Journal of Coastal Research	SI	71	107–113	Coconut Creek, Florida	2014

Towards Coastal Management of a Degraded System: Barra de Navidad, Jalisco, Mexico

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ABSTRACT

González-Vázquez, J.A.; Silva, R.; Mendoza, E., and Delgadillo-Calzadilla, M.A., 2014. Towards coastal management of a degraded system: Barra de Navidad, Jalisco, Mexico. *In:* Silva, R., and Strusińska-Correia, A. (eds.), *Coastal Erosion and Management along Developing Coasts: Selected Cases*. Journal of Coastal Research, Special Issue, No. 71, pp. 107–113. Coconut Creek (Florida), ISSN 0749-0208.

The area known as Barra de Navidad is a barrier lagoon system on the Mexican Pacific. Over the last 40 years the system has undergone serious negative changes in its dynamic processes, mainly due to the anthropogenic activities that have taken place there. The main elements that have damaged the equilibrium of the system are the removal of the distal tip of a sandspit, the dredging of a navigation channel, the construction of a breakwater, the cutting down of large areas of mangrove and the construction of tourist infrastructure on the coastal dunes. These changes have decreased the resilience of the system, thereby increasing its vulnerability. In addition, the lagoon has developed a severe problem of silting and alterations to the hydrodynamic patterns in the system have caused a dramatic retreat of the coastline. The degradation of the system has affected the population and their economic activities to such a degree that a series of hydrodynamic analyses have been carried out to propose a short-term, urgent solution which will be part of a long-term plan that will bring self-sustainable balance to the system.

ADDITIONAL INDEX WORDS: *Barra de Navidad, anthropogenic activities, coastline retreat, nearshore wave processes*.

INTRODUCTION

Barra de Navidad, on the Mexican Pacific coast (Figure 1), is a small town that has enjoyed a small but healthy tourist trade for more than 40 years. Its natural features: a large embayed beach approximately 5 km long with surf waves almost all year, large areas of mangrove, and a lagoon 3 km long and 1 km wide, which is deep enough for yachts to anchor, as well as a picturesque mountain backdrop, attracted mainly Mexican visitors. The lagoon, also called Barra de Navidad, is connected with the sea via a natural mouth, which is bordered at the south by a rocky mountain and at the north by a sandspit. The Marabasco River flows into the lagoon, supplying terrigenous sediments which are subsequently transported to the beach. The sand bar, which separates the lagoon from the sea was 250 m long in 1970 and totally undeveloped (see Figure 2), nobody realized that the system was highly fragile and vulnerable to almost any alteration and that its resilience was low.

The success of Barra de Navidad as a tourist resort brought more and bigger infrastructure to the system. The local population began to build on the coastal dunes and the sandspit: hotels, restaurants and even a concrete promenade. At the same time, many areas of natural vegetation were lost to the urbanization and the increasing population brought severe pollution problems. Then, in the 1980s, at the southern margin of the lagoon, a huge resort with marinas and artificial shorelines was constructed.

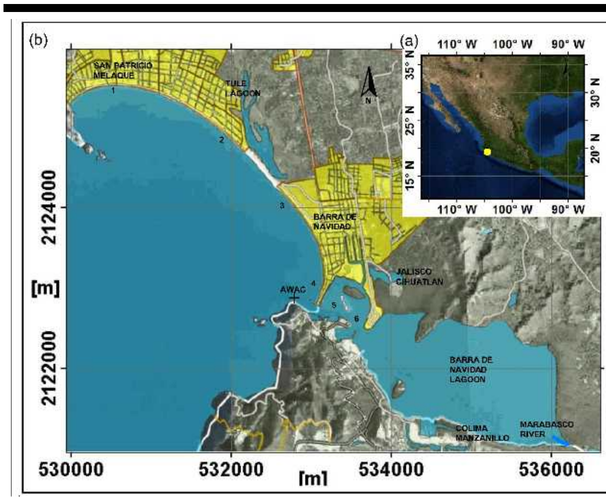

Figure 1. Study area: (a) location of Barra de Navidad, Cihuatlán, Jalisco, Mexico; (b) lagoon system.

