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Application of AHP and GIS for Determination of Suitable Wireless Sensor Network Zones for Oceanographic Monitoring in the South Caribbean Sea Upwelling Zone

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***Abstract*— The monitoring and analysis of oceanographic variables is important for several research areas in marine sciences, such as marine spatial planning and integrated coastal management, among others. But, the high costs of monitoring equipment, its installation, and maintenance, damage, destruction, theft, and loss, make it difficult to monitor the maritime territory. Equipment installed in areas with environmental risks or anthropic activities showing the lack of analysis. Therefore, this paper determined the feasibility of installing a Wireless Sensor Network (WSN) for measurement of oceanographic variables in the South Caribbean Sea upwelling zone, using Hierarchy Analytic Process (AHP) and GIS tools (Geographic Information System). Marine ecosystems, boat traffic, fishing zones, and bathymetry criteria were used. The paired comparison matrix analysis shows the most important criterion is the buoy-type monitoring system (54.82%) far away from the marine ecosystems, while the bathymetric zone is the least relevant criterion (10.75%). It was possible to find that 62.36% of the study area is highly favorable to install the monitoring network and where it is advisable to do it, within which it is possible to avoid various risks and maximize the utility of the information, considering the different ecosystems and uses of the maritime territory. A restrictive variable to do replicable this work is the presence of GSM, GPRS or satellite coverage, otherwise, there would be no way to transmit data in real-time, involving transfers to collect the data, increasing the project's costs. The method and results allow replicating this study in any coastal marine environment.**

***Keywords*— AHP; GIS; WSN; Buoy; suitability map.**

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I. INTRODUCTION

The ecosystems are vulnerable entities to the effects caused by human activity, with tourism being a relevant factor due to the large influx of nationals or foreigners who temporarily exceed the acceptable level for the physical environment of the destination areas [1]. In the case of Colombia, one of the main reasons why tourists visit its marine ecosystems is because it is the only country in South America that has coasts in the Pacific Ocean and the Atlantic Ocean, where the Caribbean covers 82% of the continental marine surface [2] and has 134 tourist beaches [3].

To preserve and guarantee the stability of the oceanic system, it is necessary to know the temporal behavior of its physical, chemical, and biological variables, such as temperature, acidity, dissolved oxygen, salinity, chlorophyll, among others [4]. To counteract any threat or predict an environmental catastrophe through the knowledge of the changes in real-time of the variables, it is necessary to have different sensors distributed spatially, creating a network of wireless sensors (WSN). These are necessary because if there is a group of sensors, a spatial density of the data can be achieved. The more sensors are spatially distributed, the better the knowledge of the behavior of the variables [5]. Within the WSN, the elements can communicate with each other and allow the changes of the variables to be transmitted in real-time by satellite or by the mobile communication system (GSM or GPRS) [6].

However, the design, implementation, and deployment of a WSN for oceanographic applications present several challenges that do not arise on land. The impact on the WSN due to the marine environment, the tides, the passage of ships, makes the sea an aggressive environment that affects its performance and requires greater protection for the devices [4]. Despite the importance of constant monitoring of oceanographic variables, for 2019, few stations present for this purpose with the periodic record in the Colombian

Caribbean Sea, despite having an extension of 1,600 kilometers of coastline [2]. Damages due to vandalism cause the loss of monitoring systems (i.e., buoys), costing more than USD 150,000. Due to the high maintenance costs, which range from seven USD 7,500 to USD 12,000 per year [7], they have difficulty accessing the areas where they are installed. As a result, the Data Buoy Cooperation Panel (DBCP) generated strategies to substantially reduce the damage suffered by these devices from acts of vandalism and other types of anthropic interactions [9]. Complying with what is proposed in the DBCP, after the installation of a wave buoy in the sea of San Andrés Island (Colombia) in 2019, fishermen and sailors must carry out their daily activities outside of one nautical mile buffer from the buoy to avoid damage [8], [9].

