Methodological approach for the calculation of coastal sensitivity indices to erosion. Application case: Bolívar Department, Colombian Caribbean

Aproximación metodológica para el cálculo de índices de sensibilidad costera ante erosión. Caso de aplicación: departamento de Bolívar, Caribe colombiano

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Johanna P. Echeverry H.* & Leonardo Marriaga R.**

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Abstract

This investigation presents a methodological proposal, based on multicriteria spatial analysis, which identifies Bolivar Department coastal areas most susceptible, and likewise the resistant ones to threats of marine origin, to improve solid basis and for the development of scientific recommendations and proposed risk management schemes. The criteria used as the basis of the analysis were geomorphology, land cover and wave climate near to the study area, on which the Analytical Hierarchy Process technique were applied for weighting the variables and finally using Geographic Information System tools, a weighted superposition of multi-criteria decision problems was performed. Spatial results were satisfactory, as the location of the most sensitive areas of the coast. However, it showed the need for primary information sources specific standards according to the objective of the study to be performed.

KEYWORDS: Spatial multi-criteria analysis, geomorphology, ecosystems, surf, coast, Geographic Information Systems.

Resumen

Esta investigación presenta una propuesta metodológica basada en análisis espacial multicriterio, mediante la cual se identifiquen las áreas costeras del departamento de Bolívar más susceptibles, y así mismo, las más resistentes ante la acción erosiva del oleaje, que sirvan a futuro para generar bases técnicas sólidas con miras a la elaboración de recomendaciones científicas y propuestas de esquemas de manejo del riesgo. Los criterios utilizados como base del análisis fueron la geomorfología, la cobertura de la tierra y los patrones de oleaje en aproximación al área de estudio, sobre los cuales se aplicó la técnica Analytical Hierarchy Process para la ponderación y asignación de pesos y finalmente mediante herramientas de Sistema de Información Geográfica, se realizó una superposición ponderada de resolución de problemas multicriterio. Los resultados espaciales obtenidos fueron satisfactorios, en cuanto a la ubicación de las zonas más sensibles del litoral. Sin embargo, evidenció la necesidad de contar con fuentes de información primaria con estándares específicos de acuerdo con el objetivo del estudio a realizar.

PALABRAS CLAVE: *análisis espacial multicriterio, geomorfología, ecosistemas, oleaje, costas, Sistemas de Información Geográfica.*

* Coastal Zone Research Group, Maritime Development Sub directorate, Maritime General Directorate. E-mail: pecheverry@dimar.mil.co
** Oceanology Research Group, “Almirante Padilla” Naval Academy, Colombian Navy. E-mail: leonardo.marriaga@armada.mil.co

Introduction

Increasing concentrations of greenhouse gases, such as carbon dioxide, methane, nitrous oxides and chlorofluorocarbons (CFC`S), are for the scientific community the fact that the global climate is being altered alarmingly, in addition to other causes of natural origin that accelerate the so-called climate change, presenting unique challenges for urban areas and their growing population: hotter or less cold days and nights across most of the earth, increased frequency of hot periods, rains and droughts in most of the planet, increased cyclone activity, as well as sea level rise (UN, 2011, P. 32).

Due Colombia is a country that has a large coastal territory, it is important of evaluating the sensitivity of the coastline to marine hazards, especially those associated with coastal erosion, according to the physiographic characteristics of the sector and the behavior of its adjacent sea in order to assess the susceptibility to its effects in specific sectors of the coast, taking into account the differences in the behavior of marine dynamics in the coastal zone, according to the circumstances of each one.

Colombia has approximately 2500 km of coastline on its Caribbean coast, where an important part of the country's population is located and vital socioeconomic, tourism and port activities are carried out, which have generated a significant investment in infrastructure, especially in cities like Cartagena. Given this context, in addition to the population and the ecosystems present, the infrastructure can also be seriously affected by the impacts generated by the rise in sea level, which together with the action of waves and coastal drift, cause erosion, leading to land losses and affecting the coastal morphology (Robertson, 2003 pp. 135-153).

It is essential for the well-being of Colombian coastal zones that instruments be applied to prevent and minimize the negative effects of events of natural and/or anthropic origin through vulnerability studies and adaptability measures for erosive effects; and monitoring and evaluation of the incorporation of risk management within municipal territorial planning. Likewise in the technical assistance for the improvement of the implementation of necessary actions for the prevention and mitigation of risks.

From this perspective, it becomes relevant that regional studies are carried out, studies of the coastal areas, since they facilitate the inclusion of marine and coastal ecosystems within the cause-effect analysis, so that this allows to advance in their recognition as an integral part and strategic of the territory. The challenge for the competent entities is to achieve the characterization and diagnosis of the coastal zones, their potentialities and threats, as well as to formulate Integrated Coastal Zone Management Plans (MIZC) articulated with the Development Plans and Land Management Schemes, always based on serious and in-depth studies using state-of-the-art technology available in the country. This in order to provide a base for research projects that consider not only the phenomena of urbanization or rural displacement, settlements in risk areas and invasions of public space, but also their interaction with natural events to which they are exposed.

Study area

The department of Bolívar is the most extensive of the eight that make up the Colombian Caribbean coast; with an area of 25975 km² it occupies 20 % of the continental territory of this region and 2.3 % of the national territory (Figure 1). It limits to the north with the Caribbean sea and with the department of Atlántico; on the south with the department of Antioquia; on the west with Sucre, Córdoba and Antioquia; and on the east with Santander, Cesar and Magdalena. Bolivar also has insular territory in the Caribbean Sea conformed of the Islands of Tierrabomba, Barú Island, Islands of Rosario, Fuerte Island, and the Islands of San Bernardo. Its capital, Cartagena de Indias is the headquarters of the Departmental Government and almost all the regional and sectional headquarters of the national government entities (Departmental Government of Bolívar, 2012).

Figure 1. General Location of the Department of Bolívar.

Figure 2. Study area: Coastal area of the Department of Bolívar (in orange).

The departmental limits of its coastal zone are between the geographic points of Salinas de Galerazamba, municipality of Santa Catalina in the north and Boca Flamenquito in the south. Its coast is made up of the towns of Galerazamba, Arroyo Grande, Punta Canoas, Arroyo de Piedra, Pontezuela, Bayunca, La Boquilla, Tierra Bomba, Caño del Oro, Bocachica, Pasacaballos, Ararca, Santa Ana, Baru, Recreo and Leticia, and includes important geographical areas such as the Ciénaga of the Virgin or of Tesca, the Bay of Cartagena, the Bay of Barbacoas, and the Islands of Rosario (Figure 2).

Historical comparison of coastline

Through an analysis of the evolution of the coastline through the application of methodologies that allow analyzing its spatio-temporal evolution, it is possible to preliminarily evaluate the erosive and / or cumulative changes that occur in the coast of the department. It is therefore possible to identify the evolution of the coastline in different years and take this as a basis to start a diagnosis of the possible causes associated with these changes thanks to the use of aerial photographs and the help of associated photogrammetric methods that allow make quantitative and qualitative comparisons. That is, this comparison, by itself, does not provide definitive or detailed information about the causes of accretion-erosion processes on the coast.

The analysis of the position of shorelines, defined as the water land boundary observed in the area photograph, was made in order to establish the initial conditions in a specific year for which old aerial images are available, captured by the Geographic Institute Agustín Codazzi (IGAC). Table 1 shows the information of available aerial photographs. The images with the greatest coverage correspond to flight C-987 of 1961, and since they are the oldest and cover most of the study area, they are the ones used for the following analysis (Figure 3).

Table 1. Aerial photographs of IGAC used for photointerpretation.

Flight	Year	Scale	Photography	Sector
C-794	1956	1:5000	101,103,111,931,951,971,991	Castillogrande
C-987	1961	1:20000	139,106,107,108,11,12,13,138,14,140, 141,142,15,153,155,156,16,276,277,2 82,283,284,285,286,287,288	Punta Canoas, Boquilla, Cartagena urbano, Mamonal, Isla Barú
R-611	1968	1:18000	213, 217, 175	Crespo, Los Morros
C-1483	1974	1:10000	124,125,126,127,129,130,131,132,133	Isla Baru
C-1845	1978	1:58000	80, 811, 821	Isla Baru
C-2304	1987	1:27400	91,101, 131, ,141, 151, 161	Isla Baru

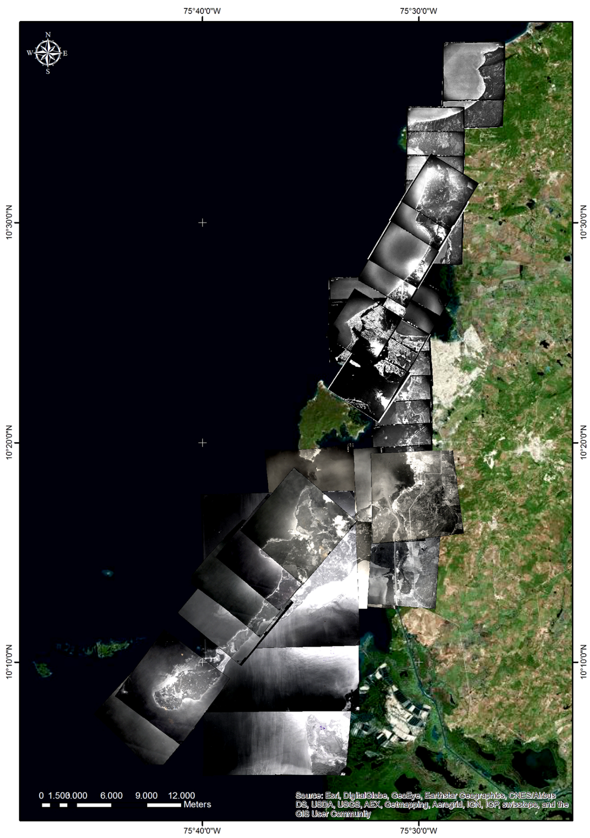


Figure 3. Coverage of old aerial photographs of the IGAC in the department of Bolívar.

