Journal of Coastal Research	SI 64	2068 - 2073	ICS2011 (Proceedings)	Poland	ISSN 0749-0208

Study of the responsible factors for the closure of an intermittent washout during a storm surge, Rio Grande do Sul, Brazil

C. G. Serpa†, M. A. R. Romeu†, J. A. S. Fontoura†, L. J. Calliari‡, E. Melo† and M. G. Albuquerque∞

†Escola de Engenharia
FURG, Rio Grande
96201-900, Brazil
christianserpa@yahoo.com.br

‡Instituto de Oceanografia
FURG, Rio Grande
96201-900, Brazil
lcalliari@log.furg.br

∞Departamento de Geociências
IFRS, Rio Grande
96201-900, Brazil
migueldaguia@gmail.com

ABSTRACT

Serpa, C. G., Romeu, M. A. R., Fontoura, J. A. S., Calliari, L. J. and Albuquerque, M. G., 2011. Study of the factors responsible for the closure of an intermittent washout during a storm surge, Rio Grande do Sul, Brazil. Journal of Coastal Research, SI 64 (Proceedings of the 11th International Coastal Symposium), 2068 – 2073. Szczecin, Poland, ISSN 0749-0208.

The washouts are water courses essential to the drainage of the water accumulated in the backshore zone, and are responsible for great ruptures in the dunes field. They supply the swash zone with large amounts of sediment. The study area is located a few kilometers south of the Patos Lagoon Inlet. This study measures the contribution of the wind, the waves, the atmospheric pressure and the tide on the elevation of the sea level in a period when the beach has suffered the impact of a storm surge. Field campaigns were performed in October and November of 2007. This data was combined with local wind and pressure data and modeled waves data from WAVEWATCH III, used by NOAA. The results showed that the southwest winds acting at the sea surface might be the main responsible for the abrupt elevation of the sea level during the period of study, because their capability of throwing sea water to the near shore by Ekman effect. However, the wave set up due to the high swell waves coming straight to the coast in the same time is a fundamental component in this elevation. In addition, there are evidences of a cyclone near the study area, which can explain some of the abnormalities studied in this work. The washout systems have been shown to be highly sensitive to this kind of storm surge, and all the sampled and modeled data suggest that the opening and closure of the washouts may occurs due to such phenomena.

ADDITIONAL INDEX WORDS: *beach washouts, storm surge, coastal water table, beach drainage, sea level rise, Cassino Beach.*

INTRODUCTION

The southern portion of the Brazilian coast, where few inlets are responsible to drain a great amount of continental pluvial water, some small creeks called washouts are formed, acting in favor of the hydrological balance between the backshore and the coast. They supply the swash zone with large amounts of sediment. Despite their environmental importance, the washouts are been treated as a tool to the urban drainage of rainwater in some coastal cities of Rio Grande do Sul state, Brazil.

Firstly studied in the Brazilian coast by Pereira da Silva (1998), these water courses were classified according to their channel shape and their permanency on the beach face. Accordingly to Pereira da Silva (1998), washouts distribution is related to three main factors: (1) morphology of areas behind the first frontal dune line; (2) physiography of the frontal dune systems; and (3) morphodynamic characteristics of the beach. Figueiredo *et al.* (2007), comparing the washouts with some similar water courses, like the pocket lagoon openings and the Australian Intermittently Open/Closed Coastal Lagoons (ICOLLs), highlights the role of the water table levels in the generating of washouts. In later studies, Figueiredo (2002) and Figueiredo and Calliari (2004) did a similar research in the northern part of Rio Grande do Sul state, showing a higher concentration of washouts near the area of the pocket lagoons. Storms along the Rio Grande do Sul coastline rarely exceed 2 meters, the higher wave level greatly increases the erosional potential on the frontal dune systems (Pereira da Silva *et al.*, 2003). Accordingly to Fontoura (2004), the storm surges are associated to high sea level elevations, piling of water along the coast and significant erosion, with the transport of large quantities of sediment. During storms, the winds that blow toward the coast or along the coast from south to north move to the beach masses of water which, associated with the migration of pressure centers, become responsible for the rise in coastal sea level. These elevations can quickly go to 1 or 2 m, causing major changes in beach morphology (Almeida *et al.*, 1997 e Calliari *et al.*, 1998). The main effect of wind occurs by Ekman transport, and this is directly related to the shear stress of the wind acting in the sea surface, so the parallel to the shore axis is used for analysis. It happens because this is the highest frequency of occurrence axis (Braga and Krusche, 2000). The morphology of a beach at any particular time is a function of its sediment characteristics, immediate and antecedent wave, tide and wind conditions, and the antecedent beach state (Wright and Short, 1984). The main objective of this study is to identify the main agents responsible for the rise in sea level during the passage of a storm surge, and try to quantify each one's role.

