ARTIFICIAL DEVIATION OF A SMALL INLET (BEVANO, NORTHERN ITALY): PREDICTION OF FUTURE EVOLUTION AND PLANNING OF MANAGEMENT STRATEGIES USING OPEN-SOURCE COMMUNITY COASTAL MODELS

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The Bevano river flows into the northern Adriatic Sea in a microtidal-low energy wave environment. The river mouth was diverted artificially in 2006 to contrast dune erosion and decrease inland river flooding. The intervention can be considered as a low impact one as the engineering works were constructed in timber and the possibility of the inlet naturally changing its course was contemplated. An ensemble of hydraulic/morphological scenarios was simulated using data from field surveys and a coupled numerical model. The aim of the modeling was to understand the morphological changes caused by extreme hydro-meteorological events and the relationships between the inlet and the adjacent beaches. Additionally, the probability of a second inlet opening either by overwashing or river breaching was another important topic considered for management purposes. The modeling found that~~,~~ a second inlet can actually be opened under a 30 year flood occurring without any significant wave action. For other conditions~~,~~ the current inlet will be the main source of water escape at sea. Finally, the modeling results confirmed the dominance of the ebb tide in creating a small ebb delta/swash bar, with many similarities with other inlets exposed to a larger tidal range. Currently the management strategy by competent authorities is a minimum maintenance option, with yearly repairs of the timber structures.

Keywords: inlet relocation; soft engineering; ebb delta; numerical models

INTRODUCTION

Tidal inlets represent one of the most challenging landscapes from the coastal management viewpoint as there is the necessity of ensuring an adequate water exchange between the back-barrier system and the open sea. The open-sea and back-barrier lagoon are normally separated by a spit or island system covered by dune and subject to overwashing during storms. As often the inlet provides navigation access to the back-barrier waterways, human alteration of the inlet’s dynamics consists in dredging, construction of training walls or jetties.

Most of the recent studies of managed coastal inlets have been dealing with large systems, for example on the eastern coast of the USA (Wang and Beck, 2012), the English channel (Robin et al., 2007) and the Ria Formosa lagoon in southern Portugal (Balouin and Howa, 2002; Vila-Concejo et al., 2004a and 2004b). In the Adriatic the only detailed study of an ebb tidal delta is the study of Fontolan et al. (2007).

CASE STUDY SITE

This paper reports on the artificial deviation of a small river inlet in the northern Adriatic Sea, the Bevano inlet (Fig. 1). The site is located south of the town of Ravenna in one of the few pristine areas of this stretch of coastline, which has been preserved as part of the Po Delta park. In this case the back-barrier system is represented by the lowest two meanders of the river, which develop along a river course that becomes parallel to the coastline. The inlet has been characterized by a continuous northward migration, following the direction of the dominant longshore transport. Historical sources confirm that this migration is typical of the system and continues till the river looses hydraulic efficiency and a new mouth opens during storms and/or floods. A common feature of the rivers of the region where the study site is located (the Emilia-Romagna), is the northward migration of the mouths that has taken place from the 1980s onwards, coupled with a decrease in sediment delivery by rivers (Regione Emilia-Romagna, 2000).

This migration was laterally eroding the dune system and the river mouth was often silted up, so that during floods the inlet was not able to cope with the increased river discharge which was causing flooding of agricultural land. In 2006 the competent Regional Authorities decided to prepare a short to medium-term coastal management strategy for the inlet, which included a number of “soft-engineering” approaches such as dredging a new inlet further south and using the dredged sand to reconstruct dunes on the barrier system. The new inlet has been protected using environmentally friendly techniques like the construction of artificial river banks with timber poles and geotextile. No external training walls or

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jetties have been built to avoid the interruption of longshore transport as the aim of the intervention was simply to “reset” the northward coastal migration and not to freeze the inlet at a given position. Water exchange between the abandoned river course, now forming a small lake, and the current inlet is ensured by a small weir with height close to mean sea level, thus allowing water inflow into the lake at high tide and guaranteeing the maintenance of good quality of the water mass (Fig. 2).

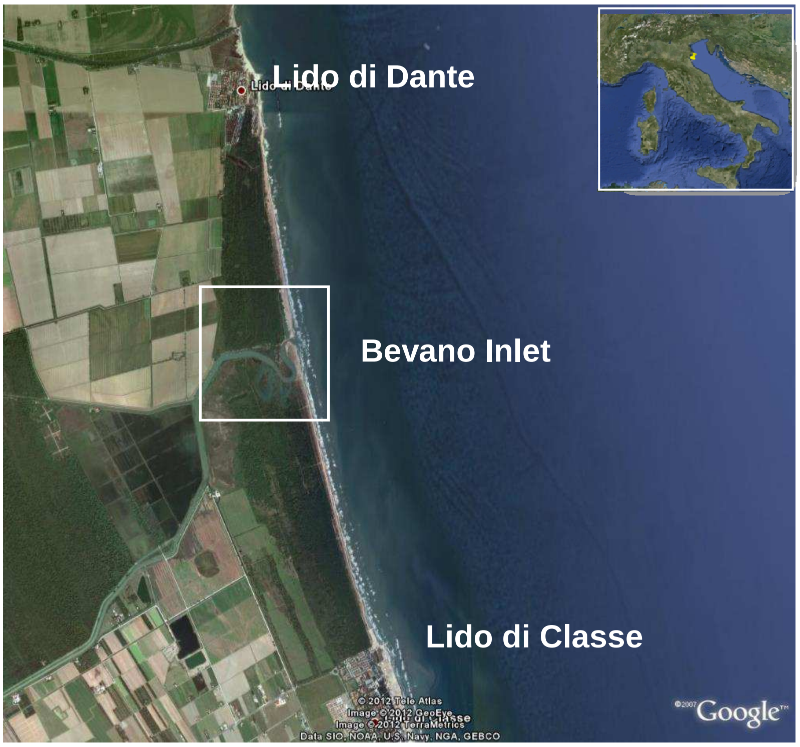

Figure 1. Google Earth Satellite Image (29/5/2011) of the study site and location

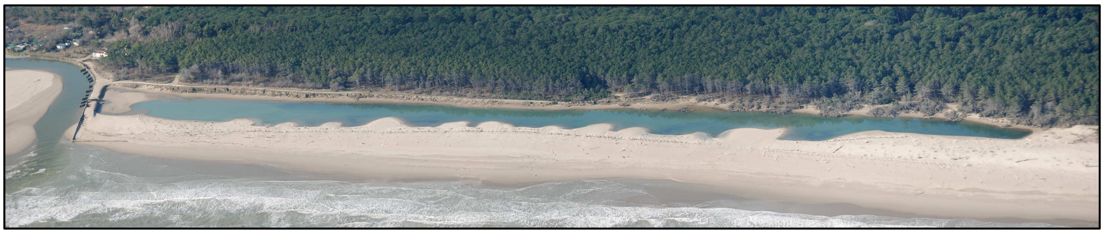

Figure 2. Oblique aerial view of the abandoned river course. Notice the weir and timber revetments on the left near the inlet and the overwash fans on the reconstructed dunes (picture supplied by RER STB Ravenna).