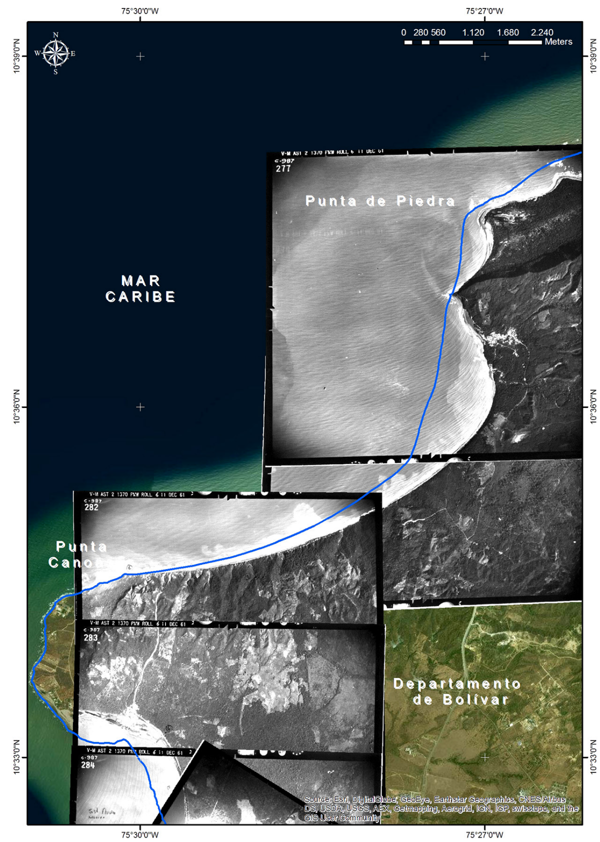


Figure 4. Coverage of photographs. Sector from Punta de Piedra to Punta Canoas.

When comparing the historical photographs with satellite images from 2015 to 2016 available in the ArcGis® basemap, it is possible to establish in a preliminary way the trend of changes in the coast line of the Department of Bolívar, in order to have an initial approximation of which are the most susceptible zones to present modifications, whether by the loss or the gain of land, and which are those that present major anthropic intervention to prevent them or to contain them.

To begin with, the northern part of the Department was analyzed by means of the photographs of flight C-987 of the year 1961 with respect to an optical image of the Digital Globe sensor of February 16, 2016, over which the blue coastline was digitized. In the period of 55 years, an accumulation of sediments of up to 1 km has occurred in the sector between Punta de Piedra and Punta Canoas (Figure 4).

The following segment, between Punta Canoas and La Boquilla, was also analyzed by means of the photographs of flight C-987 of 1961 with respect to an optical image of the Digital Globe sensor on February 4, 2015, over which the blue coastline was digitized. In the 54-year period, there was also an accretion of approximately 500 m in Manzanillo del Mar and 200 m in La Boquilla (Figure 5).

The urban part of Cartagena de Indias conformed of the Walled City, Bocagrande, Castillogrande, El Laguito and Manga, was also analyzed based on photographs of flight C-987 of 1961 with respect to an optical image of the Digital Globe sensor of 25 January 2015, on which the blue coastline was digitized. In the period of 54 years, the coast line remained stable thanks to anthropic interventions that were made to protect the land and the constructions from the transgression of the sea trying to resume its initial position. On the other hand, the Islands of Manga and Manzanillo do not present changes in their coastline because they are protected from the action of the waves by the internal bay of Cartagena. In addition, it is important to note that this is the area with the highest degree of urbanization, since it presents the concentration of homes, hotels, ports, docks and tourist attractions, so the urban area of Cartagena de Indias can be considered as the most critical area of the department when analyzing risks due to coastal erosion (Figure 6).

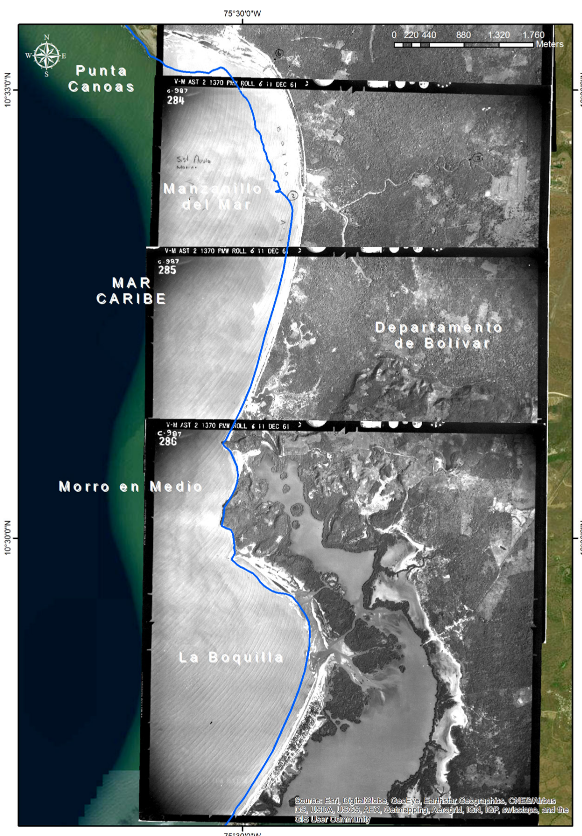


Figure 5. Coverage of photographs. Sector from Punta Canoas to La Boquilla.

As for the area known as Mamonal, it can be seen in the comparison between the photographs of flight C-987 year 1961 and the digital optical image of the Digital Globe sensor on January 25, 2015, which has presented significant changes in ground gain to the sea thanks to anthropic infill

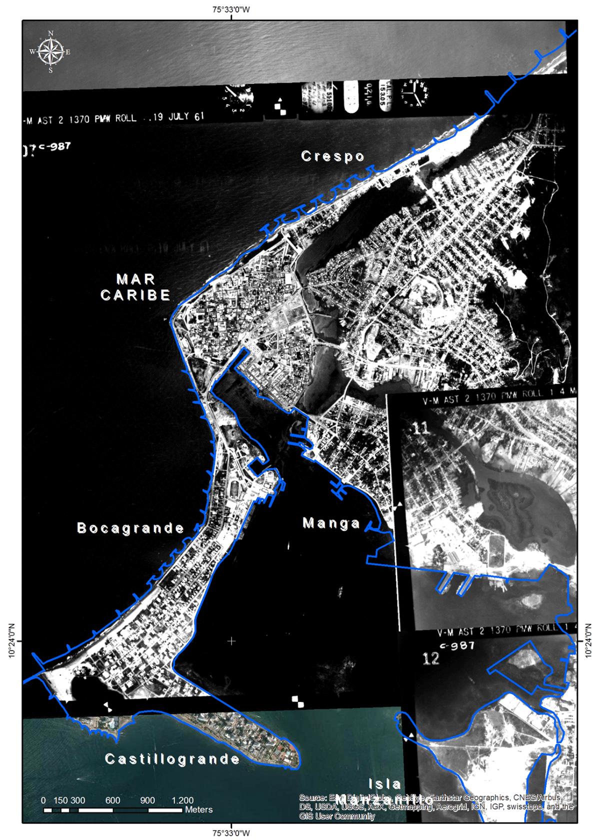


Figure 6. Cubrimiento de fotografías. Sector La Boquilla a Castillogrande, incluyendo las Islas de Manga y Manzanillo.

interventions for the construction of industrial facilities. Thanks to these rising ground levels, and the fact of being sheltered by the bay of Cartagena, this area does not present setbacks on the coastline (Figure 7).

Finally, the Barú peninsula, better known as Isla Barú, was also analyzed based on the photographs of flight C-987 year 1961 with respect to the optical image of Digital Globe on September 3, 2016, finding stability in the coastline given its geomorphological conformation, which according to the results of a study carried out by the Center for Oceanographic and Hydrographic Research of the Caribbean, correspond to high geo forms within which there are hills and rises, abrasion platforms and marine terraces (Figure 8).