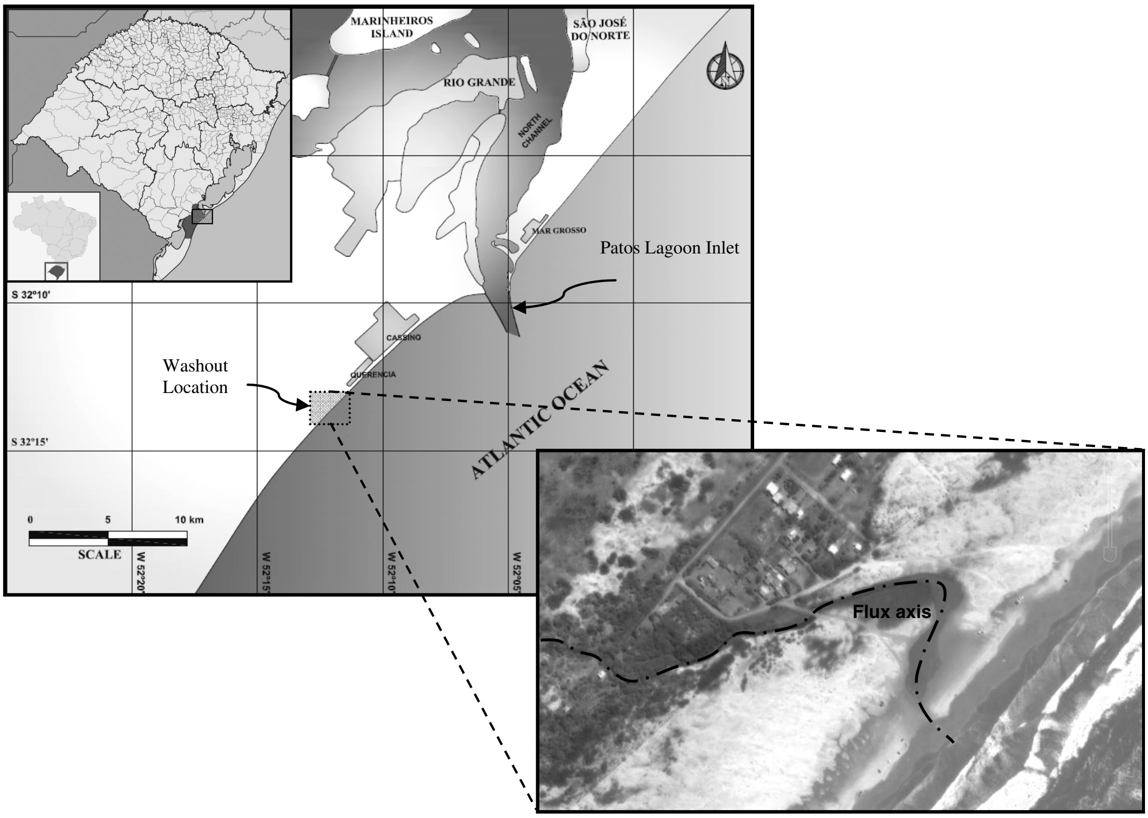

Figure 1. Study area, showing the approximate location of the washout under study (Google Earth, 2006).

STUDY AREA CHARACTERIZATION

The study area is located in Cassino Beach, Southern Brazil; a wave dominated, multibar and microtidal coast. Most of this coast has low slope because of its fine sand sediments. The single washout chosen for this study is located a few kilometers south of Patos Lagoon Inlet, near Cataventos Park, a lightly urbanized region, adjacent to Cassino Balneary (Figure 1). The mean annual precipitation rate is about 1,300 mm, with higher levels during the winter (Nimer, 1977). Winds blowing from South-Southwest (SSW), Southwest (SW) and West-Southwest (WSW) quadrants are associated to storm events and, combined with the SE and S winds, cause the pilling of water along the coast rising sea levels, especially in the winter months, when they are stronger (Delaney, 1965; Calliari, 1980; Tomazelli, 1993). Britto and Krusche (1996) studied the frontal systems that occurred from 1993 to 1995 in the region of Rio Grande, RS. The authors showed that the average seasonal cold fronts are sixteen per season and in the winter and spring they occur more frequently. The study area encompasses a portion of Cassino beach, located a few kilometers south of the Patos Lagoon Inlet.

