to A at a speed of about 4.7 $m s^{-1}$ (not shown) and it decreased in amplitude from 0.6 m to 0.4 m. On July 2, 2003 the tidal bore at site C had an amplitude of 0.4 m (Fig. 3) and it had two pronounced lee waves about 0.1 m in amplitude and with a period of about 12 s. The tide range at site C was 2.2 m on that day, while the predicted tide range at the mouth was 5.8 m. The along-channel velocity changed abruptly from about 0.15 $m s^{-1}$ (oriented downriver) ahead of the bore to -0.5 $m s^{-1}$ (oriented up-river) after the passage of the wave. The two dominant lee waves generated current fluctuations of ± 0.15 $m s^{-1}$. The bore generated no pronounced vertical velocities and no sediment resuspension (Fig. 4). A major resuspension of sediment occurred 2 min after the passage of the bore at an elevation of 0.45 m and 30 s later at an elevation of 1.26 m.

With $h_1 = 1.5$ m (initial water depth before bore arrival), $h_2 = 2$ m (water depth after the bore),

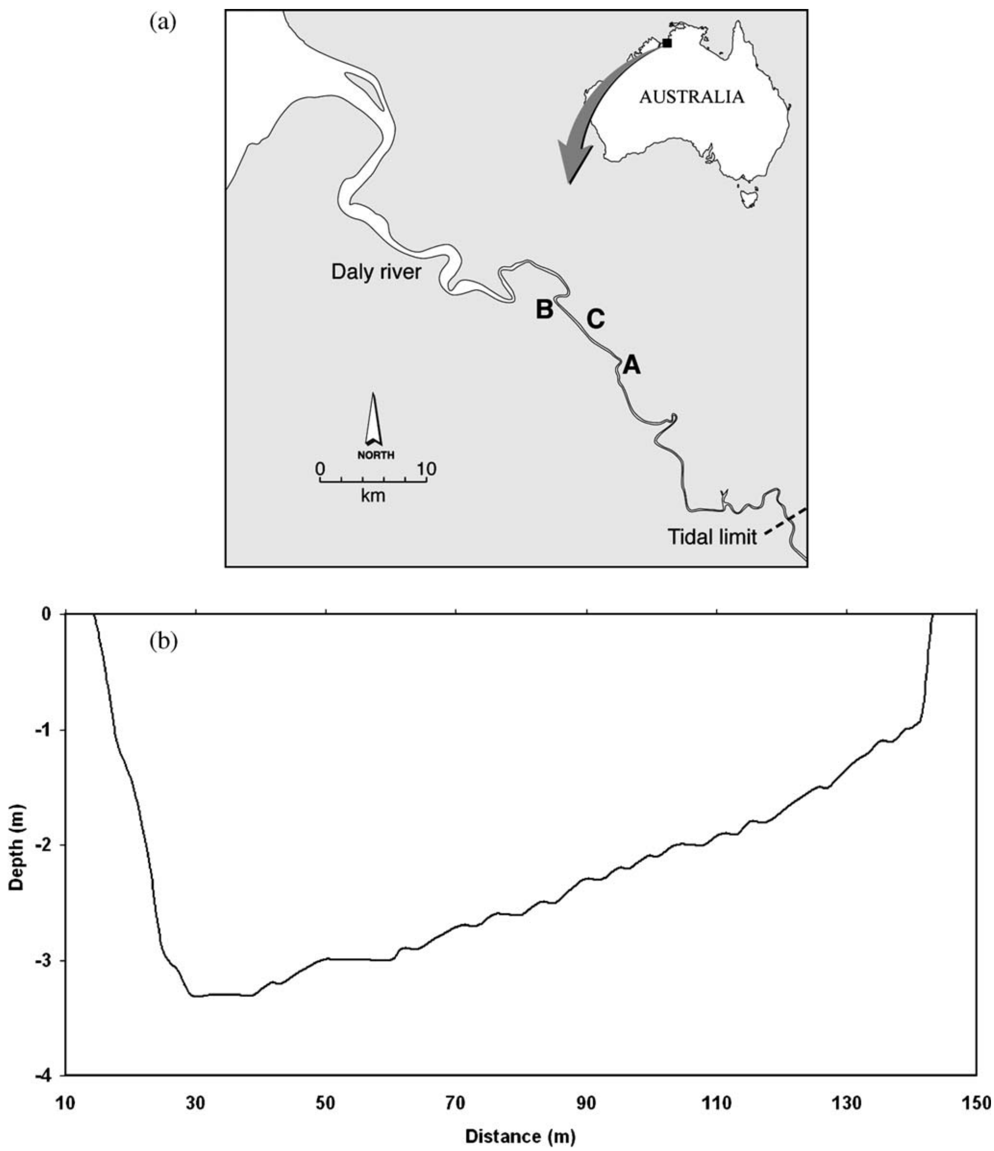

Fig. 2. (a) Location map of the Daly Estuary, Northern Australia, and mooring sites A–C. (b) Cross-section at site C at low tide.

$C = 4.5\ \mathrm{m\,s^{-1}}$ (surge celerity for an observer standing on the bank), $V_1 = +0.2\ \mathrm{m\,s^{-1}}$ (river flow velocity before bore arrival), $V_2 = -0.5\ \mathrm{m\,s^{-1}}$ (river flow after bore passage), the surge Froude number, *Fr*, defined as seen by an observer moving with the bore front (Henderson, 1966; Chanson, 1999) was:

$$Fr = (C + V_1)/(g\,h_1)^{1/2} \sim 1.22$$

About 20 min after the passage of the bore the two aluminum frames at site C were toppled. At exactly the same time the bottom-mounted ADCP in the mooring 20 m away and that did not topple, measured rapid fluctuations of along-channel velocity of $\pm 0.5\ \mathrm{m\,s^{-1}}$ at 10-s intervals, superimposed on a tidal current of $0.7\ \mathrm{m\,s^{-1}}$ (Fig. 