Allocation and co-location model for maritime activities related to marine and coastal management, Bolívar department, Colombia

Modelo de asignación y co-localización de actividades marítimas para el ordenamiento marino-costero en el departamento de Bolívar, Colombia

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Abstract

The growth trend of the maritime sector due to the increase in population, urban development and industrialization has generated a diversification of uses in marine and coastal areas, causing conflicts due to the use/space interaction. For this reason, the Colombian General Maritime Directorate (Dimar in Spanish) has developed a methodology that enables the analysis of future conditions for the development of maritime activities in Colombian waters and coasts, through its Marine and Coastal Management with a Maritime Authority Vision (MCM:MAV), using the Allocation and Co-location Model (MAYC in Spanish), which seeks to establish the most appropriate spatial location for maritime activities, considering technical and environmental criteria and efficiency/effectiveness variables established by DIMAR, depending on the maritime activity type, and the availability and coverage of the information. The model was applied in the marine and coastal area of Bolivar Department, finding, based on the criteria selected for the different activities, that 90 % of the area is suitable to carry out aquaculture projects, 84 % for offshore wind farms, and 0.39 % for the construction of marinas.

Keywords: marine and coastal management, allocation, co-location, aquaculture, marina, offshore wind farm.

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Resumen

La tendencia al crecimiento del sector marítimo debido al aumento en la población, al desarrollo urbanístico y a la industrialización, han generado la diversificación de usos en las zonas marino-costeras causando conflictos por la relación uso/espacio. Por esto la Dirección General Marítima Colombiana (Dimar), ha desarrollado una metodología que permite analizar las condiciones futuras para el desarrollo de actividades marítimas en las aguas y costas colombianas, a través del Ordenamiento Marino Costero: Visión de Autoridad Marítima (OMC:VAM), que en su proceso metodológico plantea el Modelo de Asignación y Co-localización (MAYC), el cual busca establecer la localización espacial de las áreas más adecuadas para actividades marítimas, teniendo en cuenta criterios técnicos, ambientales y variables de eficiencia/eficacia establecidos por la Dimar, tipo de actividad marítima, disponibilidad y cobertura de la información. El modelo se aplicó en la zona marino-costera del departamento de Bolívar, encontrando, con base en los criterios seleccionados para las diferentes actividades, que un 90 % del área es apta para llevar a cabo actividades de acuicultura, un 84 % es apta para instalación de parques eólicos y un 0.39 % de área es adecuado para construcción de marinas-embarcaderos.

Palabras clave: *ordenamiento marino-costero, asignación, colocalización, acuicultura, marinas, parques eólicos.*

Introduction

Some of the most important factors in the dynamics of marine-coastal zones worldwide, and which have increased the processes of change, are the rapid growth of the population, urban development and industrialization, which generate conflicts related to the use/space interaction by increasing activities in the maritime sector (Cicin *et al*., 1998; Jiménez, 2013; Christie, Smyth, Barnes and Elliott, 2014; Rivera, 2018). Official statistics show that half of the world's active population depends on the oceans, since they provide the necessary resources to meet their needs, which allows the development of economic sectors and, consequently, the generation of millions of jobs (Food and Agriculture Organization [FAO], 2014; Prato and Reyna, 2015).

It is estimated that around 90 % of products and services are transported by sea. It is also expected that by the year 2030 the global maritime industrial trade will more than double from 9 billion tons per year to 22-24 billion tons; that is an approximate annual growth rate of 3.4 % that will generate job opportunities for more than 40 million people within the capture fishery, offshore wind farm, marine aquaculture, port activity and coastal tourism sectors (Shenoi *et al*., 2015; Organization for Economic Co-operation and Development [OECD], 2016; Price WaterHouse Cooper [PWC], 2015; United Nations Conference on Trade and Development [UNCTAD], 2019). Colombia is no stranger to this boom: its connections, development and ease of trade have led it to occupy the number 3 position in Latin America and 34 worldwide, according to the 2019 Maritime Connectivity Index that evaluates 171 countries. This is due to its access to the Atlantic and Pacific Oceans, giving it a competitive advantage regarding maritime exports (Comisión Colombiana del Océano [CCO], 2015; Dirección General Marítima [Dimar], 2019a; UNCTAD, 2019; Departamento Nacional de Planeación [DNP], 2020).