METHODS

Aiming to explain the abrupt changing in the washout morphodynamic, several data was obtained and treated. Benavente *et al.* (2006) calculated the water surface elevation due to storm surges in the Cádiz Bay, Spain, taking into account three contributing factors: barometric setup, wind setup and wave setup. Therefore, trustable wave, wind and barometric pressure data was needed.

The model responsible for the generation of the deep water waves data in this study was the public domain version of the Wave Watch 3 (WW3), which is used by the United States of America National Oceanic and Atmosphere Administration (NOAA). The specific reviewed winds field data used to supply the WW3 model was obtained directly from the NOAA database. The winds field was provided every three hours with a spatial resolution of 1º of latitude versus 1.25º of longitude. The model was implemented in two nested numerical grids. The first one is a global grid, which uses the wind field with resolution 1º of latitude versus 1.25º of longitude, and the second is a local grid focused on the South Atlantic with a resolution of 0.25º versus 0.25º. The use of a global grid comes from the need to ensure that waves generated outside the region covered by the local grid may be included in the forecast. Thus, every round of the model in the global grid provides valuable information about the sea conditions on the boundary of the South Atlantic Ocean grid that are, therefore, incorporated by this round in the calculations. A detailed description of the model, including its equations can be found in Tolman (2002).

To calculate the transformation suffered by the waves while they propagate from the deep water to the depth of ten meters, was used a combined refraction and diffraction model (REF/DIF). The linear parabolic REF/DIF model used for the region of study was first developed by Melo and Guza (1991) and later refined. The spectral version of this model simply uses the superposition to model a wave spectrum, so each component is propagated independently and then added without any nonlinear interaction between them.

The local wind and barometric pressure data used in this work were supplied by the Laboratory of Meteorology of the Federal University of Rio Grande (FURG), from the FURG Automatic Station.

The wave fetch, that represents the lengthof water where the wind energy is transferred to the sea surface by shear stress, was estimated graphically from the weather charts prepared with wind and pressure reanalysis datasets from NOAA. The software used to construct the graphs was the Grid Analysis and Display System (GrADS).

Tidal range forecast values were obtained in the tidal tables, generated from harmonic components of several tide gauges, provided by the Hydrography and Navigation Directorate (DHN).

Using the expressions of Bowden (1983), it is possible to calculate the effect of the wind driven sea level rise $d\xi$.

$$\frac{d\xi}{dx} = \frac{\rho_a C_D W_{10}^2}{\rho_w g h} \quad (1)$$

Where dx represents an average wave fetch, estimated graphically in the weather charts; ρ_a is the air density; CD is a drag coefficient dependant of the wind speed; W_{10} is the wind speed at a height of 10 meters; ρ_w is the sea water density; g is gravity acceleration; and h represents the depth of wave base level. The values of air and sea water density adopted were 1.25 Kg/m^3 and 1,025 kg/m^3, respectively. The mean wave fetch dx was graphically estimated to be 750 km, taking into account the worse condition in the study area, with winds blowing parallel to the coast; h adopted as 10 meters depth; and C_D was obtained from Bowden (1983).

The value of the barometric setup was calculated considering a standard pressure value of 1020 milibar, with the expression used by Benavente (2006).

$$d\xi = (\Delta Pa)/(\rho_w g) \quad (2)$$

Where ΔPa represents the atmospheric pressure variation (in dPa) and ρ_w is the sea water density.

The increase of the water level due to the combined effects of wave set-up and wave runnup was calculated by the expression of Komar (1998), modified from Holman (1986).

$$R = 0.36 g^{0.5} H_0^{0.5} T \tan\beta \quad (3)$$

Where H_0 represent the deep water wave height; T is the wave period; and β is the beach mean slope. The beach mean slope in the study area was estimated based in beach profiles, with the value of 0,0175.

The Table 1 shows the dynamic characteristics used to calculate the sea level elevation caused by the storm surge.

