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Support of subtidal tracer studies to quantify the complex morphodynamics of a river outlet: the Bevano, NE Italy.

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ABSTRACT

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Evolution of tidal inlets or river outlets has been widely described all over the world. However, most conceptual models are based on the long term perspective and field measurements to confirm these evolution schemes are scarce. The objective of the present study is to quantify the processes occurring at a small river outlet, the Bevano, during fair weather conditions. Subtidal fluorescent sand tracer method involving a new detection tool were used in the inlet and along the adjacent coast to assess sediment transport and bypassing processes. At the river mouth, sediment fluxes confirm an efficient bypass of sand through the inlet's channel. However, this sediment transport is combined with migration processes of the channel (40 m in 2 months), and yields a self-alimentation of both updrift and downdrift coasts. As it has already been observed at small tidal inlets, migration of the Bevano river mouth results from the erosion of the downdrift coast, and readjustment of the cross-section by the longshore transport on the updrift coast. The detection device used for subtidal tracing has given encouraging results and will be improved in order to work in more dynamic environments.

ADITIONAL INDEX WORDS: *tidal inlet, fluorescent sand tracers, sand bypassing processes*

INTRODUCTION

Tidal inlets morphodynamics results from complex interactions between waves, tidal currents and river discharge. Conceptual models of these systems are often based on long term observations integrating all factors involved in the system evolution. Short term measurements to calibrate these assumptions are scarce, mainly because direct measurements in such energetic places are very often impossible.

Sediment transport characterisation and quantification by fluorescent sand tracers have been widely and successfully used on straight beaches (WHITE and INMAN, 1989, CIAVOLA et al., 1997, BALOUIN et al., in press). Recent studies (BALOUIN et al., 2001, FERREIRA et al, 2002, VILA-CONCEJO et al., 2003) have demonstrated the possible use of this technique in more energetic environments like swash bars, tidal deltas and a port harbour. However, the tracer detection in subtidal environments such as channel areas is still very difficult to realise, and to the knowledge of the authors, no experiment at the moment was successful in characterising sediment by-passing processes at a tidal inlet.

This paper focuses on the morphodynamics of a small river outlet, the Bevano, located in the northern Adriatic near the town of Ravenna (Figure 1), and on the assessment of sediment transport patterns and their quantification using a newly developed device for fluorescent sand detection.

Physical settings of the studied area

The Bevano is a small river draining a basin of 92.5 km². The river discharge (Q_{355}=0.064 m^3/s, BENATI, 2003) is very low in respect to the tidal prism ($3x10^5$ m^3) and is considered negligible during the studied period (April to June 2003) which was particularly dry. Due to the low river discharge during this fair weather period, the river mouth behaved like a tidal inlet without freshwater input.

Longshore sand transport in the area takes place from south to north (BONDESAN et al., 1978). Consequently, the southern coast of Lido di Classe is described as the updrift coast, and the northern beach of Lido di Dante, as the downdrift one.

Long term evolution of the Bevano entrance (REGIONE EMILIA-ROMAGNA, 2003, ARMAROLI et al., 2004) is characterised by a northwards migration of the inlet, followed by the breaching of the spit re-initialising the migration cycle.

Tidal regime in the Northern Adriatic is strongly asymmetric, showing both diurnal and semi-diurnal components (see Figure 2). Maximum tidal range is about 1.2 m during spring tides. Waves climate is usually a low energy one with significant wave heights less than 0.5m, mainly from the East (more than 65% of occurrences, GAMBOLATI et al., 1998). Two different storm directions prevail in the Adriatic Sea: the Scirocco from SE, and the Bora from NE.

