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Tidal Inlet Function: Field Evidence and Numerical Simulation in the INDIA Project

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ABSTRACT

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In recognition of the environmentally sensitive nature of inlets and of a requirement to improve present knowledge of their function, the INDIA project has studied a small natural tidal inlet located in the Ría Formosa, Algarve, Portugal. The project has used state-of-the-art field equipment to study present day processes, and a range of numerical models to extend the spatial and temporal range of the measurements. Underpinned by knowledge of inlet evolution over several years, and by knowledge of other inlet systems, a conceptual model describing the medium- to long-term evolution of the inlet is presented. Key elements of the model are then examined with reference to field observations and to numerical simulations of tides, waves, sediments and morphology. Supported by historical evidence of inlet evolution in the Ría Formosa, the picture that emerges of inlet dynamics is essentially one of relative simplicity and predictability in the short- to medium-term.

ADDITIONAL INDEX WORDS: *Inlet dynamics, Ría Formosa, Algarve, Portugal, inlet evolution, erosion, migration.*

INTRODUCTION

Tidal inlets and barrier islands occupying some 12% of the world's coastlines are amongst the most dynamic coastal features and have been the subject of many investigations (*e.g.* KEULEGAN, 1951; BRUUN, 1978; NUMMEDAL, 1983; SPEER and AUBREY, 1985; PILKEY *et al.,* 1989; STEIJN, 1991; DAVIS, 1994; KOMAR, 1996; MEHTA, 1996 and the US Army Corps of Engineers Inlets Research Programme[17], CIRPS). Coastal erosion in and around tidal inlets due to natural migration, tidal flooding and to storm events is commonly observed and frequently threatens adjacent communities and industry. Furthermore, inlets frequently connect the sea to sites of International ecological stature and/or areas of importance to tourism and therefore require careful management to maintain environmental quality. In total Europe spends around £150 million annually to offset the coastal erosion problems around inlets and in some European countries, as much as 50% of the total annual budget for sea defences may be allocated to nourishment schemes at inlets (*e.g.* The Netherlands). In the USA over $100 million is spent annually simply to dredge some 75 million m^3 of sediment from inlet channels.

To help prevent erosion and migration, inlets are frequently stabilised artificially using structures, and sediment-bypassing intervention is often used to restrict the growth of the ebb shoal and to nourish the downdrift coast and thus prevent erosion (*e.g.* WALKER and DUNHAM, 1977). In the case of a single discharge source, management, although costly, is relatively simple. In multiply inlet systems, changes in the hydrodynamic properties brought about by engineering works at a given inlet may give rise to instability in the system and may promote morphological change to adjacent in-

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[17] Further information can be found on the CERP web site at http://cirp.wes.army.mil/cirp/cirp.html

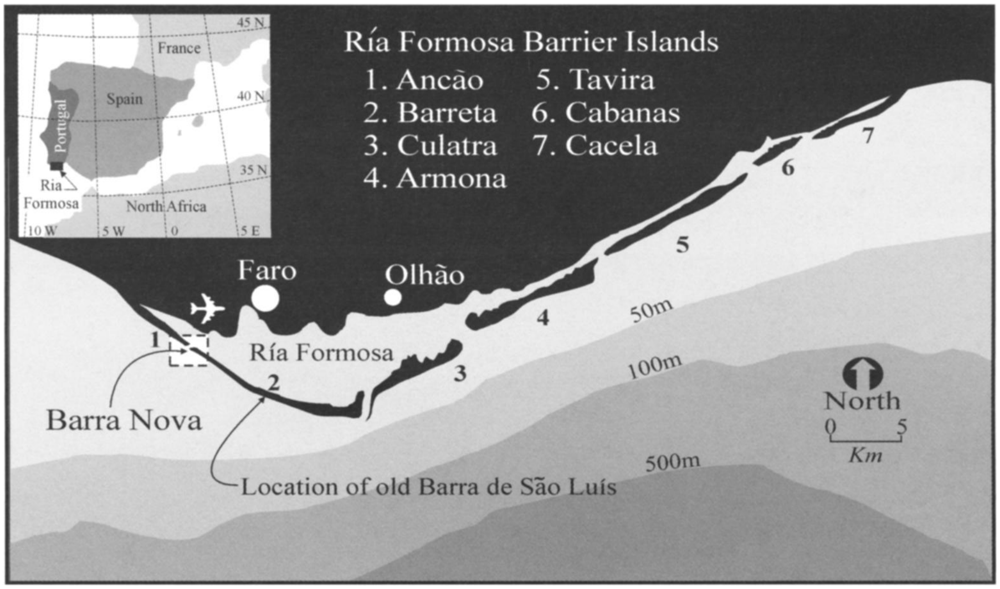

Figure 1. Location of the Barra Nova, Algarve, Portugal.

lets. In more extreme cases, intervention may lead directly to the opening and/or closure of further inlets. Management strategies for such systems are far more complex and detailed understanding of inlet dynamics is required in order to develop effective strategies within prescribed costs.

With these points in mind, the primary goal of the INDIA[18] Project (*IN*let *D*ynamic *I*nitiative—*A*lgarve) has been to understand the fundamental physical drivers of change at a natural tidal inlet and to develop and assess methodologies to predict the medium- to long-term morphodynamic behaviour. Fieldwork encompassed detailed process studies and wide-area measurements of wave conditions and surface currents. In addition numerical models have examined small-scale hydrodynamics, sediment transport and bed features and wide-area temporal changes in morphology. Following a description of the field site, this overview paper outlines a conceptual model of the inlet which aims to explain key features of inlet behaviour based upon evidence from the present site and from other inlets. The measurement campaigns and numerical models are then described before examining the validity of this model using the new information from the INDIA project.

Field Site

The field site, encompassing the Barra Nova and adjacent beaches is located in the Ría Formosa, in the Algarve region of southern Portugal (Figure 1). Whilst the origin of the Ría Formosa is still unclear, it is known that the historical landward migration of the system conforms to the classical shoreface transgression model. The barrier islands are maintained by a supply of sediment derived from erosion of cliffs to the west and are probably part of a much larger coastal cell extending eastwards along the Spanish coast towards Gibraltar. Its unusual arcuate shape is attributed primarily to the local morphology of the Algarve shelf which sustains the required pattern of wave refraction to maintain the system. In total, the barrier islands span approximately 50 km of the coastline and extend up to 6 km offshore from the mainland at the widest point. The beaches are reflective to intermediate at the western end of the system and predominately dissipative at the eastern end (DIAS *et al.,* 2000). The barrier islands are subject to a meso-tidal regime in the range 2 m to 3.5 m (Granja, 1984) and are characterised by rapid alongshore changes in morphology attributable principally to cycles of inlet opening, migration and closure. Bathymetric charts and topographic maps from *circa* 1700 to the present day indicate that the number of inlets in the Ría Formosa may be increasing over time and inlets themselves are subject to cyclical changes associated with opening, migration and closure. More rapid morphological change in the western part of the system suggests a west to east gradient in hydrodynamic forcing conditions. Further details of the Ría Formosa are given by PILKEY *et al.,* (1989) and ANDRADE (1990).

Following examination of several possible field sites in the Ría Formosa, the present research consortium originally chose in 1996 to study the Barra de São Luís, the westernmost inlet separating the Peninsula do Ancão and the Ilha da Barreta (Figure 1). Historical evidence indicated strongly that migration of this inlet and accompanying changes in morphology could be reasonably expected within the timeframe of a fieldwork programme lasting two to three months. However, partial closure by natural sedimentation of this inlet required the creation of a new artificial inlet some 3.5 km to the west of the old inlet through the Peninsula do Ancão and thus the new inlet or Barra Nova was created by dredg-

[18] See http://pol.ac.uk/India.html

ing in June 1997. Since opening, the evolution of the Barra Nova has been monitored and as anticipated, it was found to quickly naturalise and resemble the old Barra de São Luís both in terms of its hydrodynamic characteristics and its morphology by the time the field campaign got underway some 18 months after initial dredging work. The post-dredging development of the Barra Nova during the period June 1997 to July 1998 is illustrated by a series of photographs in Figure 2. These images show morphological changes occurring in the first year after opening. It is noted that the morphology of the Barra Nova shown in the last photograph in the sequence obtained on 22 July 1998 is very similar in character to the morphology of the inlet in July 2000 and typifies the morphology of past inlets at this particular location in the Ría Formosa system.

CONCEPTUAL MODEL OF THE BARRA NOVA

Building upon the pioneering work of BRUUN and GERRITSEN (1959) and BRUUN (1966) various authors have proposed conceptual or semi-empirical models that explain inlet function and morphological evolution in terms of wave or tidal flow dominance (*e.g.* HAYES *et al.,* 1970; OERTEL, 1972; HAYES, 1980; BOOTHROYD, 1985; GIBEAUT and DAVIES, 1993; FITZGERALD, 1996; FITZGERALD *et al.,* 2000). In other approaches (*e.g.* KANA and STEVENS, 1992; KANA *et al.,* 1998; ROSATI *et al.,* 1999; ROSATI and KRAUS, 1999), a qualitative conceptual sediment budget model is advocated in order to give a regional perspective on interactions with beach processes and with offshore bathymetry. In most cases, the models draw upon techniques that evaluate evolution of the ebb shoal and the inlet channel and assimilate evidence of historical changes in inlet morphology. Whilst numerical simulation of waves and tidal currents in and around inlets is now possible, at present no model is able to predict evolution of inlet morphology in the medium- to long-term in any more than a broad qualitative way and thus a need to consider inlet evolution in conceptual terms remains.

The dynamics of the Barra Nova cannot be considered in isolation from other inlets in the Ría Formosa system. Flood tide inflows through the larger inlets to the east (Figure 1) result in an elevation of water levels inside the lagoon to a height known to be much greater that could be achieve by flow through the Barra Nova alone. As a result, the discharge of water during the ebb tide is both stronger and of greater duration than the proceeding flood tide leading to an asymmetry in discharge. The balance between flood and ebb tide dominance in the Barra Nova and other inlets also depends critically upon the drainage supply and thus the location of the inlet is a critical factor in determining functionality and must be accounted for in the present conceptual model.

The inlet is also known to exhibit the physical characteristics indicative of wave dominance following storm events. Principal among these are a channel depth $O(6\text{ m})$, an inlet width $O(300\text{ m})$ and an arcuate ebb shoal located close to the shore (FITZGERALD *et al.,* 2000). The Peninsula do Ancão is a prograding feature owing to the net easterly alongshore sediment transport. Its easterly limit has a smaller cross sectional area than the adjacent Ilha de Barreta owing to the accumulation of aeolian dunes in the past. However, it has been observed that under erosive attack the dry, unconsolidated dune deposits of Ilha de Barreta are rapidly under-cut causing an imbalance in the amount of sediment released into the system between the eastern and western sides of the inlet. Taking these characteristics into account the conceptual model proposed for the Barra Nova considers the status of the inlet as a tidally-dominated or wave-dominated system and encompasses relationships between inlet morphology and the present and/or antecedent hydrodynamic conditions. In the model, reference is made to a number of morphological features defined in Figure 3a.

Using historical meteorological and offshore wave data, and defining wave direction as ψ_w and significant wave height and peak wave period offshore as H_s and T_P, respectively, it is possible to identify three hydrodynamic regimes for the Barra Nova. These are: *H1,* ebb-dominated, fair-weather conditions ($90° < \psi_w < 270°$, $H_s < 1$ m, $4\text{s} < T_P < 10$ s); *H2,* Atlantic storm, flood-dominated conditions ($245° < \psi_w < 275°$, $H_s > 3$ m, $8\text{ s} < T_P < 18$ s); and *H3,* Levante[19] storm, flood-dominated conditions ($120° < \psi_w < 140°$, $H_s > 3$ m, $6\text{ s} < T_P < 14$ s). It is known that in a normal year[20], regime *H1* dominates for at least 99% of time with regimes *H2* and *H3* occurring with varying degrees of severity for 0.6% and 0.4% of the time, respectively (PIRES, 1998). It should be noted also that whilst the low energy, fair-weather regime *H1* persists for most of the time, and is characterised by a south-west wave approach, infrequent, weak Levante conditions also occur with rather different consequences for inlet evolution and migration discussed below. Thus here it is necessary to subdivide *H1* conditions between the south-westerly, Atlantic conditions, $H1_A$, occurring approximately 85% of the time in a typical year and the easterly, Levante conditions, $H1_L$ occurring for only 15% of the time during a typical year.

It is known that in common with other tidal inlet systems, the underlying, first order driver of Barra Nova evolution is related to storm events. In simple terms, a storm forces morphological changes so that the inlet moves from an essentially ebb-tidally-dominated condition to a wave-dominated condition. Following passage of the storm, the inlet must then adjust its morphology back to a configuration determined by the fair-weather hydrodynamics. In responding to storms and subsequently reverting to an ebb-tidally-dominated state, the present model considers that the inlet may widen and/or migrate, the channel may realign and the ebb and flood shoals may accrete or erode. These irregular, cyclical changes in morphology form the basis of the present conceptual model.

Following on from the simple outline above, the three hydrodynamic regimes are proposed to give rise to, and modify, three possible morphological states (MORRIS *et al.,* 2001): *MOR1,* an ebb-tidally dominated period characterised by low waves and slow morphological change during an extended period of calm weather; *MOR2,* a post-storm, wave-produced

[19] Levante is the term used for the strong easterly wind emanating from the Gibraltar area and affecting the Gulf of Cádiz.

[20] Here we refer to average annual wind speed, precipitation, sea state and storm frequency and intensity observed over a period of 30 years.