Trying to elucidate the impact of the storm surge in the morphodinamic of the beach face, five beach profiles perpendicular to the coast are done in two moments, before and after the studied storm surge. The profiles were performed with a Nikon DTM-33 Total Station. The union of these profiles formed a 20 m regular grid that generated two digital terrain models (DTM).

RESULTS AND DISCUSSION

The changing in the weather conditions during the storm surge can be seen in the high values of wave height and wind speed (Table 1). The opened coast and light slope of Cassino beach reflects a natural flooding vulnerability, mitigated by a prominent dune field protecting the backbeach. The foredunes act as a sediment supply to the surf zone.

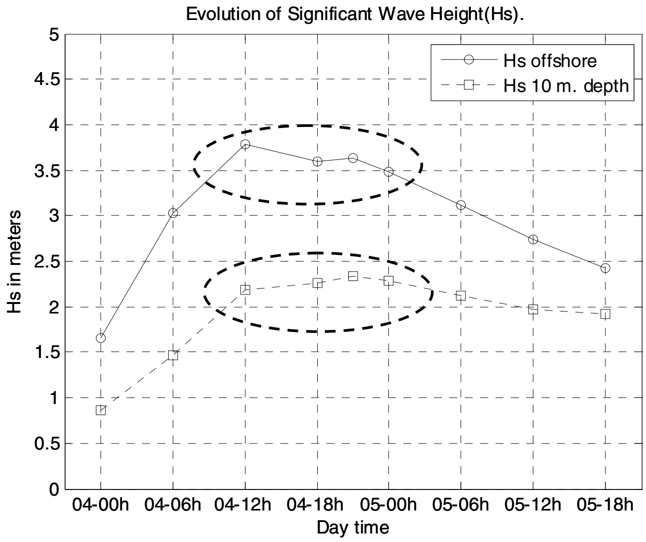

Figure 2. Wave heights variation in the most energetic moment of the storm surge.

Table 1: Wave, wind and barometric pressure data used to calculate the storm surge components.

Day	H_0 (m)	T (s)	Wind (m/s)	Atm P. (mbar)
Nov 2nd 2007	1.38	9.26	3.80	1007
Nov 3rd 2007	1.83	12.29	5.90	1003
Nov 4th 2007	3.59	11.17	10.80	1012
Nov 5th 2007	2.43	11.17	6.90	1017
Nov 6th 2007	1.11	11.17	4.50	1018

The Figure 2 shows the variation in wave height offshore and in a depth of 10 meters, with much energy concentrated in a few hours. This abrupt elevation in the height may enhance the wave set-up and runnup notably.

A low pressure area in the Atlantic, forming an extratropical cyclone (Tozzi, 1999) in phase with an area of high pressure coming from the Pacific may be responsible for the increasing in the southeastern wind, resulting in a long wind fetch (Figure 3).

The weather charts for three consecutive days showed the evolution of the wind through the period of occurrence of the storm surge. Note that on November 3rd strong winds blowing from southwest were seen near Argentinean and Uruguayan coasts. Reviewing the charts, southwest wind can be seen establishing a broad wind fetch in the Brazilian coast on November 4th, which eventually dissipates on November 5th. Note that on November 3rd strong winds blowing from southwest were seen near Argentinean and Uruguayan coasts.

This may bring out a new variable in the evaluation of sea level rise, a free long wave. A disturbance of sea level which is generated within a localized area of sea will tend to travel away from that area as a free long wave. On the continental shelf this is likely to be a Kelvin wave, which will travel with the velocity $c=(gh)^{1/2}$ (Bowden, 1983).