Nowadays, these regulations are not enough to prevent equipment's damage installed on oceanographic buoys. In developing countries, such as Colombia, fishers need to know the importance of monitoring buoys and their benefits by getting data to help identify areas where fishing is presumed to be abundant [10]. However, for the choice of the place where the WSN should be implemented, the interests are varied, and in order to satisfy the diverse requirements, there is a widely validated method called Multiple-Criteria Decision Analysis (MCDA) [11]–[15]. The Analytic Hierarchy Process (AHP) is a decision-making technique among the most prominent [16], [17]. It solves in a simple and orderly way the problem of determining which criterion is more favorable and what percentage of priority each criterion has over the others [18], [19]. AHP facilitates decision-making based on a paired comparison between each criterion [20], [21]. This technique was developed in the late 1960s by Thomas Saaty [22]. Integrated into the decision-making process, it is necessary to have a tool that allows spatial management of the criteria, such as the Geographic Information System (GIS), which allows any type of data to be related to a geographic location, which supports entering different types of information and generating an output map with the processed information [23], [24]. In this works, we applied Hierarchy Analytic Process (AHP) and GIS tools (Geographic Information System) to determine the set of areas suitable for implementing a WSN over the upwelling area in the South Caribbean Sea.

II. Material and Method

Following the work development by Nandy [25], four crucial steps were taken to produce the suitability map of the study area to place the WSN network: (i) sign factor priority, weight, and class weight (rating) to the parameters involved (ii) find factors suitable to be used in the suitability analysis (iii) generate suitability map and (iv) determination of potential areas. The method implemented in this work can be seen in Fig. 1.

A. Prioritization of factor, weight, and class weight

Zyoud and Fuchs-Hanusch [11], in their bibliometric analysis, show how the AHP method is being used in various fields of research related to remote sensing systems, site selection, land use and planning, sustainable development, risk assessment and management, supply chain, computing in the cloud, genetic algorithms, renewable energies and climate change among others. In the coastal and oceanographic field, we have found jobs related to aquaculture, construction of marinas, coastal zones, artificial corals, the risk from cyclone or tsunami, fisheries, and marine protected areas, among others (see for example [26]–[29].

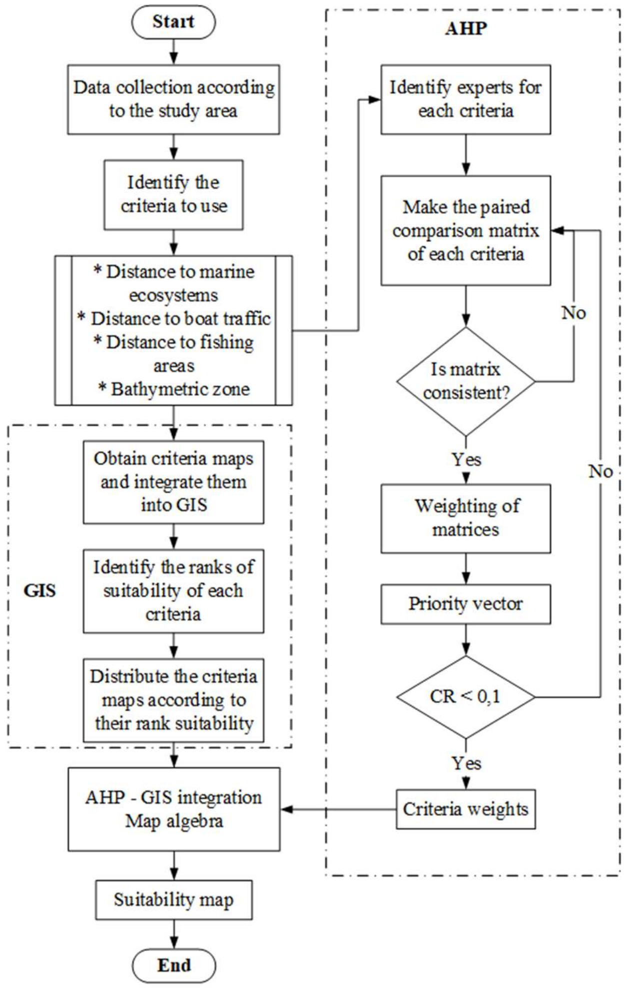

Fig. 1 The proposed method for suitability maps generation

From the studies reviewed, no evidence was obtained from previous works related to monitoring oceanographic variables, as observed in Pontificia Universidad Católica de Valparaíso [30] and World Meteorological Organization [31]. Therefore, there are no benchmarks for generating the AHP model. To determine the important factors to consider and the weight of the parameters, expert consultations were made following some previous studies [32]–[35] and considering official information available. These experts covered oceanography, communications, navigation, fishing, environmental monitoring systems, and tourism. One premise was to avoid areas where the network could be destroyed (totally or partially) or stolen as much as possible.