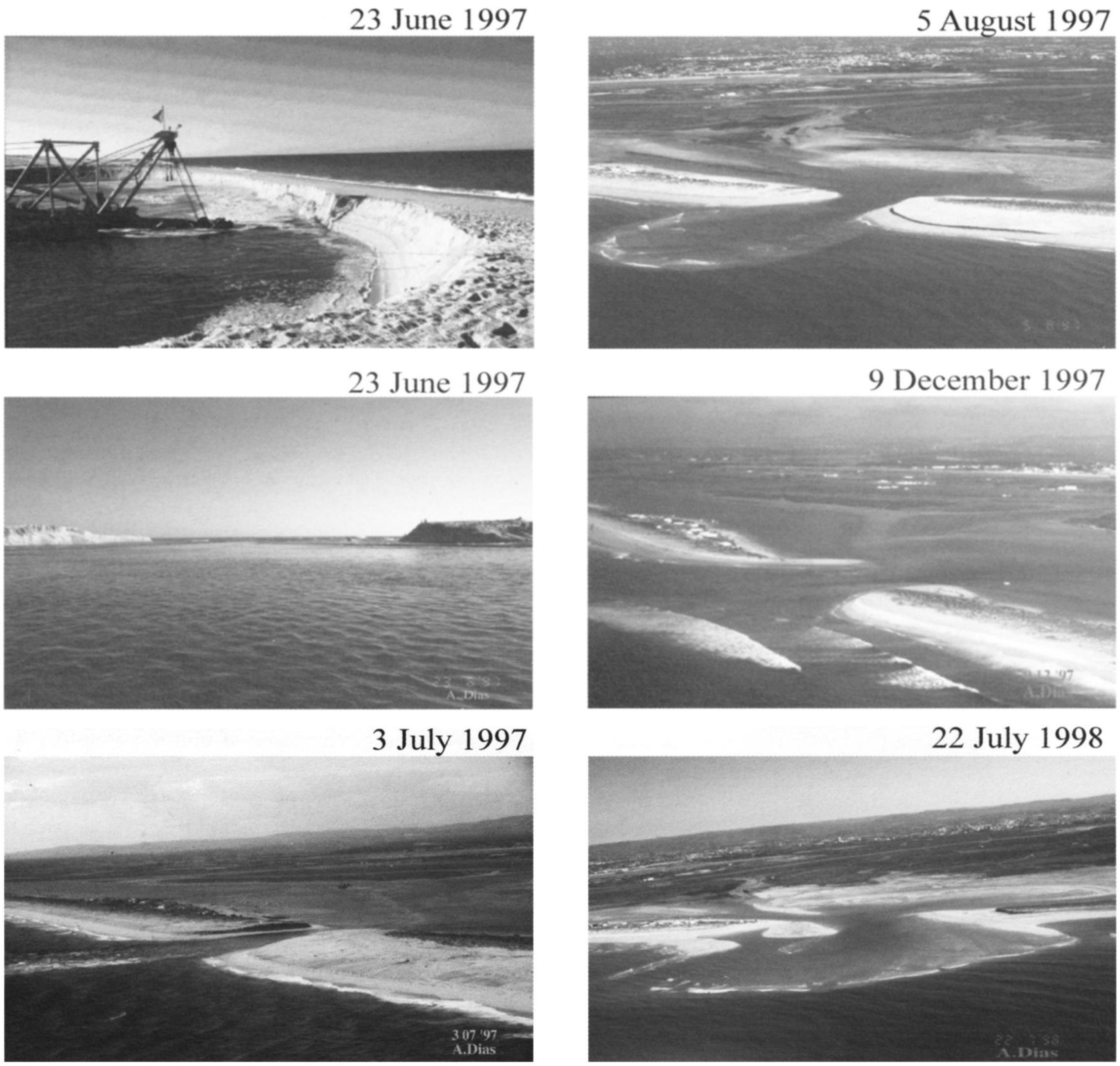

Figure 2. Aerial photographs showing evolution of the Barra Nova from 23 June 1997 to 22 July 1998.

morphological state following an *H2* or *H3* event; and *MOR3,* a transitional state when the inlet morphology adjusts back to the *MOR1* condition over a period of time. There is field evidence demonstrating that the length of time this takes is governed by the extent to which inlet morphology was perturbed from the initial condition by the storm. Present video evidence (see below), and historical meteorological evidence indicate strongly that *MOR1* is the dominant morphological state of the Barra Nova under the *H1* regime. State *MOR2* occurs after one or more storm events with south-west storms having the greatest effect owing to their duration and to the wave approach angle. Whilst the start of the *MOR2* state can be clearly defined, identifying unambiguously the end of the *MOR2* adjustment period back to the *MOR1* state is rather more problematic since the equilibrium condition is never met. Figure 3b shows schematically an annual scenario of hydrodynamic events the corresponding morphological response. As will be demonstrated later the INDIA fieldwork occurred whilst the inlet was undergoing transition following a storm event in December 1998. The figure shows also, that during a typical year, each of the hydrodynamic regimes may have a seasonal element, with storms generally occurring during the autumn and winter months, and calm periods occurring during the spring and summer.

MOR1: EXTENDED CALM

Assuming the Barra Nova has progressed through the transitional state *MOR3* to the extended calm state *MOR1,* in the normally occurring tidally-dominated regime $H1_A$, morphology of the inlet is assumed to be dominated by accretion of sediments in the spits comprising the swash platform and extending from the west shore of the inlet (Figure 3a). It is proposed here that these sediments, originating along the Peninsula do Ancão and transported by wave-induced alongshore currents, are intercepted by the Barra Nova. Following

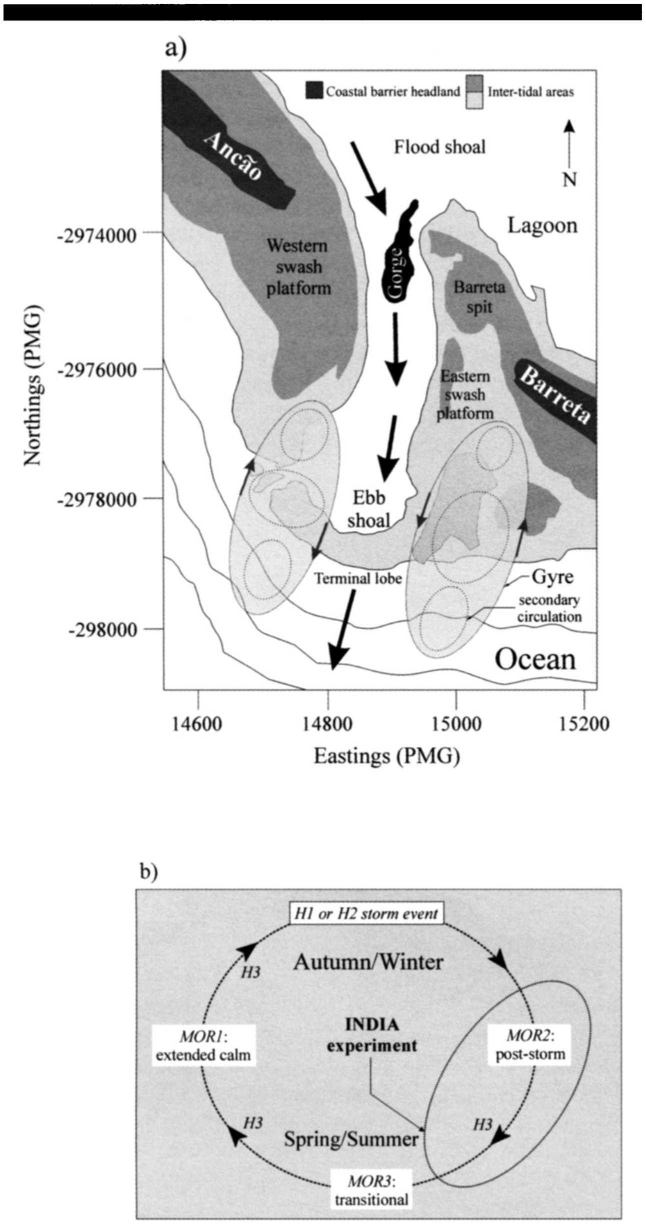

Figure 3. Schematic diagrams showing: a) morphological units in the Barra Nova (after BALOUIN and HOWA, 2000b); and b) cyclical changes in the Barra Nova referred to in the conceptual model.

FITZGERALD *et al.* (2000) it is further assumed that the slow stacking and coalescence of swash bars in the downdrift direction constricts the inlet throat causing an increase in inlet flow velocity. This in turn leads to greater scour and to the establishment of a new channel cross-sectional area in accord with inlet development described by ESCOFFIER (1940) and SKOU and FREDSØE (1990). Over time, in situations where the channel is not fixed by scour into semi-indurated sediments (historical evidence from Peninsula do Ancão confirms this assumption), the addition of sand at the updrift side of the inlet will cause the inlet channel to migrate and the ensuing erosion of the eastern shore will then drive inlet migration in an easterly direction and thereby force a corresponding migration of the ebb shoal. As the inlet migrates to the east, the lagoon drainage channels feeding the inlet also shift eastward and, it is postulated, will consume the flood shoal. In some cases the resulting deflection of the channel may reduce hydraulic efficiency, and may cause it to breach the ebb shoal and establish a more direct path to the sea (*c.f.* FITZGERALD *et al.* (2000). The old channel position will then be abandoned as the new channel claims the tidal prism and sediment downdrift of the new channel will be transported shoreward to join the littoral drift on the adjacent beach, thus facilitating bypassing. In regime $H1_L$ the eastward migration of the inlet and downdrift accretion of sediment at the end of Peninsula do Ancão ceases, and the Barra Nova may be forced westward if $H1_L$ persist.

A further consequence of flows into and out of the Barra Nova to be encompassed by the conceptual model is the formation of gyres by the tidal jet. In particular, the strong ebb tidal flows out of the Barra Nova are deflected to the west by Coriolis force as they travel southwards into the ocean possibly leading to the generation of a large gyre circulating in a clockwise fashion offshore to the west, and to a lesser extent to the east of the thalweg (Figure 3a). In the model it is considered that the resulting circulation has a capacity during spring tides to transport sediment from the inlet channel back towards the shore to be trapped in the ebb shoal and at times on the bars systems of Peninsula do Ancão, thus contributing to processes building the swash platform. During flood tides, the jet is less-well developed. However, there is a sufficiently well-defined inflow to produce a clockwise circulating gyre, in this case located to the east of the thalweg (Figure 3a). Smaller gyres will be also generated at locations in the lagoon close to the flood shoal as flood and ebb flow accelerate into and out of the Barra Nova, respectively.

In the absence of storms, the morphological state *MOR1,* maintained by the low-energy hydrodynamic regime *H1* is likely to change only slowly through time. In severe storms it has been observed historically that the inlet has a potential to widen and to migrate rapidly and occupy subsequently a new position some tens or hundreds of metres to the east in the case of regime *H2*. In the case of regime *H3* historical data show that the inlet can widen significantly in a westerly direction. In extreme cases (*i.e.* the 1 in 100 year event or less frequent), there is even historical evidence from Peninsula do Ancão showing the formation of a new inlet at a new location to leave two functioning inlets along a relatively short stretch of coastline. Thus in the model it is necessary that waves and currents during storm regimes *H2* and *H3* act in such a way as to result in significant disturbance to inlet morphology. Thus the extent of the resulting morphological change depends primarily upon the magnitude and duration of a storm event, the state of the tide (spring or neap), and upon the sequence of events impacting at the inlet.

MOR2: SOUTH-WEST STORM AND TRANSITION

Assuming that the Barra Nova is in morphological state *MOR1,* the first major effect of a regime *H2* storm will be severe erosion to the berm and spits to the west of the thalweg and to the ebb shoal by westerly storm waves. Enhanced by surge currents and waves, the direction of net sediment transport through the Barra Nova may reverse as sediment derived from strong alongshore transport and from erosion of the berm, spits and ebb shoal is forced through the inlet by wave action. It is assumed that some of this sediment will be accreted onto the flood shoal and some will be transported out of the inlet on the next ebb tide to be accreted on the ebb shoal and on the eastern shore. There is also evidence from aerial photographs that some sediment may also be displaced further into the lagoon by the tidal channels (DIAS *et al.*, 2000). The erosion by storm waves lowers bathymetry and will thereby allow larger and larger waves to penetrate into the inlet causing massive erosion of the eastern side of the channel and the formation of a spit extending into the lagoon. There is evidence also that overwash can make a major contribution to sediment transport and to the morphological development of the inlet. The changes to inlet morphology may be slight or major depending upon the severity and/or duration of the *H2* event before the inlet reverts to the post-storm, *MOR2* state (Figure 3b).

As the storm abates, fair-weather conditions once again prevail and the inlet enters the transitional state *MOR3*. During this transitional period the western berm and spits once again begin to form. Modifications to the bathymetry in the vicinity of the enlarged flood shoal result in stronger tidal flows and the ensuing erosion of flood shoal supplies sediment to the ebb delta and spit structures on the eastern shore of the inlet. The feed of sediment seawards following the storm will join the alongshore flux on the eastern side of the inlet and thus contribute in part to post-storm beach restoration. Following a period of adjustment, the Barra Nova will again approach the original extended calm state *MOR1*. It also noted that the *H2* event also impacts upon the beach of Peninsula do Ancão causing changes in the beach profile. The adjustment of the beach post-storm will occur at the same time as the inlet enters the *MOR2* condition and result in a supply of sediment alongshore greater than would normally be present for a fair-weather beach profile.