None of these actions was considered to have importance for the physical wellbeing of the area, even though beach erosion had begun to be noticed. However, when a small tsunami hit the area in 2005, followed by hurricane Jova in 2011, the vulnerability of the system was exposed.

HISTORICAL OVERVIEW

As said above, originally the Barra de Navidad system, consisted of a lagoon with a shallow inlet of approximately 93 m

DOI: 10.2112/SI71-013.1 received 12 February 2014; accepted in revision 12 August 2014.
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wide (PIM, 2011); a sandspit and a large embayed beach. Our hypothesis is that if the economic activities of the area had been continued to be low density, the ecosystem would not have suffered such rapid and dramatic damage and that the implementation of minor measures would have conserved the system and allowed the exploitation of Barra de Navidad to continue.

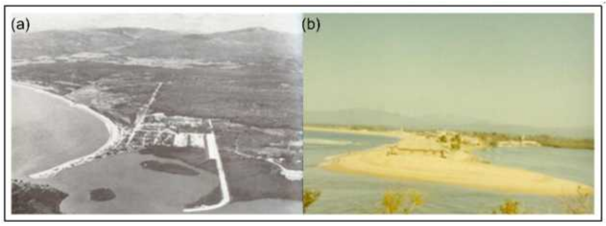

Figure 2. Changes in the coastal system: (a) Aerial view of Barra de Navidad in 1970; (b) view of the sandspit in December, 1969.

On the contrary, since the beginning of the 1970s, the system has suffered more pressure than it can handle.

It was in the 70s that the most significant alterations took place, beginning with the dredging of the mouth of the lagoon to let bigger vessels sail in. Around 10 years later a large resort and marina at the southern margin of the lagoon were constructed, for which filling and dredging of the lagoon were performed. It is not surprising that these actions changed the hydrodynamic pattern of the water body and with it the sediment distribution.

In the 1980s the inlet, now used as a navigation channel, was dredged again and it was also widened to reach approximately 190 m. In an unfortunate attempt to stabilize the inlet, a breakwater was built on its north side, as can be seen in Figure 3. The construction of this structure was never finished, so that it remains to date with one emerged and one submerged section, each 100 m long.

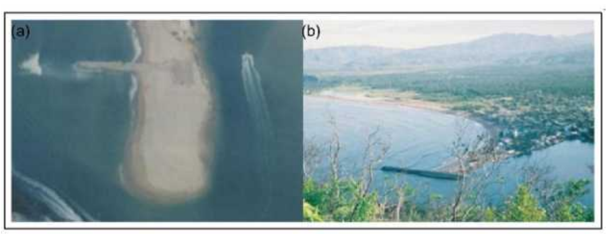

Figure 3. (a) The start of the construction of the breakwater, (b) the widened inlet to Barra de Navidad lagoon.

In the mid-1990s mayor morphologic changes were evident in the lagoon, mostly on the northern margin; a small island was artificially joined to the land to enlarge the resort area and several structures were built to improve sailing activities and to create sheltered areas for other recreation activities. Part of the inlet of the lagoon was filled reducing its width to approximately 100 meters (PIM, 2011) in order to build a marina. The population density of Barra de Navidad grew substantially resulting in a loss of 39 hectares of natural vegetation. Construction was allowed on the coastal dunes, extending along more than 1 km of coastline and inside the lagoon itself some areas were reclaimed and developed. The result of all these actions has had two major consequences: the sediment exchange through the inlet has been restricted, producing silting throughout the lagoon and as a consequence of the beach not receiving enough sediment, it is now in a permanent state of erosion. Figure 4 shows a panorama of all these factors which have altered the Barra de Navidad system.

Figure 4. Main anthropogenic actions

Figure 5. Damage to the infrastructure in Barra de Navidad beach.

From 2000, it was just a matter of time for the fragility of the system to become evident. The combination of a tsunami in 2005 with the effects of hurricane Jova in 2011 completely destroyed the beach and waves began to hit the buildings of the resort; some hotels had to close and the economy of the village was severly affected, even tourism in the surrounding area was affected. Figure 5 shows images of the present state of the beach at Barra de Navidad. Unfortunately, to date, no comprehensive recovery plans or coastal magement measures have been taken.

