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Vulnerability to Sea-Level Rise on the Coast of the Buenos Aires Province

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ABSTRACT

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The purpose of this work is to identify and quantify those stretches in the Buenos Aires province that present different degrees of risk in view of the rise of the mean sea level and to determine its nature. The study focused on the Buenos Aires province coast because its variant geomorphology represents the different morphologies along the whole of the Argentinean coastline. The aim of this article is to study the response of two of the coastal vulnerability equations to the environmental diversity and to determine which one is more suitable to be applied to the rest of the country. On verifying the equations, CVI6 was found to be more appropriate for the analysis of coasts with different morphologies. Depending on the physical characteristics of each area, the consequences would include flooding and the loss of low lands in areas such as the Samborombón Bay, Bahía Blanca Estuary, and Anegada Bay, and the eroding of the beaches between Punta Rasa and Bahía Blanca.

ADDITIONAL INDEX WORDS: *Sea-level rise, coastal vulnerability, coastal management.*

INTRODUCTION

Although variable throughout the coasts of the world, the general tendency indicates that the sea level is increasing. Its immediate impact is the loss of surface due to flooding of low lands and coastal wetlands and the erosion of beaches and cliffs, influencing the socioeconomic sphere as well as the potential development of the affected coastal area. The average sea level has risen between 1 and 2.5 mm/y in the last 100 years (GORNITZ *et al.,* 1994), and there exist diverse estimates for the next century. If we consider that the sea level is directly related to the temperature of the air, which in turn is affected by the release of anthropogenic greenhouse gases, it is very difficult to predict the magnitude of the increase accurately (WANG, 1998).

Future estimates on the sea-level rise vary between 15 and 150 cm, with a best estimation of 48 cm for the year 2100 according to the data published by HOFFMAN *et al.* (1994), NATIONAL RESEARCH COUNCIL (1994), WARRICK and OERLEMANS (1990), WIGLEY and RAPER (1994) in GORNITZ *et al.* (1994). The IPCC, on the other hand, has calculated an increase of 15–95 cm, with a best estimation of 50 cm (THIELER and HAMMAR-KLOSE, 2001). The numbers obtained by DOUGLAS (1995) state that the average sea level may rise by 1.8 mm/y in the next 100 years. For Argentina, the variations of the mean sea level lie between 1.6 ± 0.1 mm/y for the Río de la Plata Estuary, 1.4 ± 0.5 mm/y for Mar del Plata (LANFREDI *et al.,* 1998), and 1.6 ± 0.2 mm/y for Quequén Harbor (LANFREDI *et al.,* 1988).

Buenos Aires is the most important socioeconomic coastal province of Argentina (Figure 1). It possesses over 1300 km of a diverse coastline, including the low flood plain of the Río de la Plata Estuary, the wetlands surrounding Samborombón Bay, Bahía Blanca Estuary, and Anegada Bay, succeeded by the cliffs of the Mar del Plata area. The population of the province reaches 15 million inhabitants (INDEC, 2001), 90% of which live in urban centers, the largest concentration being in coastal areas. The city of Buenos Aires and its suburbs (11 million inhabitants) and the city of La Plata (540,000 inhabitants) are located along the coasts of the Río de la Plata Estuary while Mar del Plata (500,000 inhabitants and Bahía Blanca [270,000 inhabitants] are located on the Atlantic coast. Buenos Aires, Mar del Plata, Quequén, and Bahía Blanca are Argentina's most important ports. A wide variety of economic activities are developed along the coastal area, including agricultural and cattle breeding operations, as well as tourism, fishing, and industries. The latter include chemical, petrochemical, textile, metallurgical, and food-related activities.

The purpose of this article is to identify and quantify those stretches in the Buenos Aires province that present different degrees of risk in view of the rise of the mean sea level and to determine its nature. To reach this objective, the Coastal Vulnerability Index (GORNITZ *et al.,* 1997; THIELER and HAMMAR-KLOSE, 2001) will be applied. Although this methodology was developed for US coasts, it does not present limitations and is applicable to all sorts of coasts. The study focused on the Buenos Aires coast because its variant geo-