MOR2: SOUTH-EAST STORM AND TRANSITION

Again assuming that the Barra Nova is in morphological state *MOR1,* the storm regime *H3* will give rise to wave attack from the east and quickly erode the less well developed eastern-most part of the ebb delta thus allowing waves to penetrate quickly into the inlet and to erode the western shore and the associated berm and spit structures. Owing to the low beach profile known to result from inadequate supplies of sediment prior to the storm, the end of Ilha de Barreta will be subjected to wave attack causing severe erosion. Eroded sediments will then be transported through the inlet by wave action and will be deposited inside the lagoon. Waves penetrating into the inlet across the eroding ebb shoal will then in turn attack the western shore causing erosion and widening of the inlet. However, owing to the short-lived nature of Levante storms and the oblique wave incident direction, there is evidence from historical data to indicate that the Levante storms do not have the severe impact on the Barra Nova morphology of the south-westerly Atlantic storms (MORRIS *et al.*, 2001). Following a Levante storm, the inlet morphology will be displaced to the post-storm *MOR3* state. Thereafter it will enter the transitional regime *MOR2* as slowly the berm and bar systems on the western shore build and erode spits inside the lagoon on the eastern shore. After a period of time, the Barra Nova will once again approaches the *MOR1* state as regime *H1* conditions re-establish. Again, storm modifications to the updrift beaches will provide a post-storm feed of sediments alongshore towards the inlet at a greater rate than normal.

MEDIUM- TO LONG-TERM EVOLUTION

Present evidence indicates that the morphologic evolution of the Ría Formosa inlets and barrier islands result from processes operating at three temporal scales: 1) evolution in response to relative sea-level rise, on a geological time-scale $O(10^3$ years); 2) exposure to different wave and current conditions at different locations in the system, on time-scales $O(10^0$ to 10^2 years), and; 3) the effects of storms and the subsequent adaptation processes, on time scales $O(10^{-1}$ years). Here we do not consider the geological time-scale since the life-cycle of an inlet on Peninsula do Ancão is at least one order of magnitude less. Here we consider the present position of the Barra Nova on Peninsula do Ancão and the changes brought about in the future as the inlet migrates in the normal easterly direction. Firstly, migration of the inlet will lengthen the lagoon drainage pathways and thereby reduce hydraulic efficiency. This will lead directly to a reduction in both tidal flow velocity and volume leaving the inlet on ebb tides. Secondly, owing to the natural curvature of the coastline toward the east of Peninsula do Ancão, the wave incidence angle will become progressively more acute and lead to an increase in alongshore transport of sediment. Thirdly, the migration and corresponding elongation of the Peninsula do Ancão will result in a low spit which under storm and/or spring tidal conditions is overwashed. The length of the spit is determined by the migration rate of the inlet and by the rate at which aeolian dunes form on the newly deposited sediments. Together, these processes will act to eventually close the inlet at some critical position to the east of the present location.

METHODS

Fieldwork

Following breaching of a coastal barrier, either by natural or artificial means, there are few examples of studies monitoring inlet development. Dredging to create the Barra Nova thus presented a unique opportunity to investigate in the field the interplay between tidal currents, waves and sediments as the system evolved. The post-dredging development the Barra Nova covering areas of the inlet exposed at low water was monitored by repeated surveys from June 1997 to March 1999. Design of the main field campaign was guided by the questions raised by the conceptual model regarding inlet function and evolution and followed many of the techniques used in the past to study tidal inlets (*e.g.* MANN, 1993;

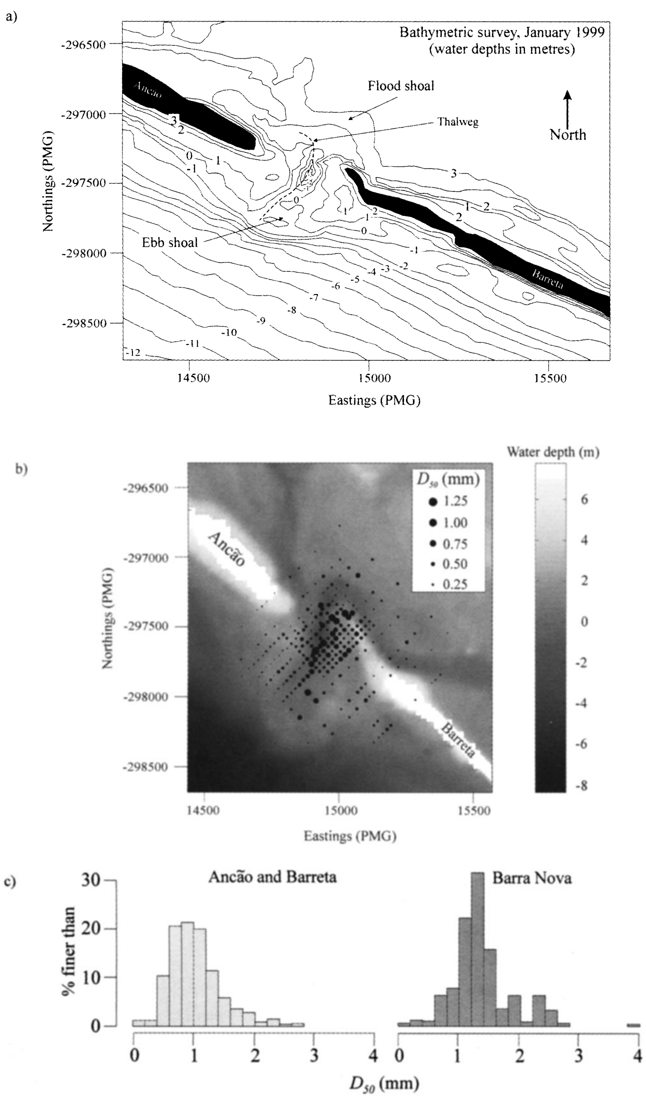

Figure 4. a) Measured bathymetry at the field site; b) median grain size, D_{50}, for location inside and outside the Barra Nova; and c) spatial variation in and adjacent to the Barra Nova of D_{50} obtained from analysis of grab samples.

HOWELL, 1996; HICKS and HUME, 1997; STAUBLE, 1998; PRATT *et al.,* 2000). Detailed bathymetric surveys were obtained in January and March, 1999 and in January 2000. Bathymetric data for offshore areas outside the prescribed limits of these surveys were obtained from Portuguese hydrographic charts. Grab samples of surficial sediments were obtained at 150 locations in the study area and were analysed to determine the grain size distribution, settling velocity and $CaCO_3$ content (HUGHES and HUGHES, 2000). These data were augmented with surficial sediment information derived from published surveys. Figure 4 shows: a) bathymetry in and adjacent to the Barra Nova (January, 1999); b) the median grain size of sediment offshore of Peninsula do Ancão and Ilha da Barreta and inside the Barra Nova; and c) spatial variation in and adjacent to the Barra Nova of median grain size, D_{50}, values. These plots use the Portuguese Melriça Grid based upon a rectilinear UTM co-ordinate system.

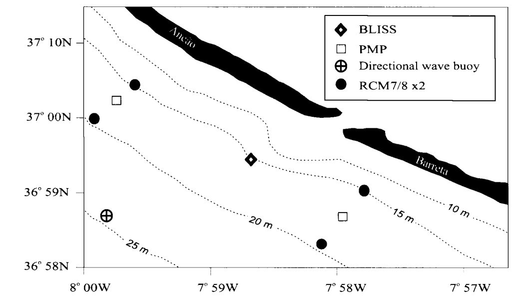

Figure 5. Location of offshore moorings.

Pressure-temperature, PT, sensors were deployed and vertical flow profiles were measured over the spring-neap cycle using an ADCP in each inlet of the Ría Formosa. Offshore, measurements of tides, tidal currents, waves, turbulence and suspended sediments were obtained using moored oceanographic instruments, HUMPHERY *et al.* (1999), (Figure 5). Meteorological data were measured at locations close to the Barra Nova (ARENS and VAN BOXEL, 2000) and at Faro airport. Wide-area measurements of surface currents and waves a regular grid of points up to 2.0 km offshore from the Barra Nova were obtained using a VHF radar (HERON and PRYTZ, 2000) and x-band radar (BELL, 1995). Changes in inlet morphology were monitored using snapshot, time-lapse and time-stacked video images from a four camera video system installed on the 30 m tower on Ilha da Barreta (MORRIS *et al.,* 2001). In the inlet, a jack-up barge was used to deploy the PIP, a multi-sensor instrument to measure in detail at several locations hydrodynamic conditions, sediment transport and bed morphology (WILLIAMS *et al.,* 2000). Surveys of the ebb delta and swash platform were undertaken at low water using a small boat equipped with an echo sounder and DGPS and total station survey methods were used to survey, the berm, beach profiles and dunes (BALOUIN and HOWA, 2000a). Hydrodynamic measurements were obtained close to the shore using moored instruments and a specially designed instrumented beach crawler (EVANS *et al.,* 2000). Cross-shore and alongshore sediment transport was measured using fluorescent tracer techniques, (HOWA and DE RESSEGUIER, 1994). Meteorological towers, sand traps, saltiphones, topographic surveys and erosion pins were used to measure meteorological conditions (especially vertical wind profiles) and aeolian transport of sand (ARENS and VAN BOXEL, 2000). Further detailed description of the fieldwork may be found in reviews by WILLIAMS *et al.* (1999). The INDIA field data set is now available on CD-ROM from BODC[21] subject to user restrictions.

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Numerical Modelling

Physical models of coastal inlets (*e.g.* HUGHES, 1993; SEABERGH, 1999) are unable to simulate accurately sediment transport processes owing to scaling problems and remain of limited use for the study of natural inlet processes or for examining the medium- to long-term morphological change. Here the only viable approach to prediction of inlet evolution is through the use of numerical models (*e.g.* TANAKA *et al.*, 1995; VAN DER KREEKE, 1996; KRAUS and MILLTELLO, 1999; KRAUS, 1999) to extend the spatial and temporal range of the field observations and thereby allow more general conclusions to be drawn regarding inlet function and evolution. Using the measured bathymetry numerical modelling focussed upon hydrodynamics, sediment transport and morphological behaviour. The various models considered tide, wind and wave driven currents; tide, wave and storm surge propagation (esp. asymmetry and over-tides); wave propagation, including reflection, refraction, shoaling, damping, steepness and depth-limited wave breaking and blocking; secondary flow effects due to wave-current interaction, Coriolis, curvature and jets; macro-scale and micro-scale turbulence; current-related and wave-related sand transport; and the spatial variations in bed sediment properties.

As no single model yet has a capacity to simulate all physical processes, the approach adopted links a number of models, each addressing different features of inlet function and morphology and parameterised with field data. At the largest spatial scale, the US Army Corps of Engineers RMA-2V model was used by SALLES (2000a) to examine multiple inlet function and stability for the entire Ría Formosa. This model examined: existing non-linear hydrodynamic characteristics (tidal distortion, ebb/flood dominance, residual flow patterns); the potential existence of sub-embayments in a coastal lagoon; and the effect of physical disturbances (change in inlet cross-sectional area, inlet migration, inlet closure/opening). At a smaller spatial scale spanning the inlet a quasi-3D model (3D-INLET, O'CONNOR *et al.*, 2000b) was used to simulate in detail waves, currents, sediments and morphology (4 km alongshore, 3.5 km cross-shore). Inshore of the Barra Nova, the 3D-INLET model interfaced with a large-area tidal model of the whole Ría Formosa system (LAGOON). At the offshore boundary, 3D-INLET used field measurements of tides and tidal currents. Waves were simulated using the spectral WAM model (*e.g.* KOMEN *et al., 1994; M*ONBALIU *et al.*, 2000) and input at the outer boundary of 3D-INLET, and thereafter propagated shoreward towards and into the Barra Nova using the spectral SWAN model (BOOIJ *et al.*, 1999).

A range of 1DV/2DV hydrodynamic and sediment micro-models were used together with field data to aid understanding of processes and to assist with estimation of sediment transport (*e.g.* JACOB and EÇA, 1999; HARRIS and O'CONNOR, 2001, and O'CONNOR *et al.*, 2000a). These provided detailed inter-wave period views of water column and bed interactions, (1D-W/C/S and 1D-SHEET, O'CONNOR, 1992; O'CONNOR *et al.*, 1992; KACZMAREK and OSTROWSKI, 1999), of water and sediment movement around individual bedforms, (2D-BED, KIM *et al.*, 1995; JACOB and EÇA, 1999), and of dynamic conditions during the wave breaking process, (2D-SURF, O'CONNOR *et al.*, 1998c; ABADE *et al.*, 1998). The model 2DH WIBATH was used to study wave, current and bed morphology changes at "frozen tidal states" during typical tides, and SHORECIRC was used to study wave-driven circulations (SANCHO *et al.*, 2000). A Boussinesq model (WAC-UP) was to study intra-wave-period processes in the presence of tidal currents close to the inlet (DO CARMO and SEABRA-SANTOS, 1998). A model of wind flow and aeolian sand transport, (2D-AEOLIAN, BOXEL *et al.*, 1999; DIJK *et al.*, 1999), was used to simulate the effect of sand interchanges by wind action between the beach and dune system and the lagoon using different meteorological scenarios. The Q3D model was run to simulate medium term morphological changes over the period of the field campaign. The other 1D, 2D and 3D numerical models were run in order to simulate field conditions and to allow intercomparison between wave-period-average and intra-wave-period results on two standard days: 2 February (a typical spring tide) and 24 February (a typical neap tide), 1999. Micro-modelling of processes has been undertaken both for these days and for other times during the experiment.