CHARACTERIZATION OF STUDY AREA

While Barra de Navidad has been a popular tourist destination for more than 40 years, there have been few major engineering works and virtually no planning for the site; historical data is limited. Interesting research was done regarding flora and fauna distribution (*e.g.*, West *et al*., 1992), fisheries (Rojo *et al*., 1999) and pollution (Hernández *et al*., 2002), but there are only a few reports on hydrodynamic conditions, such as that by Gaviño and Fernández (1987) who presented a numerical study on tidal induced free surface levels and current velocities within the Barra de Navidad lagoon. Barra de Navidad therefore presented a big challenge: the social emergency was critical and the lack of data and previous understanding of the dynamics of the system made diagnosis difficult. Hence, the work presented here has an original character as it offers a possible plan of action for similar situations.

Field Work

Given the lack of data, field work was undertaken in the study area in March 2013. The information gathered included: bathymetry in the lagoon and in the marine area up to a depth of 15 m, coastal topography, water free surface elevations and currents for the lagoon inlet and sediment sampling.

A current profiler (AWAC) was installed in the inlet of the lagoon (see Figure 1) to get an initial picture of the interaction between the lagoon and the beach. The values registered were: current profiles every 0.50 m, free surface elevation, temperature, and wave conditions (Chavez-Cardenas, 2013). Figure 6 shows the velocity profiles registered by the equipment.

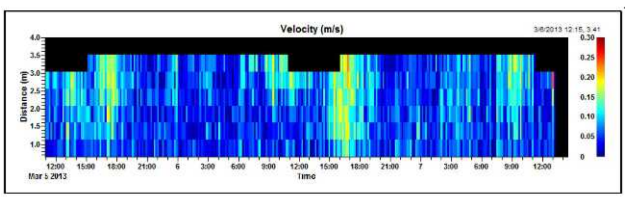

Figure 6. Mean velocity profiles registered in March 2013.

Table 1. *Properties of sediments sampled along the beach (see Figure 1).*

Zone	1	2	3	4	5	6
Latitutde	19.222	19.216	19.207	19.202	19.199	19.196
Longitude	-104.705	-104.693	-104.685	-104.684	-104.682	-104.679
			Breaking			
d_{50} (mm)	0.216	0.291	0.848	0.332	---	---
γ_r (g/cm^3)	1.962	2.277	2.817	2.397	---	---
			Swash			
d_{50} (mm)	0.276	0.388	0.803	0.564	0.334	2.045
γ_r (g/cm^3)	2.346	2.589	2.889	2.724	2.423	2.808
			Berm			
d_{50} (mm)	0.597	0.678	0.637	0.467	0.519	0.891
γ_r (g/cm^3)	2.773	2.864	2.873	2.672	2.614	2.623

Sand samples were also collected along the beach; the grain size distribution along the beach is quite relevant as it gives a qualitative idea of the sediment transport and the state of the beach, which in this case is considered invaluable information. To get the widest possible view of the sediment, the samples were taken in the breaking, swash and berm zones at various points (see Table 1); the samples were analyzed to obtain particle diameters and relative density, γ_r.

From the distribution of the sediments along the beach it is seen that the sediment transport is northerly, which means that the dominating currents in the Barra de Navidad nearshore area must be also northerly. It also noticeable that the distribution of grain sizes along the beach profiles reveals instability.

Wave and Wind Conditions

The wind and wave data used here for the analysis were taken from the Atlas published by Silva *et al*., (2007). They employed wind data taken from NCEP/NCAR and applying a hybrid wave model, presented hourly data of wind intensity and direction as well as significant wave heights for the period from 1949 to 2010. Figure 7 shows the annual wave and wind roses.

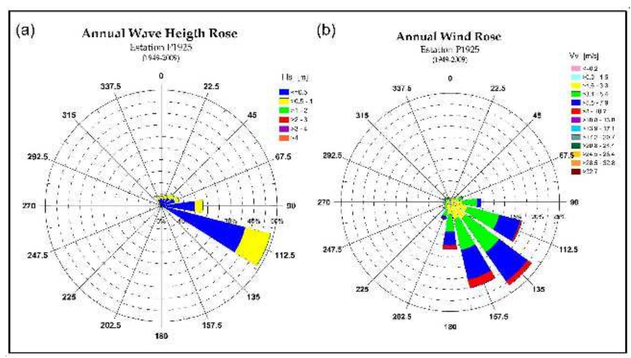

Figure 7. Annual wave height (left) and wind (wind) roses.