Within the context of maritime interests, decision makers worldwide are faced with problems that require immediate attention and that cannot be solved solely by analyzing current conditions. This is why planning allows the creation of different future scenarios with different perspectives for timely action by governments, based on the formulation and implementation of public policies that control the growth and development of maritime activities worldwide (Ehler and Douvere, 2009; Marczak *et al*., 2016; McGowan, Jay and Kidd, 2019).

Given the need to generate a planning process that allows the identification and quantification of the different uses and/or activities that are carried out in the marine-coastal area, Dimar applies its Marine and Coastal Management: Maritime Authority Vision (MCM:MAV) in order to achieve the consolidation of the country as a bioceanic power, under a holistic focus on integrated maritime, fluvial and port security, guaranteeing ecological, economic and social principles (Dimar, 2019b; Afanador *et al*., 2019).

As part of the MCM:MAV, given the gradual growth of economic activities around the maritime sector in Colombia, a six-stage methodology is established: establishment of governance elements, pre-planning, analysis of current conditions related to conflicts, analysis of future conditions, dissemination, and evaluation and feedback (Afanador *et al*., 2019). The analysis of future conditions of uses/activities is carried out through the Assignment and Co-location Model (MAYC in Spanish), with the purpose of optimizing the use of the marine-coastal space, considering the different components related to human resources, in such a way that it can be efficient in possible future management scenarios, in order to assess and minimize conflicts.

The application of this model within the MCM:MAV makes it possible to establish the most appropriate location for future uses/activities in the marine-coastal zone of the department of Bolívar, seeking to generate important benefits and opportunities to improve people's quality of life (Vanclay, Esteves, Aucamp and Franks, 2015; Kvam, 2018; Afanador *et al*., 2019).

Study Area

The MAYC model was applied to the areas between the town of Galerazamba and Matunilla Creek in the department of Bolívar, Colombian Caribbean, including the Islas del Rosario Archipelago (Fig. 1). It has a coastline of 529.86 km that extends out through zone A (which goes from the limit of public use assets established by Dimar up to 12 nautical miles) and Zone B (from 12 to 200 nautical miles).

In the Colombian Caribbean, wind, wave and climate patterns depend on the dynamics of the NE trade winds governed by the intertropical convergence zone (ITCZ) (Poveda *et al*., 2002). In the northern hemisphere summer, the trade winds decrease their intensity and end when the anticyclone that causes them moves away from the north of South America, the atmosphere restores its normal stratification and the rainy season begins. There is often a small peak in precipitation between the months of May and June as well as a rainy season when calm waters predominate (August to November), with maximum rainfall occurring between the months of October and November (Dirección Territorial Costa Atlántica [DTCA], 2004; Durango, 2009; Orejarena-Rondón *et al*., 2019; Urrea, Ochoa and Mesa, 2019).