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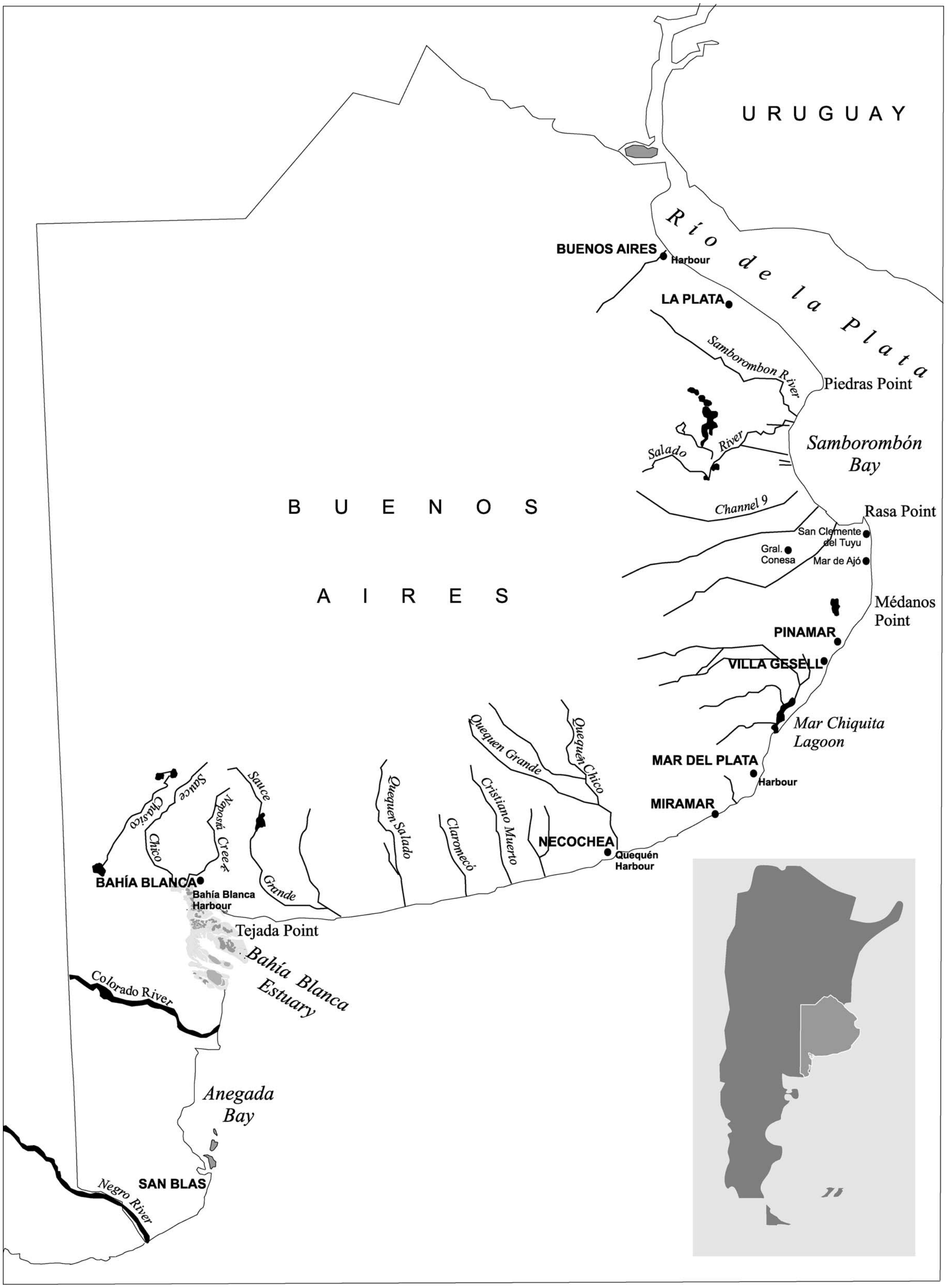

Figure 1. Study area.

Table 1. *Coastal risk classification scheme.*

Variable	Very Low (1)	Low (2)	Moderate (3)	High (4)	Very High (5)
Elevation	>12	12–9	9–6	6–3	<3
Geology	Resistant rocks	Metamorphic rocks	Sedimentary rocks	Unconsolidated sediments (gravel, glacial till, mixed lithology)	Unconsolidated sediments (mud, clay, sand, glacial drift, calcareous sediment)
Geomorphology	Rocky, cliffed coast, fiords	Medium cliffs, intended coast	Low cliffs, glacial drift, alluvial plains	Cobble beaches, estuary, lagoon	Barrier beaches, sand beaches, salt marsh, mud flats, deltas, mangrove, coral reefs
Shoreline erosion/ accretion (mm/y)	Natural accretion	Induced accretion	Stable	Incipiente erosion	Active erosion
Mean tide range (m)	<1	1–2	2–4	4–6	>6
Mean wave height (m)	<0.2	0.2–0.9	0.9–1.4	1.4–2.1	>2.1

morphology represents the different morphologies along the whole of the Argentinean coastline. Hence, this work studies the response of the possible equations to the environmental diversity in order to determine which one is the best suited to be applied to the rest of the country. In addition, the present work compares the findings with those published by DENNIS *et al.* (1995), LANFREDI *et al.* (1998), and PERILLO (1997).