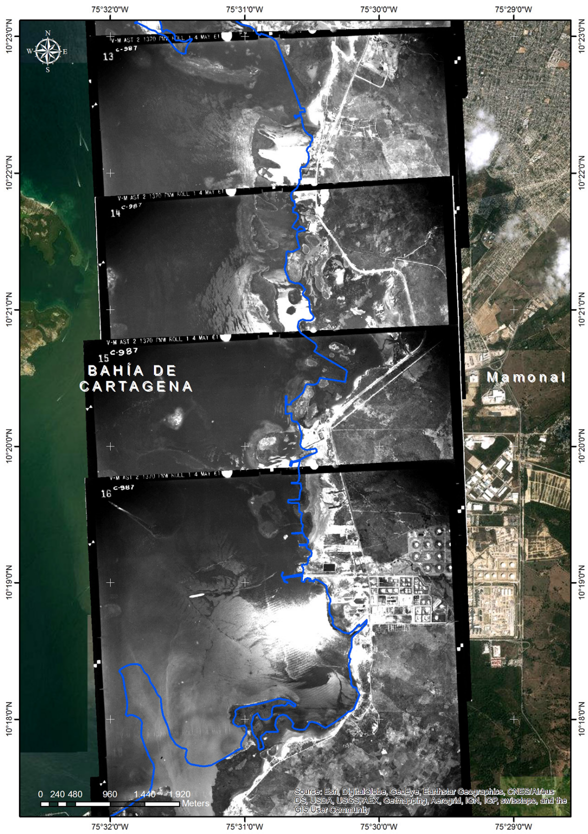


Figure 7. Coverage of photographs. Manzanillo Island Sector at the Mouth of the Canal del Dique.

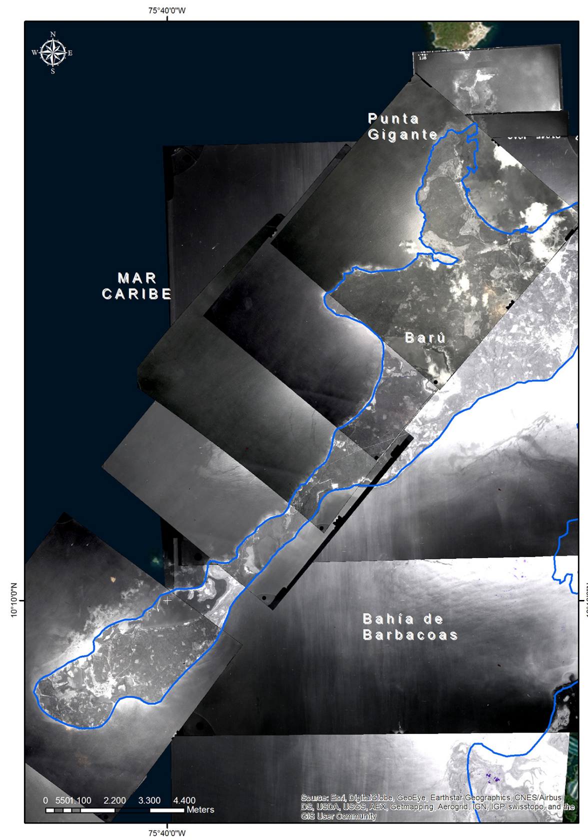


Figure 8. Coverage of photographs. Sector of Isla Barú.

MATERIALS AND METHODS

It is necessary to take into account that marine phenomena have different local manifestations than regional and national ones, which may be higher or lower depending on the bio-geophysical and socioeconomic processes that take place there. Actual conditions may be different since it is possible that there are unforeseen changes in the variables used, in addition to other factors that introduce a different degree of uncertainty (Petersen, 2002).

For the development of this research, an adaptation of the methodology "Environmental Sensitivity Index - ESI (Environmental Sensitivity Index)" (Petersen, 2002) was applied, developed as an integral component for the management of the occurrence of oil spills and the plans for contingency and response since 1979.The main objectives of the application of an adaptation of this methodology, are to describe the basic elements of a system of coastal sensitivity mapping against erosion, starting from the collection and synthesis of data, to the definition of the data structure using GIS technologies for the preparation of maps with scenarios of coastal sensitivity, which will serve as the basis for the future formulation of action plans in each of the areas of interest, necessary for the management of natural resources and territorial management.

Figure 9 below, represents the process carried out to obtain the coastal sensitivity maps, the details of which will be described later.

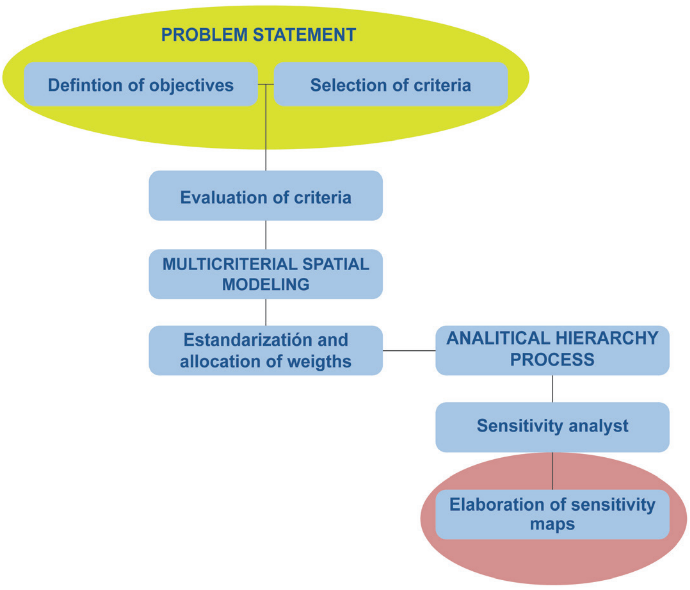


Figure 9. Methodological process for the development of coastal sensitivity indices.

Multi-criteria modeling through the application of GIS

Multi-criteria spatial analysis is required in decision-making studies, in which there is more than one criteria to consider, and so this type of analysis requires systematic procedures that allow solutions to complex problems. According to (Varela, 2005), the basic strategy is to divide the problem into small, well-defined parts, analyze each part and logically integrate all the fragments to obtain a meaningful solution.

Analytical Hierarchy Process

To weigh up the variables to be taken into account in the present study, a multi-criteria evaluation was applied, defined as a set of operations for the adoption of decisions, simultaneously considering several criteria or conditions. For this, the technique "AHP" (Analytical Hierarchy Process) was applied, created by Saaty (2000) as a tool to support decision making and forecasting.

The multi-criteria decision analysis based on Geographic Information Systems is a process that integrates and transforms geographic data and value judgments to obtain the total evaluation of the decision alternatives. For decision making at least two elements must be taken into account: one that defines action, that is, what? And another that frames the location, that is, where? As characterized by the following advantages (Franco, 2001, P.18):

- It permits a detailed classification of the objective information that favors the knowledge of the problem or situation under study, and therefore the final classification of the alternatives. This helps to reevaluate the values of the criteria initially taken, also, the problem is centered by a series of criteria and indicators known by the decision makers.

- It collaborates in a practical and coherent way in the management of different approaches to the same problem or situation. This refers to the different points of view from which the problem is analyzed.

- It offers results based on the point of view of the developer and decision-maker, allowing at the same time the possibility of contrasting several points of view for the solution of spatial problems, or generating solutions that integrate several positions in one single solution in a coherent way.

The aforementioned technique uses the following scale, based on the principle of comparison by pairs (Figure 10):

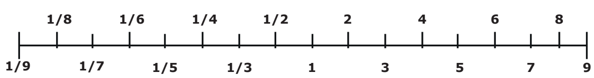


Figure 10. Paired comparison scale of the Analytical Hierarchy Process.

This scale is established by a scale of nine (9) elements corresponding to the different degrees or levels in which the intensity of the relationship between elements of a given set can be discriminated, thus ensuring that all comparisons and measurements were made in the same scale. For in considering the diversity of the study variables, it is necessary to carry out homogenized measurements. The meaning of each value of the scale is shown below (Table 2):

Table 2. Comparison of pairs in the AHP technique for cases in which the first element is more sensitive or intense than the second element.

Sensitivity	Intensity	Meaning
1	Same or different to...	When comparing one element with another, there is indifference between them
3	Slightly more sensitive / intense	When comparing one element with the other, the first is slightly more sensitive / intense than the second
5	More sensitive / intense than ...	When comparing one element with the other, the first is considered more sensitive / intense than the second
7	Much more sensitive / intense than ...	When comparing one element with the other, the first is considered much more sensitive / intense than the second
9	Absolutely or very much more sensitive / intense than ...	When comparing one element with the other, the first is considered absolutely or very much more sensitive / intense than the second

The even values (2, 4, 6 and 8) are used when in comparing two elements with each other, the first one is in a degree of sensitivity (or intensity in the case of the oceanographic phenomenon) intermediate between two adjacent values of the scale. In the case of the reciprocal values of the scale, the interpretation is completely analogous, this is shown in Table 3:

Table 3. Comparison of pairs in the AHP technique for cases in which the first element is less sensitive or intense than the second element.