5). The cross-channel velocity also fluctuated, suggesting (see Fig. 5) the presence of eddies embedded within the main (tidal) flow and rotating alternately clockwise and counterclockwise. The corresponding water level fluctuations were about 1 cm. This event lasted for about 3 min. A similar event was also observed (not shown) on August 2, 2003 when spring tides prevailed.

The mean vertical velocity measured 1 m from the bottom changed from downward to upward simultaneously with the passage of the tidal bore and although not of a pronounced magnitude corresponded with the reversal of the tidal current.

At spring tide, a marked tidal asymmetry prevailed (Fig. 6). At site C, the flood tide lasted 3 h and the ebb tide lasted 9 h. The peak tidal current was 1.5 times larger at flood than at ebb tides. The SSC fluctuated at tidal frequency, with a marked peak at flood tide and a number of smaller peaks at ebb tide.

Table 1
Details of the moorings and equipment at site C

	Height (m)	Sample rate
(a) Short-term deployment over a tidal bore. Start 18:00:00 01/07/2003. Stop 10:20:00 02/07/2003		
Nephelometer	0.45	1 s
Nephelometer	1.26	1 s
InterOcean S4 current meter	0.55	0.5 s (response time of pressure sensor = 0.06 s)
Nortek Aquadopp ADCP	0.5	0.5 s
(b) Long-term deployment over a spring–neap cycle. Start 10:45:00 05/07/200. Stop 10:10:00 02/08/2003		
InterOcean S4 current meter	0.55	15 min
Nephelometer	0.15	15 min

4. Discussion

The Daly Estuary was well-mixed in salinity and temperature, with salinity intruding about 30 km upriver at low tide in the dry seasons of 2002 and 2003. Even at high tide the water remained fresh 50 km upriver. The waters were very muddy and turbid with peak SSC reaching about 5 kg m^{-3}. The fine sediment was flocculated and the sediment was mostly inorganic, as in other muddy, tropical macro-tidal estuaries (Wolanski and Gibbs, 1995; Wolanski et al., 2001).