RESULTS AND SUPPORTING EVIDENCE FOR THE CONCEPTUAL MODEL

At the largest spatial scale field measurements and numerical modelling examined the functional relationship between the Barra Nova and other inlets in the Ría Formosa (SALLES, 2000a, 2000b). Initial runs of the model showed the system to be divided in three quasi-independent hydrodynamic cells. Here we briefly summarise some results from simulations focussed upon the western cell of the Ría Formosa encompassing the inlets Barra Nova, Faro, and Armona in which the inlet cross-sectional areas and forcing conditions were varied. The Faro, Armona and Barra Nova inlets were found to carry 60%, 31% and 9% of the total tidal prism of the western cell of the lagoon, respectively. The closure curve of the Barra Nova showed that the maximum velocity under present conditions was approximately 1.35 m/s. This is approximately in accord with the field measurements and if compared to the widely used equilibrium velocity of 1 m/s (ESCOFFIER, 1940; BRUUN, 1968; SKOU and FREDSØE, 1990), indicates that the Barra Nova may still be in a phase of growth. However, according to VILA-CONCEJO *et al.* (1999) the width of the Barra Nova has now reached a state of relative stability and thus it is suggested that the 'excess' velocity may either increase the depth of the inlet, or trigger other processes known to occur in natural inlets, such as enlargement of the ebb tidal delta or inlet migration. In terms of the flow volume the RMA-2V model showed that the response of the Barra Nova to either an increase or a decrease in cross-sectional area was the same, namely an increase in the seaward residual discharge. On one hand, the tendency to flush more effectively sediment seaward is enhanced as the Barra Nova cross-sectional area decreases from its present value, which can be regarded as a response against closure. On the other hand, as the Barra Nova cross-sectional area increases, the residual discharge increases seaward, but the residual current and maximum velocity (which are also di-

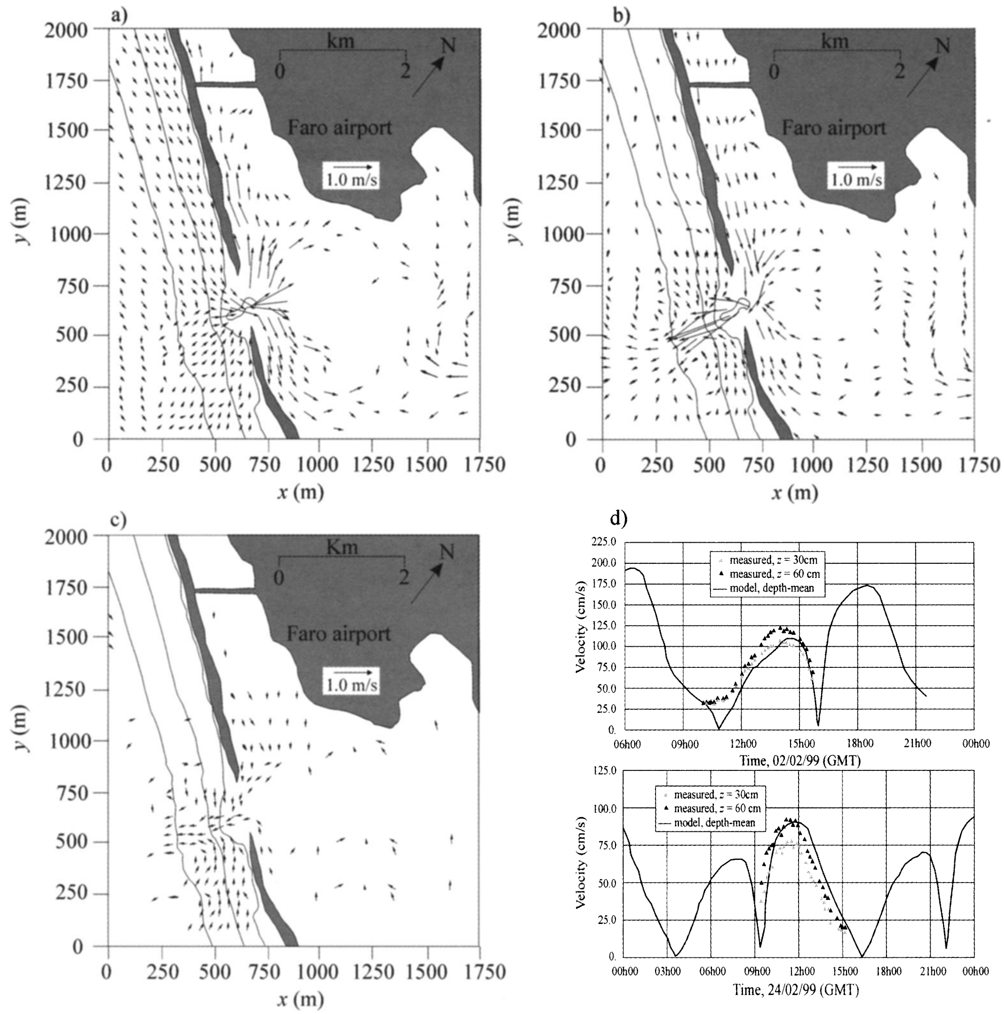

Figure 6. Results from LAGOON model at the Barra Nova: a) flood tide currents, 2/2/99; b) ebb tide currents, 2/2/99; c) residual tidal currents; and d) comparison between LAGOON results and measurements in the Barra Nova channel.

rected seaward) decrease, thus reducing the ebb transport dominance. Therefore, from a tidal hydrodynamic point of view, the RMA-2V model indicates that present width of the Barra Nova appears to sustain an approximately 'stable' condition.

The LAGOON model allowed finer-scale simulation of hydrodynamic conditions in the Barra Nova. Drawing upon the most recent bathymetric data, historical data sets and field data pertaining to water levels and currents, a fine grid version of LAGOON (25 m) was used to simulate tidal flows. Selected model output for the flood and ebb tides on 2 February 1999 showing depth-average velocities, U, is presented in Figure 6a and Figure 6b, respectively. Residual water movements are shown in Figure 6c and comparisons between computed U values and U values measured by the PIP are shown in Figure 6d. Figure 6a and Figure 6b show that maximum U values during flood and ebb tides are in the range 1.0–1.25 m/s and 1.75 to 2.0 m/s, respectively, and demonstrates the ebb dominant nature of the inlet under spring tide conditions. During neap tides, less tidal distortion is evident (not illustrated) due to reduced phase speeds between high and low water, as well as reduced bed friction. In this case maximum flood velocities are O(0.6 to 0.7 m/s) whilst ebb velocities are O(0.85 to 0.9 m/s). The ebb dominant nature of the Barra Nova is further shown by the pattern of residual currents in Figure 6c. Lagoon waters appear to be drawn mainly from the north west with less than 30% coming from the south east. Although Coriolis force will tend to straighten the channel to a more shore-normal orientation as it travels seaward, the strong pull of water from the north western part of the lagoon explains in part why the inlet axis is inclined. This figure also shows the generation of two gyres either side of the main outflow jet. The gyre circulation to the west of the thalweg is enhanced by Coriolis force; thereby reinforcing further hydrodynamics driving swash bar construction at the eastern end of Peninsula do Ancão. The use of the 3D wave-induced current SHORECIRC model for a hypothetical inlet, similar in dimensions to the Barra Nova, showed also that

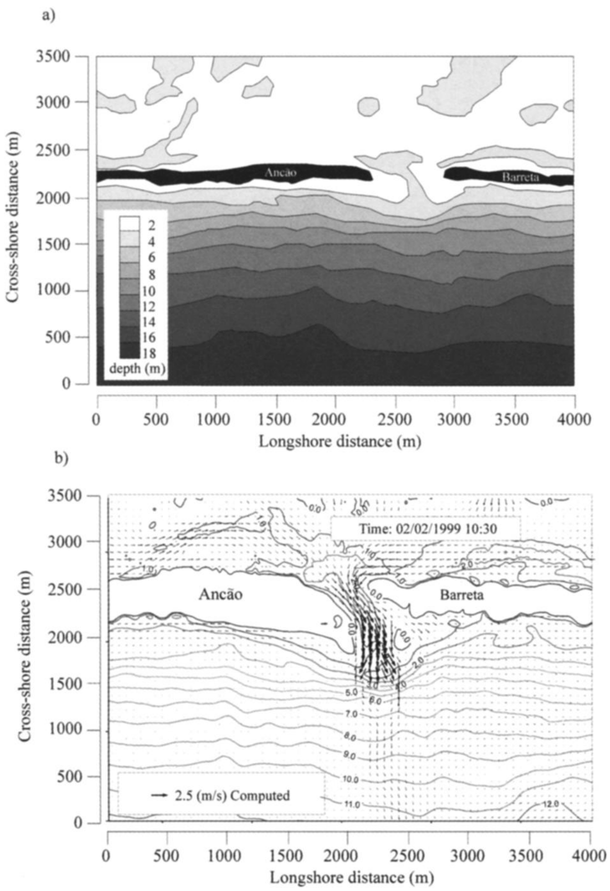

Figure 7. a) Bathymetry used in the Q3D model; and b) simulation of the ebb tide, 2/2/99.

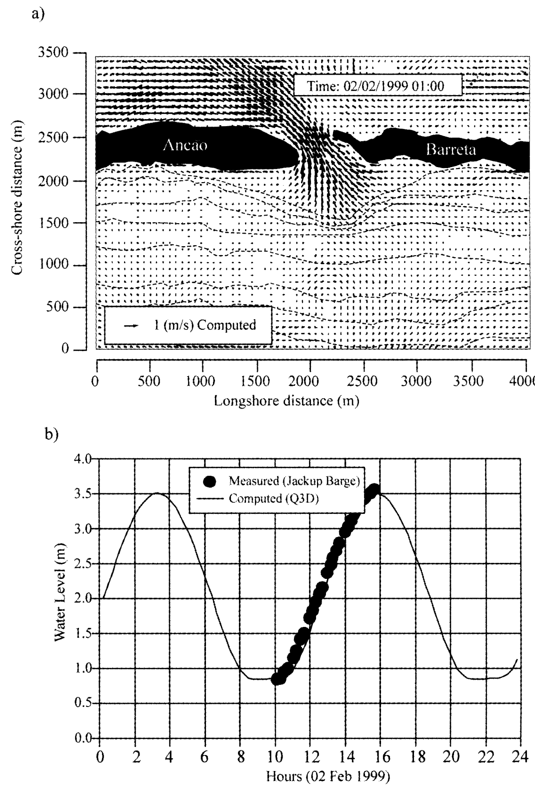

Figure 8. Results from the Q3D model showing: a) simulation of the flood tide, 2/2/99; and b) measured (PIP) and computed water level in the inlet.

wave action can produce gyres in the absence of tides. These model results thus confirm the ebb-tide dominance at the inlet and show that the tidal flow patterns conform to the conceptual model during the *H1* condition.

Figure 7a shows the 20 m gridded bathymetry used in the Q3D model. Simulations of ebb and flood tidal currents for 2 February, 1999 shown in Figures 7b and 8a, respectively, indicate peak currents $O(2.5)$ m/s in shallow areas. Again the ebb dominance of the Barra Nova system is demonstrated. Comparisons between predicted and measured water levels and tidal currents in Figures 8b, 9a and 9b show good agreement between computed and measured data. To illustrate the effect of depth limitation in the vicinity of the Barra Nova and the blocking effect to wave by the strong outflow during the ebb tide, Figure 10 shows a result from the Q3D model (H_s = 1.0 m; T_p = 6.0 sec). Field observations confirm this model result.

In Figures 11a and 11b COSRAD derived surface current vectors are superimposed upon x-band radar images obtained during the flood and ebb tides on 24 February, 1999, respectively. Here the x-band radar images have been processed to show 'rough' areas of the sea surface in dark tones and 'smooth' areas in light tones. The zone of breaking waves, defining the outer limits of the ebb delta and the surf zone along adjacent beaches, is clearly visible. In addition, the plume emanating from the Barra Nova during the ebb tide is also clearly defined and supports further COSRAD data and the modelling results. In common with other COSRAD data, Figure 11b also shows some evidence of vorticity to the east of the inlet suggesting the presence of gyre-like circulation hypotheses in the conceptual model. Results from the WIBATH model shown in Figures 11c and 11d also demonstrate the presence of gyres in the inlet. Further evidence of this came from the SHORECIRC model. Comparison between measured and predicted current speeds along the section line shown in Figure 11e are shown in Figure 11f. With the exception of the measurement station furthest offshore there is close agreement between measured and computed values thus verifying modelling results. Further discussion of COSRAD results is given below.

Figure 12 shows: a) bathymetry and the imposed flood-tide current field from LAGOON and b) the resulting surface wave pattern 37.5 s after inputting sinusoidal waves (H = 1.5 m, T = 8s) from the left. These results show that the model has a capacity to simulate the various complex wave refraction, diffraction and reflection effects in the inlet. Recently these model results have been compared with field measurements obtained using 77 GHz radar with 0.5 m spatial resolution and found to be broadly similar to the observed

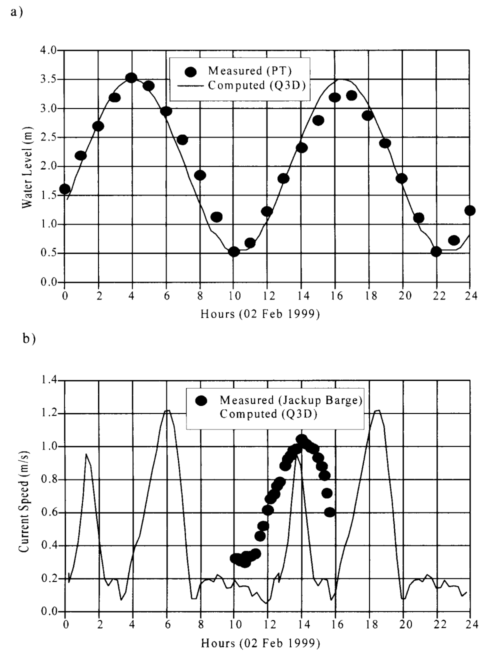

Figure 9. Results from the Q3D model showing a) measured (Barra Nova PT sensor) and computed water level; and b) measured (PIP) and computed tidal current speeds.