Sensitivity	Intensity	Meaning
1/3	Slightly less sensitive / intense than ...	When comparing one element with the other, the first is considered slightly less sensitive or intense than the second.
1/5	Less sensitive / intense than ...	When comparing one element with the other, the first is considered less sensitive / intense than the second
1/7	Much less sensitive / intense than ...	When comparing one element with the other, the first is considered much less sensitive / intense than the second
1/9	Absolutely or very much less sensitive / intense than ...	When comparing one element with the other, the first is considered absolutely or very much less sensitive / intense than the second

In this case, the values 1/2, 1/4, 1/6, and 1/8 are used in the same way as 2, 4, 6, and 8.

The results obtained after the application of the methodology will allow the assignment of the weights to each component of the analyzed factor, in which the relative degree of sensitivity to threats of marine origin is represented. For this four degrees were established (Table 4):

Table 4. Sensitivity levels defined for the coastline.

Grade	Description
1	Extremely sensitive
2	Very sensitive
3	Sensitive
4	Not very sensitive

Survey application

To obtain the results applying the proposed methodology, a survey was conducted with 10 experts in the areas of knowledge related to coasts and oceanography.

The purpose is the application of the multi-criteria analysis to establish the areas that are most sensitive to suffering erosion, considering the different classifications of the coastal zone and the fact it is spatial information. Multi-criteria decision analysis combined with the tools and potentials of the information systems, provides a technique whose results depend on the configuration, both objective and subjective, of the original data by the experts. This involves converting multidimensional data into one-dimensional values for decision making, through the realization of a sequence of activities that begin with the recognition of the problem, continuing with the identification of criteria, and the evaluation of results.

Results and discussion

Below is the application of the multi-criteria modeling for the case study, which seeks to establish the coastal sensitivity to the erosive action of the waves; so three basic evaluation criteria were selected: geomorphology, land coverage (ecosystems) and the angle of the coastline with respect to the direction of the waves for the mean and extreme cases, thus obtaining the following procedures and results:

Geomorphology

To begin the application of the methodology for the geomorphology criterion, a comparison matrix (14x14) is created, where the headings of the rows and columns correspond to the geomorphological units identified on the coast of the Department, in order to determine weights of sensitivity attributed to each of the factors. The first step to fill out the matrix is to assign the value one (1) in the diagonal of the same, and in the upper triangular zone values are assigned according to the Saaty scale (Varela, 2005). Logically, in the lower triangular part, each box will be assigned the reciprocal value corresponding to those in the upper triangular zone (Table 5).

Being:

a. Sand bar

b. Body of water

c. Sand dunes

d. Spike

e. Coastal arrow

f. Flood zone

g. Mangrove swamp

h. Alluvial plane

i. Old Playón

j. Beach

k. Salt flat

l. Hill and Rise

m. Platform

n. Terrace

After completing the matrix with each of the experts, a sum of the values of each column is made.

Table 5. Weights of sensitivity attributed to the comparison of the geomorphological units. Example of surveyed expert No. 1.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
A	1	7	5	3	3	7	9	5	7	3	3	9	9	9
B	1/7	1	1/5	1/7	1/7	1/7	1	5	7	1/7	1/3	9	9	9
C	1/5	5	1	1/5	1/5	1/7	5	7	7	1/5	1/3	9	9	9
D	1/3	7	5	1	3	5	5	5	7	3	3	9	9	9
E	1/3	7	5	1/3	1	5	5	5	7	3	3	9	9	9
F	1/3	7	7	1/5	1/5	1	3	3	7	1/5	1/5	9	9	9
G	1/9	1	1/5	1/5	1/5	1/3	1	1/3	7	1/5	1/5	9	9	9
H	1/5	1/5	1/7	1/5	1/5	1/3	3	1	5	1/7	1/5	9	9	9
I	1/7	1/7	1/7	1/7	1/7	1/7	1/7	5	1	1/9	1/9	7	7	7
J	1/3	7	5	1/3	1/3	5	5	7	9	1	3	9	9	9
K	1/3	3	3	1/3	1/3	5	5	5	9	1/3	1	9	9	9
L	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/7	1/9	1/9	1	1/7	1/7
M	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/7	1/9	1/9	7	1	3
N	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/7	1/9	7	7	1/3	1
Total	**3.80**	**45.68**	**32.02**	**6.42**	**9.09**	**29.43**	**42.48**	**48.67**	**73.43**	**11.66**	**21.60**	**112.0**	**98.48**	**101.14**

From the values that were recorded in the pairwise comparison matrix, the sensitivity vector was determined, composed of fourteen components, where each one represents the relative weight (sensitivity) of each of the geomorphological units for each of the results of the experts.

For this, each column of the matrix was normalized, dividing the value of each box of the matrix among the total of the sum of the column to which it belongs. Then, from this normalized matrix per column, the associated priority vector was obtained; which in this particular case, will represent the weights of each of the factors considered. The value of each of the components of this priority vector were calculated by the arithmetic mean of the values of each row of the matrix (Table 6).

Table 6. Priority vector results for the geomorphological units, whose values determine the order of the variables for their weighting. Example of surveyed expert No. 1.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Vector priority
A	0.263	0.153	0.156	0.467	0.330	0.238	0.212	0.103	0.095	0.257	0.158	0.080	0.091	0.089	**0.191**
B	0.038	0.022	0.006	0.022	0.016	0.005	0.024	0.103	0.095	0.012	0.018	0.080	0.091	0.089	**0.044**
C	0.053	0.109	0.031	0.031	0.022	0.005	0.118	0.144	0.095	0.017	0.018	0.080	0.091	0.089	**0.064**
D	0.088	0.153	0.156	0.156	0.330	0.170	0.118	0.103	0.095	0.257	0.158	0.080	0.091	0.089	**0.145**
E	0.088	0.153	0.156	0.052	0.110	0.170	0.118	0.103	0.095	0.257	0.158	0.080	0.091	0.089	**0.122**

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Vector priority
F	0.088	0.153	0.219	0.031	0.022	0.034	0.071	0.062	0.095	0.017	0.011	0.080	0.091	0.089	**0.076**
G	0.029	0.022	0.006	0.031	0.022	0.011	0.024	0.007	0.095	0.017	0.011	0.080	0.091	0.089	**0.038**
H	0.053	0.004	0.004	0.031	0.022	0.011	0.071	0.021	0.068	0.012	0.011	0.080	0.091	0.089	**0.041**
I	0.038	0.003	0.004	0.022	0.016	0.005	0.003	0.103	0.014	0.010	0.006	0.063	0.071	0.069	**0.030**
J	0.088	0.153	0.156	0.052	0.037	0.170	0.118	0.144	0.123	0.086	0.053	0.080	0.091	0.089	**0.109**
K	0.088	0.066	0.094	0.052	0.037	0.170	0.118	0.103	0.123	0.029	0.018	0.080	0.091	0.089	**0.085**
L	0.029	0.002	0.003	0.017	0.012	0.004	0.003	0.002	0.002	0.010	0.006	0.009	0.001	0.001	**0.007**
M	0.029	0.002	0.003	0.017	0.012	0.004	0.003	0.002	0.002	0.010	0.006	0.063	0.010	0.030	**0.014**
N	0.029	0.002	0.003	0.017	0.012	0.004	0.003	0.002	0.002	0.010	0.370	0.063	0.003	0.010	**0.035**

With the values of the resulting priority vectors for each geomorphological unit of each of the experts surveyed, statistical treatment was carried out in order to obtain a single value through an average, obtaining the following results (Table 7):

Table 7. Result of statistical treatment.