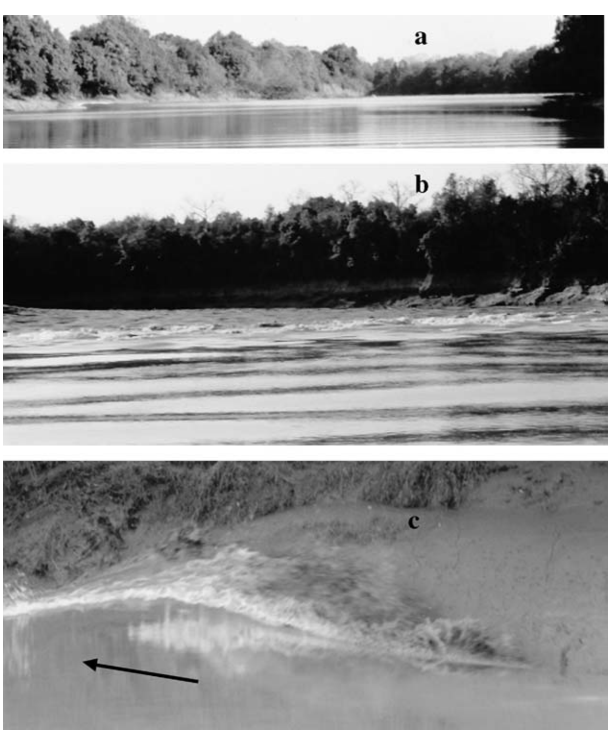

Fig. 3. Photographs on the Daly Estuary undular tidal bore on September 9, 2002, (a) from upstream of the bore, (b) from downstream of the bore, and (c) close-up of the breaking bore along the bank. The arrow points to smooth waters.

There was a pronounced tidal asymmetry in water level and tidal currents, with the ebb tide lasting much longer than the flood tide, with correspondingly larger flood than ebb tidal currents. This asymmetry observed during the dry season may result in sediment being moved into the estuary from the sea. This finding is in agreement with geomorphology studies suggesting a rapid infilling of the Daly Estuary when it was flooded by rising sea level at the end of the last Ice Age (Chappell, 1993). The suspended sediment concentration did not vary in direct relation with current speed, especially at ebb tide when a number of high turbidity events occurred without corresponding variations in current speeds (Fig. 6). This implies the advection of patches of high turbidity waters or the fluidization of the bed.

The estuary had a 0.3–0.6 m undular tidal bore at spring tide. This bore comprised a dominant leading wave and two lee waves of amplitude about half that of the frontal wave. The waves did not break except on the banks. In the mid to upper reaches of the estuary, the tidal bore propagated at a speed of 4.7 m s^{-1} and decreased in amplitude at a rate of about 5% km^{-1}. The wave speed C is consistent with the theoretical predictions (~5.3 m s^{-1}) of the speed of a hydraulic jump (Lamb, 1932):

$$C = (0.5g\, h_2(1 + h_2/h_1))^{1/2}$$

where g is the acceleration due to gravity and h_1 (~2 m) and h_2 (~2.5 m) are the depths before and after the passage of the bore.

Note in Fig. 2c the smooth surface away from the breaker. Contrary to wind-driven waves, undular bores are very smooth with no capillary waves.

The observed 2nd wave crest was very flat; this has been observed in the laboratory (Chanson, unpublished data) and the reasons remain unknown.

The bore height reduction by 0.2 m from A to B is unexplained. It could arise from diffraction of energy along the wave crest toward the breaking wave at the shoreline, fluidization of the bed, or progressive wave reflection from the rising bed and shoals. This may be better understood when a bathymetric survey has been completed.