METHODS

Morphological, hydraulic and sedimentological datasets

Monitoring of the inlet dynamics before and after the intervention has been carried out initially at tri-monthly frequency and after at seasonal and yearly frequency. Activities included echo-sounder bathymetric surveys of the nearshore sea-bed, of the inlet’s channel and detailed DGPS topographic surveys of the intertidal and supra-tidal zone (see Fig. 3 and Gardelli et al. 2007). Samples were collected along the monitored profiles in February 2006 from the back-dune to the outer base of the nearshore bar at a depth of – 3m. Additionally, samples of the inlet, lower river course and ebb-delta were collected in April 2006 and April 2009. Samples were analysed in the laboratory using a settling tower for the sand fraction and a Micromeritics Sedigraph for the mud fraction.

The hydraulic behaviour of the inlet was studied by placing a pressure transducer inside the channel (from 25 April to 12 June 2009), while an InterOcean S4 current meter coupled with another pressure transducer was located at the mouth during a spring tidal cycle on 26-28 April 2009. Local tides are available from the Ravenna tide gauge of the RMN network (44.4910° N 12.2815° E), while directional wave measurements are collected by the nearby ARPA-SIMC wave rider buoy at Cesenatico (44.2155°N 12.4766°E), located at -10 m water depth.

Data on river discharge is available from Regione Emilia Romagna (STB Ravenna) and indicates for 30 year return period flood a peak water discharge of 130 m^3s^{-1} with flood duration of about 26 hours.

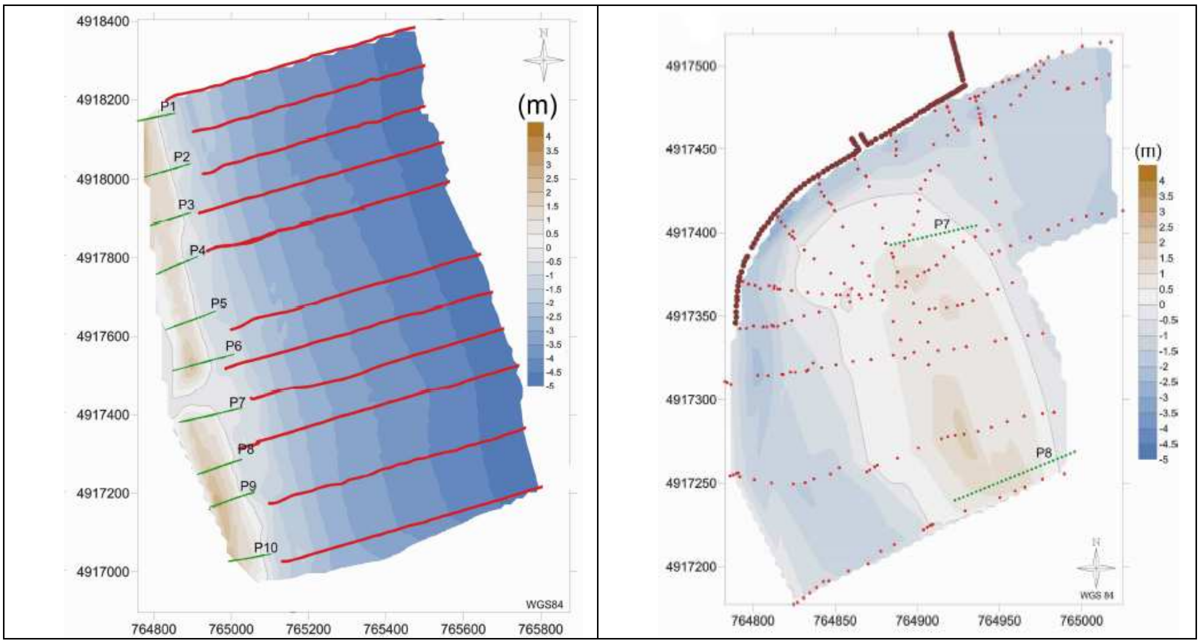

Figure 3. Left panel-monitored profile network surveyed since the opening of the inlet, the October 2008 survey is shown; right panel-detailed survey of the inlet carried out in April 2009. Notice the timber revetment on the northern edge of the inlet. The surveys are in UTM coordinates. Depth are referred to MSL, Genoa datum.

Numerical modeling

The behaviour of the inlet from a hydraulic viewpoint was characterised implementing a model train based on open-source numerical models, namely SWAN (http://www.swan.tudelft.nl/) for wave propagation and ROMS (https://www.myroms.org) for 3-d circulation and morphology change. Details about the coupled model can be found in Warner et al. (2008), while implementation examples in the Adriatic regions, albeit at different resolutions, are provided by Bignami et al. (2007) and Boldrin et al. (2009). Further details on small scale implementations of the coupled ROMS-SWAN system are described in Carniel et al. (2012). In this case, the detailed computational domain of the inlet was based on a curvilinear grid having a minimum cell dimension of 8.5 m cross-shore and 6.9 m alongshore. The grid has origin at the point with latitude 44.3437 and longitude 12.3264, with the x axis rotated about 8° with respect to the W-E axis (Fig. 4).

The models were coupled running on an MPI cluster of 96 processors at CNR-ISMAR Venice (24 PE for SWAN, 72 for ROMS), with a DT=2s, and 50 barotropic time-steps between each baroclinic time step. The offshore boundary conditions were set using the local wave and tide data, while in order to simulate the river regime and its dynamical aspects (e.g. velocity flow), a reservoir accounting for the surface area of the river outside of the model domain was added to the west of the river domain.

Sediment transport inside ROMS was schematized using for each grid point four basic sediment classes, with the dominance of each class extrapolated from grain size analysis (Fig. 5). The four classes were respectively silt to very fine sand (0.022mm-0.088mm), very fine to fine sand (0.088mm-0.210mm), fine to medium sand (0.210mm-0.420mm), and medium to coarse sand (0.420mm a

2.00mm). Finally, the presence of timber revetment piles along the northern bank was introduced in the model as non-erodible layers, locating each structure using the detailed GPS survey of April 2009 (Fig. 3).

In order to simulate the response of the inlet under different scenarios of river discharge and storms, four tests were run: a) normal tide curve under spring tide conditions and absent river discharge; b) river under flooding conditions (1 in 30 year return interval and spring tidal conditions); c) simulation of an easterly event with small waves (peak Hs = 1.47 m and Tp=8 s) but high water levels (peak WL = 0.92 m); simulation of a NE event which represented a combination of both very large waves (peak Hs = 3.91m and Tp=9 s), equivalent to about a 1 in 5 year return interval and high water levels (peak WL = 0.93 m).