Tides

The prevailing conditions for sea level variations were taken from the Tables for Tide Prediction published by the Mexican Secretaría de Marina (SEMAR, 2012), a summary of which is presented in Table 2. It should be noted that the data is for Manzanillo, 50 km south of Barra de Navidad, as there is no data available for the study site.

Table 2. *Main tide levels at Manzanillo, Colima, Mexico.*

Tidal planes	Elevation (m)
Maximum high tide registered	1.280
Upper medium high tide level	0.738
Mean high tide level	0.678
Mean sea level	0.417
Mean low tide level	0.165
Lower medium low tide level	0.000
Minimum low tide	-0.590

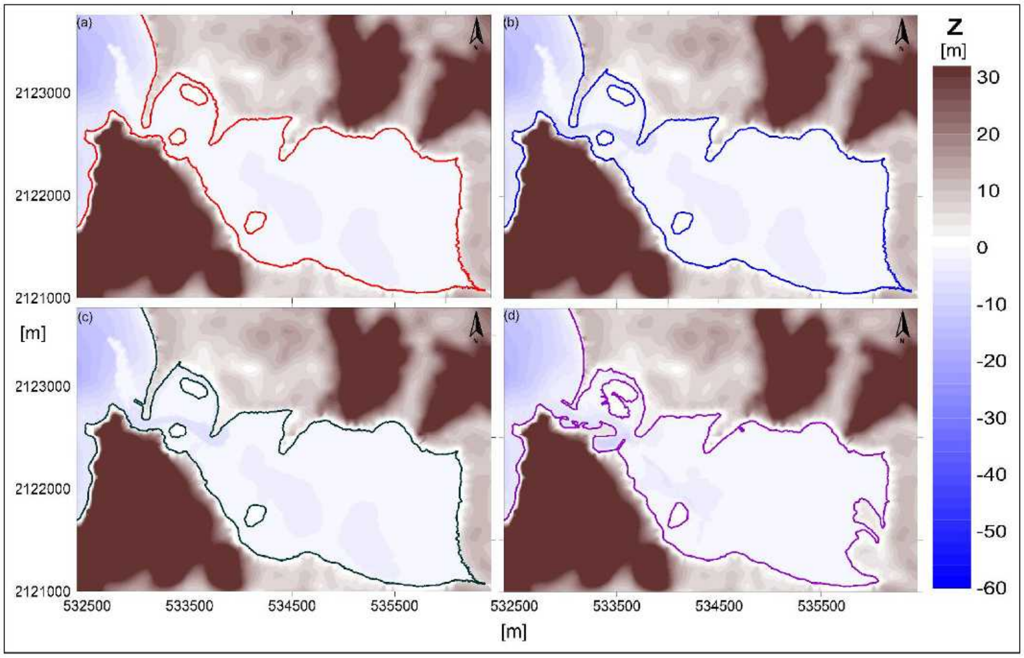

Figure 8. Constructed bathymetries for (a) 1983; (b) 1986: inlet dredged; (c) 1986: breakwater in situ and (d) 2013.

DIAGNOSIS

To get an overview of the history of hydrodynamic patterns in Barra de Navidad and of its present state, four bathymetries were constructed based on the available informationand interviews with local people, authorities and experts. The conditions selected for the study were: a) 1983; undisturbed condition; b) 1986, when the first dredging of the inlet of the lagoon was performed; c) 1986, when the breakwater to the north of the inlet was constructed but prior to the inlet widening and d) 2013 present conditions. These bathymetries are shown in Figure 8. The historical bathymetries constructed were used as input data for WAPO (Silva, 2005), COCO (Mendoza, 2007) and H2D (GIOC, 2001) models to compute wave propagation, wave induced currents and tidal hydrodynamics, respectively. From Figure 8 it can be seen that the direction S22.5W is dominant almost all year long, so the historical analysis is based on this wave direction only with a wave height of 1.19 m and a period of 6.98 s.