The US COUNTRY STUDIES PROGRAM (1994) suggests the Bruun Rule (BRUUN, 1962; HANDS, 1983) to determine the lands that will be affected by the rise of the average sea level. However, it is not recommended for the Argentinean coast (PERILLO, 1997). The main limitation of the Bruun rule lies in the coast profile. Its basic assumption demands that the coast be formed by unconsolidated sediment, mainly sand, associated to a coastal dune. In addition, the interior platform should be smooth and have no variations of depth. Consequently, the only place that complies because of its geomorphologic characteristics lies between Punta Rasa and the mouth of the Mar Chiquita Lagoon (Figure 1). However, the inner shelf of this section is particularly complex because of shoreface-connected linear ridges (PARKER *et al.,* 1978; SWIFT *et al.,* 1978), which modify the circulation of the area significantly. The rest of the coast either has rocky outcrops or the sand volume on the beaches is too low to permit an adequate use of Bruun's rule. Authors such as DENNIS (1995) and LANFREDI *et al.* (1998) have dismissed these peculiarities and have worked out estimates of coastal erosion. However, PERILLO (1997) uses the criteria of direct flooding as the model to estimate the vulnerability of the coasts, where the loss of land is related to the slope.

METHODOLOGY

In order to apply the coastal vulnerability index, it was necessary to create a database with the following physical variables:

X_1 Elevation (m), linked to the susceptibility of the coast in the event of flooding and smooth shoreline retreat

X_2 Sea-level rise (mm/y), states the increase of the global sea level (eustatic) and the effect of the local tectonic processes on the stretch of coastline

X_3 Geology (nonparametric), related to the resistance of the substratum

X_4 Geomorphology (nonparametric), indicates the characteristics and eroding levels of the coastal area

X_5 Shoreline erosion/accretion of the coastline (m/y), indicates the degree to which the coastline has changed

X_6 Average wave height (m), connected to the inundation hazards

X_7 Mean tide range (m), contributes to the inundation hazards

The elevation was obtained by means of a grid of topographic elevations extended toward the continent to the 20-m contour line starting at the coastline. The values of relative variation of the mean sea level correspond to those published by LANFREDI *et al.* (1988). The geological data was gathered from the geologic and geomorphologic map published by the FEDERAL COUNCIL FOR INVESTMENT (1975). The geomorphologic data was obtained by interpreting published topographic charts on a 1 : 50,000 scale and hydrographic charts of the inner shelf, supported by the analysis of the aerial video recording of the coast after two flights: one at 100 m and the other at 300 m (PERILLO, 1997). The data of the shoreline erosion/accretion variable was compiled from DENNIS *et al.* (1995), ISLA (2001), ISLA and VILLA (1992), LANFREDI *et al.* (1998), and PERILLO (1997). The data of tide range was obtained from the tide charts published by the SERVICIO DE HIDROGRAFÍA NAVAL (2002). Due to the lack of statistical data regarding waves for most of the Argentinean coast (with the exception of the specific data from ports), the wave-height information was provided by the Meteorological Service of the Argentinean Navy and corresponds to average values forecasted for each cell of the grid.

The work scale was delimited in a grid of 0.25° latitude by 0.25° longitude. A value of relative risk was assigned to each variable, in which the variables are qualified in a scale from 1 to 5 according to the degree of vulnerability to the increase of the sea level, where 1 represents the lowest risk and 5 the highest (Table 1). In order to graph the data, the information compiled in the grid was transferred to a vector corresponding to the coastline, where each coastal segment is linked to a cell in the grid.

