Journal of Coastal Research	SI	71	48–54	Coconut Creek, Florida	2014

Coastal Erosion in Balneario Solís, Uruguay

Rodrigo Alonso[†*], Guillermo López[†], Rodrigo Mosquera[†], Sebastián Solari[†], and Luis Teixeira[†]

[†]IMFIA - Facultad de Ingeniería
Universidad de la República
Montevideo, Uruguay

www.cerf-jcr.org

www.JCRonline.org

ABSTRACT

Alonso, R.; López, G.; Mosquera, R.; Solari, S., and Teixeira, L., 2014. Coastal erosion in Balneario Solís, Uruguay. *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, p. 48-54. Coconut Creek (Florida), ISSN 0749-0208.

Balneario Solís is a seaside resort located in Uruguay, on the northern coast of the outer Río de la Plata estuary. Its main beach has suffered an erosion process that has affected the cliffs, producing a retreat of approximately 35 m between 1980 and 2001. Nowadays, some buildings are at risk of collapse and tourism has been seriously affected. Aerial photo analysis shows a temporal coincidence between the beginning of the erosion process and a change in the growing direction of a sandspit located next to the beach. Assuming the later as a geomorphologic indicator of the net littoral transport, the erosion process was linked to littoral transport change. No human factors were clearly identified to explain this change. Therefore, two hypotheses were formulated and analyzed: climate variability and natural modifications of the bathymetry in the outer zone of the beach. Finally, beach nourishment is proposed in order to restore the beach and protect the cliffs, and some questions are formulated for guiding future works in the site.

ADDITIONAL INDEX WORDS: *Beach erosion, sediment transport, climate variability.*

INTRODUCTION

Balneario Solís (55º23' W - 34º48' S) is located in Uruguay, on the northern coast of the outer Río de la Plata estuary. It is 96 km east of Montevideo and 32 km west of Punta del Este (Figure 1). To the west it is separated from Jaureguiberry by the Solís Grande River, while to the east it borders Bella Vista, separated by the Espina Creek (Figure 2).

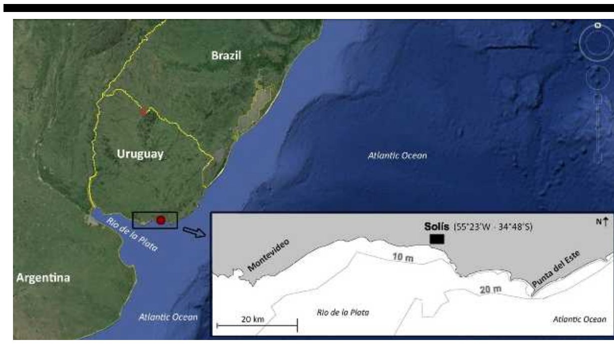

Figure 1. Location of the study site.

Like most of the Uruguayan coast, tourism is one of the main economic activities of this zone with beaches as the main tourist attraction. Solís has two beaches. One is located between Solís Grande River and Punta Ánimas headland and the other between the headland and Espina Creek (Figure 2). Erosion problems have occurred in the former beach. At present, consequences of erosion are: loss of dry sandy beach, 35 m cliff recession, damage in the road infrastructure and buildings at risk of collapse (Figure 3).

In the following sections, a description of the study site is presented, the possible causes of the erosion process are analyzed and a shoreline protection alternative is proposed. Finally, results are discussed and the main conclusions are given.

Figure 2. Satellite image of Jaureguiberry, Solís and Bella Vista beach resorts.

CHARACTERISTICS OF THE STUDY AREA

Geomorphology

The coastal system is divided in three areas in order to facilitate its description (see Figure 4).

Zone A is a stable straight beach 8 km long, whose perpendicular is oriented to S12º E direction.

Zone B is the area influenced by the mouth of the Solís Grande River. The main characteristics of the Solís Grande River basin are shown in Table 1.