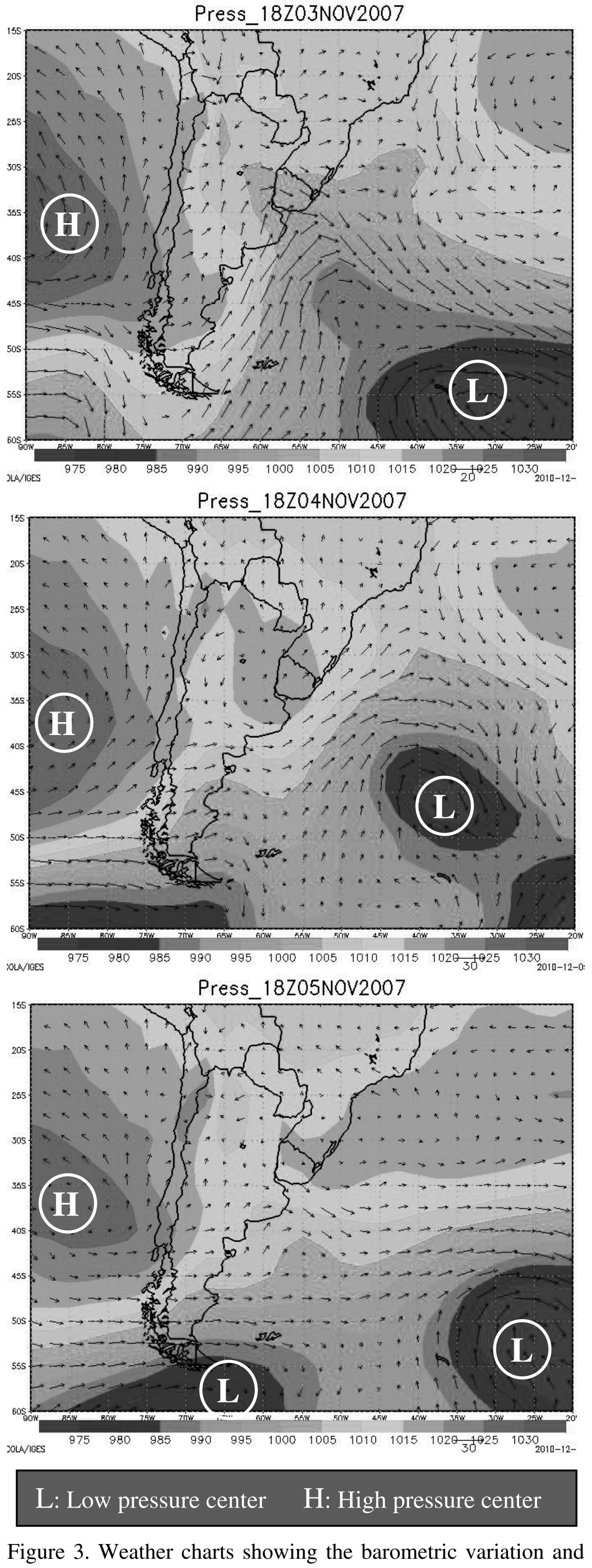

Figure 3. Weather charts showing the barometric variation and the wind field in three days, before, during and after the storm surge. The three charts are made with 18 hours P.M. data.

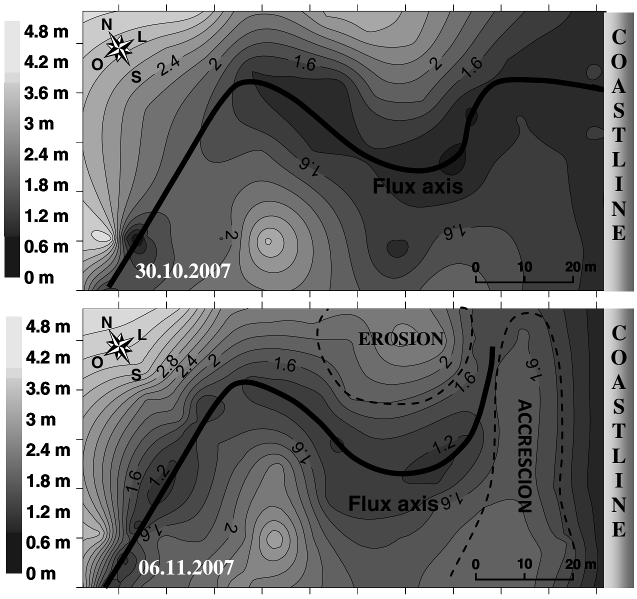

Figure 4. Digital Terrain Models in two moments, before and after the discussed event, showing erosional and accrescionary points in the beach face, modified from Serpa (2008).

Applying the formulas (1), (2) and (3), the components of the rise in sea level were calculated and presented in Table 2. The outcomes of *Total Set-up* revealed a significant rise in sea level on November 4th compared to the days before and after. Analyzing Table 2 more carefully, may be seen that the greatest anomaly is the value of November 4th Wind Set-up, with a difference in the input value of less than 5 m/s.