To determine the coastal vulnerability, the two tested formulas less susceptible to errors or information loss were applied (GORNITZ *et al.,* 1997). In both cases, the coastal vulnerability index (CVI) allows the variables to relate in a quantitative way. They are calculated as

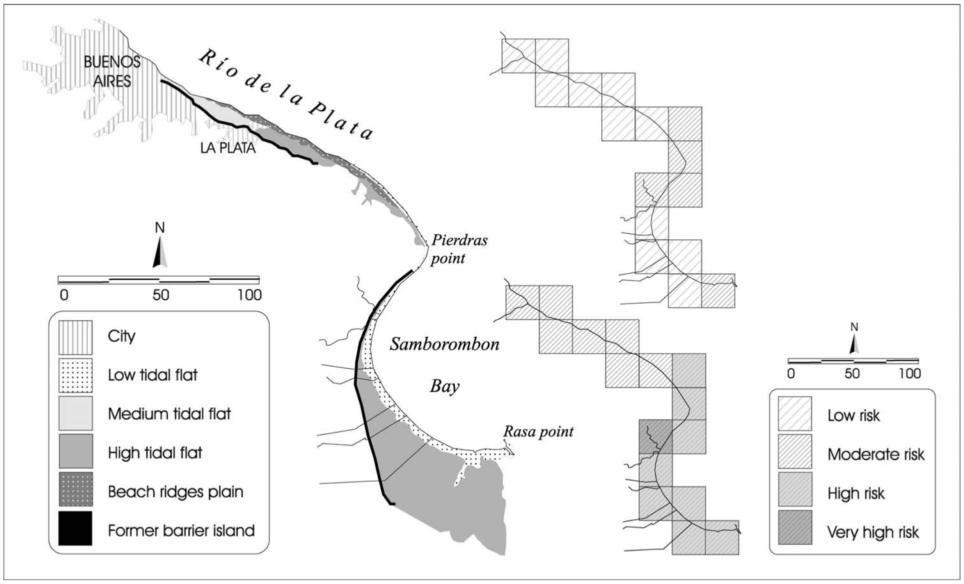

Figure 2. Map of the coastal vulnerability index (CVI) for the Río de La Plata estuary.

$$\text{CVI5} = \sqrt{(X_1 \times X_2 \times X_3 \times X_4 \times X_5 \times X_6 \times X_7)/7} \qquad (1)$$

$$\text{CVI6} = 4X_1 + 4X_2 + 2(X_3 + X_4) + 4X_5 + 2(X_6 + X_7), \qquad (2)$$

where each letter corresponds to the physical variable previously mentioned. A single index value for each cell was obtained. The data were later classified through the method of natural breaks as low, moderate, high, and very high hazards and then mapped.

RESULTS

Figures 2–4 show the CVI maps corresponding to each formula for the coast of the Buenos Aires province. In the esti-

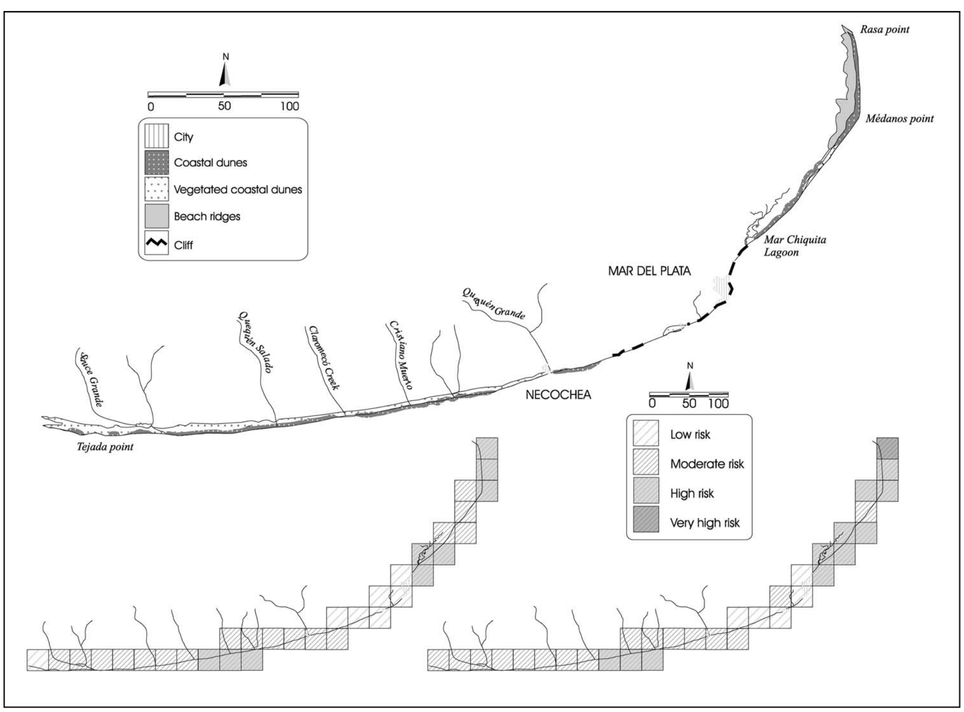

Figure 3. Map of the coastal vulnerability index (CVI) for the coast between Punta Rasa and Bahía Blanca estuary.