DOI: 10.2112/SI71-006.1 received 12 February 2014; accepted in revision 28 July 2014.
*Corresponding author: ralonso@fing.edu.uy

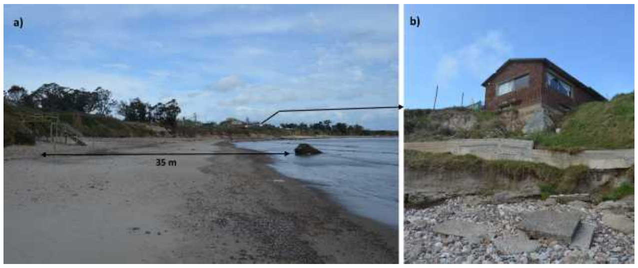

Figure 3. Evidence of cliff recession: a) 35 m linear distance was measured between old (concrete) and the new (wooden) cliff stairs; b) building at risk of collapse.

Figure 4. Division of the beach into three areas: a) a rectilinear beach; b) Solís Grande River mouth area; c) Solís resort beach between Solís Grande River mouth and Punta Ánimas rocky headland.

The time of concentration was calculated with the Kirpich formula (Chow *et al*., 1994) while extreme discharges were calculated with the NRCS method (USDA/NRCS, 2010). There is a sandspit at the river mouth with an average width of 100 m and variable length, *e.g.*, during the period 2004 - 2013 the sandspit length varied between 400 and 750 m. Based on the analysis of nearby sandspit of similar characteristics, this variation is supposed to be the consequence of a cyclic process of growth with littoral drift and breaching during river extreme discharges (Solari *et al*., 2014). As shown later in this article, this process is related to erosion problems in the west bank of the river.

Zone C is a curved coastline, limited at the east by the Punta Ánimas headland. There are soft cliffs with an average height of 10 m. Originally the beach was composed by fine sand with a mean grain diameter of 0.2 - 0.3 mm (MTOP/UNPD, 1979). Due to beach erosion, the cliff was exposed to wave action, retreating 35 m between 1980 and 2001. Nowadays, there are gravel deposits and outcrops that prevents the erosion of the cliff's toe; during the period 2004 - 2013 little recession of the cliff was measured, and it was limited to some stretches only.

At the east of Punta Ánimas headland, the coast is oriented perpendicular to the south. There is a stable mixed gravel and sand beach. The sand fraction in this zone is similar to the sand of zone C (fine sand with mean diameter of 0.2 - 0.3 mm).

Bathymetry

There is little bathymetric information at the zone; only a nautical chart with poor resolution and the detailed bathymetry map shown in Figure 5.

Table 1. *Solís Grande River basin main characteristics. M. L. is the mainstream longitude, ΔH is the difference between the highest and the lowest elevation of the basin, Tc is the time of concentration, $Q_{1\ year}$ and $Q_{2\ years}$ are extreme discharges corresponding to a return period of 1 year and 2 years, respectively.*

Area (km^2)	M.L. (km)	ΔH(m)	Tc (hs)	$Q_{1\ year}$ (m^3/s)	$Q_{2\ years}$ (m^3/s)
1360	99.2	287	22.2	340	112

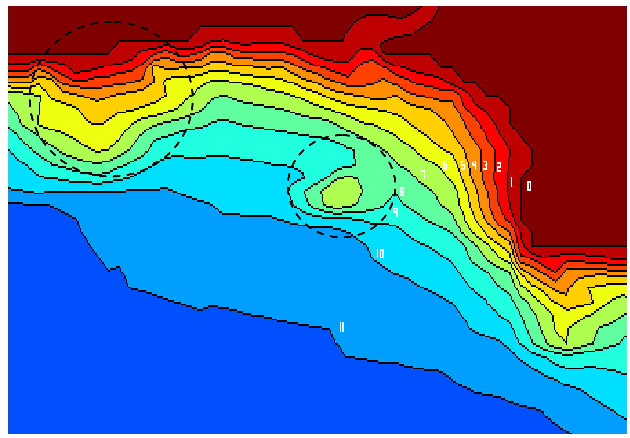

Figure 5. Bathymetry of the study site; shoals mentioned in the text are circled (survey done by Maldonado Municipality on March 2008).