	Exp.1	Exp.2	Exp.3	Exp.4	Exp.5	Exp.6	Exp.7	Exp.8	Exp.9	Exp.10	Peso	Weight %
A. Sand bar	0.191	0.059	0.137	0.224	0.031	0.097	0.174	0.097	0.140	0.136	0.129	**12.874**
B. Body of water	0.044	0.034	0.044	0.009	0.195	0.041	0.010	0.041	0.024	0.044	0.049	**4.875**
C. Sand dunes	0.064	0.250	0.245	0.287	0.214	0.028	0.068	0.028	0.058	0.254	0.150	**14.952**
D. Spike	0.145	0.078	0.067	0.135	0.201	0.109	0.089	0.109	0.205	0.067	0.120	**12.047**
E. Coastal arrow	0.122	0.078	0.067	0.135	0.105	0.109	0.038	0.109	0.215	0.067	0.104	**10.429**
F. Flood zone	0.076	0.216	0.344	0.016	0.213	0.029	0.312	0.029	0.066	0.344	0.165	**16.464**
G. Mangrove swamp	0.038	0.230	0.286	0.029	0.013	0.109	0.307	0.109	0.015	0.286	0.142	**14.222**
H. Alluvial plane	0.041	0.029	0.034	0.055	0.259	0.221	0.217	0.221	0.033	0.034	0.114	**11.430**
I. Old Playón	0.030	0.031	0.027	0.022	0.031	0.018	0.188	0.018	0.056	0.056	0.048	**4.780**
J. Beach	0.109	0.270	0.229	0.057	0.178	0.036	0.110	0.036	0.117	0.117	0.126	**12.593**
K. Salt flat	0.085	0.199	0.320	0.073	0.165	0.060	0.323	0.060	0.055	0.055	0.139	**13.946**
L. Hill and Rise	0.007	0.008	0.008	0.034	0.017	0.007	0.030	0.007	0.007	0.007	0.013	**1.331**
M. Platform	0.014	0.018	0.016	0.043	0.023	0.269	0.020	0.269	0.022	0.022	0.072	**7.163**
N. Terrace	0.035	0.008	0.008	0.041	0.020	0.269	0.016	0.269	0.034	0.034	0.073	**7.341**

Given the above, it was established that the weighting according to the coastal sensitivity based on the geomorphological units present, is headed by the flood zone, the sand dunes, the mangrove swamp and salt flat, because they are considered as geomorphological units that are extremely sensitive to erosive agents (Classification 1), followed by the sand bars, beaches, spikes, alluvial planes, coastal arrows and terraces with a weight of two, because they are very sensitive (Classification 2). Also, a weighting of three (Classification 3) was assigned to the platforms and bodies of water, these being sensitive to the erosive agents and finally, the old playón and the hills were in the last place of weighting (Classification 4) because they are not very sensitive (Table 8).

Table 8. Weighting of the geomorphological units, classified in the four proposed ranges.

Weighting	Geomorphological unit	Weight %
1	Flood zone	16.464
2	Sand dunes	14.952
3	Mangrove swamp	14.222
4	Salt flat	13.946
5	Sand bar	12.874
6	Beach	12.593
7	Spike	12.047
8	Alluvial plane	11.430
9	Coastal arrow	10.429
10	Terrace	7.341
11	Platform	7.163
12	Body of water	4.875
13	Old playón	4.780
14	Hill and rise	1.331

Land coverage

Now, applying the methodology described above to the land coverage variable, the weights corresponding to areas with greater sensitivity were assigned to the areas defined as mostly transformed, where the intervention of man has caused imbalances in the coastal dynamics, and the minimum to the mostly natural areas, given their resilience (tables 9 and 10).

Table 9. Sensitivity weights attributed to the comparison of land coverage. Example of surveyed expert No. 1.

	Mostly transformed	Agro-systemic	Mostly natural	Wet areas and water surfaces
Mostly transformed	1	7	7	7
Agrosystemic	1/7	1	1/7	1/7
Mostly natural	1/7	7	1	5
Wet areas and water surfaces	1/7	7	1/5	1
Total	**1.43**	**22.00**	**8.34**	**13.14**

Table 10. Priority vector results for the land coverage, whose values determine the order of the variables for weighting. Example of surveyed expert No. 1.

	Mostly transformed	Agro-systemic	Mostly natural	Wet areas and water surfaces	Priority vector
Mostly transformed	0.70	0.32	0.84	0.53	0.60
Agrosystemic	0.10	0.05	0.02	0.01	0.04
Mostly natural	0.10	0.32	0.12	0.38	0.23
Wet areas and water surfaces	0.10	0.32	0.02	0.08	0.13

Therefore, the areas mostly transformed, composed of the urban area of Cartagena de Indias and other areas that are mostly altered, represent 54.31 % of the total weight, as they are the areas that are most sensitive to erosive events (Classification 1). The agrosystemic areas (Classification 2) and the most natural areas (Classification 3), which include natural forests, secondary vegetation, shrub lands, grasslands, and bare areas such as beaches and rocky outcrops, have a weight of 26.96 % and 28.05 % respectively, classifying them as the following most sensitive areas. On the other hand, wet areas such as mangrove forests are classified in fourth place with a percentage of 10.78 % thanks to their resilience before this type of event (Classification 4) (Table 11).

Table 11. Weighting of land coverage, classified in the four proposed ranges.

Weighting	Coverage	Weight %
1	Mostly transformed	54.31
2	Agrosystemic	26.96
3	Mostly natural	26.05
4	Wet areas and water surfaces	10.78

Extreme wave regime

As mentioned above, the definition of sea states took into account the grouping of the data according to their direction, in addition to the significant wave height and its period, considering that the direction is fundamental because the position of the coast with respect to the predominant pattern of the waves is decisive for its affectation, suffering a lesser exposure when positioned angularly to these, than when in a parallel direction.

In the case of the extreme regime, the selection criterion of sea states was related to the variable Hs12 obtained in the analysis of wave patterns, since this variable represents the portion of significant wave heights that are exceeded only 12 hours per year. Similarly to the previous case, this variable was interrelated with the probability of occurrence of the directions of the sea states, obtaining the combinations shown in Table 12.

Table 12. Probability of occurrence of sea states in extreme regime.

Direction	Probability	Hs	Tp	Hs_{12}
NNE	0.6482	1.3380	5.0860	3.5880
N	0.1677	0.7974	4.2900	2.8090
W	0.0251	0.5471	3.6265	2.4301
WSW	0.0161	0.6176	3.4470	2.3530
NE	0.0091	0.6324	4.6640	2.2451

It is important to note that, given the methodology used to select the sea states, sea states from the NW and W directions were taken into account, cases that are considered atypical, however, due to their nature and their energy level, when they occur they can have great impacts on the coastal area in a shorter time than that produced by the cases of the average regime.

Creation of coastal sensitivity index maps

When analyzing the sensitivity to the threat of marine origin, it was established which of the factors has the most prevalence in terms of affectation, applying the AHP methodology to the three criteria analyzed (tables 13 to 15):

Table 13. Application of the methodology for the three variables analyzed. Factor weights.

	Geomorphology	Land coverage	Sea state for the mean and extreme wave regime
Geomorphology	1	5	1/3
Land coverage	1/5	1	1/7
Sea state for the mean and extreme wave regime	2	5	1
Total	3.20	11.00	1.70

Table 14. Priority vector results for the three factors analyzed, whose values determine the order of the variables for their weighting.

	Geomorphology	Land coverage	Sea state for the mean and extreme wave regime	Priority vector
Geomorphology	1	5	1/3	0.35
Land coverage	1/5	1	1/7	0.09
Sea state for the mean and extreme wave regime	2	5	1	0.56

Table 15. Weighting of the variables, classified in the four proposed ranges.

Weighting	Factor	Weight %
1	Sea state for the mean and extreme wave regime	55.59
2	Geomorphology	35.37
3	Land coverage	9.04

With the weights for each of the criteria and the corresponding total, we proceeded to create in ArcMap 10.5®, a model through the Model Builder tool, a visual programming language that is used to create, edit and manage workflows that link sequences of geoprocessing tools and supply the output of one tool to another tool as input (Esri, s.f) (Figure 11).

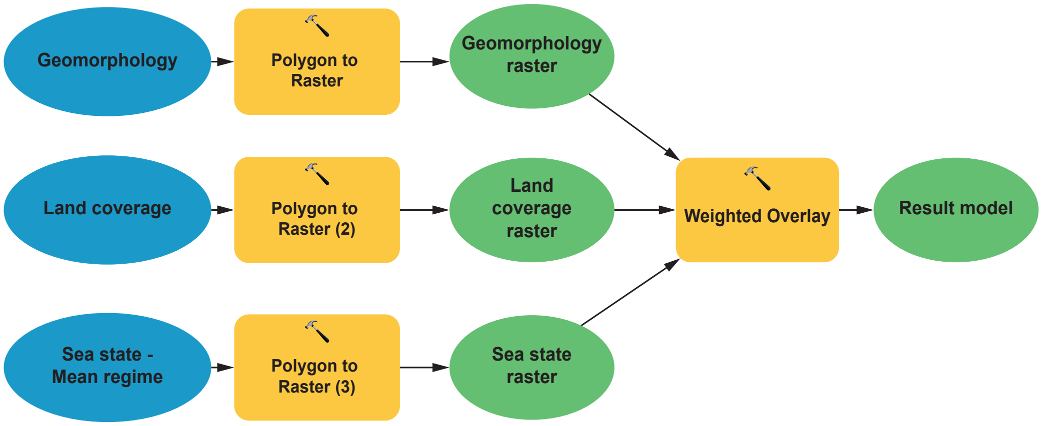


Figure 11. Design of Model Builder for the analysis of steps of the variables analyzed.

The created model contains two fundamental tools in its workflow:

Polygon to Raster. It converts the polygon entities to raster, which in its simplest form, consists of an array of cells (or pixels) organized in rows and columns in which each cell contains a value that represents information (Conversion toolbox, set of raster tools, sf) (Figure 12).