B. Factors Used in the Suitability Analysis

To determine the suitable areas where the installation of the WSN in charge of the measurement of oceanographic variables is carried out, in the Magdalena-Guajira upwelling system (southern Caribbean Sea), the criteria of marine ecosystems, boat traffic, fishing zones, and bathymetry, compiled from official sources (Table 1). There are three main reasons for selecting these criteria. The first of these is that the criteria used in this study are adequate to determine the appropriate areas to develop oceanographic monitoring that considers the care of ecosystems, which helps to have additional elements for sustainability in the extraction of marine resources and that is scalable to more specific topics, such as, for example, monitoring of sources of emergence or establishment of areas for aquaculture. The second reason is that, because the study was not carried out for a certain ecosystem type or specific environmental, social, or commercial use, the parameters wind, precipitation, sea surface temperature, salinity, turbidity, and nutrients are unnecessary. Third, the spatial data on the criteria used have already been generated and made available to the related institutions in Table 1.

TABLE I
DATA LIST AND ORIGINAL SOURCE

Data	Source
Marine ecosystems Bathymetry Fishing areas Concession areas	Sistema de Información Ambiental Marina (SIAM) [36]
Boat traffic route maps	Wikiloc [37] and Shipmap [38]

The concession areas are criteria to consider because it would not be possible to install the monitoring system in these areas, since they are in use by some entity, for which it has been decided to cut the study area from these criteria, preventing an area from entering the analysis in which it would be impossible to place the WSN. The concession areas include the anchoring areas and those used by the National Hydrocarbons Agency (ANH), which can be seen in Fig. 2.

On the other hand, "Shipmap" is a web application in which you can observe the movements of the world merchant fleet in 2012 [38], which is used to draw a polygon that represents the routes that pass through the study area. However, the polygon is not obtained directly from the web application.

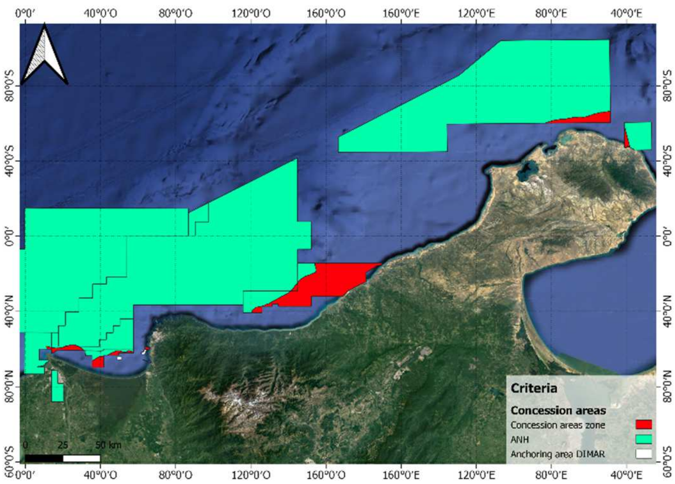

Fig. 2 Map of concession areas

C. Suitability Map Generation

The calculated and specialized AHP weights were used in the suitability map production process. From the AHP method, the priority vector of the criterion is obtained, which means, how important is a criterion against others. In parallel, geographic information of each criterion is sought and indexed GIS software. After that, it will be possible to know the appropriate areas for the installation of a WSN.

The criteria have a range of suitability: favorable, moderately favorable, or unfavorable to install the WSN. The result of this stage is the suitability in one pixel (x_i), where the area covered has a ratio of 1 píxel^2 /98 m^2, in a range between 1 and 3. 1 being the representation of a pixel within the area where the installation of the WSN is suitable, 2 moderately suitable and 3 unsuitable.

D. Determination of potential areas - AHP Methodology

The AHP method allows evaluating the percentage contribution of each criterion. It admits the inclusion and qualitative and quantitative updating as well. The hierarchical map is expressed in Fig. 3, where the objective, criteria, and alternatives are observed.