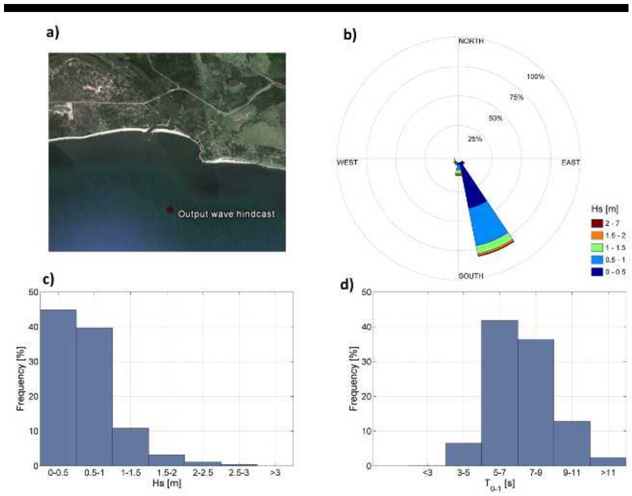

Figure 6. Wave climate: a) location of the model node that is closest to Solís; b) wave rose for this node; c) spectral significant wave height (Hs) frequency histogram and d) mean period (T0-1) frequency histograms.

The detailed bathymetry shows two shoals not included on the nautical chart: one shoal in front of the Solís Grande river mouth, approximately 800 m offshore, and another shoal attached to the coast westward of the river mouth. These shoals do not appear in the nautical chart.

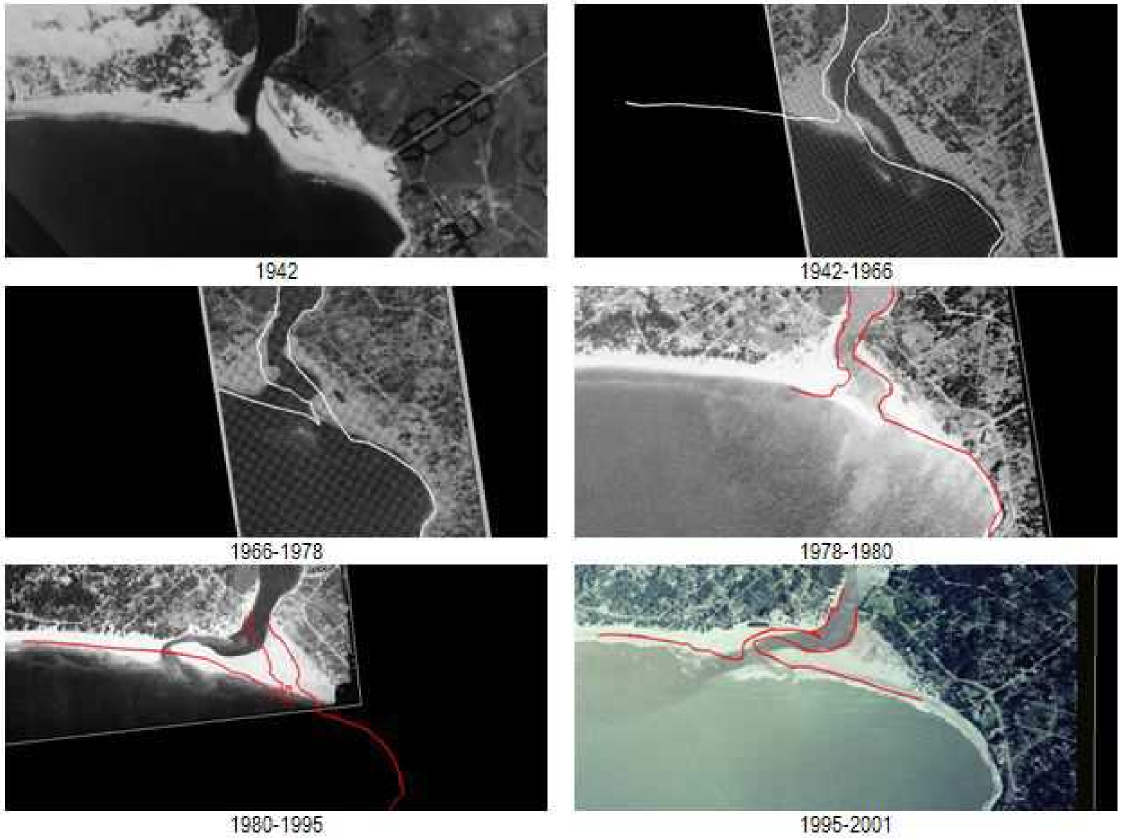

Figure 7. Shoreline evolution of zones B and C, for the period 1942 -2001, from aerial photos provided by Uruguayan Air Force.