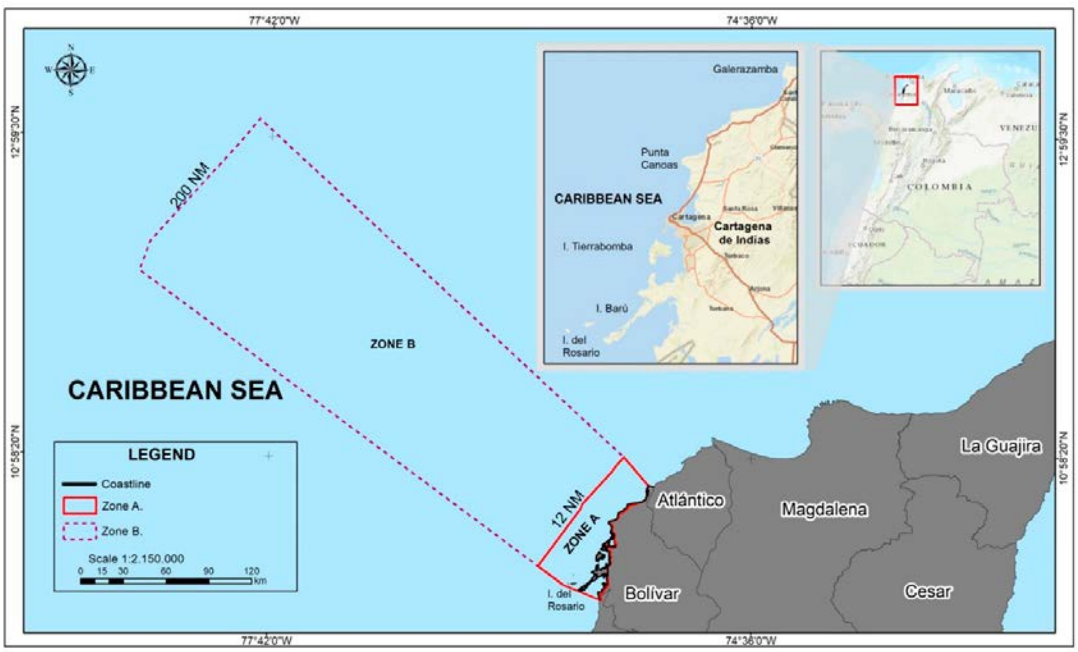

Figure 1. Location of the study area.

Geologically, the Colombian Caribbean is within a compressional tectonic environment, caused by the interaction between the South American continental plate and the Caribbean and Nazca oceanic plates. In Colombian marine territory, the Caribbean Plate is formed by geological provinces where the Nicaraguan Promontory (elevation) and the Colombia Basin stand out, surrounded to the west by the Graben (tectonic rift) of Providencia and to the east by the Beata crest. (Trenkamp, Kellogg, Freymueller, and Mora, 2002; Audemard and Audemard, 2002; Dimar-CIOH, 2013). The vast majority of the rocks that outcrop in the Caribbean subregion are of sedimentary origin, deposited in a marine-continental transition environment, and later folded and faulted. During the Tertiary orogeny they were covered by extensive Quaternary deposits of fluvial, fluvio-marine and lacustrine origin. The formations in the area are mainly made up of sequences of sandstones (lithic, quartzose), claystones, siltstones, mudstones, beach deposits, colluvial, coastal plain, pelagic and hemi-pelagic limestone, with ages ranging from the Paleocene to the Pliocene (Reyes, Guzmán, Barbosa and Zapata 2001).

In the study area, geomorphological units associated with high and low coasts have been characterized, represented by hills, coral terraces and marine terraces, and beaches, marshes, and coastal and flood plains, respectively (Trenkamp *et al*., 2002; Audemard and Audemard, 2002; Dimar-CIOH, 2013). There are also submarine geoforms located on the continental shelf (which presents variable amplitudes) and in the Colombia Basin, corresponding to banks, canyons and submarine channels, shallow reefs and areas with low to moderate slopes. There is an influence from continental sediments transported by the Magdalena River, mainly associated with the dynamics of the Dique Canal (Tabares *et al*., 2009).

The department of Bolívar boasts the largest coverage of coral reefs in the Colombian Caribbean, located in the Rosario Islands archipelago. They were formed about 5 000 years ago due to the activity of a mud volcano that caused uplift of the seabed, providing the necessary conditions for the growth of calcareous algae which contribute to the development of coral reefs, leading to the development of fringing, patch, and platform reefs, and coral banks, with an approximate extension of 145.3 km^2, of which 67.6 km^2 correspond to significant living coral cover (Díaz *et al*., 2000; Alvarado, Pizarro and Sarmiento, 2011; Gómez-Cubillos *et al*., 2015).