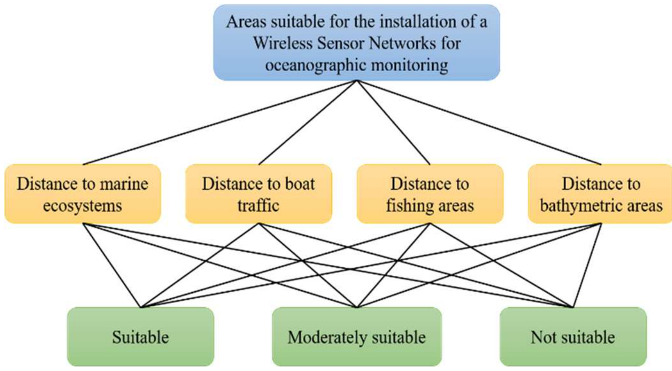

Fig. 3 Hierarchical map of the problem

Then, the relative importance between each criterion is evaluated by concepts of experts in several subjects, to determine which criteria and levels or weights affect the suitability of water use. A nine-point scale was used for these evaluations. For example, if marine ecosystem areas are compared with fishing areas, a score of 1 indicates they are equally relevant to the suitability assessment. A 9 score indicates it is more important to consider areas of marine ecosystems than fishing areas. All scores can be assembled into a Pairwise Comparison Matrix (PCM) with diagonal with one's values and reciprocal scores in the lower left triangle. The pairwise comparisons generated for the hierarchy levels contain the expert's opinion concerning the relative importance of the criterion. In Table 2, values 2, 4, 6 and 8 are used when the importance between the factors cannot be clearly defined [39], [40].

TABLE II
SAATY COMPARISON SCALES. ADAPTED FROM [41]

Score	Condition
1	If criterion "A" is equally important as criterion "B"
3	If criterion "A" is moderately more important than criterion "B"
5	If criterion "A" is much more important than criterion "B"
7	If criterion "A" is much more important than criterion "B"
9	If criterion "A" is extremely more important than criterion "B"

The next step is to evaluate the pairwise comparison matrix. A standardized eigenvector is extracted in this process, which allows us to assign weights to the criteria, indicating their relevance for suitability areas to installation WSN. Initially, a geometric mean of the pairwise comparison matrices is carried out, to find a matrix M to work to get the eigenvector (w). These contain the percentage of importance of each criterion in the study, being, being λ an eigenvalue. The vector w of a matrix M is a vector such that:

$$M \times w = \lambda \times w \quad (1)$$

The values of the parameter λ corresponding to the vector w, called characteristic values of M. That is, w is a characteristic vector of M if it is a non-trivial solution of:

$$(M - \lambda \times I)w = 0 \quad (2)$$

Where "I" is the identity matrix and the components of the vector w constitute a set of solutions of a linear system of the previous matrix. Because the System has a trivial solution, (1) must be a singular matrix. Being (3) an equation of degree n, called the characteristic equation of M, which is equal to 0 if λ is replaced by M, producing a matrix equation, where the roots are the characteristic values that were obtained from the priority vector, from of the solution of the corresponding systems of equations [42], [43].

In the fourth and final step, it is necessary to know if the pairwise comparison matrix has been consistent and to be able to accept the results of the weighting. The consistency index (CI) is calculated:

$$CI = (\lambda\_max - n)/(n-1)$$

In the fourth and final step, it is necessary to know if the pairwise comparison matrix has been consistent and to be able to accept the results of the weighting. The consistency index (CI) is calculated:

$$CI = (\lambda\_max - n)/(n-1) \quad (3)$$

Where λ_max is the largest or main eigenvalue of the matrix and n is the order of the matrix. This CI must be compared with that of a reciprocal matrix, of the same order, whose elements have been determined at random. The consistency index of the random matrix is called the Random Index (RI), so the ratio, CI / RI, is the Consistency Ratio (CR).

As a rule of thumb, CR should be kept for the matrix to be consistent. Homogeneity of the factors within each group, a lower number of factors in the group and a better understanding of the decision problem improve the consistency index. If this consistency index does not reach the threshold level, the responses to the comparisons will be re-examined. The RI values are previously determined according to the order of the matrix, as shown in Table 3.