Figure 8. Shoreline evolution of zone B, for the period 2004 - 2012, from satellite images.

Tides, Winds and Waves

Uruguayan coast is micro-tidal, with astronomic tide amplitudes under 0.5 m and meteorological tide amplitudes on the order of 1 m (Santoro *et al*., 2013).

Due to the relatively close proximity, the wind climate of Montevideo is used in this work. Predominant winds come from the E-S quadrant with mean velocities of 3 - 6 m/s. Winds from S-W are less frequent but more intense.

Regarding waves, a 31 year (1980 - 2010) wave hindcast at the Río de la Plata and South Atlantic Ocean is available (Alonso, 2012). The hindcast model node closest to the study site is marked in Figure 6a. In Figures 6b, c and d, the wave climate is shown. This hindcast was calibrated and validated with altimetric data and two in-situ measurements.

Figure 9. Beach erosion on the east side of the river mouth. Comparison of 19/12/2004 and 21/8/2012 satellite images.

Shoreline Evolution

Aerial photos from the years: 1942, 1966, 1978, 1980, 1995, 2001 and 2004, and Google Earth satellite images (2004, 2010, 2011 and 2012) were georeferenced, superimposed and compared. In the analyzed period, there are no significant variations of the shoreline position at the straight beach in Zone A (Figure 4) and at the beach to the east of the headland. Shoreline evolution in zones B and C is shown Figure 7.

It is observed that between 1980 and 1995 the direction of growth of the sandspit changed. Before 1980 the sandspit was eastward oriented and shorter, while after 1995 the sandspit is westward oriented and longer. During the latter period an intensification of the beach erosion process was also observed.

Regarding zone C, no significant cliff recession was observed in the last years (2004 - 2012). During this period, as is shown in Figure 8, the most significant changes took place in Zone B (Jaureguiberry beach). These changes were bank erosion on the west bank of the river and beach erosion eastward of the river mouth. The latter is shown in Figure 9, where 36 m of dune front recession along 600 m of shoreline were measured over a period of less than 8 years (19/12/2004 - 21/8/2012). Considering a closure depth (Hallermeier, 1978) of approximately 4.5m, a berm height of 1.5 m and no change in the beach profile (*e.g*., one-line model hypothesis), this recession implies a mean annual sand loss rate of around 8000 m^3/year. This rate is taken into account when calculating the net littoral sediment transport in the area.

Sediment Transport

Notwithstanding the difficulties in estimating longshore sediment transport (Cooper and Pilkey, 2004), the littoral sediment transport for the straight beach at the west of the river mouth (Zone A) was estimated using the CERC formula (see *e.g*., USACE 2002, Dean and Dalrymple 2002). To this end, wave data introduced previously was propagated to breaking conditions by means of linear wave theory (see *e.g*., Dean and Dalrymple 1991) and a modified Miche criterion (USACE 2002).

The results were an annual mean littoral transport of 378,000 m^3/year to the west and 213,000 m^3/year to the east. Therefore, annual mean net littoral transport is 165,000 m^3/year to the west and annual gross littoral transport is 591,000 m^3/year. Net littoral transport obtained with CERC formula is one order of magnitude higher than the reference value obtained from analyzing aerial and satellite photos. This issue is discussed in greater detail in the following section.

Regarding river sediment supply to the coast, Solís Grande sediment discharge was estimated by MTOP/UNDP (1979) in 169,000 t/year. That means 108,000 m^3/year in terms of deposited sand volume, assuming a sand density of 2.6 t/m^3 and a porosity of 0.4. This quantity provides evidence of the important role of the river in the sediment budget of this coastal cell. Therefore, changes in the river flow regime might affect coastal stability. However, it must be noted that there is no record of any major intervention in the river or watershed (*e.g*., dam constructions, river diversion, important land-use change, etc.) that could affect the flow regime.