The undular bore did not generate a measurable vertical velocity and a recirculation bubble that would resuspend sediment underneath the bore, contrary to the situation in laboratory flumes (Fig. 1). Hence there was no significant vertical motion occurring between a trough and the following wave crest. This situation contrasts with that in stationary tidal bores in laboratory flumes where such vertical motions are prevalent and are due to non-hydrostatic effects (Montes and Chanson, 1998; Chanson, 2001). This major difference between field observations and laboratory may be due to differences in bottom friction, and possibly also to

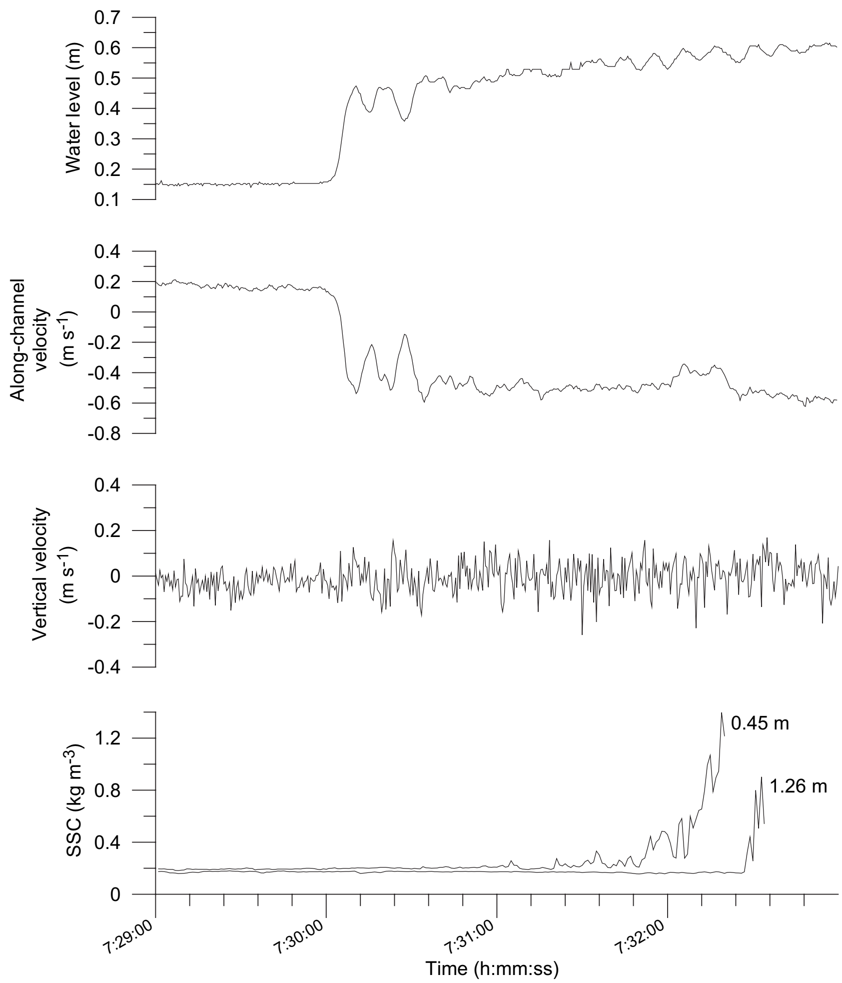

Fig. 4. Time series plot during the passage of the undular bore in the morning of July 2, 2003, at site C, of the water level, the velocity at 0.55 m from the bottom, the vertical velocity at 1 m from the bottom, and the suspended sediment concentration (SSC) at 0.45 and 1.26 m from the bottom. The nephelometers saturated at about 1 kg m^{-3}.

a non-prismatic channel cross-section. It is conceivable that large natural roughness and bed forms significantly perturb the flow field next to the bottom and dampen upward sediment motion. However, the observed bore had a slightly lower surge Froude number than the flow conditions investigated in the laboratory ($Fr = 1.35$ and 1.6). Present findings also suggest that the numerical techniques for simulating the vertical flow structure of hydraulic jumps (e.g. Stelling and Busnelli, 2001) may not be applicable to propagating undular bore with low Froude numbers. An undular bore thus may contribute little to the dissipation of tidal energy, contrary to the case of a breaking bore (Simpson et al., 2004-this issue).