The wave propagation results are presented in Figure 9. It can be seen that in 1983 and 1986 the system had much more sediment, resulting in a shallower nearshore area; this is evidenced by the fact that the breaking zone of the waves was located farther from the coast than the present one. This change means that a lot more energy can reach the coast in both mean and storm conditions. It is also noticeable in Figure 9 that the energy distribution is very similar in the four cases despite the morphological changes. This is, in part, the reason why many of the coastal activities around Barra de Navidad did not report major inconveniences until the erosion problem made them untenable.

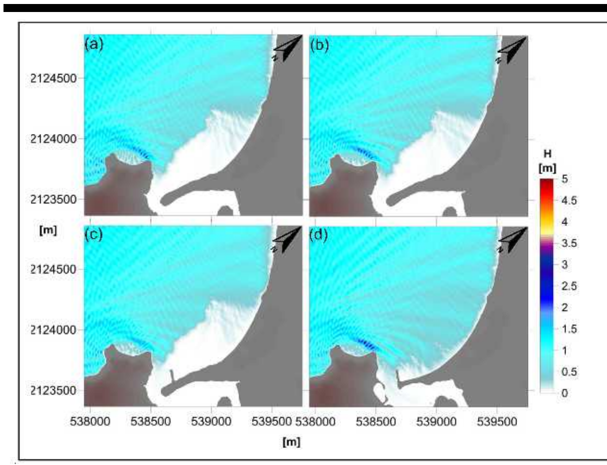

Figure 9. Wave propagation for (a) 1983; (b) 1986i; (c) 1986 ii and (d) 2013.

Figure 10 shows the pattern of wave induced currents for the four bathymetries in which, again, the general distribution of intensities and directions show little historical change except for the breaking zone prior to 2013 where greater velocities were found. This feature is important because these were the currents responsible for carrying sediment to the northern part of the beach. Figure 10 also shows that the dominant sediment transport is and has been northerly and that the currents that used to reach 15 to 20 cm/s are today less than 10 cm/s.

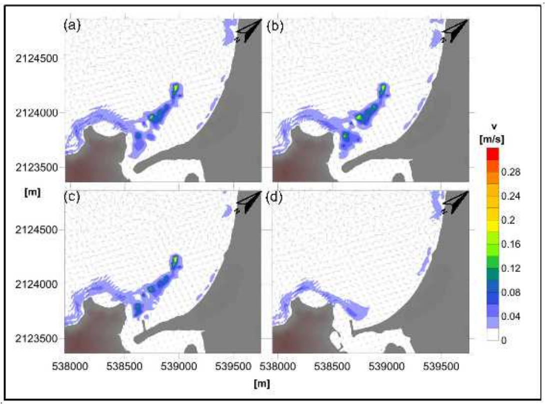

Figure 10. Wave induced currents patterns for (a) 1983; (b) 1986i; (c) 1986 ii and (d) 2013.

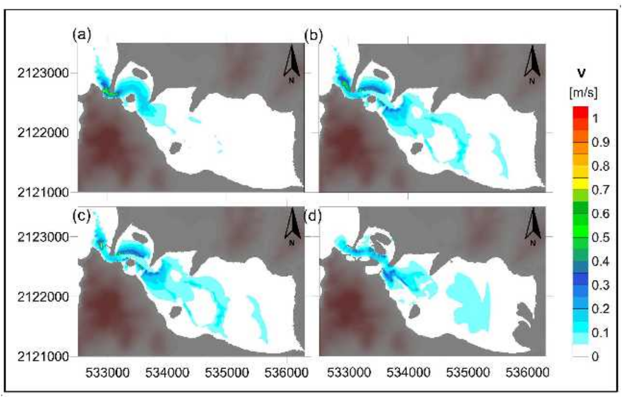

Figure 11. Low tide velocities (a) 1983, (b) 1986i; (c) 1986 ii and (d) 2013.