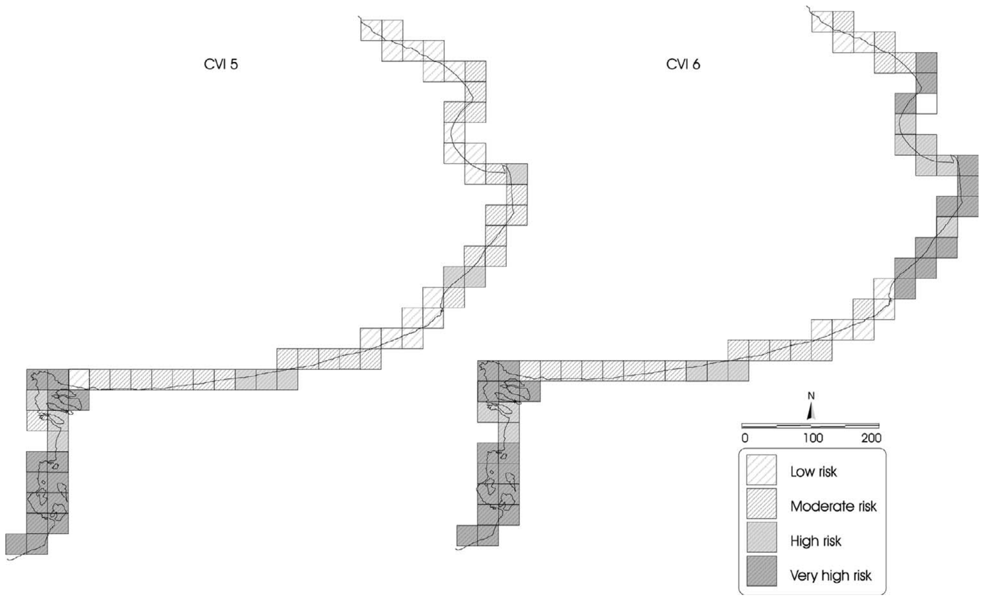

Figure 4. Map of the coastal vulnerability index (CVI) for the coast between Bahía Blanca estuary and Negro river.

mation of the index, certain variables have more weight than others. For the CVI5, the value range varies between 2.9 and 58.5. The mean is 23.9, the mode is 26.2, and the median is 19.6. The standard deviation of the data is 10.2. For CVI6, the range varies between 48 and 86, the mean is 68.8, the mode is 60, and the median 68. The standard deviation is 10.4.

The values obtained were divided into low-, moderate-, high-, and very high-risk categories by the natural break classification method. For a better analysis of the results, the coastal line was divided in to three sectors: (1) Coast of La Plata River, (2) Punta Rasa–Bahía Blanca, and (3) Bahía Blanca–northern coast of the Negro River.

Coast of the Río de La Plata Estuary

The Argentinean coast of the Río de la Plata Estuary extends from the delta of the Paraná River to Punta Rasa (Figure 2). It is a low coast subject to periodic flooding by storm waves induced by local phenomena called sudestadas (strong winds from the southeast). The combined actions of the winds and the tides induce over-elevations that have reached up to 4.5 m (PERILLO, 1997). The coastal plain comprises the fringe extending between the 5 m isoline and the sea level. There are sandy shell ridges with elevations that vary from 2.5 to 5 m and low areas with marshlands with elevations that rarely exceed 2.5 m (CAVALLOTTO *et al.,* 1999). The Samborombón Bay corresponds to a system of ancient barrier islands located between Punta Rasa and General Conesa and an extensive complex of tidal flats and low salt marshes associated with the Salado River basin, located between the islands mentioned and the sea (CODIGNOTTO and AGUIRRE, 1993).

The former barrier islands are subparallel to the current coastline and distributed along 120 km. In the Punta Piedras area, there are small spits circumscribing the barrier islands to the west. In the north, the islands are only 2 km from the coastline but they drift away as far as 30 km from the sea in the General Conesa area. The barrier islands are represented mainly by sandy shell sediment. The tidal flats were formed in a low-energy environment during the last part of the post glacial rise of the sea level. The salt marshes are also an accretion area in a low-energy environment and consist primarily of silty clay (to the north of the bay up to Canal 9) and high percentages of sand (Punta Rasa), due to an important influence of the littoral drift (BÉRTOLA and MOROSI, 1997).