There were major discrepancies between the lee waves behind the bore in the field and the laboratory. At the mooring, the surge Froude number was about 1.2. For this value of Fr, the ideal fluid flow theory (Chanson, 1996) predicts a wave length (L) and height (Dd) of about $L = 9{-}10$ m and Dd = 0.25 m, respectively. Hence, based on these observations, the time between successive wave crests would be expected to be about $L/C \sim 2.2$ s. In the field the first three wavelengths took about 22 s, which yields about 7 s per wavelength. The observed and predicted wave heights are in agreement and there is some discrepancy for the wavelength. The reasons for this discrepancy are uncertain. It is worth mentioning that in the laboratory the predicted wavelength is inversely proportional to $(Fr - 1)$ (Chanson, 1995). Hence, an error on the estimate of Fr may yield a large error in the predicted wavelength. Another reason may be the three-dimensional flow field generated by the complex bathymetry comprising channels, shoals and meanders that constantly radiate and reform the waves. Three waves were observed on July 1, 2003, and four waves on September 9, 2002. This suggests that the number of waves depends on the tidal range.

For $Fr \sim 1.2$, the laboratory studies (Chanson, 2001) suggest that the wave height measured using a bottom-mounted pressure sensor could be under-estimated by 10%. Due to the absence of a recirculation bubble non-hydrostatic effects were probably not important in the Daly River tidal bore.

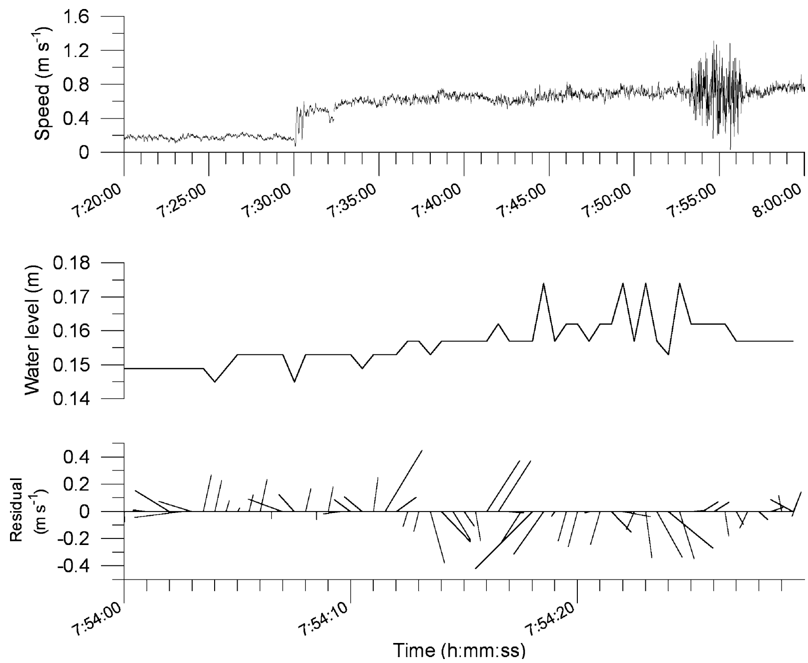

Fig. 5. (Top) Time series plot spanning 40 min during the passage the undular tidal bore, on July 2, 2003, of the water speed at site C at 0.55 m from the bottom. Note the 3-min-duration patch of macro-turbulence around 0755 h on July 2, 2003. (Middle and bottom) Time series plot spanning 30 s of the sea level and the residual velocity during the macro-turbulence event.

Accelerating tidal currents resuspended the sediment 2 min after the passage of the undular bore. This situation contrasts with breaking bores where the resuspension of sediments under the bore is nearly instantaneous (within a few seconds; Wolanski et al., 2001; Simpson et al., 2004-this issue).