Lastly, from Figure 5 it is concluded that there is no discontinuity in the bathymetry around Punta Ánimas, so there may be sediment transport across the headland.

DIAGNOSTICS

Coastal erosion could have antrophic and/or natural causes. Coastal structures interfering with the littoral transport are probably the most common of the human causes. Another typical antrophic source of erosion is the reduction of sediment supply due to river damming. Neither of these factors are identified in this problem. The existing coastal structures (Piriápolis port and groin field in Piriápolis beach) are far enough from the study site and the discharge of the Solís Grande river is not regulated. The main anthropic interventions in the area (coastal zone and river basin) are related to urban development and forestations of the dune. However, it is considered that the impact of these human factors on the study site is minor and the main causes of the erosion are natural.

Shoreline evolution analysis showed a time coincidence between the intensification of beach erosion in Balneario Solís and the change in the growing direction of the sandspit. The growth of the sandspit is a geomorphologic indicator of the net littoral transport direction (USACE, 2002). Therefore, a change in its direction is an evidence of a variation in the hydrodynamic processes that determine the littoral transport. Hence, it is hypothesized that Solís beach erosion and the change in direction of the sandspit are related to a modification in the littoral transport due to a change in the nearshore wave climate. Two hypotheses are proposed to explain this change: climate variability and variations in the bathymetry of the outer zone of the beach.

The climate variability hypothesis was analyzed with the 31 year long wave hindcast data series introduced previously. Interannual variability of the mean annual wave energy flux is shown in Figure 10. Interannual variations of 10% on the magnitude and variations of 3º in the direction of the mean annual wave energy flux were observed. Furthermore, the moving average shows that interannual variation of mean energy flux responds approximately to a 10-year cycles.

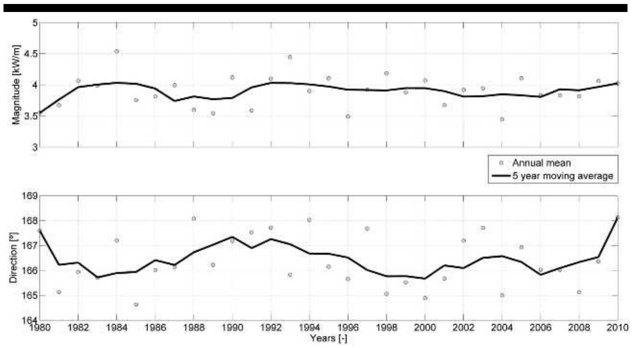

Figure 10. Annual mean wave energy flux variability: (a) magnitude; (b) direction.

In order to examine the influence of wave climate variability on morphodynamic process in the study site, interannual variability of the net littoral transport in the straight beach at the west of the river mouth, calculated with CERC formula, is shown in Figure 11a. The results show that net littoral transport was westward for all the years. However, since the wave direction has a strong influence on the littoral transport, a sensitivity analysis to wave direction was performed. The results with a 2º and 3º eastward bias are presented in Figures 11b and 11c respectively. These bias values are within the expected bias for wave hindcast data (see *e.g.*, Kamphuis, 1991). In these cases net eastward littoral transport was obtained in some years. Moreover, when using a bias correction of 3°, the mean net littoral transport obtained is similar to the sand loss rate estimated in previous section by means of aerial and satellite photos.

Based on the results obtained with original data (Figure 11a) the climate variability hypothesis may be discarded for explaining changes in the growing direction of the sandspit and beach destabilization. Nevertheless, sensitivity analysis shows that 2º eastward bias in wave direction is enough to modify the direction of the net littoral transport in 5 of the 31 analyzed years. In the same way, a 3º eastward bias modifies the direction of the net littoral transport in 12 of the 31 analyzed years and, in addition, result in a net sediment transport rate that is in agreement with the observed evolution of the shoreline.

The other hypothesis proposed to explain the change of the sandspit direction is the change of the offshore bathymetry. A shoal that does not appear in the nautical chart is observed in the detailed bathymetry map of the study site (Figure 5). Due to its dimensions and proximity to the shoreline, this shoal affects the morphodynamic processes that take place in both Solís beach and Solís Grande River mouth. However, as there is no other detail bathymetry map available, there is not enough information to analyze the origin of the shoal and its time evolution, and to link it to the recent evolution of the sandspit and the shoreline.