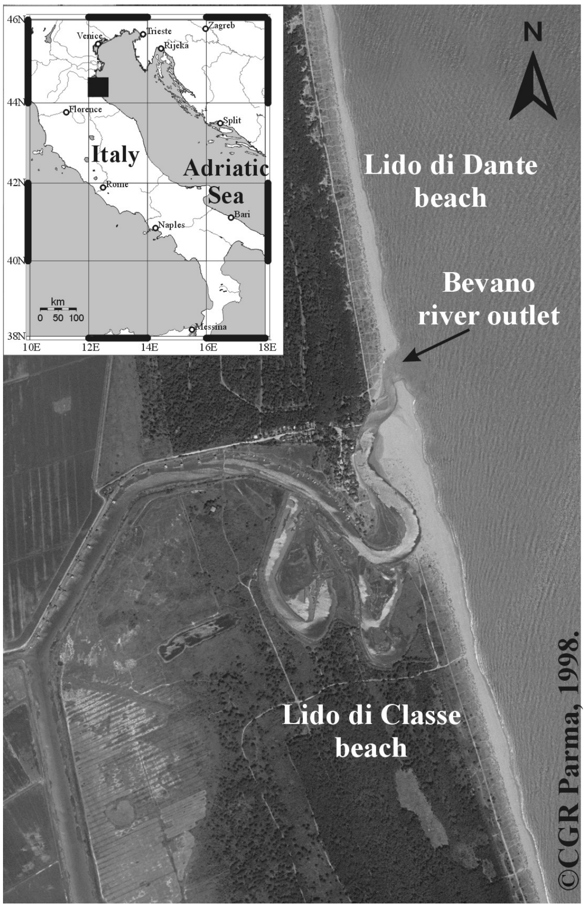

Figure 1: Location of the Bevano river mouth in Northern Adriatic.

METHODS

Classical monitoring methods were used, involving regular topographic surveys of intertidal areas, bathymetry, and hydrodynamics measurements in the inlet with an Aanderaa RCM9MKII and in the nearshore zone with an ADCP able to measure waves. Moreover, within the EU project COASTVIEW, intensive fieldwork was performed from 13/04/03 to 26/04/03 on the Bevano inlet and the adjacent downdrift beach, the Lido di Dante. In order to quantify sediment transport, fluorescent sand tracers were injected: 50 Kg of red one in the main channel and 25 Kg of green one on the updrift littoral zone. Superficial detection (Spatial Integration Method, WHITE and INMAN, 1989) was performed during the successive low tide, using a subtidal device to quantify fluorescent tracer dispersion.

The detector/counter was conceived to trace, *in situ* and without any disturbance, the displacement of fluorescent grains within the upper sand layer. The present subtidal system is a prototype developed at the University of Bordeaux, based on a previous intertidal detecting/counting device (De RESSEGUIER, 1987, HOWA et al., 1994, PEDREROS et al., 1996, MICHEL and HOWA, 1999, BALOUIN et al., 2001). Measurement takes place in a vertically mobile dark box (20x20x30 cm), which is lowered on to the sediment surface during data acquisition, at each grid node. The sediment surface is illuminated by two 360nm Ultraviolet tubes, which excite the tracer grain luminescence. At the top of the dark box, a CCD camera provided with a narrow spectral range filter selects the light spectrum corresponding to the colour of the chosen dye. In the central unit onboard, a Matrox Meteor grabber captures a monochrome picture coming from the video camera. This image is analysed line after line, resulting in the count of illuminated pixels. Size in pixels of fluorescent grains is previously calibrated taking into account the natural background fluorescence, in order to obtain the number of fluorescent grains from the image analysis routine. When the whole image analyses routine is accomplished, data are converted in terms of number of fluorescent grains per surface unit and recorded.

At the moment, the system is equipped with a 4m cable, permitting the detection until depths of 3.5m. During operation of detection, the boat is moved along the sampling grid, and the counting device is lowered at each grid node. The position of each sampling point is obtain by a GPS system.

The combined use of the detector/counter with small coring allows to accurately determine the 3D geometry of the tracer cloud. When the recovery rate is good (e.g. more than 60 % of the immersed tracer is recovered) the quantification of the transport (direction and rate of transport) is possible. In this study, more than 80 cores were taken to assess the vertical distribution of sediment transport. Twenty cm long cores were sub-sampled every 2 cm, and each sample was analyzed using the same device to obtain the fluorescence density.

RESULTS

Hydrodynamics of the Bevano area

Wave energy during the survey was very low, with $0.4 < Hs < 0.7$ m, $4 < Ts < 6$ s, and mean direction from the East, almost cross-shore (Figure 2).

Measurements were taken in the inlet throat during the tracer experiment, in a neap-tide period. They have an almost diurnal tidal curve, with a strong ebb-tidal dominance. Ebb tide was 16h long, with maximum speeds before low tide, reaching 1.7 m/s. The tidal prism for the present configuration of the inlet is about $3x10^5$ m^3. Due to the strong meandering of the river entrance, ebb-