TABLE III
INDEX MATRIX

Order	**0**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41

E. Integration between AHP and GIS

Each AHP criterion is interpreted as a vectorized map that includes individual characteristics to be processed in GIS software. After weighting them from AHP results, overlapping these maps produces a composite map, which we will call a suitability map. The study scenario is the upwelling zone of the southern Caribbean Sea, which has an upwelling period in the months of greatest intensity of the trade winds (December-March), with temperatures below 25.5 °C and concentrations of chlorophyll-a greater than 0.8 mg m – 3, which can be observed in the Fig. 4 Above the Sea Surface Temperature (°C), average January-March for the period 2010-2019 (calculated from data obtained in https://podaac.jpl.nasa.gov/MEaSUREs-MUR?sections=about%2Bdata). In black outlines Chlorophyll-a (mg m-3) taken and calculated from the MODIS Aqua sensor (https://oceancolor.gsfc.nasa.gov/), in the period 2003-2019. The red line indicates the 200 m isobath (taken from ETOPO 1, coastwatch.pfeg.noaa.gov). This scenario is delimited considering the 200 m isobath, covering approximately 9.887 km^2 (Fig. 4).

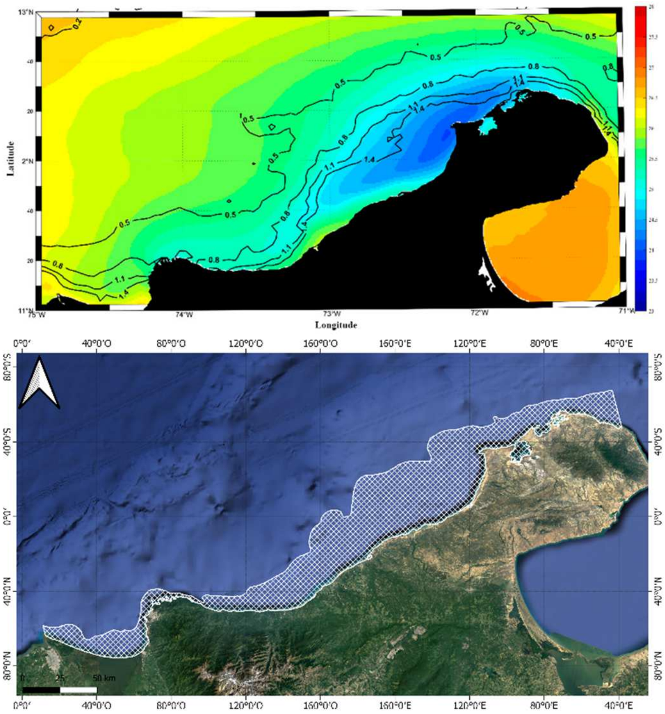

Fig. 4 Top: South upwelling zone of the Caribbean Sea. Bottom: Delimitation of the study area showing the 200 m isobath in the upwelling zone of the Colombian Caribbean coast

Each of the criteria is converted to a raster format, in this case, each pixel represents whether that geographical position is suitable for the installation of WSN, it is represented numerically and graphically, with red being an unsuitable area, orange being moderately suitable, and green is a suitable area for the monitoring buoy to be installed.

When integrating the results obtained by the AHP methodology with GIS software, the values of the priority vector are converted into criteria weights (w_i). Then, with the results obtained from the interviews with experts, the suitability range of each pixel in each criterion (x_i) was determined. The weighted linear combination of w_i and x_i provides a fitness index for each pixel of the corresponding criterion. The formula to obtain the weight is as follows:

$$S = \sum_{i=1}^{n} (w\_i \times x\_i) \quad (4)$$

S: Suitability index of each pixel
w_i: Weight criterion i
x_i: Criteria score i

The above equation is represented graphically in Fig. 5, where four criteria are observed in a 2x2 pixel map, in which each pixel has its x_i value that represents the suitability or not of each pixel in the analysis, with the value of 1 being the suitable pixels, 2 the moderately suitable and 3 the unsuitable pixels.