The values obtained through the use of the two formulas differ considerably. For CVI5, this stretch of coast has mainly low risk, with some values of moderate risk, while CVI6 shows high and moderate risks. However, the tendency is the same, *i.e.,* the coastline extending from Buenos Aires city to the vicinity of Punta Piedras is less vulnerable to the rise of the mean sea level than the stretch from there to Punta Rasa, including the Samborombón Bay, where the risk increases significantly. This variation is mainly due to a decrease in the average elevation of the area. The top vulnerability is located in Punta Piedras, where low height and erosion of the coastline affect the sector.

Punta Rasa–Bahía Blanca

NE to SW, the coast extending between Punta Rasa and Bahía Blanca (Figure 3) consists of sandy beaches backed by coastal dunes and, in some parts, by cliffs and rock outcrops. The Mar Chiquita Lagoon is the only typical microtidal coastal lagoon of Argentina. The coast between Mar Chiquita and the city of Miramar presents cliffs formed by semiconsolidated Pleistocene sediment (loess). Cliff heights range from a few meters to 25 m. These cliffs border orthoquartzitic rocks from the lower Paleozoic that correspond to the eastern border of the Tandilia Hill System. These rocks are in the center of the coast of Mar del Plata city.

For this stretch of coast, the results of the CVI formulas do not present great differences between them. From Punta Rasa to the Mar Chiquita Lagoon, the risk values are high to moderate for CVI5 and high, with some very high and moderate values, for CVI6. The risk in this sector is related to the geomorphology and the eroding processes directly linked to the increase in the wave height.

The coast surrounding Mar de Ajó corresponds to the formation of successive barrier spits extending from Villa Gesell to Punta Rasa, with a variable width of 10–15 m and littoral ridges 5 m high (CODIGNOTTO and AGUIRRE, 1993; PARKER *et al.,* 1978). It is an area of natural accretion, with strong and active eroding phenomena induced by poor coastal management, mainly related to the extraction of sand for construction and the buildings erected in the area. These geomorphologic characteristics together with the increasing wave height to the south, low height, and active eroding processes determine the high vulnerability of the coastline in the event of the rise of the mean sea level. The Mar Chiquita Lagoon is another sector that presents high risk. It is a chocked, long inlet coastal lagoon developed in a microtidal environment (FASANO *et al.,* 1982; PICCOLO and PERILLO, 1997), located in a low area backed from behind and to the west by a 2.8–3-m-high low plains subject to flooding.

In the outskirts of Mar del Plata, the risk diminishes abruptly from high to low due to a high slope and the presence of cliffs. The combination of these low-risk variables conditions the results of the index. The following sectors of the coast (SW) with low vulnerability are stretches where large slopes are combined and associated with semiconsolidated loess cliffs. Even though these coastal stretches are under erosion due to beach sand exploitation affecting the sandy deposits and increasing the rate of retreat of the cliffs (MARCOMINI and LÓPEZ, 1999), the index result is not affected by this high-risk variable.

The coasts of Mar del Plata are themselves affected by active eroding processes, caused mainly by the elimination of the coastal dunes through urbanization or deforestation processes (PERILLO, 1997). Despite the situation, both formulas indicated that the coastline sector possesses low vulnerability to the rise of the sea level, due to the presence of rocky cliffs, as mentioned above, and heights that reach 30 m falling within the low- and very low-risk range.

To the south, between Necochea and Punta Alta, there are no differences in the results of the formulas. In both cases, the coast presents moderate risk to the rise of the mean sea level. The heaviest variable is the wave height linked to eroding processes, mainly in the area of the mouth of the Cristiano Muerto Creek, where the risk becomes high. The wave height is used as an indicator of its energy. This energy increases as the square of the wave height and is related to the capability to transport sediment along the beach (DENNIS *et al.,* 1995). The sector includes wide beaches of low slope with dune ridges of great expansion and a height of less than 10 m, with the exception of the Punta Tejada area, where CVI5 showed low risk directly related to the exposure of semiconsolidated sediment.

Bahía Blanca–Northern Coast of the Negro River

The remnant of a deltaic complex system forms the coast from the Bahía Blanca Estuary to San Blas (Figure 4). The current delta of the Colorado River has a N–S coast between the Bahía Blanca Estuary and Anegada Bay of about 60 km, setting a clear example of coastal retreat. Both environments present extensive tidal flats with concentrations of low salt marshes. They are in an advanced erosional stage due to the lack of sedimentary contributions from both the rivers and the inner shelf (PERILLO, 1995).