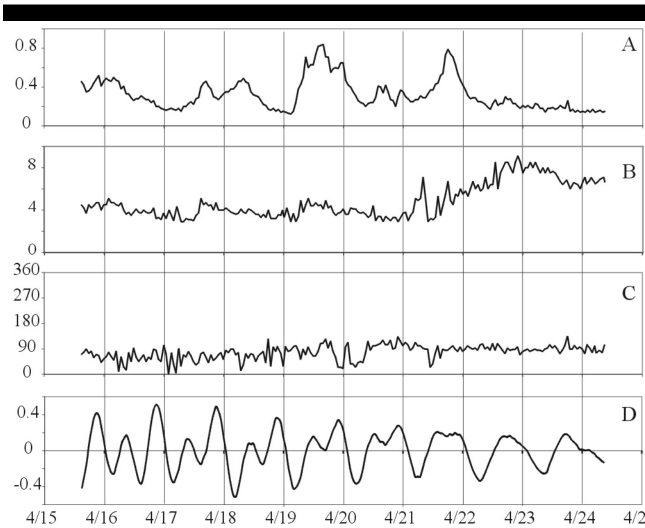

Figure 2: Wave characteristics during the intensive fieldwork in April 2003. a) significative height (m), b) peak period (s), c) wave peak direction, d) tidal levels.

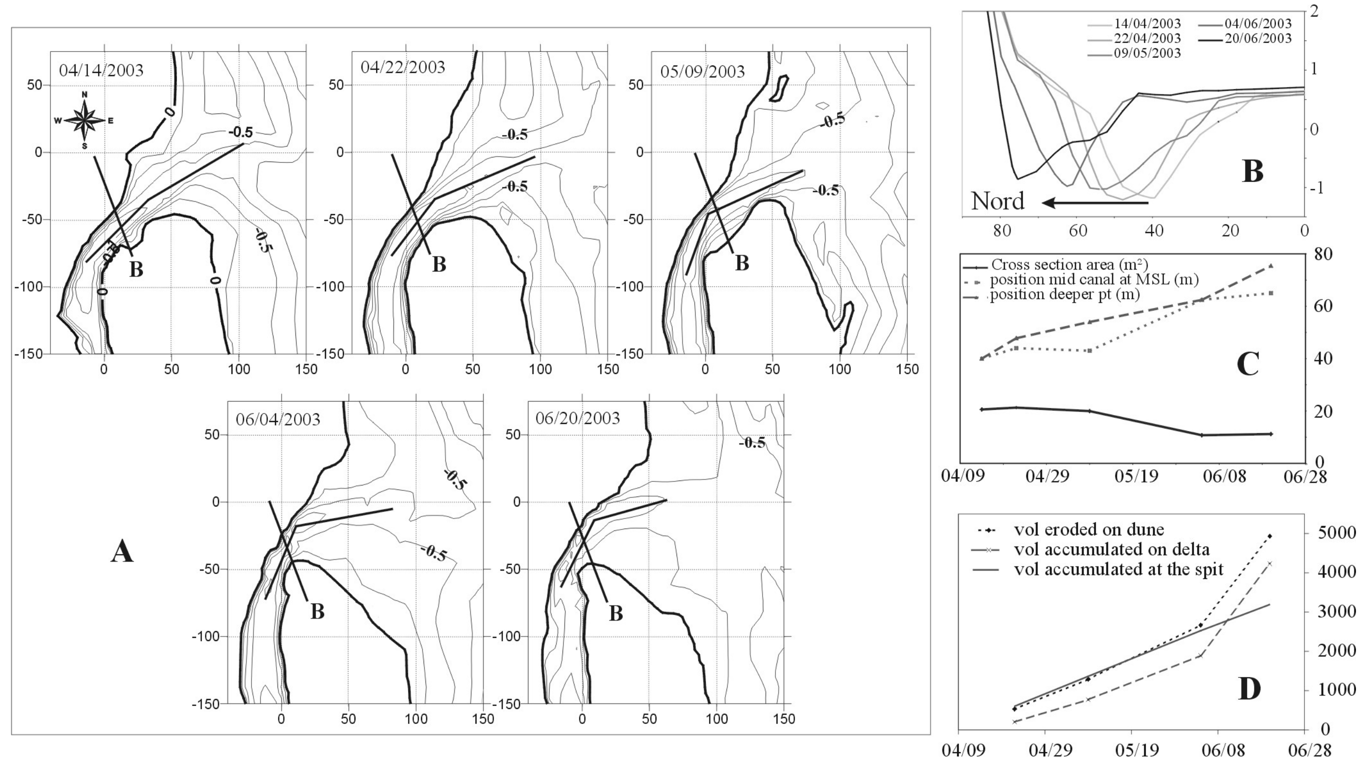

Figure 3: Morphological evolution of the Bevano inlet during fair weather conditions. A) topobathymetry of the Bevano entrance illustrating the progressive northward migration of the system, and rotation of the main channel (black lines); b) lateral migration of the inlet throat (m) (see location of the section in A)); c) Evolution of the cross sectional area (m²) and changes in the position of the inlet throat; d) Cumulative volume variations (m^3) on the ebb-tidal delta, at the extremity of the updrift spit and on the downdrift dune during the same period.

currents reaching the river mouth are directed northwards, generating strong forces on the downdrift flank of the inlet.