The patterns of tidal induced hydrodynamics are shown in Figure 11, where the low tide condition has been drawn. As expected, the main feature of note is the narrowing of the inlet which caused a velocity increase, 25 – 30 cm/s. Widening and dredging the inlet resulted in a decrease in velocity, 10 cm/s, which, in combination with infrastructure and land reclamation are responsible for the silting of the lagoon. This is a chronic problem; worsening with time. This, combined with the wave induced currents, going out from the lagoon westwards, accounts for the lack of stability of the beach, as the sediment that comes out of the lagoon is being lost offshore. The numerical results for high tides showed similar patterns. Even though there is not enough data available to perform an adequate validation of the numerical results, it can be seen that the computed currents are in the same order as those measured (Figure 6).

In summary, human activities have severely disturbed the dynamics and balances at Barra de Navidad, so that under storm conditions, the beach is eroded and is unable to recover. This is because its resilience at present is much lower than before human interventions. The erosion is now so severe that infrastructure is being damaged and therefore the "do nothing" scenarios non-viable; protection and restoration action need to be taken.

SHORELINE PROTECTION ALTERNATIVES

Two solutions are proposed which correspond to different time scales but which are both part of the same solution. This scheme has been adopted because the economic activities of Barra de Navidad are in need of urgent action while it also allows time for a permanent solution to be implemented.

Short-Term Solution

The short-term solution that was selected is the construction of two submerged breakwaters in the area where greatest erosion has been reported. This kind of structural solution has the advantage of having no visual impact as well as creating an artificial reef. Furthermore, this solution is compatible with the aquatic sports carried out in the area.

Two submerged barriers are proposed; one 100 m long, 50 m north of the breakwater, at 3.5 m depth, the second, 60 m long, 300 m north of the breakwater (this means that the gap between the barriers is 100 m), also placed at a depth of 3.5 m. The mechanical design of the structures follows the methodology of Vidal *et al*., 1992, from which the mean weight of the design cross section was obtained. With this weight, an equivalent geotextile tube section was designed; the reason for using this material is, as was said before, the urgency of the situation although this kind of material can last up to 10 years in good conditions. The proposed location and the design cross-section are shown in Figure 12.

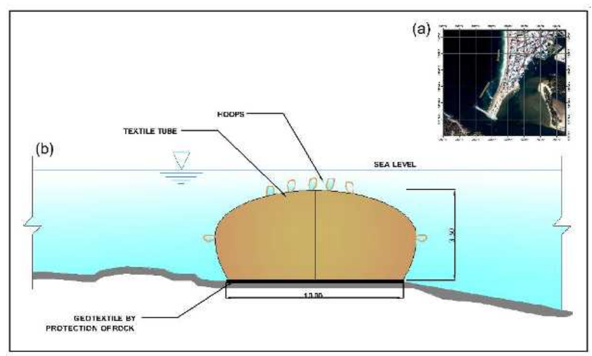

Figure 12. Location and cross-section of the submerged structures.

The proposed solution was numerically tested, again with WAPO, COCO and H2D models to view its performance. Given the small size of the structures, the numerical solutions differ little from the ones obtained with the 2013 bathymetry (Figures 9 and 10). The results of wave propagation and wave induced currents are shown in Figure 13 where it can be seen that the structures generate a shadow area (panel a) showing that the wave energy has been reduced (the waves at the coast are noticeably lower than the incident ones). The wave induced currents (panel b) show a slight change of direction in the vicinity of the structure located nearer to the inlet, due to the presence of the structures. These currents, although small in magnitude, less than 10 cm/s, will favor the carrying of suspended sediment northerly. This long-shore transport will also help to restore the sediment balance in the system.

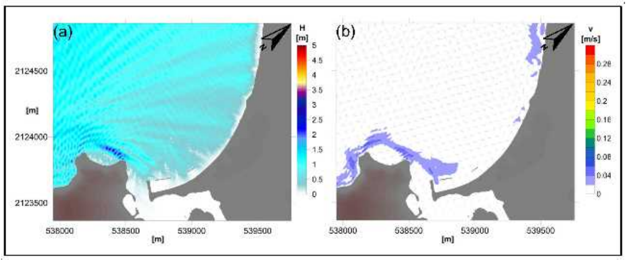

Figure 13. Hydrodynamics imposed by the proposed solution (a) wave field and (b) wave induced currents.