This is the sector that poses the highest vulnerability to the rise of the sea level in the studied area. In almost the whole of the south coast of the Buenos Aires province, the index presented a very high inundation risk. Within these areas, we find the Bahía Blanca Estuary, Anegada Bay, and the coast of San Blas diminishing to high risk in the Verde Island area. In this case, both formulas show equal results.

The Bahía Blanca Estuary is a mesotidal, coastal plain estuary (PERILLO, 1995). It presents different morphological units that allow the interconnection of the continental and marine environments (MELO *et al.,* 2003). Within this estuary, tidal flats, salt marshes, and islands are separated by a wide size spectrum of tidal channels. These characteristics plus the low slope determine the result of the coastal vulnerability index. The mouth area of the Colorado River presents deltaic features, formed by sandy beaches with very low slopes. Inland, low dune formations can be observed. In the delta area, washovers, small flats, and salt marshes can be seen, which extend all along Anegada Bay. This area presents a moderate- to high-risk level, mainly related to an erosional stage due to the total elimination of sedimentary contributions of continental origin (PERILLO, 1997).

DISCUSSION

Even though the formulas employed are the ones recommended by GORNITZ *et al.* (1997), the numbers obtained with CVI5 showed that the equation is very unstable to small changes in the variable values. Should just one of the physical variables deviate its category from the others, the total results of the index could be completely modified: the totally different results obtained at the Samborombón and Anegada bays and the Bahía Blanca estuary are a clear example of this because the two environments have similar geomorphologies and both are strongly compromised by a mean sea-level increase. The main difference lies in the values of the wave height and tide range variables, going from very low in Samborombón to very high in the Bahía Blanca Estuary. CVI 6 produces a different result.

PERILLO (1997) proposes a planned retreat as a warning precaution in these three sectors because they correspond to areas that could be affected by direct flooding if the mean sea level increases. Due to the difference in the results, the index was recalculated varying the value of the mean sea level according to the published data in LANFREDI *et al.* (1998) (Figure 5).

The new results obtained with CVI5 did not show important differences with respect to the previous ones. This is due to the fact that the new mean sea-level data did not modify the range of values significantly, and hence, in their reclassification, only the limit of the first class varied, producing a similar outcome. Samborombón Bay presented low and moderate risks once more. Only between Punta Rasa and the Mar Chiquita lagoon was the risk reduced from high to moderate.