The time lag between resuspension and the passage of the bore may be attributed to the time it takes to diffuse

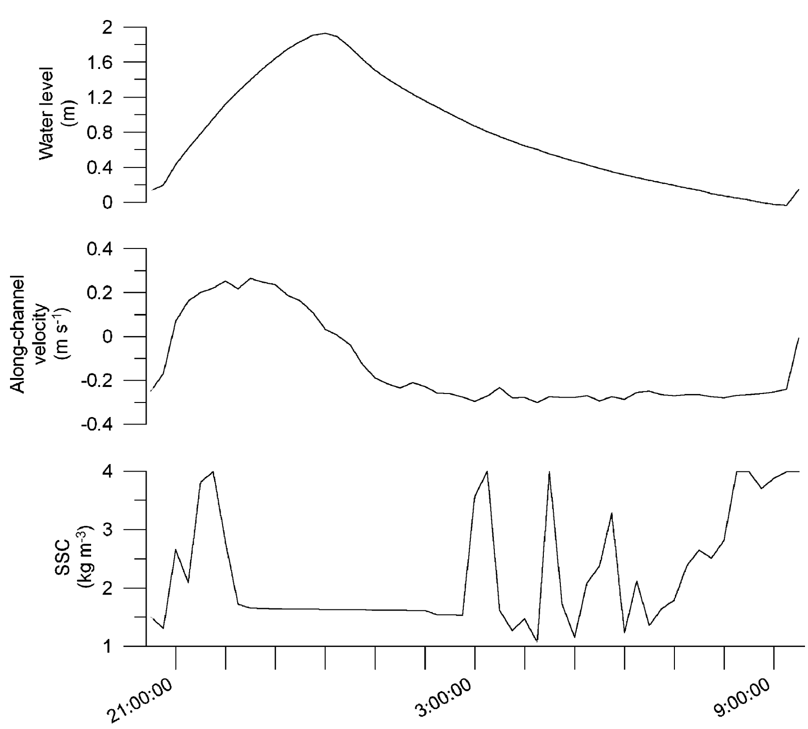

Fig. 6. Time series plot spanning one tidal cycle on July 5–6, 2003, of the sea level, the along-channel velocity at 0.55 m from bottom, and the suspended sediment concentration (SSC) at 0.15 m from the bottom.

sediment upwards. The velocity reached $0.6\ \mathrm{m\,s^{-1}}$, fast enough to resuspend sediment. The data imply that it takes 2 min to diffuse the sediment in the water column by $h = 0.45$ m from the bottom (Fig. 3). The diffusion time scale T is

$$T = (z^2/K)$$

where z is the elevation above the bottom and K the vertical eddy diffusion coefficient. The data show that $T = 120$ s for $z = 0.45$ m, which yields $K = 0.0017\ \mathrm{m^2\,s^{-1}}$. At $z = 1.26$ m, $T = 150$ s, which yields $K = 0.01\ \mathrm{m^2\,s^{-1}}$. Theoretical estimates of K suggest (Fischer et al., 1979)

$$K = ku_*z$$

where $k = 0.4$ is the Karman constant, u_* = shear velocity $\sim 0.05u$ (Wolanski et al., 1988), and u = free stream velocity. Taking $u = 0.5\ \mathrm{m\,s^{-1}}$ under and after the bore, results in $K = 0.0045\ \mathrm{m^2\,s^{-1}}$ at $z = 0.45$ m, and $K = 0.0125\ \mathrm{m^2\,s^{-1}}$ at $z = 1.26$ m. These predictions are in qualitative agreement with observations.

The undular bore may still contribute measurably to sediment dynamics. The bore broke along the bank where it resuspended the fine sediment (Fig. 2). This erosive power was evidenced by a definite level on the near vertical river bank sections where the bore has undercut the banks. At many places the undercutting had reached a critical level and a columnar bank had collapsed. This contributed to channel widening or migration, and was a source of sediment loading to the stream.