The numerical result of the dynamics induced by the submerged barriers suggests that artificial nourishment may also be part of the solution as the long shore currents will distribute the sand along the beach; furthermore if the sediment flow through the inlet is also restored, the presence of the barriers will also enhance the beach stability.

The tidal hydrodynamics were also numerically modeled, as shown in Figure 14. It is clear that the placement of the barriers, given their size, is incapable of modifying the present conditions.

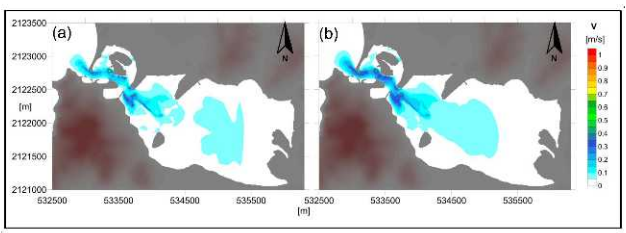

Figure 14. Tidal conditions with structure (a) Low Tide; (b) High Tide.

Long-Term Solution

The long-term solution is conceived as a set of actions that lead to a sustainable system in which human activities, physical dynamics and environmental wellbeing coexist.

One of the first actions necessary is to reestablish the hydrodynamics of the lagoon as this is the only source of sediment for the beach. This means that the lagoon needs to be dredged to a sufficient depth so that the suspended sediment from Marabasco River can make its way out to sea. Secondly, the material removed from the bottom of the lagoon can be used for the artificial nourishment that was suggested earlier. This material is useful for nourishment as was demonstrated by PIM (2011). A third action would be to remove the unused reclaimed land in the lagoon, to improve the flow towards the inlet. Finally, the submerged part of the breakwater at the northern margin of the inlet should be removed to facilitate the distribution of the sediment from the lagoon to the beach. The emerged part of the breakwater and the depth and width of the inlet should not be changed as they are important for navigation purposes.

A further necessity is to implement a permanent monitoring program to opportunely detect any further undesirable response of the system; this program should be part of an integrated coastal zone management plan in which the allowed uses of the beach, economic activities and density must be defined. The policies for the preservation of the ecosystem should be detailed as well, involving all the actors with interests in the area as much as possible.

DISCUSSION AND CONCLUSIONS

There is really no possibility of placing instruments and performing a complete study of the area, so this paper presents the interpretation of the available data and explains the use of some reliable tools as a methodology to generate knowledge, understand past and present dynamics of the system and to propose an emergency solution that will allow further studies and analysis to be carried out. The use of numerical models allowed visualization of the expected results of the barriers and also the suggestion of alternative options, such as artificial nourishment of the beach and the dredging of the Barra de Navidad lagoon. It was found that the most important element which needs to be reestablished is the sediment supply and the hydrodynamic conditions that allow the sand to be transported to the beach instead of it being lost offshore. Once that is done, the long-shore currents will distribute the sediment all along the beach.

It is common to find coastal systems where human intervention has broken physical and environmental balances. This imbalance is normally the result of a gradual occupation of the coastal zone or of aggressive and poorly planned changes in land use. The case of Barra de Navidad is a combination of both, with the aggravating factor that the most serious damage has been induced by the shortsightedness of developers and authorities, while the results are felt by those with no power to change the conditions. The situation in Barra de Navidad is made worse because all the developments and activities were undertaken without any formal analysis or proper characterization of the system or forecasting of probable consequences.

Reaching a solution here is not easy as there are several groups with conflicting interests in the area and there is a lack of regulatory instruments to form the basis of recovery through a comprehensive coastal management program. It is concluded that the stabilization of the beach is feasible and that the system can become stable again. However, strict regulations must be implemented to avoid repeating the mistake of allowing infrastructure that might once again break the balance in Barra de Navidad.

The short-term solution proposed, a pair of submerged breakwaters, seems to be viable as it lets the population recover their quality of life while the long-term solution and the integrated management coastal plan forthe area are developed and implemented. It is important to note that some activities will be probably not compatible with the new regulations, so the short-term solution is also a means to give time to the different actors to find their own means of facing future circumstances.