Short term morphodynamics during fair weather

Five detailed surveys of the inlet area were undertaken from April to June 2003. Comparison between these surveys was used to quantify the morphological evolution of the inlet and its ebb-tidal delta for fair weather conditions. Main results are shown in fig. 3.

Morphodynamics of the inlet during this fair weather period is characterized by:

- a rapid northward migration of the main channel (40 m / 2 months in the inlet throw, Figure 3 A and B), and a consequent erosion of the downdrift platform (30 m retreat) and then of the dune (10 m retreat).
- this migration is associated with a slight decrease of the cross-sectional area (Figure 3C), and the progressive northwards rotation of the inlet throat while the main channel becomes more cross shore oriented due to accumulations on the northwards downdrift coast.
- the important amount of sand eroded on the downdrift flank is flushed out while the volume of the ebb-tidal delta increased proportionally.

This migration of the system is followed by an accumulation on the updrift spit, tending to restore an equilibrium cross section. Intertidal bars of the updrift beach reach the extremity of the spit and yield the formation of curved bars.

On the downdrift swash platform, newly formed swash bars migrate northwards, providing sediment to the Lido di Dante beach.

Sediment transport patterns

The migration of the Bevano inlet is associated with an important sediment dynamics, involving sand by-passing the inlet, strong erosion of the downdrift dune, and accretion on the ebb-tidal delta, providing sediment to the Lido di Dante beach on the downdrift coast.

Tracer results

Tracer experiments undertaken in the inlet channel and along the updrift coast have given interesting keys to understand sediment transport pattern during these calm but dynamic period.

Green tracer immersed on the updrift coast was transported northward (fig. 4) despite a very low wave angle to the coast. At the extremity of the sand spit, sand tracer was trapped on a small bar, tending to be transported onshore participating to spit progradation. The recovery rate of the tracer was relatively good (63%), permitting to quantify the residual sediment transport along the updrift coast, which was about 1.68 10^{-6} $m^3/s/m$. This