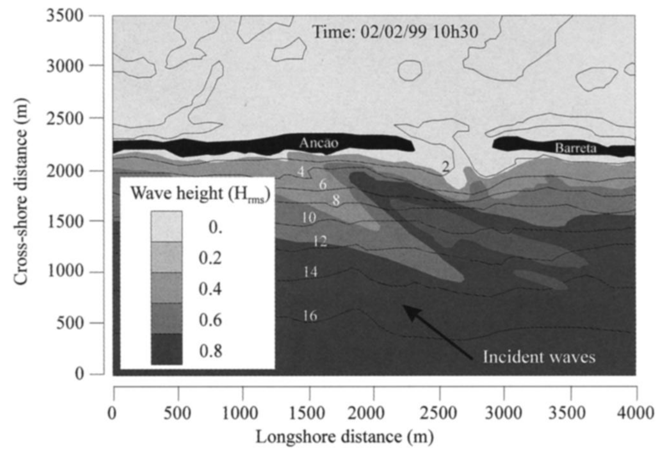

Figure 10. Results from the Q3D model showing computed wave heights.

wave patterns in the inlet and across the ebb shoal. Waves were also studied using the spectral wave model SWAN. Offshore wave conditions at the outer boundary of the SWAN model were specified by the wide area WAM wave model and currents were imposed from the Q3D model. The spatial distribution of wave energy dissipation for approximately 10h00 GMT on 2/2/99 shown in Figure 13a shows clearly the breaker line and surf zone close to the beaches of Peninsula do Ancão and Ilha da Barreta and a high dissipation region coincident with the location of the western swash platform and ebb delta structures. Wave blocking by the ebb current is again demonstrated. Figure 13b shows a processed snapshot image of the wave field obtained at the same time using x-band radar. Here the waves close to the shore steepen before breaking resulting in stronger radar reflection as indicated here by the darker shading. This region is approximately coincident with the areas of maximum wave dissipation in the SWAN model. Figure 13c shows good agreement between wave vectors computed by the Q3D model and the x-band radar image.

Results from bathymetric and topographic surveys covering the period August 1997 to May 1999 are summarised in Figure 14 which shows: a) a plan view of morphological evolution; and b) evolution of the inlet channel profile. In common with other examples (*e.g.* BENARD and DAVIES, 1999) rapid changes to inlet morphology occurred immediately after opening. In the present case the inlet is shown to widen from some 70 m a few days after dredging and attain a relatively stable width of some 300 m after approximately 12 months. The ebb and flood shoals are constructed seaward and shoreward of the inlet, respectively, and swash platforms are accreted on either side of the inlet. Changes to the inlet width shown in Figure 14, through westwards expansion between August 1997 and April 1998, are at odds with most historical trends. However, Levante conditions, with strong easterly winds and high waves were far more prevalent than normal during this period and explain these observations. From April 1998 onwards Figure 14 shows the gradual extension of Peninsula do Ancão eastwards and a corresponding erosion of the western shore of Ilha da Barreta.

The morphology evolved in a step-like fashion, with major changes occurring during storm events which caused breaching of the ebb delta and erosion of the inlet margins and adjacent shorelines as described in the conceptual model. Morphological changes occurring during low to moderate energy wave conditions were small by comparison and were manifest by the accretion of spits and bars which slowly deflected the channel eastwards. It is noted also that since opening, the rate at which the Barra Nova width has increased has declined at an approximately exponential rate.

The historical development of the Peninsula do Ancão inlet reviewed by VILA-CONCEJO *et al.* (1999) draws on studies by WEINTHOLTZ (1964), GRANJA (1984), ESAGUY (1986), PILKEY *et al.* (1989), ANDRADE (1990) and BETTENCOURT (1988, 1994). All authors propose a net eastern migration of the inlet with variable migration rates, I_m. These range from O(50 m/year), (*e.g.* PILKEY *et al.,* 1989; BETTENCOURT, 1994), to an extreme value of O(700 m/year), (GRANJA, 1984). Using a series of vertical aerial photographs of the Barra de São Luís (Figure 1) from the years 1976, 1985, 1989 and 1996 VILA-CONCEJO *et al.,* 1999 estimate I_m = 53 m/year for the period 1976 to 1985. This increased subsequently to 130 m/year during the period 1985–1989 before final closure of the inlet *circa* 1996. This latter value for inlet migration rate is consistent with model predictions for I_m using an SPM-type of bulk alongshore transport formula with corrections for grain size (MUIR-WOOD and FLEMMING, 1981), see also Figure 14c. The model also predicts that storm events have a profound impact

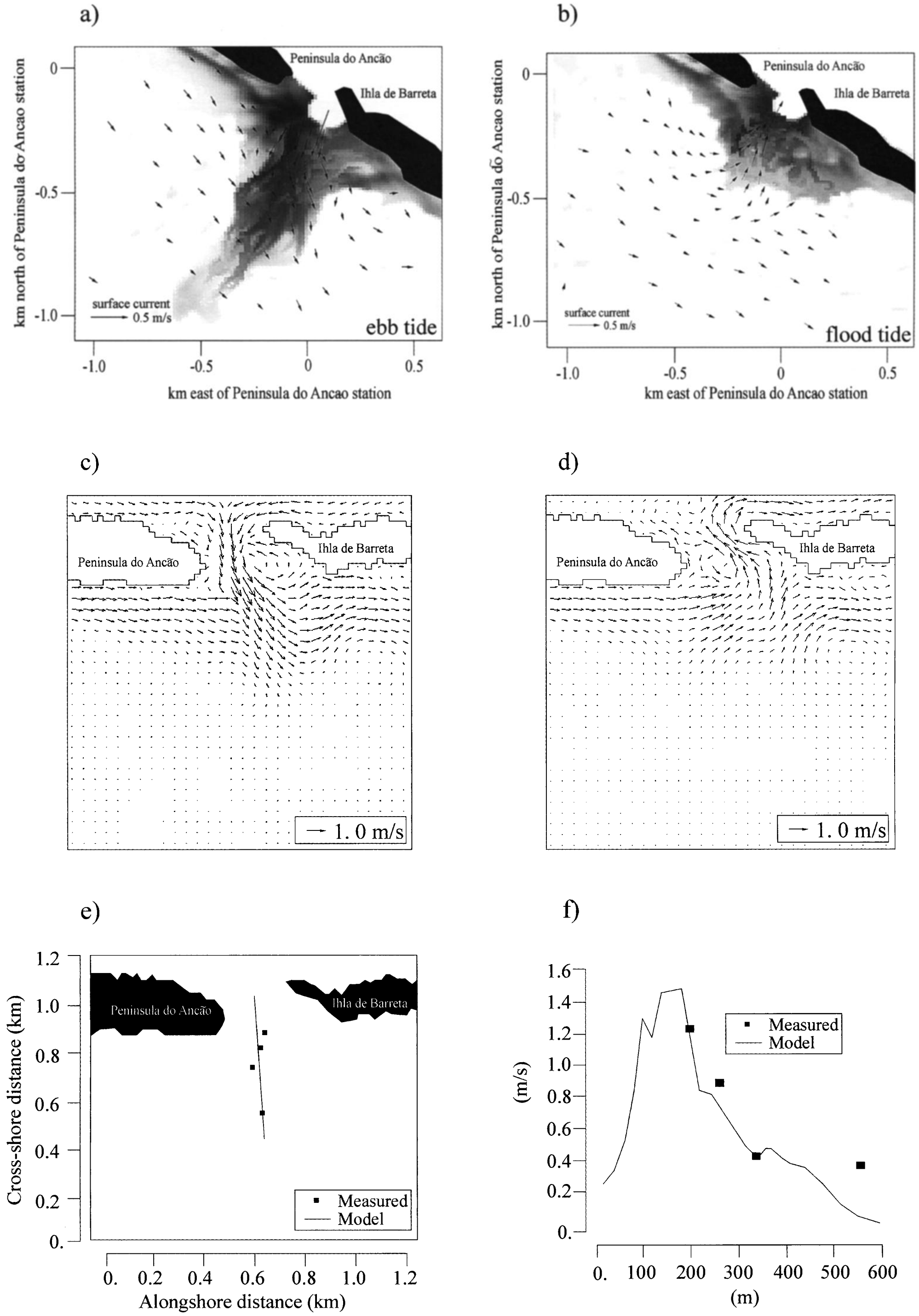

Figure 11. Comparison between JCU COSRAD HF radar and the Q3D model: superposition of COSRAD and x-band radar data for a) an ebb tide (1200hrs, 24/2/99, note the ebb tide plume) and b) a flood tide (1500hrs, 24/2/99); c) WIBATH simulation of ebb currents (1200hrs, 24/2/99); d) WIBATH simulation of flood tidal currents (1500hrs, 24/2/99); e) WIBATH section line; f) Comparison between measured (COSRAD) and simulated (WIBATH) tidal current speed.

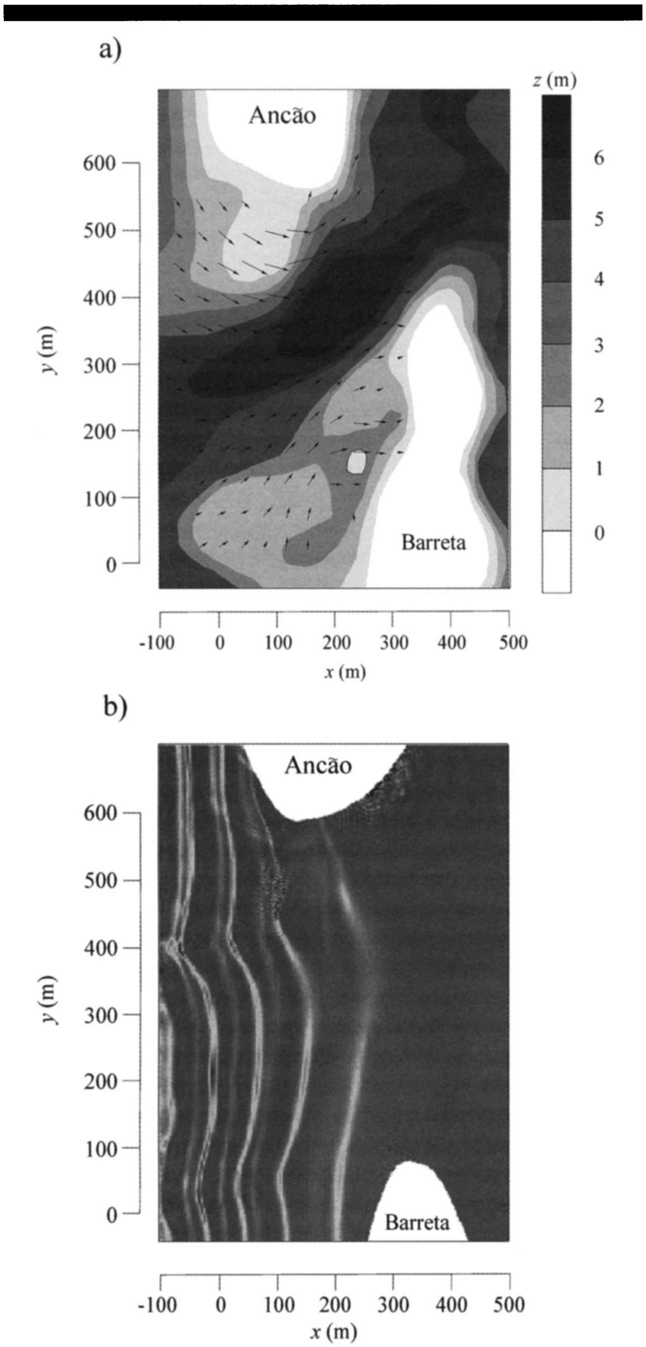

Figure 12. WACUP modelling for 2/2/99: a) bathymetry and imposed maximum flood tide current field (from LAGOON); b) surface wave pattern 37.5 s after beginning the simulation (sinusoidal wave, H = 1.5 m, T = 8 s).

on inlet location with migration distances O(300 m) possible in the 1 in 50 year event for this location.

Data pertaining to the width of the inlet, the location of the channel and the morphology of the flood and ebb shoals were obtained from the video images. Some results are shown using plan-view composite video images in Figure 15 for the periods a) 3 December 1998 to 9 January 2000, and b) 3 December 1998 to 20 January 1999. Simplified sketches showing the principal morphological features in the video images are shown in the lower panels of each figure. Figure 15a shows that the Ilha da Barreta has eroded approximately 156 m. Some of the sediment loss on the eastern side of the Barra Nova has been compensated for by the growth on the bars comprising the swash platform on the western side of the inlet. In common with historical values the video data show an average erosion rate of 140 m/year for the inlet. Since completion of the field campaign the inlet has continued to migrate in an easterly direction by some 200 m at approximately this rate up to February 2002 (VILA-CONCEJO, 2002, *personal communication*).

Figure 15b shows that from December 1998 to July 1999, erosion along the shoreline of Ilha da Barreta bordering the Barra Nova was estimated to be 90 m ($\approx$0.42 m/day) and the position of the inlet channel migrated 55 m ($\sim$0.25 m/day) toward Ilha da Barreta in a south-eastern direction. This observation is consistent with the prevailing direction of alongshore sediment transport and very similar to value (90 m) produced by the simple SPM-type modelling. The orientation of the inlet channel also underwent significant shifts of up to 35°/month between across-shore and north-south alignment during these seven months. These shifts were largely de-coupled from wave activity suggesting relocation may have resulted from a requirement to achieve greater hydraulic efficiency.