In this sense, the tool was applied to the polygon-type vector layers corresponding to the geomorphological units, the land coverage, and the classification of the coastal areas according to their angles for the mean and extreme wave regimes, obtaining three raster-type layers as a result, on which the analysis described below was applied:

The advantages of storing the data in raster form are the following:

- Simple data structure: matrix of cells with values that represent a coordinate and that, sometimes, is linked to an attribute table.
- Powerful format for advanced spatial and statistical analysis.
- Ability to represent continuous surfaces and carry out surface analysis.
- Ability to store points, lines, polygons and surfaces evenly.
- Ability to perform rapid overlays with complex datasets.

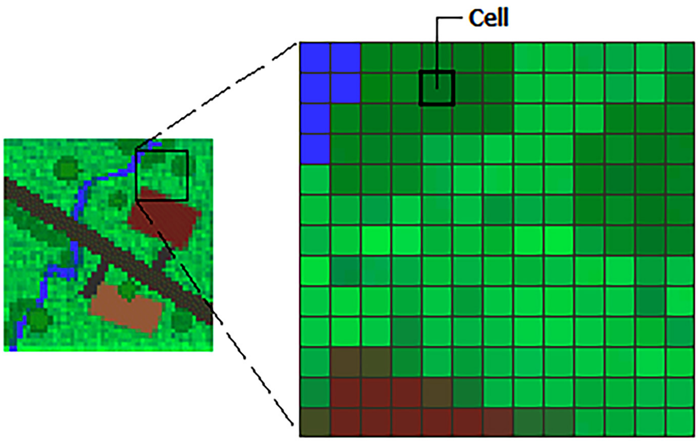


Figure 12. Representation of a raster structure. Source: Saaty, 2000.

Weighted Overlay. Weighted Overlay is a tool that applies one of the most used methods for overlay analysis, to solve multi-criteria problems such as site selection and aptitude models. In a weighted overlay analysis, each of the steps of general overlay analysis is followed by another step of the general overlay analysis (Spatial Analyst toolbox, concept set of overlay tools, sf) (Figure 13).

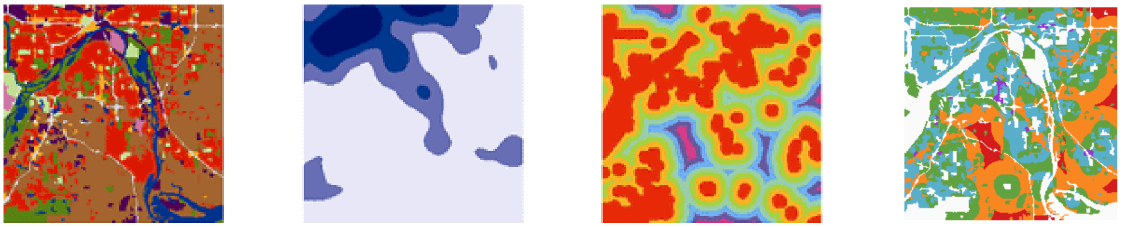
As with all overlay analysis, in the weighted overlay analysis, you must define the problem, break the model into sub-models, and identify the input layers.

Since the input criteria layers will be in different numbering systems with different ranges, to combine them in a single analysis, each cell of each criterion must be reclassified in a common preference scale, such as from 1 to 10, with 10 being the most favorable. A preference assigned in the common scale implies the preference of the phenomenon for the criterion. The preference values are on a relative scale. That is, a preference of 10 is twice as preferred as a preference of 5.

The values of preference should not only be assigned in relation to another within the layer, but should have the same meaning among other layers. For example, if a location is assigned a preference criterion of 5, it should have the same influence on a second criterion.

Each of the criteria in the weighted overlay analysis may not be equal in importance (Figure 13). You can weigh the important criteria more than the other criteria. The input criteria are multiplied by the weights and add up.

The final step of the overlay analysis process is to validate the model to make sure that what the model indicates is in a site really is there.



Criterion No. 1 | Criterion No. 2 | Criterion No. 3 | Raster output

Figure 13. Representation of the operation of the Weighted Overlay tool. Source: Modified by the author (Saaty, 2000).

The following maps correspond to the results of the application of the analysis for the mean and extreme wave regimes, in which the areas classified in each of the five established grades are indicated, giving the following results (figures 14 to 21).

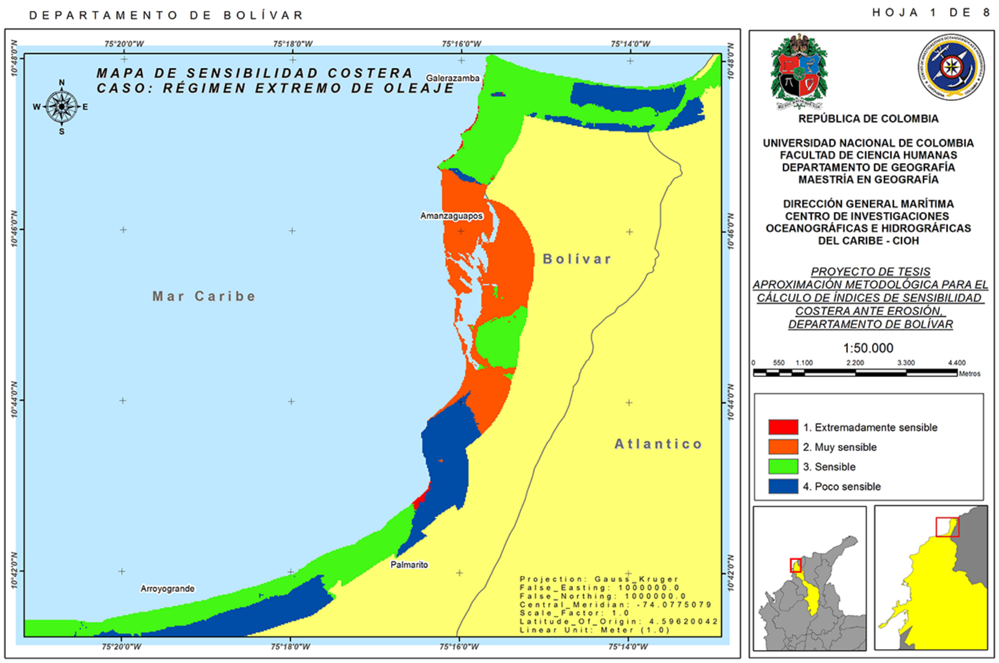


Figure 14. Map No. 1. Coastal sensitivity. Case of extreme wave regime.

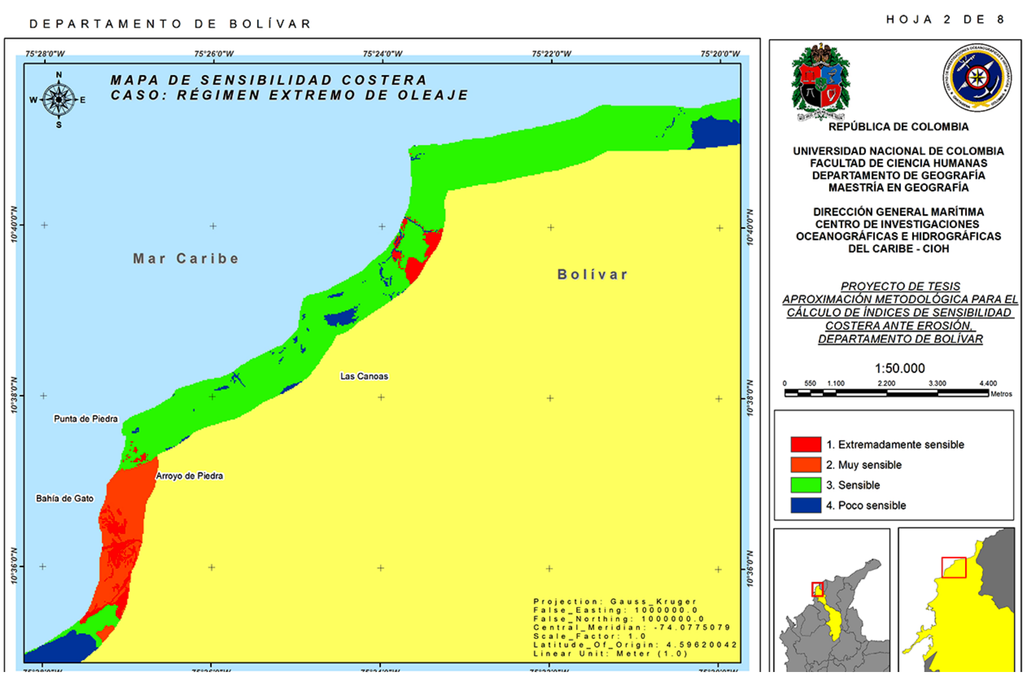


Figure 15. Map Nº 2. Coastal sensitivity. Case of extreme wave regime.