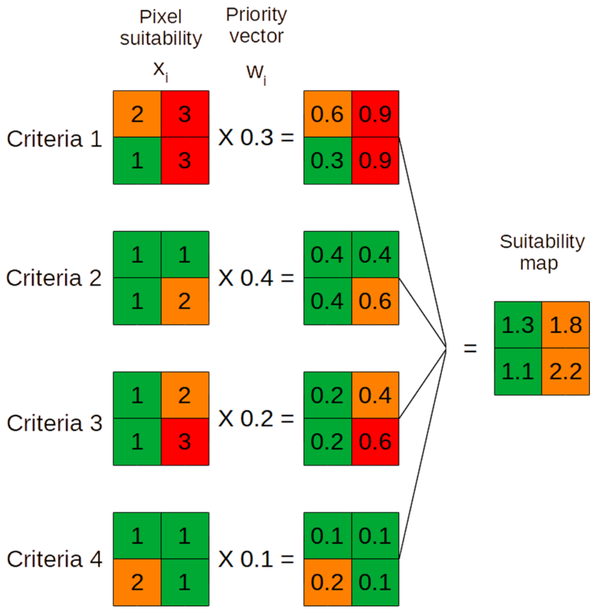

Fig. 5 AHP - GIS integration example

III. Results and Discussion

According to methodology, the criteria that generate the greatest relevance when having a buoy-type monitoring network are separated from marine ecosystems, boat traffic, fishing areas, and within a suitable bathymetric zone, not within a concession area and GSM, GPRS or satellite network coverage. GSM or GPRS coverage in the study area is low or null. Despite this, the range of satellite coverage is quite wide in this area, depending on its intertropical geographical location [44]. If any of these data transmission systems are available, the information must be collected *in situ* through removable devices such as USB or Bluetooth, or Wi-Fi [45].

Table 4 presents the paired comparison matrix of the weighted sum of the expert responses.

TABLE IV
Expert Weighted PCM

Criteria	**Distance to marine ecosystems**	**Distance to boat traffic**	**Distance to fishing areas**	**Bathy metric zone**
Distance to marine ecosystems	1,00	4,05	4,16	3,01
Distance to boat traffic	0,25	1,00	0,58	1,86
Distance to fishing areas	0,24	1,73	1,00	2,45
Bathymetric zone	0,33	0,54	0,41	1,00

Map algebra is performed (Fig. 5) from the weighting of each criterion (Table 5). The spatial representation of suitability installation of a WSN for measuring buoy-type oceanographic variables is shown in Fig. 10.

From the analysis of the paired comparison matrix of Table 4 the priority vector presented in Table 5, where the weighted weight of each criterion is presented, obtaining that the most important criteria are that the buoy-type monitoring system is far from the marine ecosystems, while the bathymetric zone is the least relevant criteria. To validate the AHP model, the priority vector is acceptable if when calculating the consistency relationship, it does not exceed the value of 0.1 [46]. Based on Table 3, since it is a study with 4 criteria, the random index is 0.9, and based on the results of Table 4 the consistency index is calculated as 0.05868, so the consistency ratio obtained in this study is 0.0652, from which it can be inferred that the model is valid.

TABLE V
Priority Vector

Criteria	**Weight**	**Percentage of weight**
Distance to marine ecosystems	0,5482	54,82%
Distance to boat traffic	0,1423	14,23%
Distance to fishing areas	0,2020	20,20%
Bathymetric zone	0,1075	10,75%

The distance considered prudential to install the buoy using selected criteria is presented in Table 6. The range of separation of the fishing zone is defined by the Meteorological Service of the Colombian Maritime Authority (DIMAR) and the System for the Measurement of Oceanographic and Marine Meteorology Parameters (SMPOMM). The specification indicates that boats engaged in fishing operations should be kept far away one nautical mile from the buoys [11]. The remaining criteria and their ranges are defined from an interview with several researchers from the Marine and Coastal Research Institute (INVEMAR).

TABLE VI
Ranks of Suitability for the Criteria

Criteria	**Decision criteria**	**Assigned rates**	**Suitability**
Distance to marine ecosystems	>150m	1	Suitable
	70m - 150m	2	Moderately suitable
	<70 m	3	Unsuitable
Distance to boat traffic	>100 m	1	Suitable
	50m - 100m	2	Moderately suitable
	<50m	3	Unsuitable
Distance to fishing areas	>1 nautical mile	1	Suitable
	<1 nautical mile	2	Moderately suitable
	Fishing areas	3	Unsuitable
Bathymetric zone	50m -200m	1	Suitable
	20m - 50m	2	Moderately suitable
	<20 m	3	Unsuitable

Figures 6 to 9 show the maps of each criterion, as well as its suitable zone within the study area. It is observed that the red area refers to the unsuitable areas, the oranges are the moderately suitable areas, and the green areas are the suitable areas where the installation of WSN is favorable.