The results Figure 4 presents the impact on the beach due to the meteorological tide that occurred in November 4th, 2007. The results showed a morphodynamic variation in the beach face, caused by a shift in the position of the surf zone that generated large sediment transport in a short time. An erosional point was identified in the lower part of the foredunes, and an accrescional aerial sand bar was formed in the beach face, burying the washout channel.

Before this research, the most accepted theory to the closing of the washouts was based in the meteorological balance between precipitation and evaporation rates, and also in the sediment transport through the wind. Storm surges and the consequent sea level rises (meteorological tides) were related previously to the erosion of the foredunes and to the formation of the washouts, but not the opposite.

In order to confirm the theory that the storm surge was the responsible factor for the closure of the studied washout, some samples were collected in particular points of the beach and were analyzed in laboratory. The grain size analysis was performed following the methodology of Suguio (1973).

The results are shown in the histograms in the Figure 5. Analyzing the obtained results, it is possible to observe the most marked similarity between the Sample 2 and the Sample 3. The presence of heavy mineral traces in both Sample 2 and 3 reinforces the previous finding. Heavy mineral concentrations are also shown to be sensitive to the high-energy event, presenting an expected overall increase in its concentration (Siegle and Calliari, 2008). The frequency distribution of Sample 1 suggests dunes field type sediment, moved through air transport into the washout. The grain

Table 2: Results of the elevation above the mean water level due to the meteorological conditions.

Day	Astronomical Tide (m)	Wind Set-up (m)	Wave Set-up (m)	Barometric Set-up (mbar)	Total Set-up (m)
02.11.2007	0.7	0.138	0.215	0.129	1.182
03.11.2007	0.7	0.380	0.328	0.169	1.577
04.11.2007	0.6	1.633	0.418	0.080	2.731
05.11.2007	0.6	0.550	0.344	0.030	1.524
06.11.2007	0.4	0.203	0.232	0.020	0.855