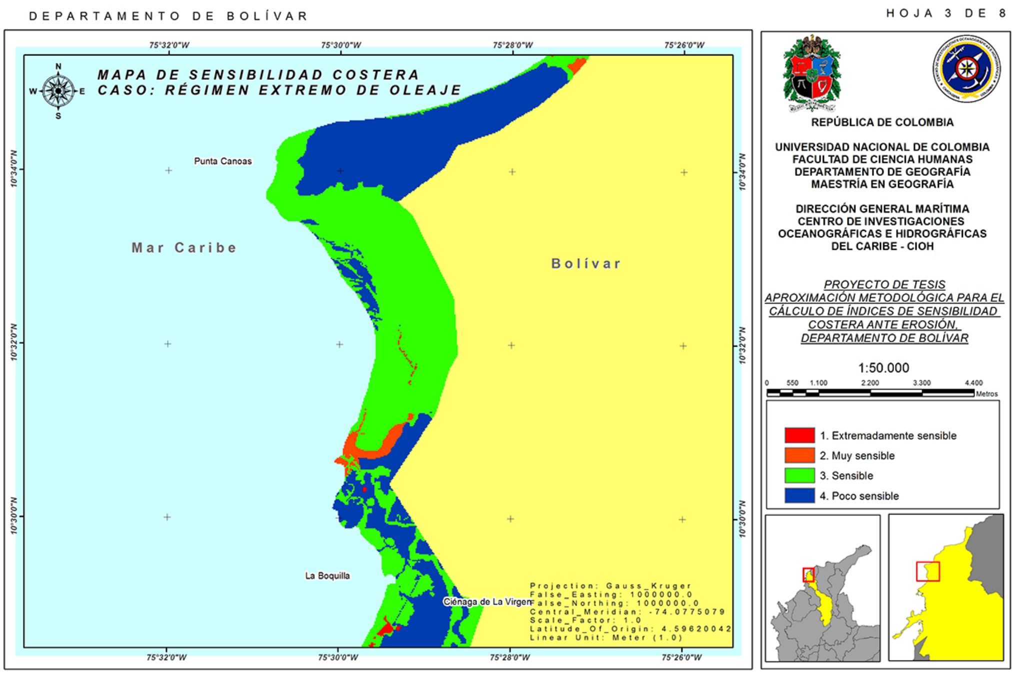


Figure 16. Map Nº 3. Coastal sensitivity. Case of extreme wave regime.

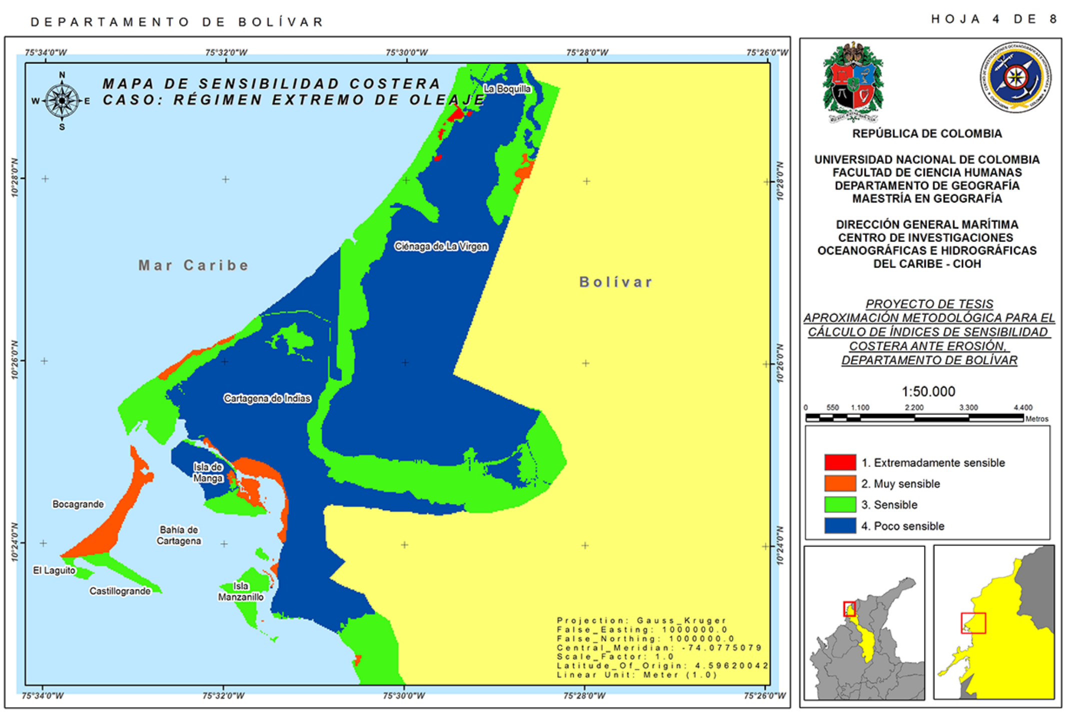


Figure 17. Map Nº 4. Coastal sensitivity. Case of extreme wave regime.

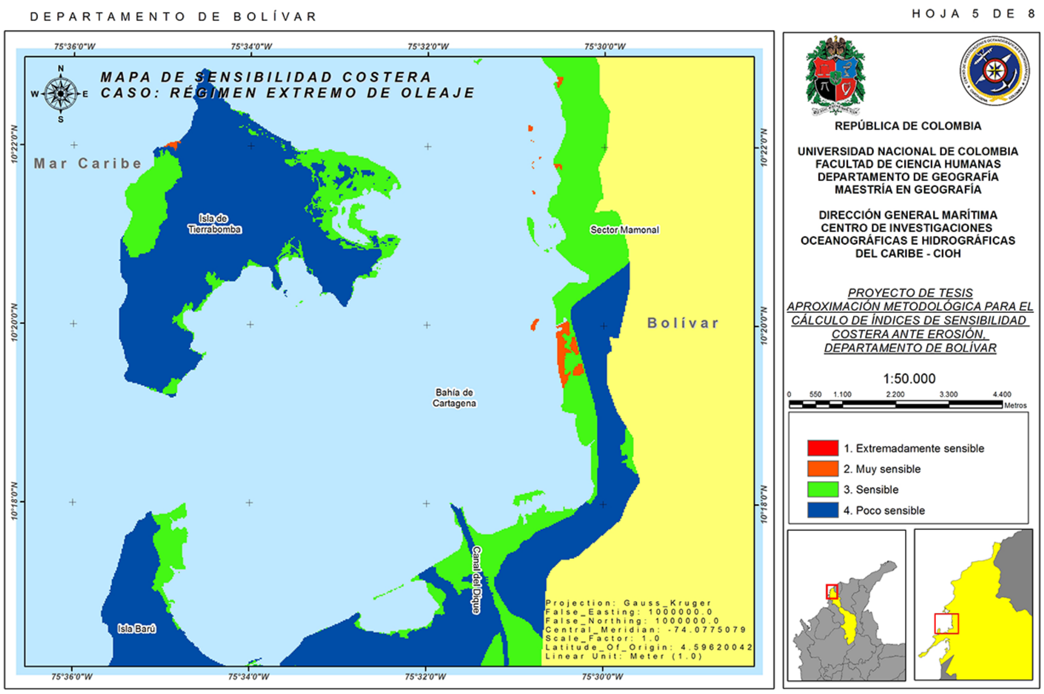


Figure 18. Map Nº 5. Coastal sensitivity. Case of extreme wave regime.

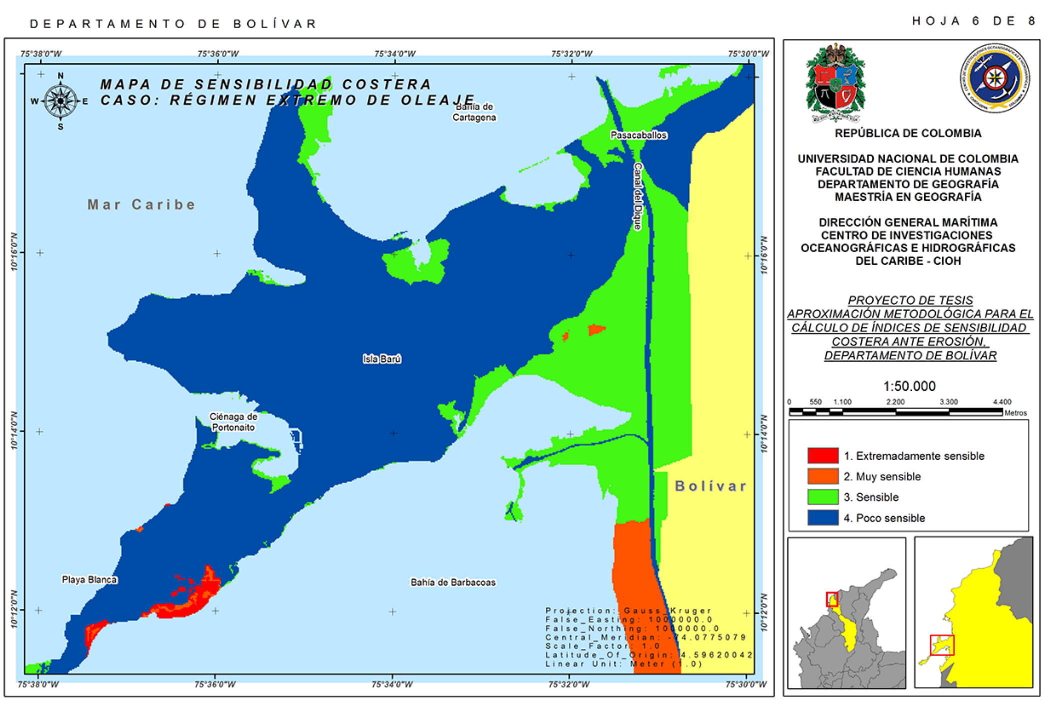


Figure 19. Map Nº 6. Coastal sensitivity. Case of extreme wave regime.