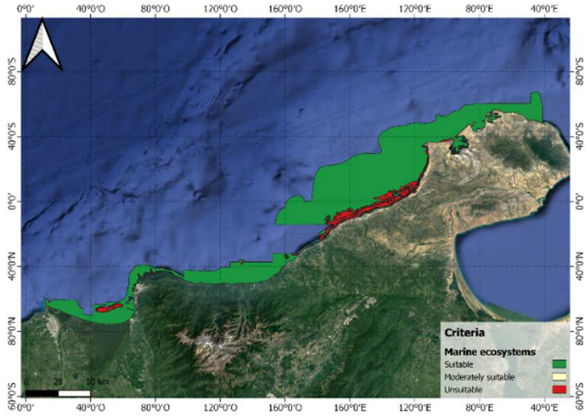

Fig. 6 Map of classified criteria: Distance to marine ecosystems

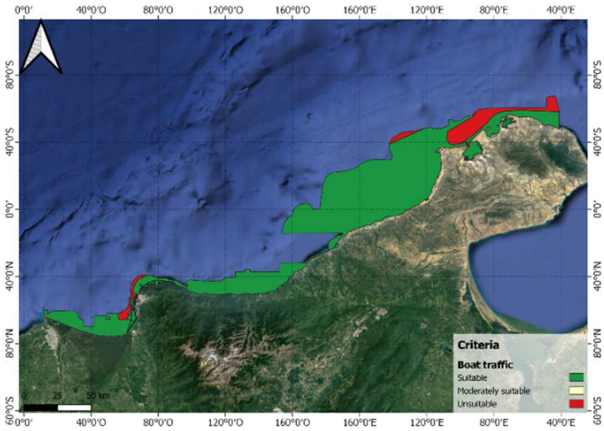

Fig. 7 Map of classified criteria: Distance to boat traffic

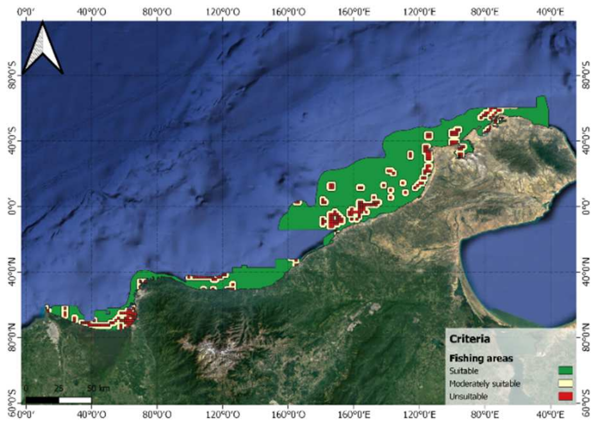

Fig. 8 Map of classified criteria: Distance to fishing areas

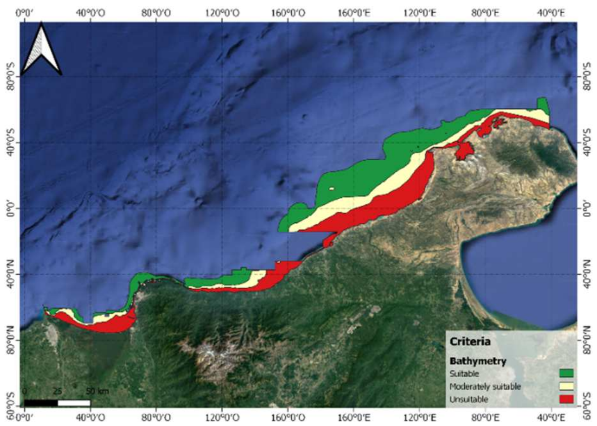

Fig. 9 Map of classified criteria: Bathymetry

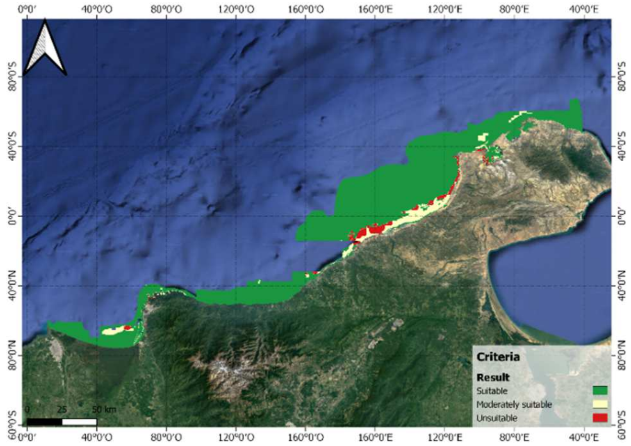

Fig. 10 Suitability map to the installation of a buoy-type WSN in the upwelling zone of the southern Caribbean Sea

A. Interpretation of results

The suitability map for the study area, delimited by the 200 m isobath in the upwelling zone of the southern Caribbean Sea, shows us that 62.36% of the area is suitable for the installation of the WSN, 30.88% moderately suitable, and, finally, 6.76% not suitable. In the case of being able to establish cooperation agreements with the companies that have the concession areas, the area considered suitable could increase.

When evaluating a WSN type buoy installation in a coastal marine environment, it is important to consider criteria that can affect relevance and allow the probability of loss, damage, or theft to be reduced. In this study, the criteria with which it was possible to obtain information within the upwelling zone of the southern Caribbean Sea were analyzed. Due to the lack of information in the area, several criteria could not be considered. However, if expanding the investigation is wanted, it is advisable to include the wave field (exceedance probabilities), winds (with a spatial resolution less than 25 km x 25 km), bathymetric gradient, tides, water discharges, and water discharges and sediments of the rivers to the sea. Additionally, for the specific study of monitoring oceanographic conditions in upwelling foci, the sea surface temperature, sea level, currents, chlorophyll, and diffuse attenuation coefficient, among others, can be added to the analysis. In addition to the above, the availability, type of boats, and their autonomy could be considered to monitor artisanal fishing areas and the above.

A restrictive variable to consider, for the model to be replicable, is the presence of GSM, GPRS or satellite coverage, otherwise, there would be no way to transmit the data in real-time, involving transfers to collect the data, increasing costs of the project.