An estimated 58 maritime uses/activities occur in the study area, mainly associated with the fact that its capital, Cartagena de Indias, is the main tourist destination in the country, where a high number of national and international passengers arrive by air, land and sea. Likewise, due to its proximity to the maritime trade routes (Panama Canal), it is located within the nation's largest connectivity node to global networks. Additionally, it has three of the largest companies in the shipbuilding sector in Colombia and is home to the second most important oil refinery in the country and the main exporter of chemical substances, which is why it is considered an industrialized city that makes an important contribution to the national economy (Agencia de inversiones de Cartagena de Indias y Bolívar, 2012; Martínez y Malagón, 2014; Centro de Estudios para el Desarrollo y la Competitividad [CEDEC], 2018; Afanador *et al*., 2021).

Methodology

The MAYC model proposed by Dimar (Afanador *et al*., 2019; Afanador *et al*., 2021) is used as part of the implementation of the Coastal-Marine Ordering of jurisdictional waters and coasts of Colombia (inland waters, territorial sea, contiguous zone and exclusive economic zone). The allocation analysis of this model seeks to determine the most suitable geographical location for the different maritime uses/activities in accordance with economic development trends, evaluating technical and environmental criteria in zones free of uses/activities, in such a way that the space is optimized, while ignoring the areas in which strategic ecosystems such as mangroves, corals and sea grasses are found. Additionally, the co-location analysis allows future uses to be added to areas where other activities are already carried out by making use of compatibility criteria, with the purpose of reducing conflicts to the lowest possible level (Hennessey and Sutinen, 2005; Farahani and Hekmatfar, 2009; Marine Management Organization, 2013; Lester *et al*., 2013; Coccoli, *et al*., 2018; Dimar, 2019b; Afanador *et al*., 2021).

This model is applicable in three possible situations that can be presented to the Colombian Maritime Authority: *i)* Pre-established spatial location, in which the user requests permission for a use/activity, while providing the project's own specifications, such as the geographic coordinates and all the technical documents required in the process, *ii)* Unknown spatial location, based on the assumption that the user has the information related to the general characteristics of the use/activity but has not defined its spatial location, and finally, *iii)* analysis in the current area, in which a user has the information related to the use/activity (geographical coordinates) but, at the moment of locating it spatially, it is in a space where other uses/activities already occur (Afanador *et al*., 2019). Under these three situations, we defined the steps to follow (Fig. 2), which give a broad panorama of the conditions that initially generate uncertainty, providing an idea of how to approach the allocation of locations for future maritime activities from an objective standpoint and as technical support for decision-making (World Energy Council, 2019).