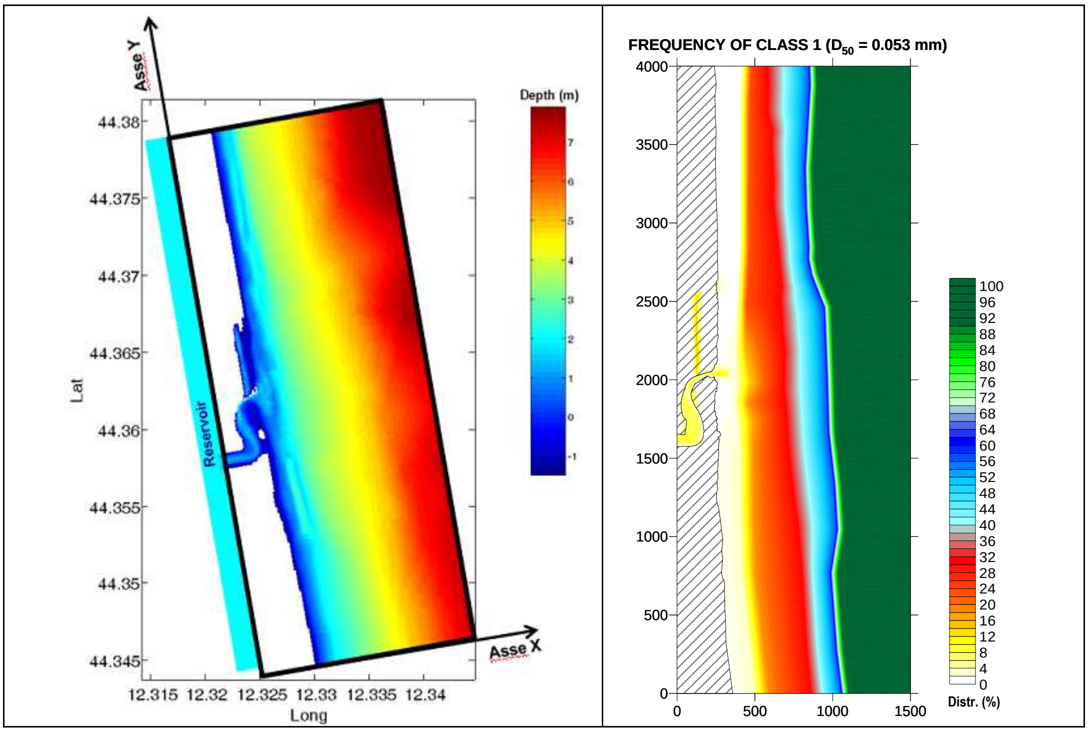

Figure 4. Left panel-computational domain used for the modeling, notice that depths below MSL have positive sign; right panel-example of sediment distribution.

RESULTS

Test 1. Normal tide curve under spring tide conditions and minimum river discharge

The water elevation time-series used for evaluating the role of tidal processes at the inlet can be seen in Fig. 5. ROMS can be forced using measured time series of water elevation and currents at the open-boundary, but as these were not available, it was decided to use a tidal prediction using the tidal module inside the model, based on the Oregon University code (http://volkov.oce.orst.edu/tides/). The eight main tidal harmonics of Ravenna, plus two long term moon components were introduced. The simulated period in Fig. 5 corresponds to the time-interval from 00:00 of 26 April 2009 to 00:00 of 30 April 2009. To notice that comparison between the Ravenna tide gauge and the temporary gauges installed at the mouth showed negligible shift changes in the curve except when river or wave set-up processes are acting.

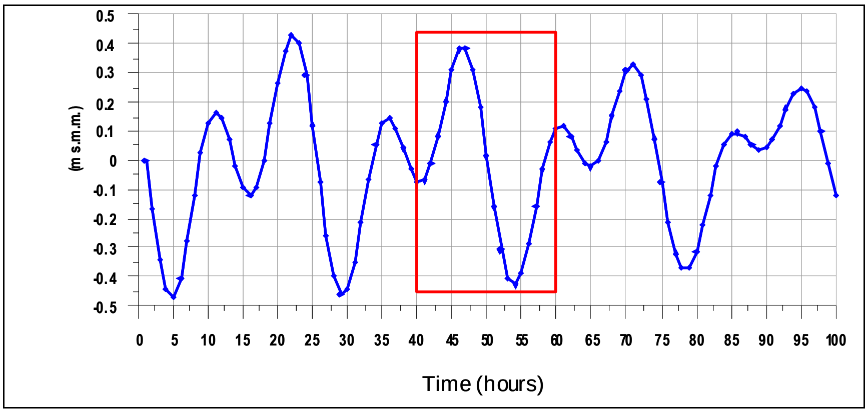

Figure 5. Top panel-tidal cycles used test 1, the time goes from 00:00 26 April to 00:00 30 April 2009; the inset shows the period when the 3-d- components were activated.

After warming up the model for three tidal cycles (40 hours) runs were extracted for a flood-ebb cycle as in Fig. 5. In Fig. 6 the peak surface velocities predicted for the ebb and flood tide are plotted. There is no clear separation between the ebb and flood tide in the channel of the inlet, mainly because of its limited cross-section. In both cases, next to the timber revetment along the northern bank speeds in the order of 1 ms^{-1} are reached. This is in agreement with the problems of under-excavation of the poles observed by the Regional authorities immediately after the completion of the works and throughout the life of the project.