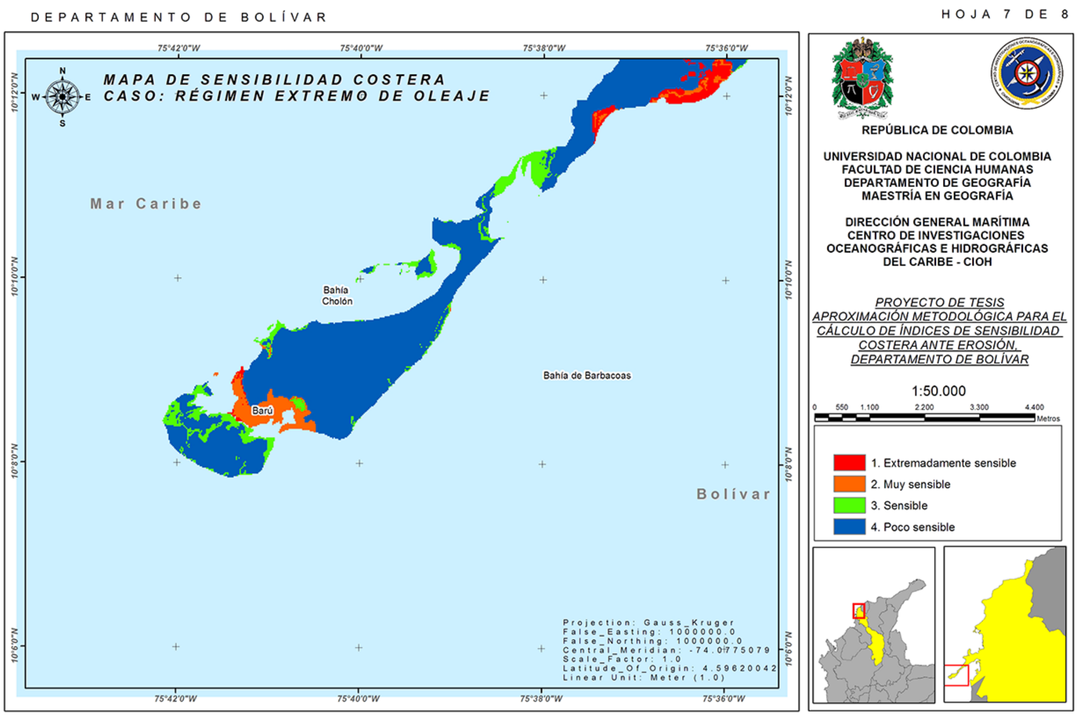


Figure 20. Map Nº 7. Coastal sensitivity. Case of extreme wave regime.

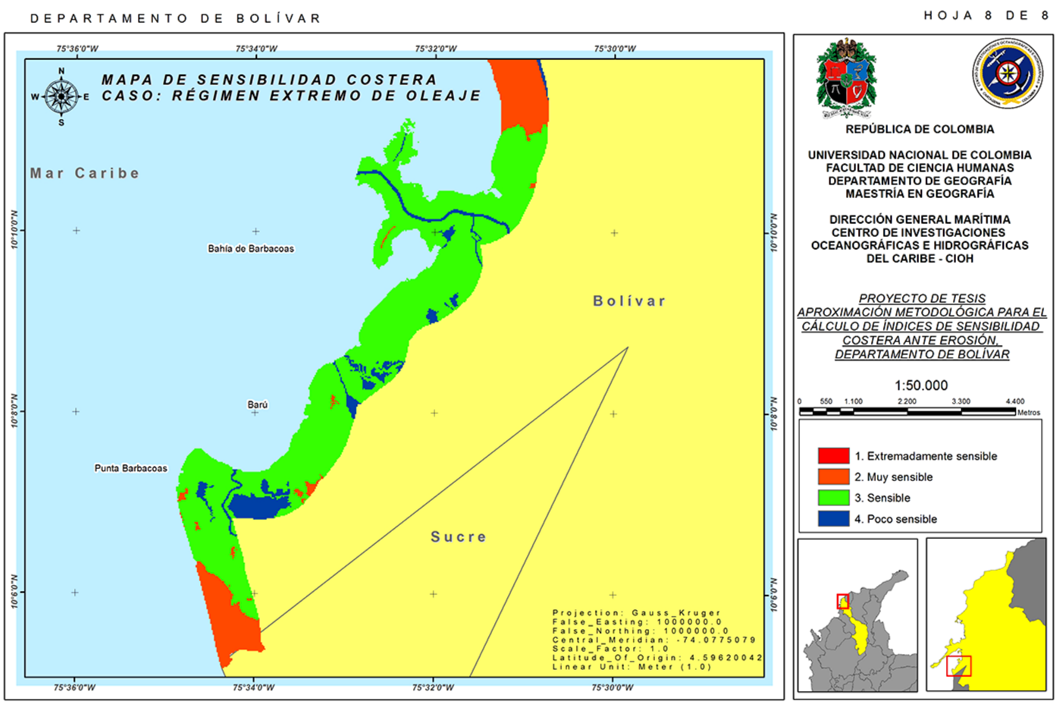


Figure 21. Map Nº 8. Coastal sensitivity. Case of extreme wave regime.

Conclusions

The coastal erosion is closely related to natural processes that act on the coast. This is why, beyond being a problem in itself, it is in fact the result of transforming agents that have always shaped the coasts of all the continents. However, the natural coastal system and its impacts cannot be assessed in isolation without considering the human factor and the result of socio-economic and cultural activities that define the use of land by man along the coast.

The application of a methodology for indexing is a complex task for which there is no single valid path, since it depends on the selection of certain variables considered as representative, and the allocation of weights to each one of them.

To assign relative weights to each of the variables, we must initially count on the knowledge that the individual (observer / expert) has about a certain variable and its possible impact on the structuring of the index.

The selected variables represent a classification criterion that catalogues the units of analysis. Its integration defines indices that provide aggregate information regarding the phenomenon studied beyond its capacity for representation on its own.

In carrying out the research a methodological proposal was elaborated for the creation of sensitivity indexes to coastal erosion, applying the method developed by Varela (2005). This yielded very satisfactory results, with the historical comparison made using old images, the rigorous and consistent assignment of the weights to the variables, and the interpretative capacity of the experts surveyed, which gave an intermediate position in the discussion of objectivity / subjectivity in the weighting of variables.

To classify the sensitivity zones, three criteria were selected as representative and appropriate: 1. Geomorphological units present on the coastal areas of the department of Bolívar; 2. Ecosystem land coverage; 3. Angles of the coastal line of the department with respect to the north, for the extreme wave regime.

The applied model was the Analytical Hierarchy Process (Varela, 2005), using ArcGIS software version 10.5, giving satisfactory results. However, it is important to keep in mind that the quality of the product obtained depends directly on the spatial and temporal resolution of the source information used, as well as its accuracy, precision, completeness, etc.

Therefore, it is necessary to consider that in multi-criteria spatial analysis, it is important to correctly review the source of geographic information, as well as the secondary information used as the basis of knowledge of each selected criterion.

Finally, it is worth highlighting that the use of Geographic Information Systems based on multi-criteria analysis is essential in the analysis of spatial information, given the need to use and integrate a large amount of spatial data from diverse sources and indices, to achieve the characterization of the criteria and indicators.

Recommendations

The methodology based on multi-criteria analysis can be used for any area of knowledge in which different criteria, indicators, variables or quantifiable parameters are involved, as long as there is an expert in the subject who qualifies them, in the area of study.

When considering that the variety of sources or authors, purposes for which the spatial information was created, requires a correct analysis, it will be used as a basis for study scales for the creation of the criteria, among other factors, given that awareness is taken to which the results obtained in the analysis can be altered or the modeling processes that allow the generation of the resulting geographic information can be strengthened.

In order to carry out a more detailed study about the sensitivity of the coastal zone, it is important to have more detailed basic information of the area, in order to analyze at a detailed level the social impact on the communities that settle there. This can be achieved by establishing community participation schemes that give the community the chance to participate as experts according to their social and economic experiences.

To reduce the subjectivity that can occur in the qualification of the criteria and indicators, it is considered necessary to have the support of experts in the area of knowledge that is being evaluated, in this case, geomorphology, ecosystems and coastal dynamics, and that they also have knowledge of the study territory. This activity does not guarantee the complete elimination of subjectivity since it will always be there, and will be part of the analysis of processes of uncertainty in these models.

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