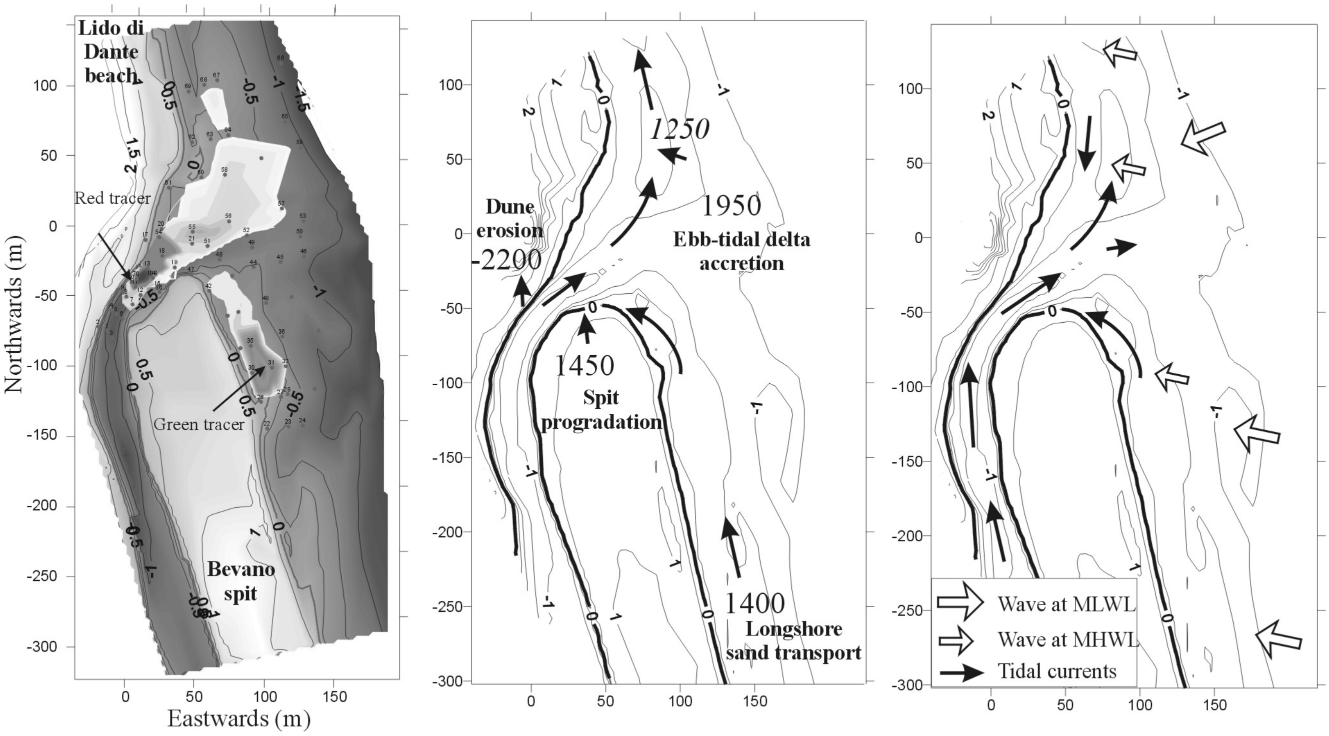

Figure 4. Tracer results, sediment budget and sediment transport pattern in the Bevano tidal inlet. Left: tracers advection clouds, middle: sediment budget of the Bevano entrance (all values are in cubic meters per month). In italic is indicated the part of the ebb-tidal accumulation which is transferred to the updrift beach, right: conceptual sediment transport pattern by waves and tidal currents.

value is confirmed by theoretical computation using CERC and KAMPHUIS (1991) formulae that give between 4 and 9. 10^{-5} m^3/s for the entire transport area. This result permitted to extrapolate the longshore transport for the studied period (68 days), giving a residual transport of 2990 m^3.

Using wave statistics (111 statistic classes) obtained from the PCB platform records (IDROSER, 1996), the longshore drift on this strait of coast was computed. The residual longshore transport approximates 37000 m^3/year northwards (REGIONE EMILIA-ROMAGNA, 2003).

In the inlet channel, red sand tracer was transported offshore by ebb-tidal currents, and tracer grains were recovered at more than 150 m from the source (fig.4). The resulting residual sand transport is about 4. 10^{-6} $m^3/s/m$ (with a recovery rate of 65% of the immersed sand tracer). This result is very closed to the theoretical sand transport in the inlet computed with ENGELUND-HANSON (1967) formula, giving 5.6. 10^{-6} m^2/s for the measured tidal cyle. However, this sand transport is probably underestimated. Indeed, a great part of the transported sand was furnished by erosion of the downdrift flank of the channel, partially covering the tracer source. Moreover, the sand falling from the dune scarp is transported in suspension without any resuspension processes, and thus increases the rate of offshore sediment transport.

Sediment transport out of the inlet does not reach the terminal lobe. Sand accumulates mainly on the downdrift swash platform, where a large swash bar develops.

Sediment dynamics

The morphological evolution during the surveyed period combined with the tracer results permit to understand and quantify sediment dynamics during fair weather (Figure 4).

In the inlet channel, the downdrift flank is eroded by ebb-tidal currents, yielding the progressive erosion of the platform, and afterwards, the erosion of the dune. After the survey period of 68 days, 4900 m^3 (e.g. 2200 m^3 /month) were eroded on the downdrift flank of the channel. This process leads to a very rapid migration of the main channel. As demonstrated by the tracer results, the largest part of this sediment amount is flushed out from the channel by tidal currents, and accumulates on the ebb-tidal delta, mainly on the downdrift swash platform. Total amount of sand on the ebb-tidal delta was 4250 m^3 (e.g. 1950 m^3 /month) during our survey, and 2700 of them were accumulated on the bar forming the downdrift swash platform (e.g. 1250 m^3 /month). This bar progressively migrates onshore providing an important sand transfer to the Lido di Dante beach.

In the meantime, sand transport occurs on the updrift beach, where the estimated littoral sand transport is about 3000 m^3 (e.g. 1400 m^3 /month). Most of this sand is trapped at the extremity of the spit providing material for the progradation of the spit that compensates the cross section increase. The quantity of sand involved in the spit progradation is about 3200 m^3, and thus corresponds to the total amount from the updrift coast.

Considering the stability of offshore bars in the area, it could be reasonably assumed that offshore sediment amount is negligible, as well as sediment support from the Bevano river during this dry period.