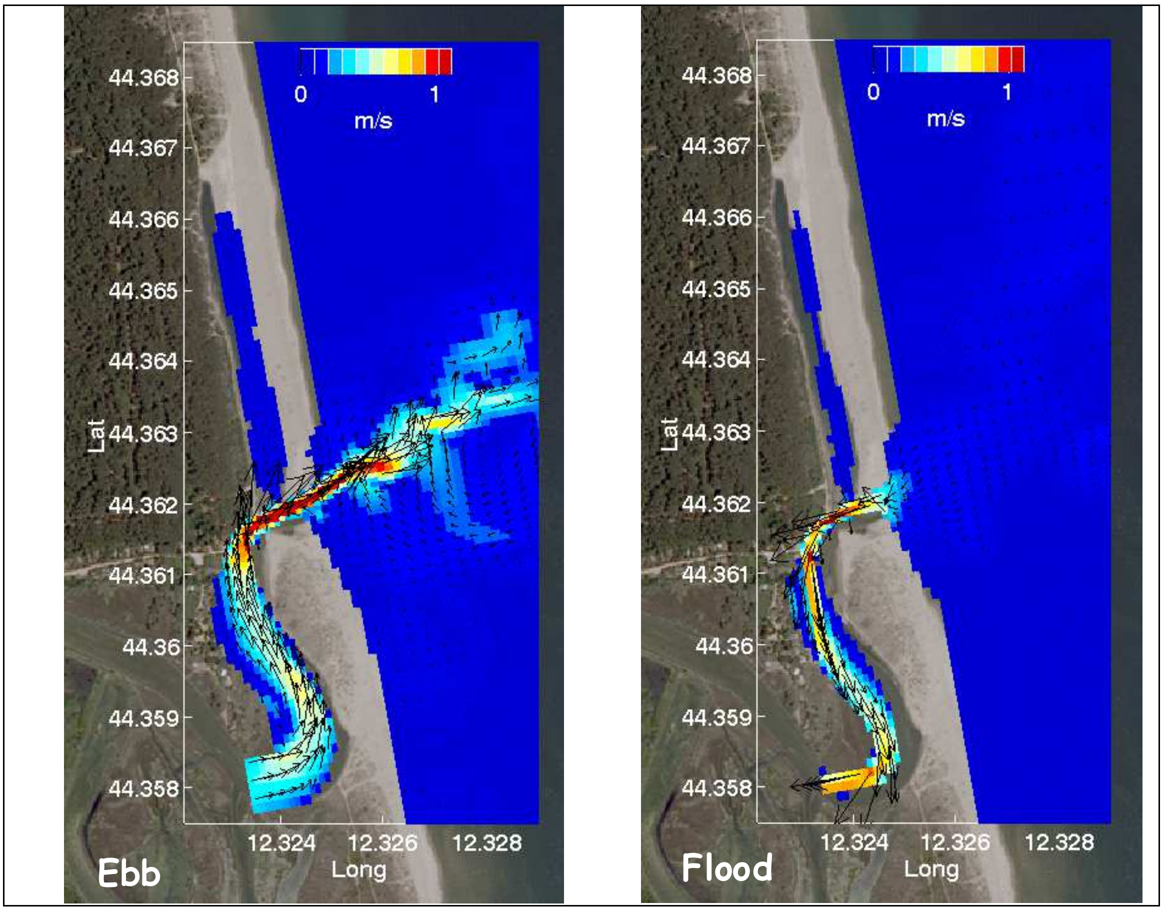

Figure 6. Left panel-surface speed at peak ebb tide; right panel-surface speed at peak flood tide.

In any case the inlet results to be largely ebb-dominated, despite the fact that the flooding tide propagates inside the river course well beyond the innermost meander. According to Ciavola et al. 2005, it is necessary to move about 4 km inland from the mouth to completely exclude any tidal effect on the river flow.

It is interesting to compare the simulations of near bed velocities (not shown in Fig. 6) with the time series of currents measured at the exit of the channel between 26-28 April 2009 (Fig. 7). The model predicts a near bed maximum speed of 0.8 ms^{-1} while measurements are in the order of 0.5 ms^{-1}. Regarding the flood, the model predicts at the bed 0.7 ms^{-1} while the measurements are in the order of 0.2-0.3 ms^{-1}.

It is to be noticed that overall this qualitative comparison sheds a positive light onto the model's predictions, as the field conditions explain some of the discrepancies between measurements and model outputs. First, during the measurements there was some wave dissipation at low tide, as confirmed by the current peaks in the morning of 27 April 2009, due to waves breaking on the ebb delta that were being propagated inside the inlet. Second, it has to be considered that the current meter was buried at the end of the experiment, thus a reduction of local water depth was possibly changing the flow patterns of the flood tide.

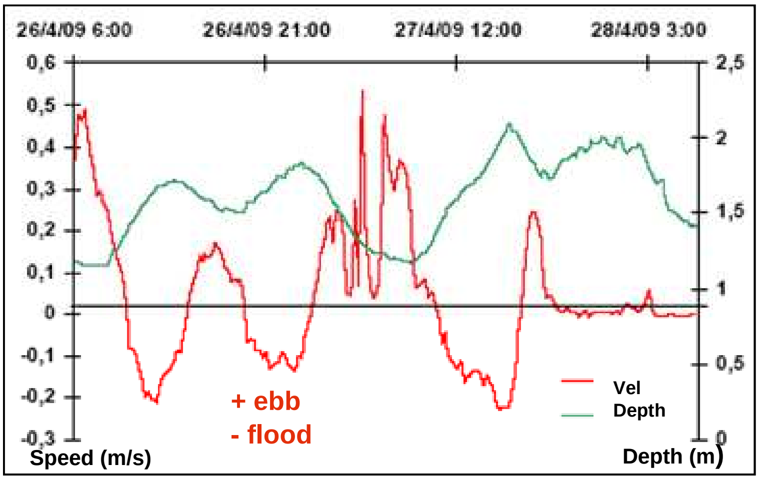

Figure 7. Water elevation (green line) and current velocity at 40 cm above the bottom measured at the inlet between 26-28 April 2009. Notice the noise at ebb tide on the morning of 27 April 2008 due to wave activity.

Test 2. 30 year River Flood and Spring Tide

The water elevation time-series used for evaluating the role of tidal processes at the inlet were now used to simulate river-tide interaction during a 30 year flood (Fig. 8). The peak of the river flood was made coinciding with high water to estimate the maximum interaction between the two processes. The surface speed at the peak of the flood is now much larger than in the tide-controlled simulations, reaching 1.8 ms^{-1} in the main channel of the inlet (Fig. 9).

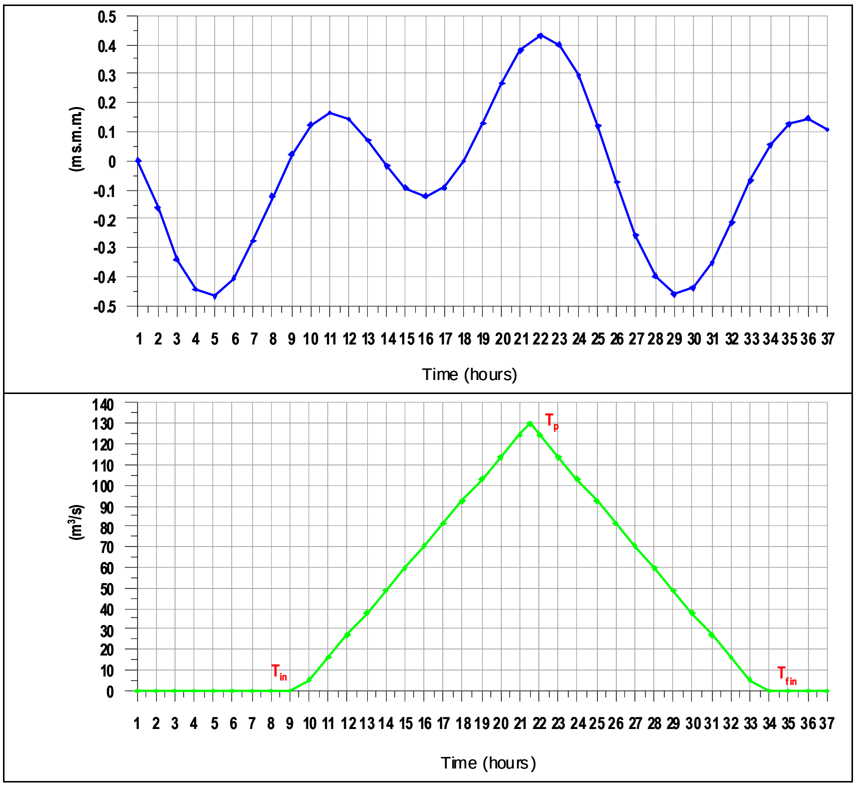

Figure 8. Top panel-tidal cycle used for simulation of river flooding under spring tides; bottom panel-water discharge during the river flood.