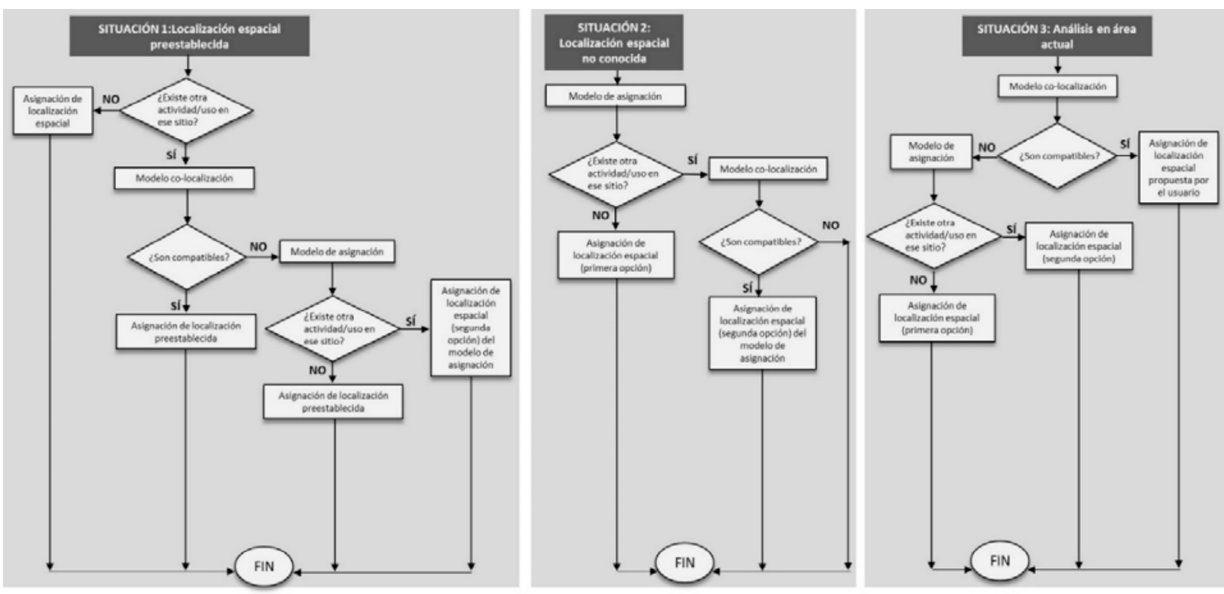

Figure 2. Flow charts for the application of the MAYC model in the three situations established by Dimar.

Definition of uses for analysis

The uses and/or activities chosen correspond to aquaculture, marinas-piers and wind farms, which are the ones with the greatest trend towards growth in economic and social terms (Ministry of Commerce, Industry and Tourism [MINCIT], 2013; CIOH, 2017; Lee and Zhao, 2020), based on national figures because this is the focus of the Coastal Marine Planning: Maritime Authority Vision and due to the limited availability of information at a local level. This analysis is carried out through interactions between different sectors, stakeholders and times, in order to enable sustainable growth for the activities and marine-coastal ecosystems that are threatened by climate change and excessive exploitation of seas and oceans (Rodríguez, 2002; International Energy Agency, 2010; Zangrando and Brioñes, 2017).

Aquaculture: According to the FAO, world consumption of edible fish increased at an average annual rate of 3.1 % between 1961 and 2017, a rate that was double the annual world population growth during the same period (1.6 %). In 2018, 63.6 million tonnes of fish were farmed, while their capture production was 26 million tonnes (Christie *et al*., 2014; FAO, 2020).

The State of World Fisheries and Aquaculture (SOFIA) report, published by the FAO in 2020, analyzes the increase in production and consumption of fishery products. It is reported that the world consumption of fish per capita reached a record of 20.5 kg per year and it is expected that it will continue to increase to 21.5 kg by 2030, as global food security improves. The data obtained show that total fish production will increase to 204 million tons by 2030, which is 15 % more than in 2018 and means an increase in aquaculture of 46 %.

In Colombia, aquaculture is carried out in fresh and marine waters. The total national fishing production (fishing and aquaculture) in 2017 was approximately 187 500 tons, of which aquaculture contributed 53 %. The human resource dedicated to this activity is estimated at a total of 581 416, of which 105 234 people work in aquaculture and the rest in different fishing categories (FAO, 2019).

Marinas-piers: A significant number of marinas-piers are limited to coastal and insular populations that do not have other communication routes, which means they constitute the only means of transporting products and people, fulfilling a social function for the benefit of the communities (Leal, Taborda, Sandoval and Isaza, 2011). In 2013, the projected growth in Latin America for this type of activity was approximately 10 % per year; Costa Rica, Panama and Ecuador were the countries with the largest number of projected marinas (MINCIT, 2013).

In Colombia, nautical facilities are limited compared to different countries in the Caribbean and Mediterranean regions, such as Spain and Italy, among others. They are divided into public (65 %) and private (35 %) facilities located in the departments of Atlántico, Bolívar and Valle del Cauca (Ministerio de Transporte [Mintransporte], 2008; Superintendencia de Puertos y Transporte [Superpuertos], 2016). According to the National Nautical Tourism Plan, by 2013 the country had 26 facilities, eight of them located and endorsed by Dimar in Cartagena de Indias. It is estimated that in Colombia by the year 2028, 11 marina projects will be built to increase the availability of these facilities, representing an approximate growth of 42 % (MINCIT, 2013; CIOH, 2017).