In Colombia, we could not find references applied to oceanographic applications. However, some references studied the solar plants in rural areas, the composting of biological waste, sustainable renewable energy plans, sustainable use of productive soils, innovation in the AEC industry, selection of concrete suppliers, and sustainable management of the supply chain and its effect (see for example [47]–[50]). In this sense, we present a methodological framework for monitoring environmental variables that can be replicated with the necessary terrestrial, oceanographic and coastal characteristics. This implementation can contribute to adequate planning of joint efforts among institutions and the investments that take place.

IV. Conclusion

Multicriteria analysis methods are a tool that, when integrated with GIS, allows spatial analysis and offers the set of solutions for a specific project, allowing to know the suitability of the use of areas in a specific area based on several criteria, admitting the use of quantitative and qualitative criteria to know how relevant the criterion is in the study area. Due to the versatility and simplicity of the applied methodology, it is adjusted so that it can be carried out in any other marine ecosystem. This allows the planning and identification of suitable areas for the location of a WSN, considering that the environmental and network parameters are generic.

By applying this research methodology, it is possible to know a set of suitable areas for the installation of a WSN. Despite this, when installing the WSN it is necessary to carry out another decision process that analyzes which area offers better benefits than the others, such as separation from the coast, ease of access, and installation permission. About 62.36% of the study area delimited under the 200 m isobath in the upwelling zone of the southern Caribbean Sea is suitable for installing the WSN. If be able to establish cooperation agreements with the companies that have the concession areas, the area considered suitable could increase. While 30.88% of the area is moderately suitable and only 6.76% is not suitable, but despite being a significantly low percentage, it covers a large part of the coastal area of the city of Santa Marta and the department of La Guajira, where the WSN could easily be connected to the GSM / GPRS network.

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