It must be considered that during the engineering works part of beach corresponding to the inner meander was levelled at an elevation of 0.5 above MSL, aiming to provide an escape route for the water discharge during river floods. This is confirmed by the numerical test, as it is possible to see in Fig. 9 the formation of a second inlet. This second inlet is short-lived because a buried timber pole revetment, which top is located at MSL and covers the whole stretch levelled at +0.5 m above MSL, prevents the excavation and further development of the inlet. When the sea level and river discharge decrease, river sedimentation and littoral transport tend to close the inlet again. The timber pole revetment was simulated using a non erodible layer, covered by a 0.5 m thick layer of sand, which erosion allows for breaching during floods as represented in the figure.

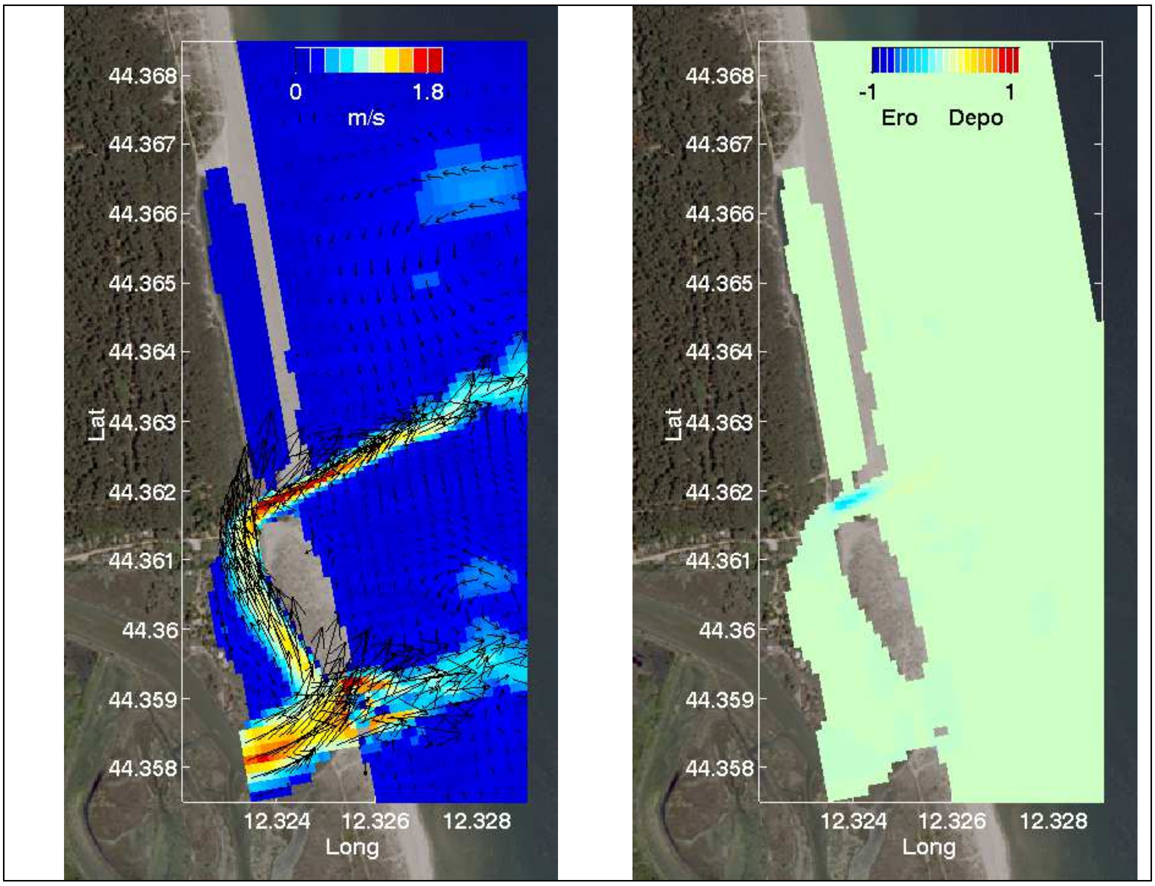

Figure 9. Left panel-surface speed at the peak of the flood; right panel- non-dimensional sea-bed variation between the beginning and the peak of the flood.

Test 3. NE storm (9-10 March 2010)

This event represents the type of storm which normally has a considerable impact on this coastline typology, as the locally defined storm threshold (H_s>2 m) of Armaroli et al. (2012) was exceeded for 24 hours starting at 18:00 of 9 March. Note that the storm caused consistent wind and wave set-up, which was recorded by the Ravenna tide gauge (Fig. 10). The average wave direction during the storm was at around 60°N.

Before simulating the storm record, the model was brought to equilibrium under tidal forcing as in Test 1. Afterwards the water level was forced till it reached the water level recorded by the tide gauge at the peak of the storm (0.7-0.9 m above MSL).

During the peak of the storm, longshore currents (Fig. 11) reach their maximum speed along the outer edge of the nearshore bar north of the inlet and are diverted by the ebb delta. Only limited wave penetration is observed in the inlet. Beach erosion takes place on both sides of the inlet but it is more evident on the southern spit. The bed variation map of Fig. 11 confirms the role of the longshore current in redistributing the sediment around the bar, a process that according to Armaroli and Ciavola (2011) could lead to a transition of morphodynamic state from rhythmic to linear bar during storms. Another interesting point is that the model predicts no overwashing of the beach where the “emergency inlet” is located.