Wind farms: At a worldwide level, wind energy has become a real option to generate electricity. Wind farms have the capacity to provide large amounts of energy to different geographical areas. It is considered that this system manages to reduce greenhouse gas emissions since it replaces the use of fossil fuels, contributing to the sustainable development objectives of the Agenda 2030 (Cranmer and Baker 2020; Akhtar *et al*., 2021; Bastidas-Salamanca and Rueda Bayona, 2021).

By the year 2030, wind energy is expected to supply approximately 20 % of electricity worldwide, which would generate about 2.4 million jobs. Similarly, the accumulated capacity of the offshore wind market is expected to increase from 154 to 193 gigawatts (GW), that is, 25 % more in this industry (Lee and Zhao, 2020).

In Colombia there is great wind potential, according to measurements, studies and research carried out on the Caribbean coast, mainly in the department of La Guajira and in some areas in the departments of Santander, Boyacá and Huila (Pinilla, 2008). Despite this, wind energy in Colombia only represents 0.1 % of the total generation. The country has the necessary conditions for the implementation of large-scale projects; however, this underdevelopment is due to different legal, social, cultural, economic and technological limitations. However, in 2014, Law 1715 of 2014 was approved, establishing incentives to promote the development of alternative energy sources and their integration with the energy market, hoping to increase production from 1.5 to 4 GW by 2030 (Ministry of Mines and Energy [MinMinas], 2015; González, 2019).

The Colombian Maritime Authority, together with the Ministry of Mines and Energy, carried out the validation of the areas of interest proposed by the World Bank in the "Roadmap for the deployment of offshore wind energy in Colombia" (The Renewables Consulting Group and ERM, 2022) by applying the MAYC model. Taking into account the results, the central Colombian Caribbean was nominated as the area for the development of offshore wind farm projects through Resolution No.40284 of 2022 of the Ministry of Mines and Energy and Dimar.

Assignment model

The development and application of the Assignment Model in the marine-coastal zone of the department of Bolívar aims to lead to the zoning of suitable and moderately suitable areas for the location of aquaculture facilities, marinas-piers and wind farms, in such a way that certain technical and environmental criteria are met. This process was carried out executing the stages presented in Figure 3.

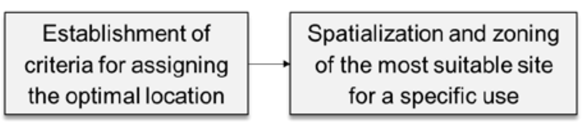

Figure 3. Methodological stages for analyzing the assignment of uses/activities in free areas.

Establishment of criteria for assigning the optimal location

This process uses multicriteria evaluation, based on criteria and sub-criteria established through a bibliographic review, expert judgment and the availability of spatial information, to ensure the efficient development of each use/activity, seeking to establish the geographical location (in areas free of uses/activities) of the sites in which these conditions are met, in such a way that a possible balance between economic, social and environmental aspects can be achieved (Farahani and Hekmatfar, 2009; Coccoli *et al.*, 2018).

Once the technical and environmental criteria of each use/activity have been identified, the weights of the criteria and sub-criteria are calculated as follows:

$\forall\ Use_x$, where $Crit_i$ is the i-th criterion that defines its most appropriate location:

$$U_{Use_x} = \{Crit_1, Crit_2, Crit_3, \dots, Crit_n\}$$

Also, $\forall\ Crit_i$ has $SCrit_k$, which corresponds to the sub-criteria that define the most appropriate location of Use_x:

$$U_{Crit_i} = \{SCrit_1, SCrit_2, SCrit_3, \dots, SCrit_n\}$$

W_iCrit_i is the weight of the criterion i, established based on the available literature review on criteria for the optimal location of uses/activities, defined as follows:

$$W_iCrit_i = W_i \times Crit_i \qquad \textbf{(1)}$$

For $Crit_i$:

$$\sum_{i=1}^{n} W_iCrit_i = 1 \times 100 \qquad i = 1,2,3,\dots,n \qquad \textbf{(2)}$$

Where a W_iCrit_i close to a 100 is the most important criterion for assigning a location to Use_x, as established by expert judgment.