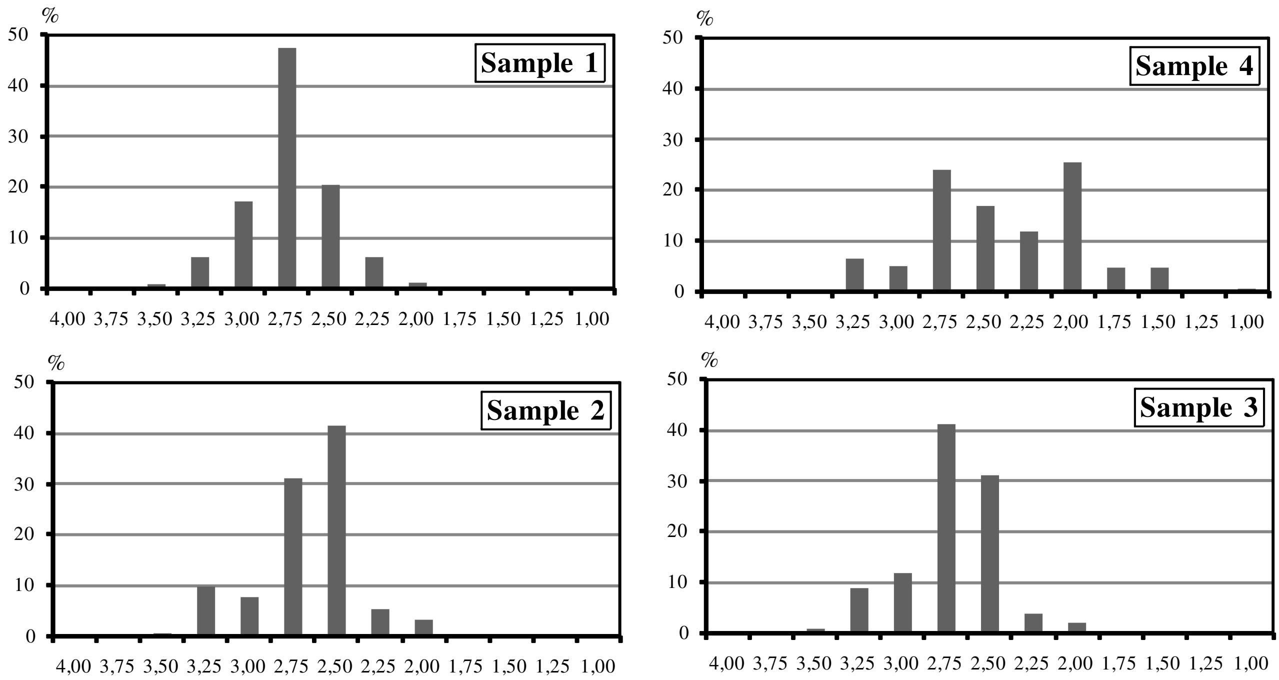

Figure 5. Results of the grain analysis for the samples collected in distinct points of the study area on November 6th, after the storm surge. Sample 1: washout bed; Sample 2: foredunes (erosion zone); Sample 3: beach face (accrescion zone); Sample 4: swash zone (modified from Serpa, 2008).

analysis of the Sample 4 showed a well-distributed particle size, with some bioclastic traces, a common swash zone distribution after high-energy events.

CONCLUSION

Accordingly to the classification of Pereira da Silva (1998), the studied washout can be classified as intermittent as to its permanence on the beach, and as meandering as to its shape.

Obtained wind results have shown that strong southwest winds acting at the sea surface might be the main responsible for the abrupt elevation of the sea level during the period of study, due to their capability of throwing sea water to the near shore by Ekman effect. However, the wave set up due to the high swell waves coming straight to the coast in the same time cannot be neglected; it could be an important component in this elevation. In addition, there are evidences of a cyclone not so far from the study area during the higher energy days, which can explain some of the abnormalities studied in this work. The weather charts showed strong winds parallel to the coast blowing from the southwest in the Argentinean coast on November 3rd, one day before the maximum sea level elevation, so a free long wave traveling across the continental shelf cannot be discarded. The measurement of waves and water column pressure would be of a great value to confirm this assumption.

The washout systems have been shown to be highly sensitive to the kind of storm surge verified in this research, and all the sampled and modeled data suggest that the opening and closure of the washouts occur due to such phenomena. The morphodynamic result after this event was the closure of the washout waterway by the transport of sediments into this. The grain size analysis suggests the foredunes eroded sediment (Sample 2) as the main source to the creation of a sand bar (Sample 3), interrupting the washout flux. Some large washouts present near the study area, which are responsible for draining the exceeding pluvial water of the backbeach, do not have their adjacent dune field restored during the dry season. So, these water courses, when showing an intermittent or permanent character, may create a perennial flooding susceptible area.

The Rio Grande do Sul coast and all its beach structures are quite sensitive to any change in the sea level, and needs to be further investigated to do a prediction of the possible impacts in the future. The presence and development of the urbanization in the Southern Brazilian coast should be governed by strict laws that take into account the morphodynamic changes in the coastal environment, and are capable to predict the future impacts of this growth.

ACKNOWLEDGEMENT

The authors would like to thank the Coastal Technology Center (CENTECO) and the Geological Oceanography Laboratory (LOG) for giving support to this study, and also to CAPES and CNPq for the financial support.

LITERATURE CITED

Almeida, L.E.S.B. and Rosauro, N.M.L., 1997. Análise preliminar das marés na barra do Rio Tramandaí (RS-Brasil). *Simpósio Brasileiro de Recursos Hídricos - ABRH,* 12 (4), pp. 559-566.

Benavente, J.; Del Río, L.; Gracia, F.J. and Martínez-del-Pozo, J.A., 2006. Coastal flooding hazard related to storms and coastal evolution in Valdelagrana spit (Cadiz Bay Natural Park, SW Spain). *Continental Shelf Research,* 26, 1061-1076.

Bowden, K.F., 1983 *Physical Oceanography of Coastal Waters*. New York: Wiley, 302p.

Braga, M.F. and Krusche, N., 2000. Padrão de ventos em Rio Grande, RS, no periodo de 1992 a 1995. *Atlântica,* 22, 27-40.

Britto, F. and Krusche, N., 1996. Freqüência e intensidade das frentes frias em Rio Grande. *IX Congresso Brasileiro de Meteorologia*. Campos do Jordão, 01: 185-188.

Calliari, L.J., 1980. Aspectos sedimentológicos e ambientais na região estuarial da Lagoa dos Patos. Porto Alegre, Rio Grande do Sul: Universidade Federal do Rio grande do Sul. Master's thesis, 190 p.