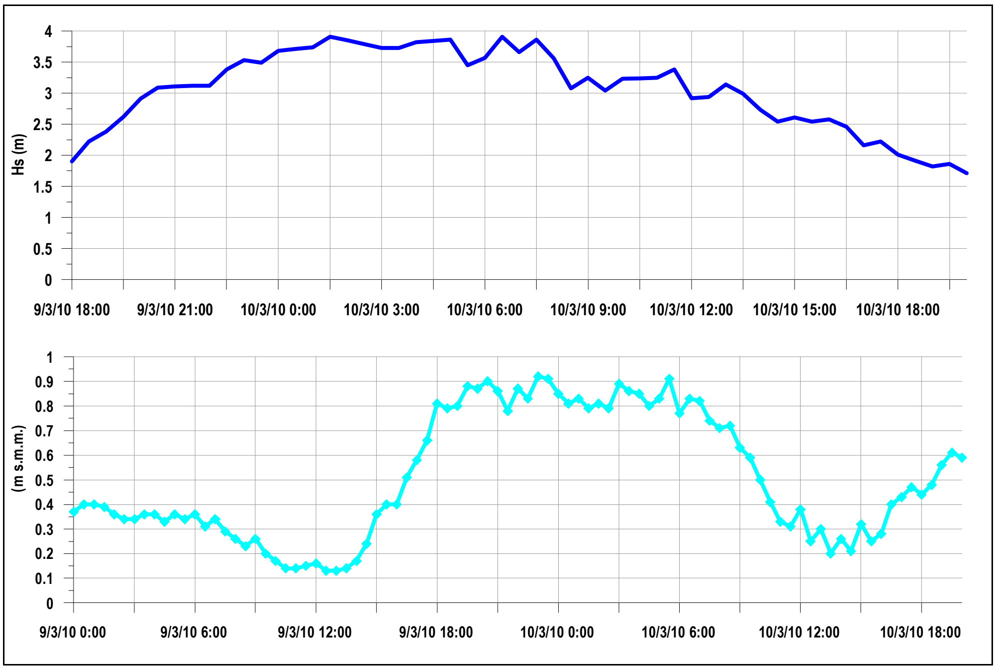

Figure 10. Characteristics of the 5 year return period storm of 9-10 March 2010. Top panel-offshore significant wave height at the Cesenatico buoy; bottom panel-water elevation recorded at Ravenna Port.

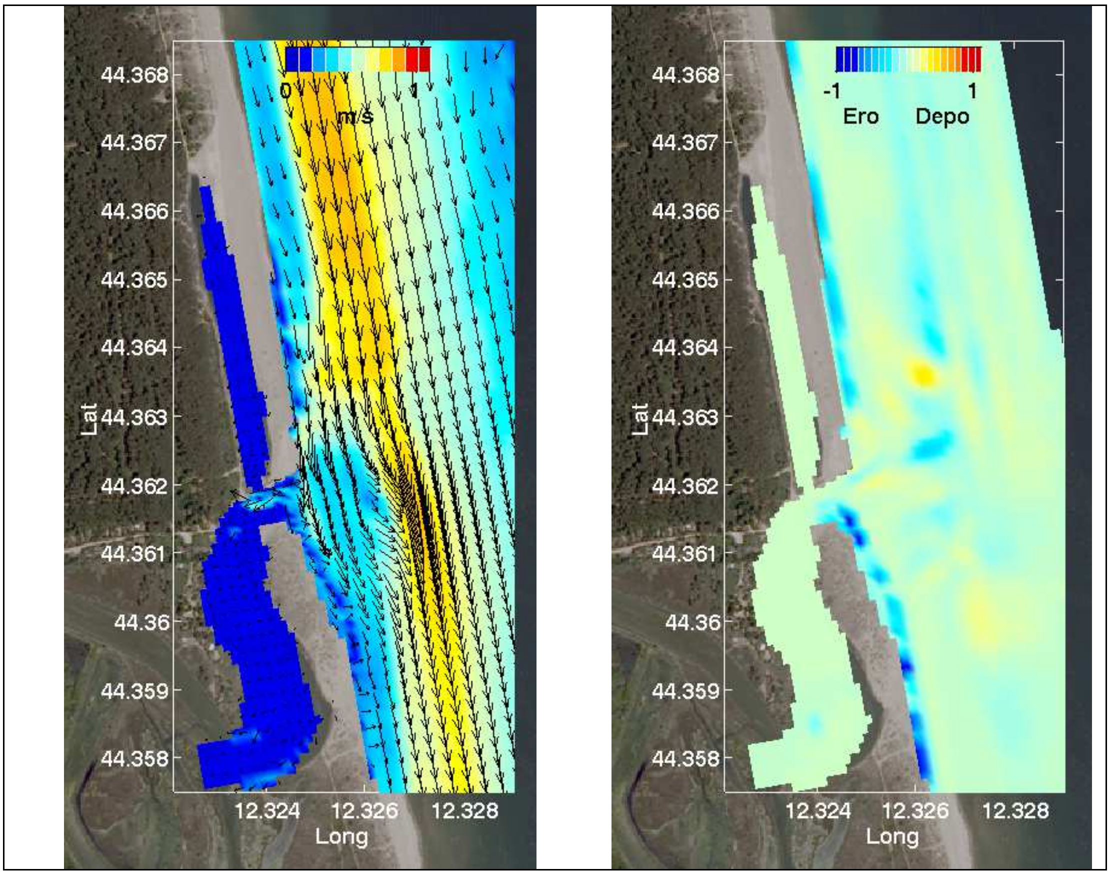

Figure 11. Left panel-surface currents during the 9-10 March 2010 storm; right panel- non-dimensional sea-bed variation between the beginning and the end of the storm.

Test 4. SE storm (1 December 2008)

This event is a peculiar storm surge scenario which caused one of the highest tide levels recorded by the Ravenna tide gauge (0.97 m) in the morning of 1 December 2008. As documented by Sedrati et al. (2011), the event generated widespread overwashing of the reconstructed dunes north of the inlet (see Fig. 2). During the event, field observations by the authors confirm wave overtopping of the beach berm at the “emergency inlet”.

As done previously for the other tests, the model was first warmed up with a number of tidal cycles before forcing the level to the same values observed at Ravenna.

To notice in Fig. 12 that the peak of the wave action was not coinciding with the peak of the high tide, thus the surge was caused by barometric and wind effects rather than wave set-up.

In this test the water circulation patterns indicate sediment transport from the southern beach towards the inlet channel, with erosion of the southern spit as confirmed by the sea-bed variation map of Fig. 13. The longshore currents is strong over the crest of the bar north of the inlet, confirming the hypothesis of Armaroli and Ciavola (2011) that the inlet’s sediment deposits supply the bar system.

The model predicts large erosion of the spit at the mouth (Fig. 13) and of the beach but fails to reproduce the overwashing of the dunes to the north observed by Sedrati et al. (2011). Likewise the overtopping of the beach berm at the height of the innermost meander is not reproduced.

These limitations are due to a number of factors, including the need of a better parameterization of swash and wave run-up processes.