Before considering storm response of the system it is important to note that during the period proceeding the field experiment from July 1988 to December 1998 both meteorological and offshore wave data showed the weather was calm (conditions *H1*) giving rise to morphological state *MOR1* for the inlet characterised by strong ebb-tidal dominance. Video evidence reported by MORRIS *et al.* (2001) showed clearly that the bulk of erosion on Ilha da Barreta (80%) occurred during storms with the most significant event occurring between 29th December 1998 and 1st January 2000. During this time swell from the south west (H_s O(4 m); T_p O(9 s), Ψ_w O(220°)) was coincident with peak spring tides O(2.7 m) on 31 December 1999. The width of the Barra Nova was measured to increased from 360 m to 425 m due largely to erosion of Ilha da Barreta and the western swash platform and resulted in accretion of a large sand spit extending from Ilha da Barreta into the lagoon (Figure 15b). This moderate storm event shifted the inlet from the extended calm *MOR1* state to the post-storm *MOR3* state described in the conceptual model.

Changes to inlet morphology were also brought about by another *H2* event on 12th March 1999 (H_s O(3 m); T_p O(8 s), Ψ_w O(220°)). During the event the shore of Ilha da Barreta was again eroded, the width of the inlet increased from 430 m to 470 m and the channel shifted by approximately 10 m eastwards without change in orientation. The remaining spit extending from Ilha da Barreta from the proceeding storm was completely eroded during this time. In the case of this second *H2* event, the storm was coincident with neap tides O(1.4 m), and thus wave penetration into the inlet was less effective. Further, storm duration was only two days thus reducing further wave impact upon morphology.

On 23rd March 1999, during Levante conditions, the Barra

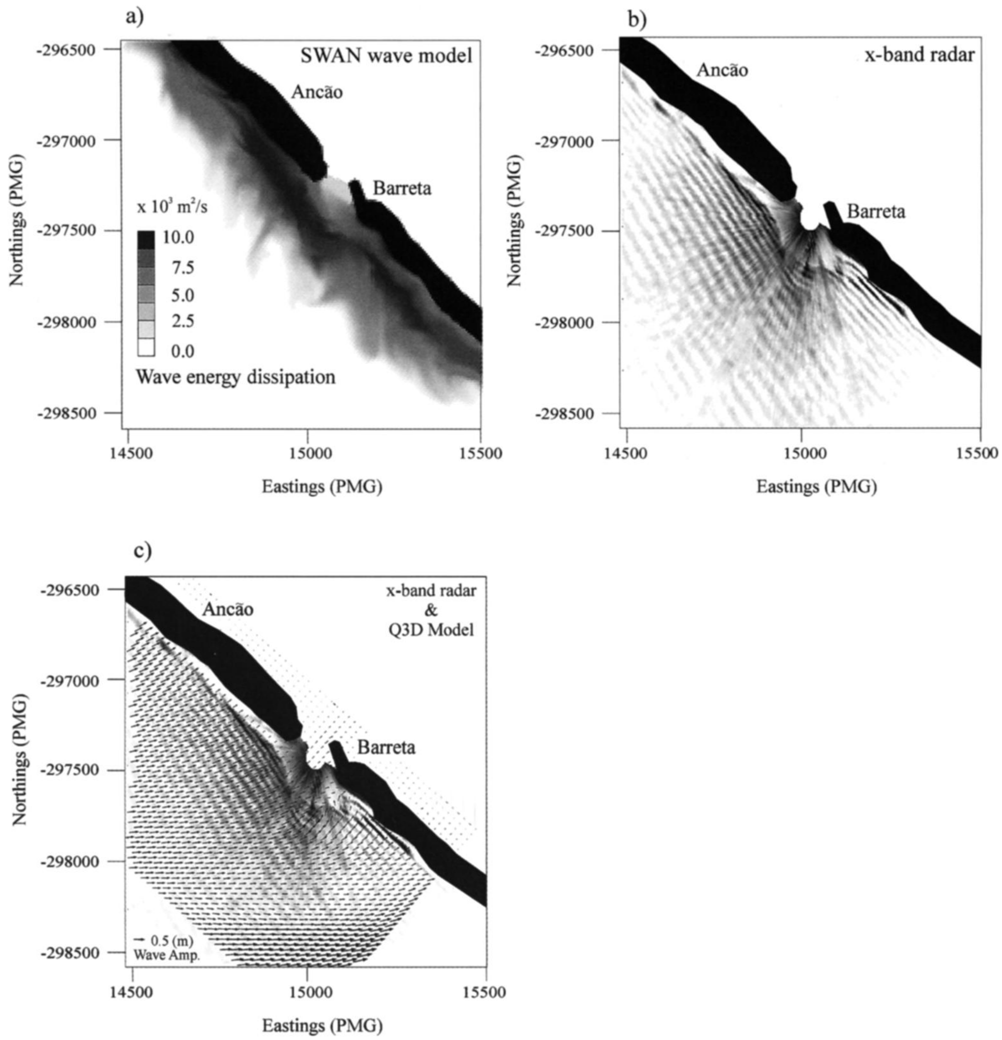

Figure 13. Examples of results from a) the SWAN spectral wave model, b) x-band radar; and c) the Q3D wave/current interaction model on 18 February 1999.

Nova was subjected to an *H3* event with swell emanating from the south east. Although swell height and period were similar to the 12th March storm (H_s O(3.5 m); T_p O(7 s), Ψ_w O(130°)), the event resulted in only moderate amounts of erosion to the ebb delta and swash platform and to the western shore of the Barra Nova and no change in the location of the channel was detected. In common with the second *H2* event, this storm only lasted two days and was coincided with neap tides O(1.8 m), thus again reducing significantly the effectiveness of the waves.

In the post-storm *MOR2* recovery period, morphological changes were observed to occur gradually as sediments were slowly re-worked by the tidal currents and smaller waves from the south west. Video evidence indicated that sediments lost from the bars on the western swash platform during the storm were slowly replaced by sediment transported alongshore by small waves from the south west and by a net transport of sediments out of the lagoon by the ebb tide (MORRIS *et al.*, 2001). Re-establishment of tidal ebb-dominance caused the ebb shoal to enlarge and to build further offshore using material transported seaward by the inlet channel. If rates of morphological change are examined (*e.g.* area of the swash platform), it is apparent that although slowing down, the Barra Nova was still in the *MOR2* state following the December 1998 storm when the first March 1999 storm hit. However, subsequent to the second March 1999 storm, the weather entered a period of extended calm, and after approximately 3 months, the rate of morphological change attained a near-constant value at a range of locations in the Barra Nova. It appears therefore that after a series of winter storms, the inlet takes approximately 3 months to adjust back to its preferred fair weather morphology.

By dividing the Barra Nova into three morphological units VILA-CONCEJO *et al.* (2000) estimated the sediment budget for the period 1997 to July 1998 using survey data. In the analysis these units were further sub-divided on the basis of

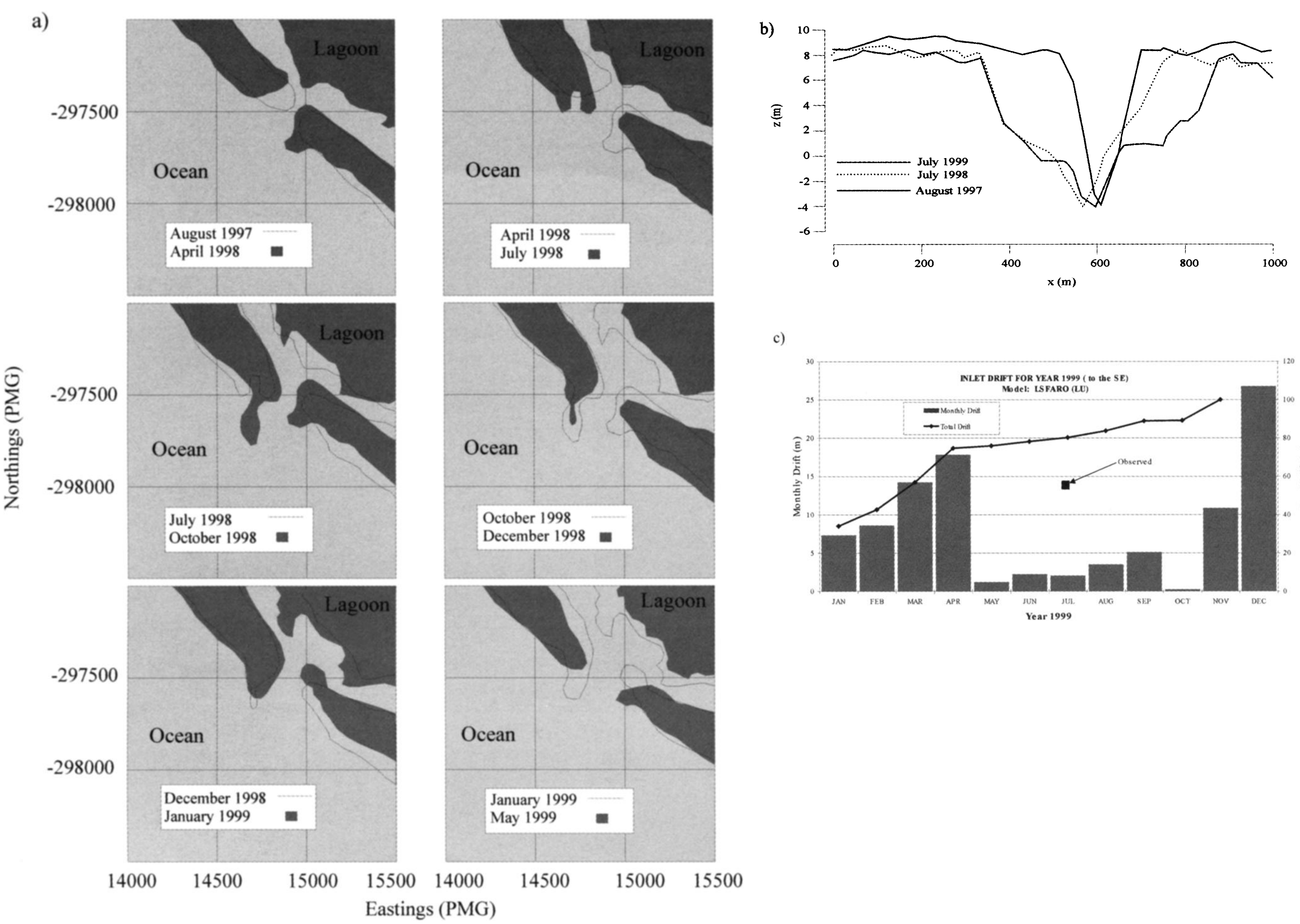

Figure 14. a) Morphological evolution of the Barra Nova from survey data during the period August 1997 to May 1999; b) inlet channel evolution from August 1997 to July 1999; and c) predicted inlet evolution for 1999 compared with observation, O'CONNOR *et al.* (1999).

their elevation relative to hydrographic zero (*i.e.* 2 m below mean sea level) into: a) the flood shoal >0.5 m; b) the inner channels <0.5 m; c) beaches and spits >1.0 m; d) the inlet channel <1.0 m; e) the swash platform >1.0 m; and f) the ebb shoal <1.0 m. Results of this analysis are presented in Table 1. Not unexpectedly there were considerable changes in the volume of sediment bodies in the vicinity of the Barra Nova in the period between August 1997 to July 1998 following opening of the inlet with major gains of sediment occurring on the flood and ebb shoals respectively and a significant loss of sediment from the Barra Nova channel. In total there was a net gain of some 366 $\times$ 10^3 m^3 of sediment during this period, a value some 3 time larger than the alongshore supply of sediment of approximately 130 $\times$ 10^3 m^3/year measured in fair weather conditions (BALOUIN and HOWA, 2000b). In the period between July 1998 to July 1999 there was a modest net loss of sediment from the Barra Nova system of some 56 $\times$ 10^3 m^3 of sediment. Thus, over a two-year period, there was a net gain of 310 m^3 of sediment to the Barra Nova morphology.

Owing to a relatively steep beach slope of 0.11 alongshore transport of sand is confined on a relatively narrow berm. Following the methodology described by HOWA and DE RESSEGUIER (1994) and HOWA *et al.* (1997) fluorescent tracer experiments to quantify the alongshore sediment transport rate were performed on 12/02/1999 and 28/02/1999. Results showed that sediment supplied to the inlet system by the adjacent updrift coast was approximately 10500 m^3/month, (BALOUIN *et al.,* 2000; BALOUIN and HOWA, 2000a; BALOUIN and HOWA, 2000b) which compare favourably with alongshore transport values computed using the KAMPHUIS *et al.* (1986) and KAMPHUIS (1991) formulae.