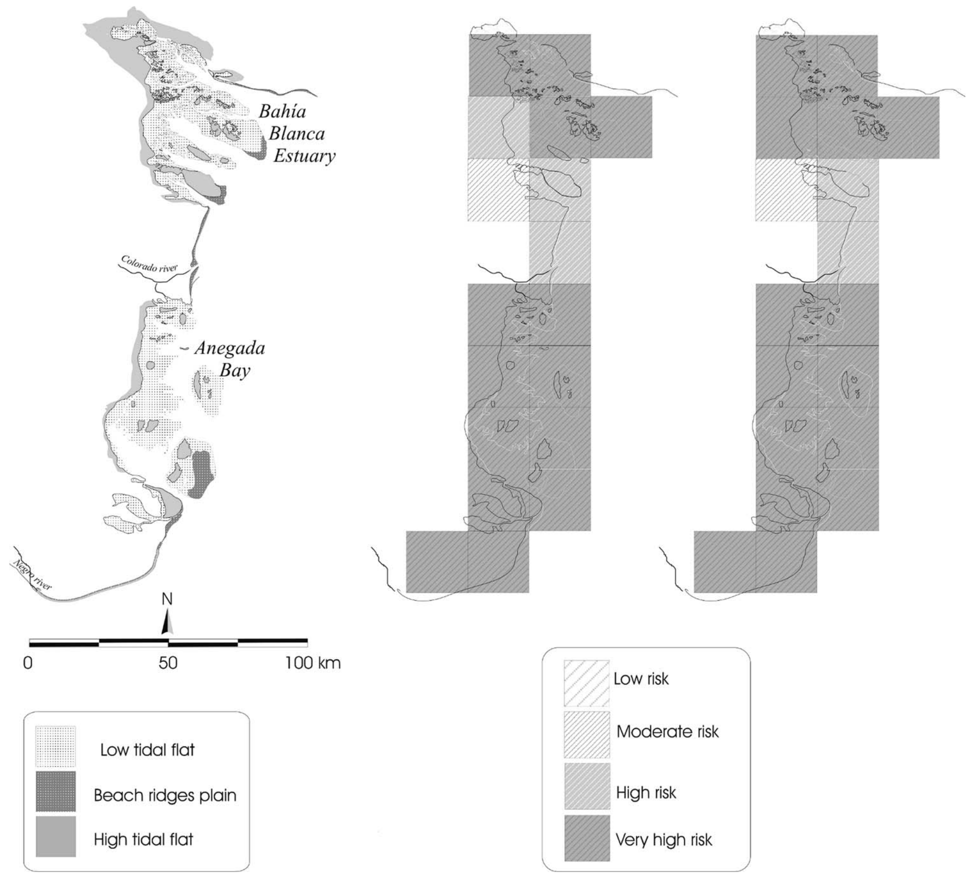

Figure 5. Map of the coastal vulnerability index (CVI) for the Buenos Aires province coast. CVI was recalculated varying the value of the mean sea level.

On the other hand, the CVI6 formula did vary with the new mean sea-level values. In the area that lies between Punta Piedras and the Mar Chiquita Lagoon, the risk increased from high to very high, while in the rest of the coast, there were no significant variations with respect to the previous classification. The last calculations proved that CVI6 is more appropriate for the analysis of the coast of the Buenos Aires province because it is responsive to its environmental diversity.

No important differences were found in the new numbers compared with the results published by PERILLO (1997). In the low areas, Samborombón Bay, the Bahía Blanca Estuary, and Anegada Bay (including the delta of the Colorado River), both methods responded similarly. The high vulnerability assigned by the index matches the direct inundation forecasted by Perillo to the 2.5-m contour line. This line lies inland, provoking a possible loss of effectively occupied land. In Samborombón Bay, besides the loss of fields, there is the effect that the inundation could have on the rivers emptying into the bay. The whole of this area is subject to periodic flooding because it functions as the point of convergence of the rivers flowing from the province of Buenos Aires itself, Córdoba, and La Pampa. The levels of inundation vary depending on where the draining originates. The way in which the basin empties will be affected by the change in the level of the base. When it increases, the level of the riverbed diminishes, causing the decrease in the river discharge. As a result, the period of emptying increases, extending the flooding of the fields and, therefore, causing a series of economic and social damage.

In the stretch that lies between San Clemente and Bahía Blanca, where a protection system by repopulation of sandy beaches with the appropriate sand for each sector and the typical energy of each place is recommended (PERILLO, 1997), the index subdivides the area in sections of different vulnerability. It classifies the stretch between Punta Rasa and Mar Chiquita as of very high risk, Mar del Plata as of low risk, and from there to Bahía Blanca as of moderate risk, emphasising the relevance of the average wave height and the coastline erosion/accretion.

The sector that lies between Punta Rasa and Mar del Plata is undergoing an eroding process with the current sea level and a retreat of 0.31 m/y is calculated if the sea level increases by 1.6 mm/y (LANFREDI *et al.,* 1998). DENNIS (1995) assures that the main impact of the rise of the sea level would concentrate north of the city of Mar del Plata. Although these results do not differ from those found by PERILLO (1997) and the CVI, they are not entirely reliable because they were calculated by means of the Brunn Rule, which is not advisable for the Argentinean coast, as stated before.

CONCLUSIONS

From the verification of the proposed equations, CVI6 was found to be the most appropriate for the analysis of coasts with different morphologies. The Buenos Aires province served as a pilot test for the verification of the methodology and for the selection of the equation to be utilized in a second stage of the research in the rest of the Argentinean coast.

The results showed that the increase of the sea level would impact on the coastline of the Buenos Aires province significantly. Depending on the physical characteristics of each area, the consequences would include flooding and the loss of low lands in areas, such as the Samborombón Bay, Bahía Blanca Estuary, and Anegada Bay, and the eroding of the beaches between Punta Rasa and Bahía Blanca.

The lack of socioeconomic information in risk assessment is a restriction to the coastal vulnerability index, especially if we consider that the north of the Buenos Aires province concentrates the largest population of the country distributed in coastal cities of great magnitude and that Buenos Aires, Mar del Plata, Quequén, and Bahía Blanca are four of the most important ports in Argentina. In order to implement the adequate strategies before the rise of the sea level, the areas at risk have to be objectively identified. In this respect, the created database, along with the associated risk maps, provide a useful guide for a first approach of coastal management policies tending to counteract the effects of the sea-level rise.

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