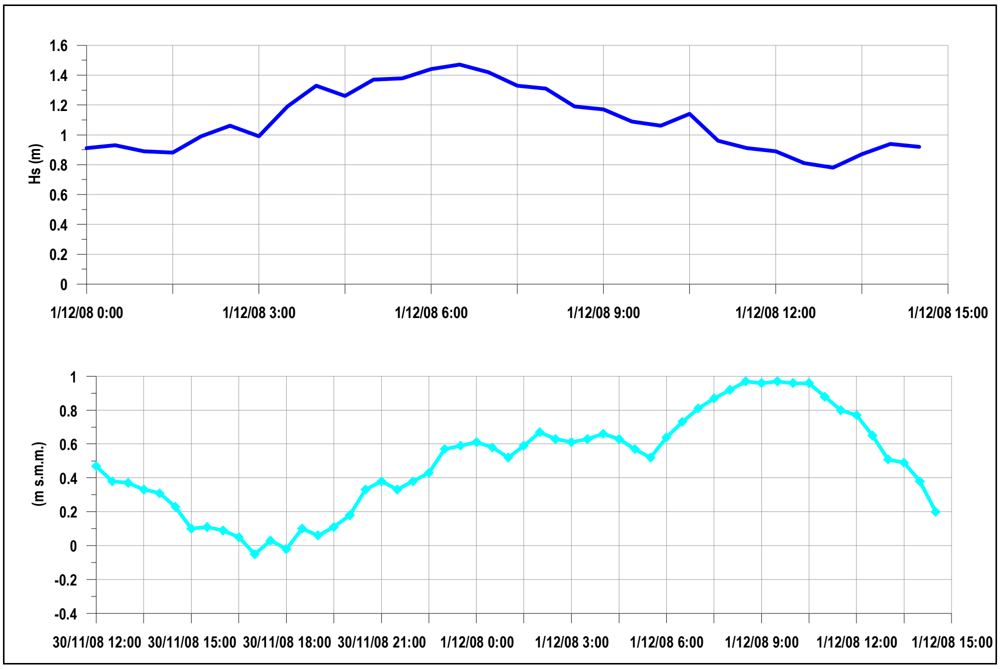

Figure 12. Characteristics of the storm surge of 1 December 2008. Top panel-offshore significant wave height at the Cesenatico buoy; bottom panel-water elevation recorded at Ravenna Port.

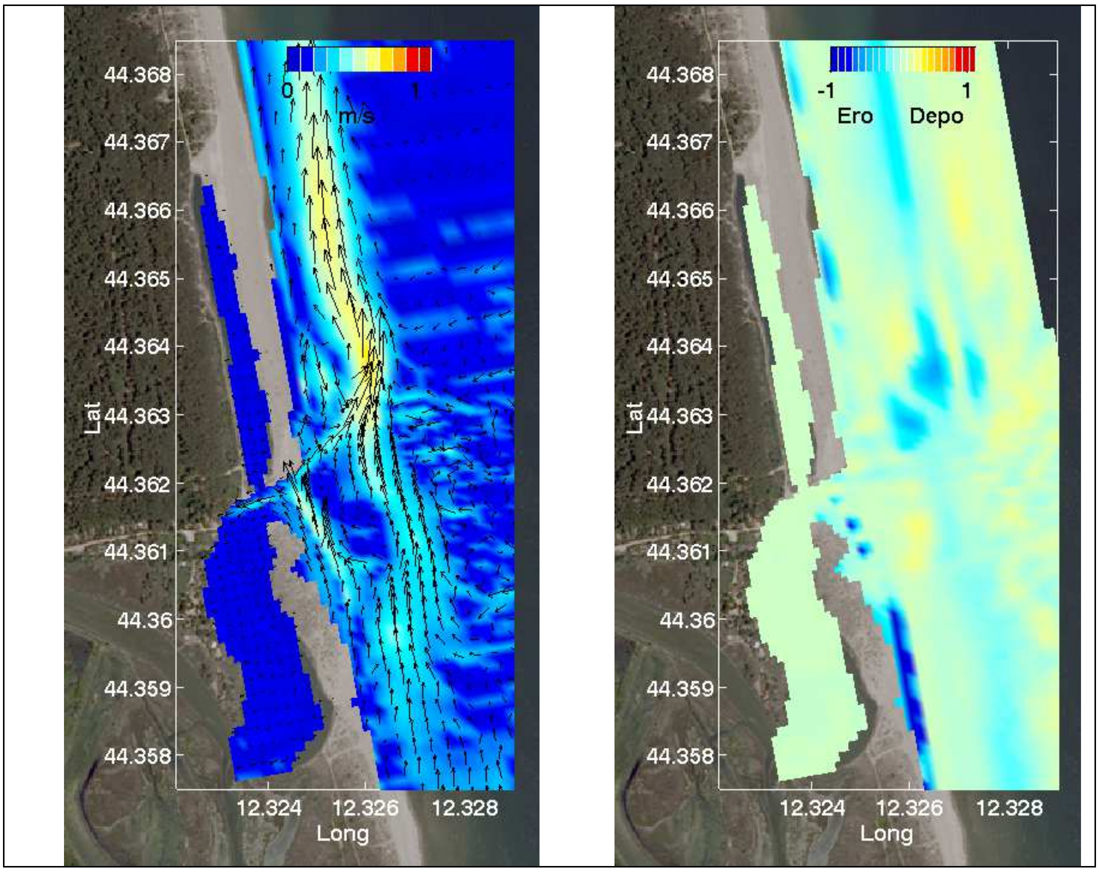

Figure 13. Left panel-surface currents during the 1 December 2008 storm; right panel- non-dimensional sea-bed variation between the beginning and the end of the storm.

DISCUSSION

The model has been able to predict most of the relevant phenomena occurring during extreme tidal and flood events, reasonably simulating the scour phenomena at the toe of the training wall and the breaching of the barrier induced by the flood. Beyond this, morphology changes in the ebb delta seem to reproduce what has been observed during the monitoring performed after the opening of the inlet (Gardelli et al., 2007).

The ebb delta is indeed dominated by marine processes: river floods do not seem to produce any significant seabed change, with the exception of the scour at the toe of the training wall. The role of the ebb delta and swash bars at the sides of the inlet is likely to play an important role in the sediment budget of the whole coastline to the north. Recent field studies on larger and much more energetic systems like the Ria Formosa inlets in southern Portugal have confirmed the role that ebb-tidal deltas have in trapping longshore drift and releasing it again during periods of increased wave activity (Pacheco et al., 2011). In the case of the Bevano, Balouin et al. (2006) and Armaroli and Ciavola (2011) had already supposed a strict relationship between the inlet's morphologies and nearshore bars as it is evident even from simple aerial photography (Fig. 14).

According to the formulation of the model used in this paper, erosion and breaching induced by runup of waves are not reproduced; hence the results of simulations of extreme storms cannot provide indications on the overwash and its consequences. More specific modelling like that done by Harley et al. (2011) should be undertaken.

Regarding the effectiveness of the soft measures to control river mouth evolution, the model allowed for the simulation of a 30 yr extreme flood, which indeed has never been observed in the last decades. Should this happen, most of the peak discharge will flow through the second mouth, easily eroding the sand layer above the timber weirt. After the peak of the flood, the river would follow the normal course and the barrier would continue to be dominated by wave and wind processes.