Calliari, L.J.; Speransky, N. and Boukareva, I., 1998. Stable focus of wave rays as a reason of local erosion at the Southern Brazilian Coast. International Coastal Simposyum. Proceedings. Fort Lauderdale, pp. 19-23.

Delaney, P.J.V., 1965. Fisiografia e geologia da superfície da planície costeira do Rio Grande do Sul. Universidade Federal do Rio Grande do Sul, Porto Alegre. *Escola de Geologia*. Special Issue No. 6, pp. 1-195.

Figueiredo, S.A., 2002. Distribuição espaço-temporal dos sangradouros na costa gaúcha no trecho São José do Norte – Farol de Mostardas. Rio Grande, Rio Grande do Sul: Universidade Federal do Rio Grande. Graduation Thesis, 43p.

Figueiredo, S.A. and Calliari, L.J., 2004. Sangradouros: distribuição espacial, variação sazonal, padrões morfológicos e implicações no gerenciamento costeiro. *Gravel, 3,* 47-57.

Figueiredo, S.A.; Cowell, P. and Short, A., 2007. Intermittent backbeach discharge to the surfzone: modes and geomorphologic implications. *Journal of Coastal Research,* Special Issue No. 50, pp. 610-614.

Fontoura, J.A.S., 2004. Hidrodinâmica costeira e quantificação do transporte longitudinal de sedimentos não coesivos na zona de surfe das praias adjacentes aos Molhes da Barra do Rio Grande, RS, Brasil (Aplicação às praias do Cassino, Mar Grosso e adjacências dos Molhes Leste e Oeste da desembocadura do estuário da Lagoa dos Patos). Porto Alegre, Rio Grande do Sul: Universidade Federal do Rio grande do Sul. Ph.D. thesis. 223 p.

Holman, R.A., 1986. Extreme value statistics for wave run-up on a natural beach. *Coastal Engineering* 9, 527–544.

Komar, P.D., 1998. *Beach Processes and Sedimentation.* Prentice Hall, Englewood Cliffs, NJ. 544 p.

Melo, E. and Guza, R.T., 1991. Wave propagation in jettied entrance channels. I: Models, *Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE*, 117 (5), 471-492.

Nimer, E., 1977. Clima. Geografia do Brasil, região Sul, Rio de Janeiro. IBGE, pp.35-79.

Pereira da Silva, R., 1998. Ocorrência, distribuição e características morfodinâmicas dos sangradouros na zona costeira do Rio grande do Sul: trecho Rio Grande - Chuí, RS. Porto Alegre, Rio Grande do Sul: Universidade Federal do Rio grande do Sul. Master's thesis, 146 p.

Pereira da Silva, R.; Calliari, L.J. and Tozzi, H.A.M., 2003. The influence of washouts on the erosive susceptibility of the Rio Grande do Sul coast between Cassino and Chuí beaches, Southern Brazil. *Journal of Coastal Research,* Special Issue No. 35, pp. 332-338.

Serpa, C.G., 2008. Estudo da influência dos fatores climáticos, hidrológicos e morfológicos no ciclo morfodinâmico praial de um sangradouro intermitente, Praia do Cassino, Brasil. Rio Grande, Rio Grande do Sul: Universidade Federal do Rio Grande. Master's thesis, 95 p.

Siegle, E. and Calliari, L.J., 2008. High-energy events and short-term changes in superficial beach sediments. Brazilian Journal of Oceanography, 56(2), 149-152.

Suguio, K., 1973. Introdução à sedimentologia. São Paulo, Edgard Blucher, 317p.

Tolman, H.L., 2002. User manual and system documentation of WAVEWATCH-III, version 2.22. NOAA / NWS / NCEP / MMAB. Technical Note 222, 133 pp.

Tomazelli, L.J., 1993. O regime de ventos e a taxa de migração das dunas eólicas costeiras do Rio Grande do Sul, Brasil. Pesquisas, 20 (1), 18-26.

Tozzi, H.A.M., 1999. Influência das tempestades extratropicais sobre o estoque subaéreo das praias entre Rio Grande e Chuí, RS. Porto Alegre, Rio Grande do Sul: Universidade Federal do Rio grande do Sul. Master's thesis, 115 p.

Wright, L.D. and Short, A.D., 1984. Morphodynamic variability of surf zones and beaches: A Synthesis. Marine Geology, 56, 93-118.