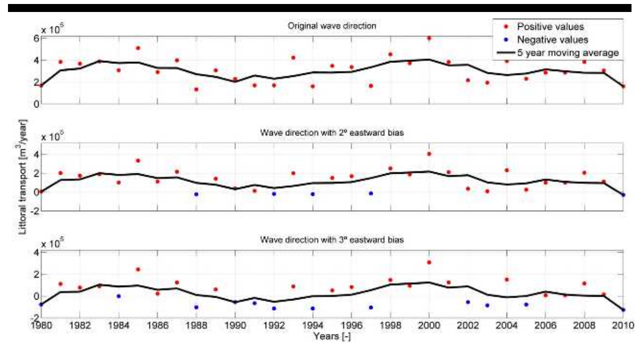

Figure 11. Mean annual littoral transport obtained with the original wave directions (a) and with 2° and 3° eastward bias, (b) and (c) respectively. Positive values corresponds to westward transport (red dots), eastward transport corresponds to negative values (blue dots). 5 year moving average in continues black line.

SHORELINE PROTECTIONS ALTERNATIVES

In order to mitigate the adverse effects the recent erosive processes have on Solís beach, a beach nourishment of the 800 m long eroded beach is proposed. This solution has two significant benefits. On one hand, the touristic value of the beach is recovered. On the other hand, cliffs are protected from wave impacts, stopping the recession, avoiding road infrastructure damage and building collapse. In this regard and as a preliminary figure, Everts (1991) suggested that a 40 m beach width would provide significant protection to cliff erosion.

It is planned to use the sandspit and the shoal that is westward of the river mouth as borrow areas for the nourishment (see Figure 12). To borrow sand from the same system ensures that the borrowed sand has similar characteristics to that of the native sand. Furthermore, opening the sandspit in a position similar to that of the 80's has two benefits. On one hand, it contributes to sand retention in the nourished area due to the blocking of the littoral transport that is provided by the river discharge. On the other, the dynamics of the river mouth is moved away from the present western bank of the river, reducing the erosion problem in Jaureguiberry.

Beach nourishment must be followed by a periodic monitoring of bathymetry, shoreline position and sediment characteristics. It is also convenient to carry out in-situ wave and current measurements in order to calibrate a morphodynamic numerical model of the study site. Monitoring, measurements and numerical modeling will allow the optimization of the design of further nourishment projects in case they are necessary. Numerical modeling should be done by means of process-based models able to explain the incidence of the shoal on beach dynamic. Other alternatives, such as doing nothing or hard solutions were rejected. Economic losses related to collapsing buildings and infrastructure damage due to a non intervention policy are similar to beach nourishment cost. Therefore, the economic benefits of restore the beach as well as its social impact turn the nourishment more convenient. On the other hand, hard solutions like a breakwater in the headland were also dismissed, partly due to its high cost but mainly due to its negative impacts in adjacent beaches.

Figure 12. Proposed beach nourishment scheme.

DISCUSSION AND CONCLUSIONS

A description and diagnosis of the erosion problem in Balneario Solís was presented. From the analysis of the available information it was concluded that the erosion has mainly natural causes and began after 1980. Two hypotheses were formulated in order to explain the causes of the erosion process: climate variability (*i.e.* wave climate) and a change in the bathymetry of the outer zone of the beach.

Climate variability was analyzed with wave hindcast data. In a first approach the calculated interannual variations were unable to explain a change in littoral sediment transport direction. However, a sensitivity analysis shows that by assuming a biases of 3° in the hindcast wave directions, the resulting interannual variability could explain changes in the mean annual littoral transport direction. Moreover, the long-term sediment transport rate obtained assuming this bias is in good agreement with the rate estimated from the analysis of the evolution of the shoreline. Therefore, in order to confirm this hypothesis, it is proposed to carry out a quality analysis of the wave direction data and to extend the wave hindcast to before 1980.