About 20 min after the passage of the undular bore, a 3-min-duration patch of macro-turbulence was observed. Horizontal eddies with peak velocity V of about $0.5\ \mathrm{m\,s^{-1}}$ were imbedded within a prevailing tidal current of about $0.7\ \mathrm{m\,s^{-1}}$. This unsteady motion was sufficiently energetic to topple moorings that had survived much higher, quasi-steady currents of $1.8\ \mathrm{m\,s^{-1}}$ (Wolanski et al., 2001). Both clockwise and counterclockwise rotating eddies were observed. Since these eddies lasted typically 10 s, their horizontal dimensions were about 7 m in depth of about 3 m. These eddies were associated with water level fluctuations not exceeding 1 cm. If these eddies were in horizontal, solid body rotation, water level fluctuations η could be computed by a balance between the centrifugal acceleration and the hydrostatic pressure:

$$\eta \sim V^2/2g \sim 1.2\ \mathrm{cm}$$

This suggests that the eddies were quasi two-dimensional, rotating around a vertical axis, as sketched in Fig. 1b.

The reason for the presence of a 3-min-long patch of macro-turbulence in the estuary about 20 min after the passage of the undular bore, as sketched in Fig. 1b, is unknown. The macro-turbulence may be due to horizontal or vertical shear instability. Patriot (in Bazin, 1865) conducted some experiments in the Seine River in 1855. Floats were introduced at several heights prior to the arrival of the tidal bore. The float direction was observed after the bore passage. In one case, the surface float continued to float downstream for about 2 min after the bore, while the bottom float flowed downstream only for 1.5 min. Afterwards the floats flowed upstream. In the Daly Estuary, the horizontal shear after passage of the bore was considerable because floating logs and debris were entrained by energetic eddies away from the banks and towards the middle of the channel. The patch of macro-turbulence 20 min after the passage of the bore may also be due to a hydrodynamic, estuarine-wide instability generated by the bore. Indeed, from the two water level recorders in the estuary, the water level slope was calculated. The slope (not shown) increased continuously with rising tides, except that 20–30 min after the passage of the tidal bore it remained constant for about 10 min, while the tide kept rising. At that time presumably bottom friction could not dissipate the kinetic energy and the flow became unstable, generating macro-turbulence. Lateral shear instability may also be responsible for generating macro-turbulence because of the sloping bottom (Fig. 2). There is no evidence from visual observations for a topographic source for separating eddies that would come into play at a critical tidal level.

A comparison of the 1980 topographic map and a 2000 satellite image (not shown) shows that the estuary has migrated laterally by up to 500 m in the lower reaches. A rough calculation indicates that $\sim 2.4 \times 10^6\ \mathrm{m^3}$ of soil has been moved from two locations in this 20-year period which is enough to block the channel at the location where we encountered a 30-km-long sandbar starting at the mouth. This adds to the shoaling at the mouth of the estuary and thus presumably helps to maintain the tidal bore.

5. Conclusions

There are unexplained differences between the propagating undular bore in the Daly Estuary and the stationary undular bore in the laboratory. One main reason for this discrepancy may be the role of bottom friction. At the time of bore arrival, and immediately after the bore front, the depth is very shallow especially compared to the bottom width. Hence, bottom friction is likely to have a major effect, especially in view of the complex bathymetry comprising channels, sand bars and meanders. Laboratory experiments were performed with a narrower, straight channel. The laboratory experiments are steady and provide a realistic picture of the ideal fluid flow region, as long as the boundary layer is thin. In the flume experiments of Chanson (2001) and Donnelly and Chanson (2002), the inflow conditions were designed to achieve a ratio of upstream boundary layer thickness to upstream flow depth less than 0.5 (∼0.35 to 0.4). However, the flow region next to the bottom in the field, where turbulence and boundary friction effects are important, cannot be reliably modelled either by ideal fluid flow theory or by steady-flow flume experiments. The Daly Estuary data further illustrate this point.

Acknowledgements

It is a pleasure to thank Cary McLean, Ingrid Chudleigh, AIMS and DIPE. JH Simpson, WH McAnally and S Mitchell criticized and improved an earlier version of this paper.

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