Taking into account errors derived from volumes calculation, the sediment budget of the inlet during this fair weather period is almost equilibrated. The quantity of sand reaching the downdrift coast during this period is almost equivalent to the one arriving on the updrift side.

When the 4m dune scarp was eroded, after the erosion of the whole downdrift platform (e.g. mid-may), the amount of sediment transferred to the channel increased, reducing the cross section area (Figure 3) and enhancing current velocities. This resulted in a strong accumulation on the entire ebb-tidal delta whose mean elevation increased by 0.5 m. At low tide, the delta was emerged, and the tidal inlet almost closed.

DISCUSSION

The Bevano river entrance was surveyed during a two month fair weather period, and a bi-coloured sand tracer experiment was performed using a subtidal detection device.

Measured tidal prism versus longshore transport (BRUUN and GERRITSEN, 1959, BRUUN, 1966, 1978, 1986) is about 1. Moreover, the seaward limit of the natural inlet jet field (OERTEL, 1988) is approximately equivalent to the littoral zone width. Following OERTEL (1988) and BRUUN (1986), the inlet is expected to migrate and to shoal. For both models, this ratio indicates a strongly instable inlet. This is in agreement with the historical observation of the Bevano entrance that has a migration/spit breaching cyclic behaviour.

Directions of transport and sediment fluxes obtained permitted to characterize and quantify the functioning of the tidal inlet during typical summer conditions prevailing in this area.

Due to the configuration of the inlet, with a very strong meandering of internal channel, ebb-tidal currents reaching the throat are almost parallel to the coast, and strongly erode the downdrift north flank of the channel. This results in an increase of the cross sectional area, and decrease of mean currents velocities (ESCOFFIER, 1940). Consequently, sediment deposition at the updrift spit extremity is possible. This progradation of the spit is realized by the trapping of the sand transported northward by the longshore drift along the southern coast. All the longshore transport is trapped and participates to the construction of the spit. That means the direct by-pass of sediment from the updrift to downdrift coast is inexistent in such summer climate.

In the main channel, quantity of sediment eroded on the north flank is flushed out by ebb-tidal currents. However, the transport efficiency of these currents rapidly diminishes and all sand is transferred on the ebb-tidal delta whose seaward extension is very limited. The most important part of this sand arrives on the downdrift swash platform, where the mean swash bar progressively migrates onshore. This process furnishes a large quantity of sand to the Lido di Dante beach on the downdrift coast.

The longterm migration and spit breaching process observed in the Bevano area has been widely documented at tidal inlets (FITZGERALD et al., 1978). However, the short term functioning of the tidal inlet during fair weather conditions points out several interesting processes: i) the bypassing process, and ii) the migration process.

i) The bypassing of sediment at the Bevano entrance diverges from the known models (see FITZGERALD et al., 2001). The by-pass of sand results from channel processes as it is described in stable inlets. However, combination of this process with the lateral migration yields a self-alimentation of both downdrift and updrift coasts. The updrift sediment is trapped at the spit, and is thus not transferred to the downdrift beach. In the other hand, alimentation of the downdrift coast results from the erosion of the proper downdrift dune. In other terms, an updrift to downdrift sand by-pass was not observed at the Bevano tidal inlet.

ii) The inlet migration processes are also very specific. Usually described migration due to the longshore drift that “pushes” the inlet was not observed. The main process here is the erosion of the downdrift flank, yielding the increase of the cross sectional area, and then, progradation of the spit occurs to compensate the variation (ESCOFFIER, 1940). This behaviour was already observed on the Barra Nova system of the Ria Formosa in southern portugal (BALOUIN and HOWA, 2002).

It is obvious that this evolution process would be perturbed if erosion of the dune stops. In such case, it would be expected a accumulation of the longshore transported sand on the updrift swash platform, followed by bypassing processes or closure of the system as predicted by the long term evolution scheme.

CONCLUSION

The Bevano mouth morphodynamics has been quantified during a fair weather period. The inlet is very dynamic despite the very low regime. Bypass processes yield an equilibrated sediment budget, suggesting a low perturbation of the littoral transport by the tidal inlet.

At the Bevano entrance, where migration appears to result from northwards fluxes in the internal channel, wave impact seems to play a very secondary role. However, measurements during storm conditions are necessary to fully understand the importance of fair weather and storm periods on the long term evolution of such systems.

The tracer detection technique used in this study has given very encouraging results, permitting to obtain sediment fluxes and transport patterns. The field deployment has still to be improved to facilitate the tracer detection, and to work in more energetic environments.

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