Net sediment transport pathways were estimated from surficial sediment data using a grain size trend analysis performed following a modified McLaren procedure described by GAO and COLLINS (1992) with the DERSEDI software (© Service Hydrographique et Océanographique de la Marine Nationale). At the largest scale investigated Figure 16a shows that alongshore transport of sediment is directed toward the inlet throat by exchanges between bars *B1, B2* and *B3* and confirms sediment transport from the Peninsula do Ancão extremity to the seaward edge of the ebb delta and the

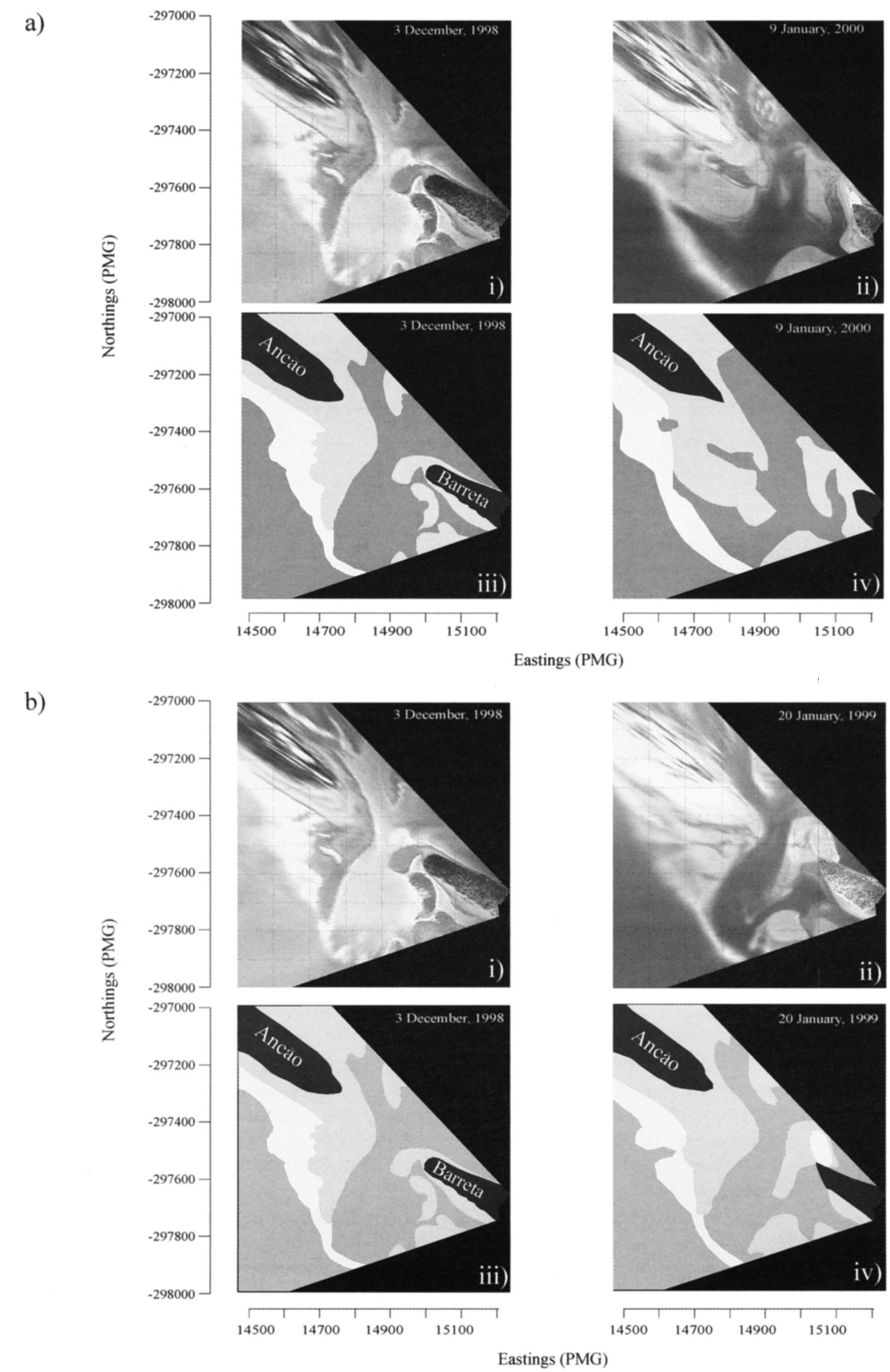

Figure 15. a) Rectified composite video images of the Barra Nova spanning approximately 24 months: i) 3 December, 1998; and ii) 9 January 2000. These images are shown in a simplified form in iii) and iv); b) rectified composite video images of the Barra Nova showing the inlet before and after the December 1998 storm: i) 3 December 1998 and ii) 20 January 1999 with accompanying simplified figures in iii) and iv), respectively.

Table 1. *Volumetric sediment losses (−) and gains at locations in the Barra Nova during the period August 1997 to July 1998. Data units are 10^3 m^3.*

	Lagoon		Barra Nova		Ocean		
	Flood Shoal	Inner Channels	Beaches and Spits	Channel	Swash platform	Ebb shoal	Net loss/gain
Year	>0.5	<0.5	>1.0	<1.0	>1.0	<1.0	
1997	150	0	−14	−315	−67	612	366
1998	−80	29	−40	m^3	−2	40	−56

eastern lagoon channel is responsible for the bulk of sediment transport in the lagoon. Transport vectors show a convergence of the sediment transport into the inlet throat. The validity of the grain size trend analysis was tested against data from a fluorescent tracer experiment on the western swash platform. Results presented in Figure 16b show broad agreement between computed and measured trends for this location in the inlet.

Tracer experiments and survey data were also used to examine rates of accumulation and erosion on the western swash platform. This area comprised three large inter-tidal sand bars including a) *B1* attached to the western end of the berm, b) *B2,* extending over the major part of the area, and c) *B3* located on the southeast end of the berm, Figure 16c. Accumulation rates on *B1* of some 11000 m^3/month account for all the alongshore transport measured by tracer experiments resulting in rapid migration toward the inlet. Using the grain size trend analysis, residual transport over bar *B2* was $O(7.0 \times 10^{-5}$ $m^2/s)$ and is in good agreement with a predicted rate of 6.9×10^{-5} m^2/s, (VAN RIJN, 1989). The sediment flux over bar *B2* was $O(70)$ m^3/tide, or around 4300 m^3/month. Erosion by the ebb current at the western shore of the inlet (Peninsula do Ancão) was $O(4000$ m^3/month). This was manifest as migration of ebb-oriented megaripples along the channel. Eroded sediment was accreted to form sandy spit *B3* connected with the terminal lobe at the extremity of the platform. The data confirm the redistribution of Peninsula do Ancão sediments to the extremity of the swash platform and that sediments reworked at the Peninsula do Ancão spit are balanced by the accumulation on the platform (Figure 16c). During the period of observations, the accretion on the swash platform was approximately 11500 m^3 a value close to the measured alongshore drift supply.

Measured bed elevation changes occurring between the periods 22 January 1999 to 18 February 1999 and from 18 February 1999 to 18 March 1999 are shown in Figure 17. It can be seen that generally sediment accretes with areas of erosion being largely confined to the north east portion of the surveyed area where as much as a 3 m depth of sediment has been eroded in approximately 1 month. A net growth in the swash platform is achieved by accretion of sediments over a large area. Since during the measurement period considered here, weather conditions were essentially categorised as Regime 1, the observed accretion and ensuing extension eastwards of the swash platform adjacent to Peninsula do Ancão conforms to the hypotheses in the conceptual model outlined above.

The smaller swash platform comprising two bars located on the eastern side of the inlet was disturbed during the December 1998 storm. This resulted in erosion of the swash platform and the shoreline of Ilha da Barreta. Eroded sediments were transported through the inlet and were accreted to form a long spit extending into the lagoon (Figure 15b). Survey data showing the virtual absence of a berm indicated of sediment starvation in this area. Consequently, the beach at this location provides little protection from wave attack making the loosely consolidated dunes on Ilha da Barreta very vulnerable to erosion and facilitated the process of inlet migration in an easterly direction.

Depth-mean tidal currents in the Barra Nova can peak at around 2.5 m/s during 3.8 m spring tides and swell waves can cross the ebb shoal into the inlet channel as shown by Q3D computer modelling, O'CONNOR *et al.* (2000a). Analysis of grab samples obtained in the Barra Nova showing that surficial sediments were coarser than 350 μm (Figure 4b) and visual evidence of mega ripples and dune-like bed features at most locations in the inlet (*e.g.* Figure 18) indicate strongly that the majority of sediment is transported as bedload. Hydrodynamic conditions, suspended sediments and the dimensions and migration rates of mega ripples were measured using the PIP deployed at various locations in the inlet from the jack-up barge. Detailed analysis of PIP data is reported by WILLIAMS *et al.* (2002).

Owing to the course nature of bed sediments (*i.e.* $D_{50} = 1.2$ mm), the presence of current ripples in the Barra Nova is not predicted by conventional theory (*e.g.* VAN RIJN, 1989). Results from a bedform model based upon hydrodynamic considerations developed by O'CONNOR (1992) are shown in Table 2. These indicate that the presence of current-generated ripples at certain tidal states with height and wavelength characteristics similar to those measured by the PIP. At high flows the ripples become washed out whilst a low flows they are not predicted as the model assumes an unrealistic instantaneous development and destruction time. In common with many empirical formulae (*e.g.* VAN RIJN, 1989) the bedform model also predicts the presence of dunes with a height and wavelength of 0.77 m and 25 m respectively, assuming a sufficient depth of easily eroded sediment. Whilst, these bedforms were not measured by the PIP, nor were they evident in surveys, there is clearly a need to investigate bed conditions further at the site. The bedform model has also been run to include waves (Table 2b). The principle effect is shown to be a reduction in the height of both current-ripples and dunes. Table 2 also shows that the roughness coefficients (Manning n) predicted by the model are also realistic and were very similar to these used by the LAGOON/RMA-2V tidal models. Detailed flow processes are individual bed forms have also been studied in the Project, JACOB and EÇA (1999).

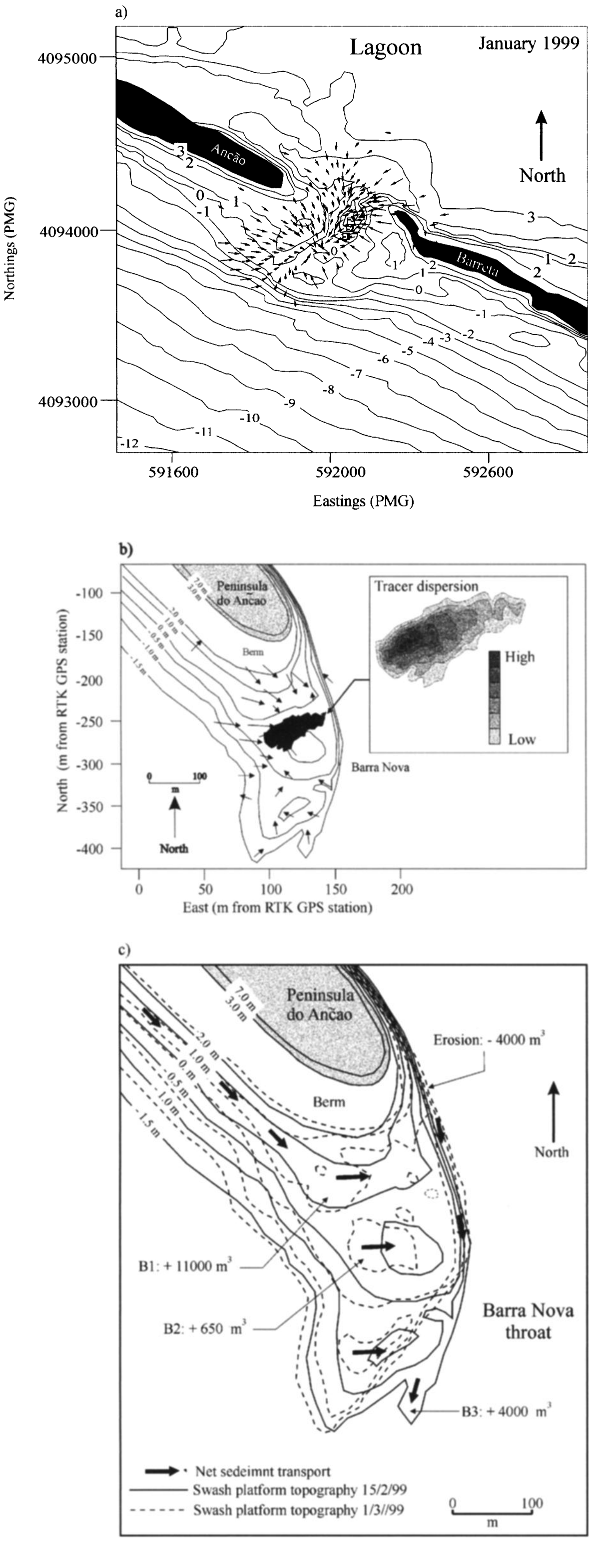

Figure 16. Results of grain size trend analysis and tracer studies: a) Barra Nova; b) western berm and spits showing sediment transport pathway and dispersion of fluorescent tracer grains; and c) morphological evolution and net sediment transport pathways Peninsula do Ancão swash platform between 15/02/99 and 01/03/99.

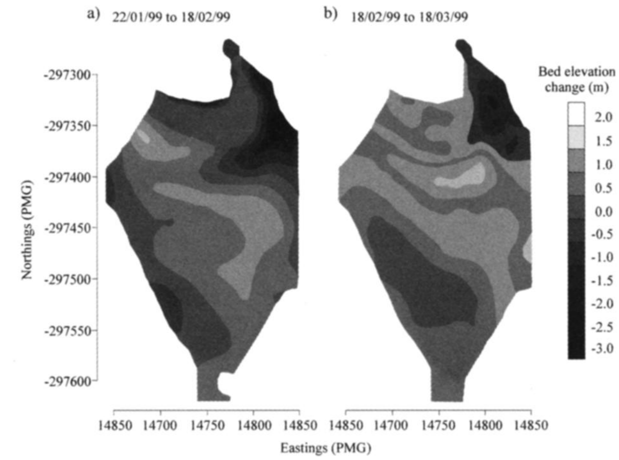

Figure 17. Measured changes in bed elevation on the Peninsula do Ancão swash platform between a) 22/1/99 to 18/2/99 and b) between 18/2/99 and 18/3/99.