The second hypothesis was formulated because a shoal that does not appear in the nautical chart is observed in the only detailed bathymetry map of the study site. The shoal is in front of the river mouth, 800 m offshore. It is not known what the effect of the shoal on the morphodynamic of the beach is, nor on the river mouth and if the shoal changes in time. Therefore, new bathymetric surveys are necessary to confirm whether the shoal changes in time and numerical model simulations are necessary to analyze the impact of possible variations of the dimensions and position of the shoal on the beach and on the river mouth.

Lastly, a beach nourishment is proposed in order to restore the beach and protect the cliff. Borrowed sand is obtained from the sandspit and from the shoal at the west of the river mouth. The opening of the sandspit, in addition to allowing sand to be borrowed, temporarily changes the position of the river mouth. This new position has two benefits. On the one hand, it contributes to sand retention in the nourished area, due to the littoral transport block produced by the river discharge. On the other hand, the dynamics of the river mouth are moved away from the erosion problem in Jaureguiberry.

In order to optimize further nourishment designs and to improve the understanding of the system, bathymetry monitoring, wave and current measurements and numerical model implementations are proposed. These studies must address the following questions: (i) how much sediment comes to Solís beach from the east of Punta Ánimas?, (ii) where is it deposited and what is its pathway?, (iii) is this pathway related to the shoal?, (iv) is the shoal changing its size and position?, (v) and if so, what are the consequences of these changes?

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 Nacional Autónoma de México for their participation in this EXCEED project

Most of the work was done under the project "Estudio de Problemas Costeros" funded by the Municipality of Maldonado, Uruguay. The first author acknowledge Agencia Nacional de Investigación e Innovación (ANII) for partially funding this research under its Ph.D. scholarship program (POS_NAC_2012_1_8936).

LITERATURE CITED

Alonso, R., 2012. Evaluación del potencial undimotriz de Uruguay. Montevideo: Universidad de la República, Master’s thesis, 276 p. (in spanish).

Chow, V.T., Maidment, D.R. and Mays L.W., 1994. *Applied hydrology*. McGraw-Hill International Edition, 584 p.

Cooper, J.A.G. and Pilkey, O.H., 2004. Longshore drift: trapped in an expected universe. *Journal of Sedimentary Research,* 74, 599-606.

Dean, R. G. and Dalrymple, R.A., 1991. *Water Wave Mechanics for Engineers & Scientists*. Advanced Series on Ocean Engineering 2. World Scientific, Singapore, 353 p.

Dean, R. G., and Dalrymple, R.A., 2002. *Coastal Process with Engineering Applications*. Cambridge University Press. Cambridge, U.K., 488 p.

Everts, C.H., 1991. Sea cliff retreat and coarse sediment yields in southern California. *Quantitative Approaches to Coastal Sediment Processes*, Seattle, Washington, 1586-1598.

Hallermeier, R. J., 1978. Uses for a calculated limit depth to beach erosion. *Proceedings 19th International Conference on Coastal Engineering (*Hamburg, Germany), pp.1493-1512.

Kamphuis, J.W., 1991. Alongshore sediment transport rate. *Journal of Waterways, Port, Coastal and Ocean Engineering*, ASCE, 117(6), 624-641.

MTOP/UNDP, 1979. *Conservación y mejora de playas*. Montevideo, Uruguay, 1000 p (in spanish).

Santoro, P.E., Fossati, M. and Piedra-Cueva, I., 2013. Study of the meteorological tide in the Río de la Plata. *Continental Shelf Research*, 60, 51-63.

Solari, S., Chreties, Ch., López G. and Teixeira L., 2014. Analysis of the recent evolution of the sand spit at the Solís Chico River mouth. *In*: Green, A.N. and Cooper, J.A.G. (eds.), *Proceedings 13th International Coastal Symposium* (Durban, South Africa), *Journal of Coastal Research*, Special Issue 70, pp. 616-620.

USACE, 2002. *Coastal Engineering Manual*. Engineer Manual 1110-2-1100, U.S. Army Corps of Engineers, Washington D.C. (in 6 volumes).

USDA/NRCS, 2010. *National Engineering Handbook-210-630-Hydrology*. United State Department of Agriculture, Washington D.C.