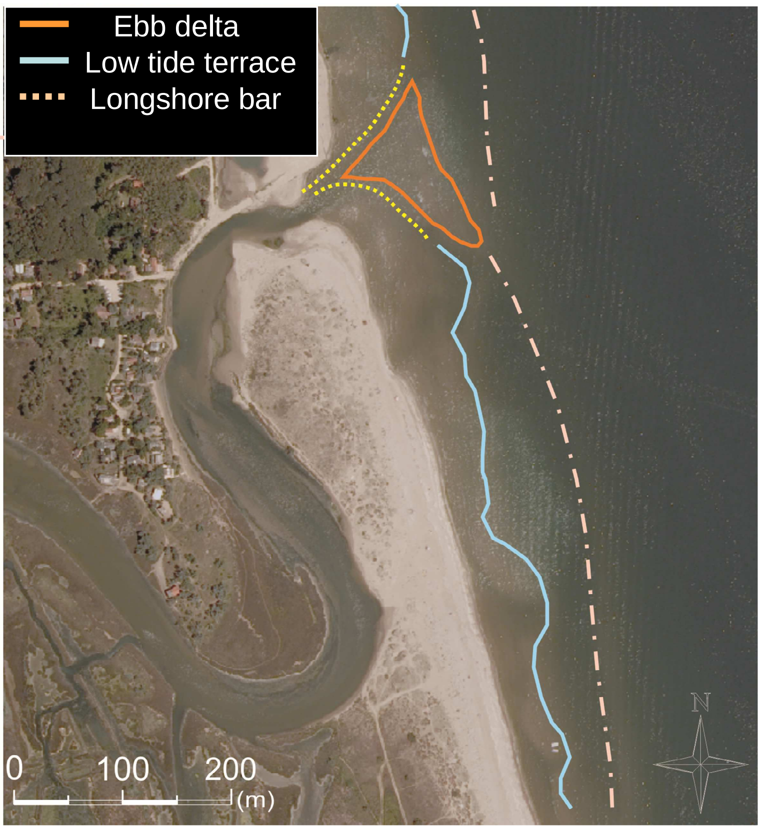

Figure 14. Morphology observed at the mouth of the Bevano in 2008.

CONCLUSIONS

The modelling concluded that under flooding conditions an additional inlet would open and would provide an escape route for river discharge. However, the inlet would not be self-sustained and during peaks of wave activity it would close On the other hand, despite the strong longshore currents, NE storms would not breach the barrier. Finally, SE storms would only generate some overtopping of the beach berm along the southern part of the barrier but the opening of the new inlet would be constrained by the presence of an artificial revetment installed to prevent that the system would go out of control.

Local authorities are currently using the results of the conceptual model which concluded that, despite this is a limited tidal range system, the inlet is essentially behaving as an ebb-tide dominated one, confirmed by a developed ebb delta. It was decided not to carry out any further intervention except the maintenance of the timber revetment of the inlet, waiting for the response of the inlet to a flood, which so far has not occurred. On the other hand, since 2006 several significant storm events have been obssrved, but the inlet remained in place, requiring only some minor maintenance. Given the “temporary” nature of the intervention, should the bank protections fail, it is foreseen to stop any further works and let the system restart its natural northward migration.

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REFERENCES

Armaroli, C., Ciavola, P., 2011. Dynamics of a nearshore bar system in the northern Adriatic: A video-based morphological classification. *Geomorphology* 126, 201-216.

Armaroli, C., Ciavola, P., Perini L., Lorito, S., Valentini, A., Masina M., 2012. Critical storm thresholds for significant morphological changes and damage along the Emilia-Romagna coastline, Italy. *Geomorphology*, 143-144, 34-51.

Balouin, Y., Howa, H. , 2002. Sediment transport pattern at the Barra Nova inlet, south Portugal: a conceptual model. *Geo-Marine Letters* 21, 226–235.

Balouin, Y., Ciavola, P., Michel, D., 2006. Support of subtidal tracer studies to quantify the complex morphodynamics of a river outlet: the Bevano, NE Italy. *Journal of Coastal Research*, SI 39, 602-607.

Bignami, F., Sciarra, R., Carniel, S., Santoleri, R., 2007. The variability of the Adriatic sea coastal turbid waters from SeaWiFS imagery. *Journal of Geophysical Research – Ocean*, 112, C03S10. DOI: 10.1029/2006JC003518

Boldrin, A., Carniel, S., Giani, M., Marini, M., Bernardi Aubry, F., Campanelli, A., Grilli, F., Russo, A., 2009. The effect of Bora wind on physical and bio-chemical properties of stratified waters in the Northern Adriatic. *Journal of Geophysical Research – Ocean*, 114, C08S92. DOI:10.1029/2008JC004837

Carniel, S., Sclavo, M., Tondello, M. and Ciavola, P., 2012. Modelli numerici integrati in aree costiere: un esempio di applicazione nel nord Adriatico. In press, *Quaderni ARPA-EMR*, ISSN-XX (in Italian and English).

Ciavola, P., Billi, P., Armaroli, C., Preciso, E., Salemi, E., Balouin, Y., 2005. Valutazione della morfodinamica di foce del Torrente Bevano (RA): il ruolo del trasporto solido di fondo. *Geologia Tecnica ed Ambientale*, 2005/1: 41-57. (in Italian).

Fontolan, G., Pillon, S., Delli Quadri, F., Bezzi , A., 2007. Sediment storage at tidal inlets in northern Adriatic lagoons: Ebb-tidal delta morphodynamics, conservation and sand use strategies. *Estuarine, Coastal and Shelf Science* 75, 261-277.

Gardelli,, M., Caleffi, S., Ciavola, P., 2007. Evoluzione morfodinamica della foce del torrente Bevano. *Studi Costieri* 13, 55-76. (in Italian).

Harley, M., Armaroli, C., Ciavola, P., 2011. Evaluation of XBeach predictions for a real-time warning system in Emilia-Romagna, Northern Italy. *Journal of Coastal Research* SI 64, 1861-1865.

Pacheco, A., Williams, J., Ferreira, Ó, Garel, E., Reynolds, S., 2011. Applicability of sediment transport models to evaluate medium term evolution of tidal inlet systems. *Estuarine, Coastal and Shelf Science* 95 (1), 119-134.

Regione Emilia-Romagna, 2000. Relazione sullo stato dell’ambiente in Emilia Romagna 1999, Bologna, Italy, pp. 448. (in Italian)

Robin, N., F., Levoy, O., Montfort., 2007. Bar morphodynamic behaviour on the ebb delta of a macrotidal inlet (Normandy, France), *Journal of Coastal Research*, 23, 1370–1378.

Sedrati, M., Ciavola, P., Armaroli, C., 2011. Morphodynamic evolution of a microtidal barrier, the role of overwash: Bevano, Northern Adriatic Sea. *Journal of Coastal Research*, SI 64, 696-700.

Vila-Concejo, A., Ferreira, Ó, Matias, A., Morris, B.D., Dias, J.A., 2004a. Lessons from inlet relocation: examples from Southern Portugal. *Coastal Engineering*, 51, 967-990.

Vila-Concejo, A., Ferreira, Ó, Ciavola, P., Matias, A., Dias, J.A., 2004b. Tracer studies on the updrift margin of a complex inlet system. *Marine Geology*, 208, 43-72.

Wang, P., Beck, T. M., 2012. Morphodynamics of an anthropogenically altered dual-inlet system: John's Pass and Blind Pass, west-central Florida, USA, *Marine Geology*, 291-294, 162-175.

Warner, J.C., Sherwood, C.R., Signell, R.P., Harris, C., Arango, H., 2008. Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model. *Computers and Geosciences*, 34: 1284-1306