ACKNOWLEDGMENTS

This publication is one of the results of the Latin American Regional Network global collaborative project ‘‘EXCEED – Excellence Center for Development Cooperation – Sustainable Water Management in Developing Countries’’ consisting of 35 universities and research centres from 18 countries on 4 continents. The authors would like to acknowledge the support of the German Academic Exchange Service DAAD, the Centro de Tecnologia e Geociências da Universidade Federal de Pernambuco, the Fundação de Amparo a Ciência e Tecnologia do Estado de Pernambuco-FACEPE and the Instituto de Ingeniería of the Universidad NacionalAutónoma de México for their participation in this EXCEED project.

Thanks to the municipality of Barra de Navidad, Cihuatlan, Jalisco, Mexico, for their hospitality and availability for fieldwork.

LITERATURE CITED

Chavez-Cardenas, X., 2013. *Reporte de perfilador de corrientes, Barra de Navidad, Jalisco, México*. Instituto de Ingeniería, UNAM, *Internal Report* (in spanish).

Gaviño J., and Fernández, E., 1987. Modelación hidrodinámica numérica de la albúfera Barra de Navidad, Jalisco. *Proceedings 7th Congreso Nacional de Oceanografía* (Ensenada, Baja California, México). (in spanish).

GIOC, 2001. *Manual de Referencia Modelo Numérico H2DLL*. Grupo de ingeniería Oceanográfica y de Costas, Universidad de Cantabria (in Spanish).

Hernández, J.F.; Mariscal, J.; Ramos J.L., and Flores, R., 2002. Impactos de la actividad económica sobre los recursos de la laguna de Barra de Navidad, Jalisco, México. *Proceedings 13th Congreso Nacional de Oceanografía* (Puerto Vallarta, Jalisco, México), (in Spanish).

Mendoza E.; Silva, R.; Baquerizo A., and Losada M.A., 2007. Quad tree basednumerical model for coastal hydrodynamics simulation. *In*: *Ocean Engineering Research Advances*. Alan I. Prescott (ed.). Nova Publishers, New York, USA, p. 243-266.

PIM, 2011. Plan Integral de Manejo y Conservación de la Laguna Barra de Navidad, Jalisco: Estrategias y Acciones para la Restauración y Rehabilitación. *Departamento de Estudios para el Desarrollo Sustentable de Zonas Costeras*, adscrito al Centro Universitario de la Costa Sur de la Universidad de Guadalajara. Secretaría de Turismo del Gobierno del Estado de Jalisco (inSpanish).

Rojo, J.A.; Arreguín, F.; Godínez, E., and Ramírez, R., 1999. Selectividad de redes de enmalle para el pargo lunarejo (*Lutjanus guttatus*) y el pargo (*Lutjanus argentiventris*) en bahía de Navidad, Jalisco, México. *Ciencias Marinas,* 25(1), 145-152 (in spanish).

Secretaria Armada de México (SEMAR), 2012. Tablas numéricas de predicción de mareas para el Golfo de México y el Mar Caribe. *Dirección General de Investigación y Desarrollo*, México D.F. (in spanish).

Silva, R.; Borthwick, A.G.L., and Eatock-Taylor, R., 2005. Numerical implementation of the harmonic modified mild-slope equation. *Coastal Engineering*, 55(5), 391-407.

Silva, R.; Ruiz, G.; Posada, G.; Pérez, D.; Rivillas, G.; Espinal, J., and Mendoza, E.; 2007. *Atlas de clima marítimo de la vertiente Atlántica Mexicana*. UNAM, Mexico (in spanish).

Vidal, C.; Losada, M.A.; Medina, R.; Mansard E.P.D., and Gomez-Pina C., 1992. A universal analysis for the stability of both low-crested and submerged breakwaters. *Proceedings of the 23th International Conference on Coastal Engineering* (Venice, Italy), p. 1679-1692.

West, A.; Zuccarello, G.C.; PedrocheF.F., and Karsten, U., 1992. Marine red algae of the mangroves in Pacific Mexico and their polyol content. *Botanica Marina,* 35, 567-572.