Data from the PIP have been used to estimate bedload transport by considering bedform translation rates, (SOULSBY, 1997; WILLIAMS *et al.,* 2000b). Values for measured bedload transport and bedload transport predicted by the VAN RIJN (1993) formula were found to agree well, with Van Rijn

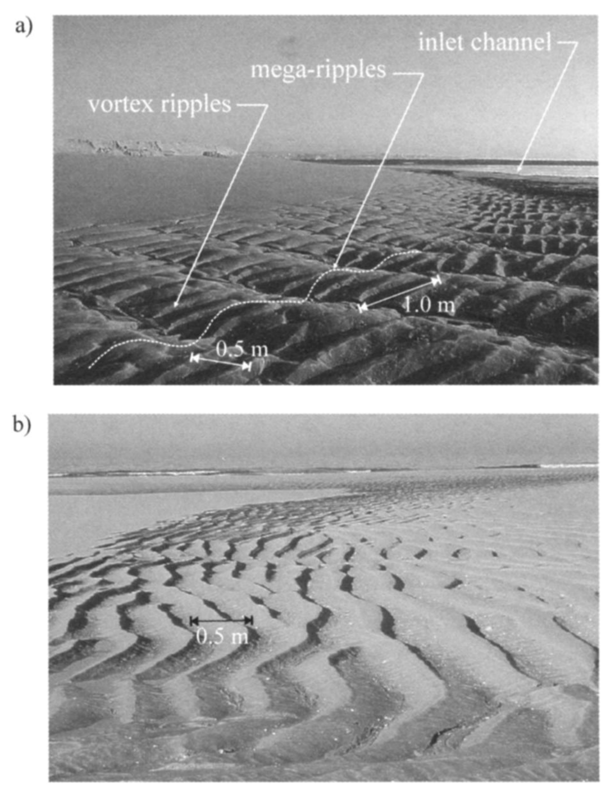

Figure 18. Typical bedforms on the Peninsula do Ancão swash platform: a) mega-ripples with superimposed vortex ripples; and b) current ripples.

Table 2. *Results from the 2D BED model for a) current-only; and b) combined wave-current conditions.*

a) Predicted Bed Forms (LU Model): Currents

D (m)	U (m/s)	h_r (cm)	λ_r (m)	h_p (m)	λ_p (m)	Manning n
5.0	2.5	0	1.27	0.774	25	0.031
4.0	1.5	0	1.27	0.774	25	0.029
6.0	1.5	0	1.27	0.774	25	0.033
3.9	1.0	4.8	1.27	0.774	25	0.032
6.2	1.0	4.3	1.27	0.774	25	0.035
3.8	0.5	3.8	1.27	0.774	25	0.031
6.2	0.5	6.2	1.27	0.774	25	0.036
3.8	0.3	0	1.27	0.774	25	0.030
6.2	0.3	0	1.27	0.774	25	0.031

U_{max} = 2.5 m/s; D_{mean} = 5 m; D_{35} = 1.06 mm; D_{50} = 1.27 mm; D_{65} = 1.53 mm; D_{90} = 2.24 mm; θ = 10° C.

b) Predicted Bed Forms (LU Model): Currents and Waves

D (m)	U (m/s)	h_{cr} (cm)	λ_{cr} (m)	h_p (m)	λ_p (m)	h_{wr} (m)	λ_{wr} (m)	Manning n
5.0	2.5	0	1.29	0.60	25	1.93	11.6	0.033
4.0	1.5	0	1.29	0.60	25	1.93	11.6	00322
6.0	1.5	0	1.29	0.60	25	1.93	11.6	0.032
3.9	1.0	4.6	1.29	0.60	25	1.93	11.6	0.032
6.1	1.0	4.8	1.29	0.60	25	1.93	11.6	0.031
3.8	0.5	4.6	1.29	0.60	25	1.93	11.6	0.032
6.2	0.5	4.4	1.29	0.60	25	1.93	11.6	0.034
3.8	0.3	0	1.29	0.60	25	1.93	11.6	0.032
6.2	0.3	0	1.29	0.60	25	1.93	11.6	0.034
3.8	0.1	0	1.29	0.60	25	1.93	11.6	0.032
6.3	0.1	0	1.29	0.60	25	1.93	11.61	0.034

U_{max} = 2.5 m/s; $D_{,ean}$ = 5 m; D_{35} = 1.06 mm; D_{50} = 1.27 mm; D_{75} = 1.53 mm; D_{90} = 2.24 mm; θ = 10° C; H_s = 0.3 m; T_p = 4 s; U_o = 0.121 m/s; λ_{wr} = 22.1 m.

overestimating by a factor of approximately 1.7. To extend the spatial and temporal application of these measurements, and to investigate thereby possible reasons for loss of material, a numerical model has been used to predict net sediment

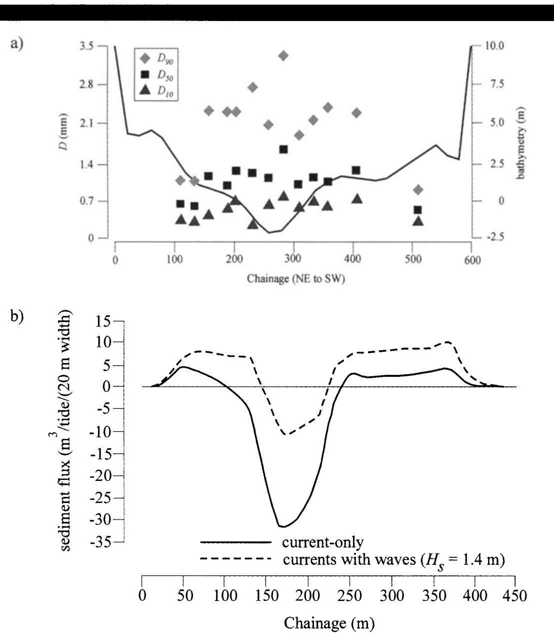

Figure 19. a) Bathymetry and variation in sediment grain size across the Barra Nova; and b) computed net bedload transport in the Barra Nova in current-only and wave-current conditions.

transport through the inlet over tidal, monthly and annual time-scales. The 3D-INLET model centred on the Barra Nova, and interfaced to LAGOON to simulate the correct water slope in the inlet, was set up to predict tide and wave conditions in the Barra Nova on a 20 m × 20 m grid. The model used measured bathymetry together with measured tide and wave conditions to define the offshore boundary conditions. VAN RIJN's (1993) bedload transport formula, modified for wave action, and reduced by a factor of 1.7 in accord with observed values was used to calculate bedload transport through the tidal cycle and across the width of the inlet using time-series of hydrodynamic conditions predicted at locations across the inlet. Predicted net tide-only bedload transport over a single ebb tide of height 3 m, assuming the full width of the inlet was ebb dominated, was 81 m^3. Scaling-up, this equates to the transport of some 4×10^3 m^3 of sediment seaward for the spring-neap tidal cycle, (Figure 19). By considering the full range of possible tidal conditions the net annual sediment flux seaward is computed to be $O(6 \times 10^4$ $m^3)$. This figure is approximately 50% of the measured annual fair-weather alongshore transport of sand reported above. If a reduced inlet width with total ebb dominance is assumed, a net annual loss of some 235×10^3 m^3 which is of a similar order to the net losses calculated from the topographic data reported above. The model was also used to investigate the effect of waves on the net sediment transport in the Barra Nova. For H_s = 1.4 m in the inlet, the model showed that the principal effect of wave action was to reduce the flux, principally by increasing the net landward transport of sediment along the flanks of the inlet (Figure 19). Increasing the wave height further resulted in a net landward transport of sediment through the inlet.

In accord with the conceptual model outline above, these numerical modelling results indicate that over the medium term, say 5 years from present, it would be expected that adjustment of inlet morphology would achieve a net zero transport where sediment transported into the inlet by the action of flood tides and waves is balanced by a export of sediments during ebb conditions. Over longer time scales $O(20$ years), slow migration of the inlet would reduce ebb efficiency of the inlet as it moves down-coast and lagoon drainage channels become increasing hydraulically inefficient. Eventually a location will be reached when the inlet can no longer purge sediments driven inshore during storms and will close. Draw-down of material from other locations on the beach unless replaced by beach re-change, will then encourage the establishment of a new inlet and a repeat of the natural inlet migration-closure cycle.

As a final note in this section attention must be draw to the fact that at the time of measurement, sediment supply in the Barra Nova was probable not source limited owing to the deposition of sediment during the December 1998 storm. It is considered that it is primarily for this reason that the measured bedload rates conform to formulae. It may be speculated that when the inlet has reverted to ebb-tidal-dominance during the post-storm *MOR2* recovery period, all available sediment is transported seaward and the channel then begins to scour. Evidence of a much deeper channel during the summer of 1998 supports this suggestion. If this is the case, inlet scour is likely to further restrict migration of the channel and thereby reduce the overall rate of morphological change.

The presence of moderately developed, hummocky, partially vegetated aeolian dunes adjacent to the inlet and the existence of larger, well-developed dunes at other locations in the Ría Formosa indication that under certain conditions, sediments were mobilised by wind action and transported. Whilst on the beach face, the sand is locally coarse (> 1 mm) the grain size at the upper part of the beach and in the dunes averages 0.35 mm. During a storm just prior to the field campaign in December 1998, recorded wind speeds reached 86 km/hour resulting in almost complete burial of dune vegetation and probably substantial transport of sand over the dunes and into the lagoon. Whilst events of this magnitude make only a small contribution to the overall sediment budget of the Barra Nova ($< 0.1\%$) there is strong anecdotal evidence that during strong wind events aeolian sand transport can be significant and has lead in the past to the partial burial of houses and roads on Peninsula do Ancão. Its role during storms cannot be neglected entirely when assessing sediment budgets for the Barra Nova or at other locations in the Ría Formosa.

SUMMARY AND CONCLUSIONS

Historical evidence has demonstrated a west to east decrease in inlet evolution rates and an increase in the number of inlets in the Ría Formosa through time. The hydrodynamic function of the western inlets has been shown to be interdependent thus highlighting the problems of managing multi-inlet systems. Over a period of two years following opening of the Barra Nova a net loss of up to 6.3×10^5 m^3 of sediment has occurred with the bulk of this loss occurring during the first few months as the inlet naturalised. Since opening, the rate at which inlet width has increased has declined at an approximately exponential rate. Over the seven-month period from December 1998 to July 1999 Ilha de Barreta was eroded a distance of 90 m and the inlet channel was shifted 55 m south eastwards. In accord with expectations the Barra Nova is now ebb-tidally-dominant with a net annual easterly migration alongshore $O(100$ m). In extreme cases inlet migration distances $O(300$ m) were predicted at this location for the 1 in 50 year event. Measurements and modelling have shown that more than 80% of inlet migration occurs during storms with the effectiveness of a storm of given magnitude and duration determined critically by tidal elevation. Individual storms have been found to have a greater impact on inlet width than on inlet depth with up to 60 m of vegetated dunes being lost from Ilha de Barreta in a single storm event with little change occurring in channel bathymetry. Atlantic storms from the west and Lavante storms from the east force different morphological response that must be accounted for when assessing future inlet behaviour. After a series of winter storms, the inlet takes approximately three months to adjust back to its preferred fair-weather morphology.

Measured and predicted tidal currents in the inlet and offshore agreed well and modelling showed a major reduction in wave heights (60–70%) between offshore and inshore locations. Owing to the coarse nature of the barrier island sediments, modelling studies and measurements showed that bedload accounts for the bulk of sediment transport in the inlet and on the swash platforms and ebb delta areas. Measured rates of sediment transport in the inlet agreed well with engineering transport equations. Modelling studies have shown that wave action in the inlet can reverses the net direction of sediment transport. Whilst measured bedform dimensions compared favourably with predicted values obtained using a drag-partitioning approach, the observed bedform are not predicated by existing engineering equations. During a given tidal flow direction it is considered that insufficient time elapses for bedforms to develop fully. Predicted rates of alongshore sediment transport agreed well with estimates from tracer studies. Survey data have shown that the net easterly alongshore sand transport is trapped by the swash platform and ebb shoal of the Barra Nova causing the swash platform to migrate toward the inlet. This migration leads to a rotation of the platform that is balanced by an easterly migration of the main inlet channel thus preventing closure. These results imply that sediments do not bypass the Barra Nova during fair weather conditions thus raising questions regarding the mechanisms at work maintaining the beach on Ilha da Barreta exposed to oblique wave attack. Aeolian sand transport occurs only during high storm events (1–2 per year). The aeolian flux was found to be very sensitive to the state of the dune vegetation. Whilst aeolian event are rare, when they occur, appreciable quantities of sand may be transported as witnessed by the substantial dunes present in older, more stable locations in the Ría Formosa.

Together field evidence and numerical modelling results provide compelling evidence to support the description of tidal inlet function in the conceptual model proposed here. The inlet is shown to respond to storm events in a predictable way and follows historical trends for inlets at this location in the Ría Formosa. If present trends continue, the inlet will continue to migrate eastwards before sedimentation forces closure some 2 km east of its present location by approximately 2020. However, what is less clear is how the system will respond to a gradual rise in mean sea level and a possible increase in the magnitude and frequency of storm events. Clearly elevated sea levels and more frequent severe storms are likely to impact significantly on fragile coastal systems such as the Ría Formosa possible leading to barrier island destruction and lagoon inundation by the sea. Studies to examine the combined effect of sea level rise and storms are required therefore if appropriate, sustainable management strategies are to be devised for the Ría Formosa and other barrier island systems along the coastlines of the world.

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