Q_kSCrit_k, the weight of the criterion k, is calculated as follows:

$$Q_kSCrit_k = Q_k \times SCrit_k \qquad \textbf{(3)}$$

For $Crit_i$:

$$\sum_{k=1}^{p} Q_kSCrit_k = 1 \qquad k = 1,2,3,\dots,p \qquad \textbf{(4)}$$

Based on expert judgment, the sub-criteria are classified as optimal, moderately optimal, and non-optimal, where a $QSCrit_k$ close to 1 is the most optimal sub-criterion within $Crit_i$.

Let:

$$RSCrit_k = W_iCrit_i \times Q_kSCrit_k \qquad \textbf{(5)}$$

Where $RSCrit_k$ corresponds to the weighted average of the sub-criterion k of the criterion i.

In a crossed matrix, all the criteria of each use are included, with their respective optimal and moderately optimal sub-criteria and the associated weighted averages. Initial intersections (∩) are performed by pair using Geographic Information System (GIS) software (Table 1):

Table 1. Cross-criteria matrix for each use/activity.

			$Crit_1$		$Crit_2$		$Crit_3$	
			$SCrit_1$	$SCrit_2$	$SCrit_1$	$SCrit_2$	$SCrit_1$	$SCrit_2$
		$RSCrit_k$	$RSCrit_{1,1}$	$RSCrit_{2,1}$	$RSCrit_{1,2}$	$RSCrit_{2,2}$	$RSCrit_{1,3}$	$RSCrit_{2,3}$
$Crit_1$	$SCrit_1$	$RSCrit_{1,1}$	N/A	N/A	∩	∩	∩	∩
	$SCrit_2$	$RSCrit_{2,1}$	N/A	N/A	∩	∩	∩	∩
$Crit_2$	$SCrit_1$	$RSCrit_{1,2}$	∩	∩	N/A	N/A	∩	∩
	$SCrit_2$	$RSCrit_{2,2}$	∩	∩	N/A	N/A	∩	∩
$Crit_3$	$SCrit_1$	$RSCrit_{1,3}$	∩	∩	∩	∩	N/A	N/A
	$SCrit_2$	$RSCrit_{2,3}$	∩	∩	∩	∩	N/A	N/A

Let A be the first criterion ($Crit_1$), B the second criterion ($Crit_2$) and C the third criterion ($Crit_3$), in such a way that:

$$SCrit_{1,A} \cap SCrit_{1,B}$$

$$SCrit_{1,A} \cap SCrit_{2,B}$$

$$SCrit_{1,A} \cap SCrit_{1,C}$$

$$SCrit_{1,A} \cap SCrit_{2,C}$$

$$SCrit_{2,A} \cap SCrit_{1,B}$$

$$SCrit_{2,A} \cap SCrit_{2,B}$$

$$SCrit_{2,A} \cap SCrit_{1,C}$$

$$SCrit_{2,A} \cap SCrit_{2,C}$$

$$\vdots$$

$$SCrit_{n,m} \cap SCrit_{p,q}$$

Where $SCrit_{n,m}$ is the sub-criterion n of the criterion m intersected with $SCrit_{p,q}$, which corresponds to sub-criterion p of criterion for Use_x.

For each intersection:

$$I = RSCrit_{n,m} + RSCrit_{p,q}$$

Where I is the sum of the weighted averages of each intersection, $RSCrit_{n,m}$ is the weighted average of the sub criterion n of criterion m and $RSCrit_{p,q}$ is the weighted average of the sub-criterion p of criterion q.

Spatialization and zoning of the most suitable site

The intersections found represent the geographic spaces where there are two sub-criteria defining the most suitable sites to assign a location for Use_x:

$\forall\ SCrit_k$: The one with the greatest weight is considered optimal;

The sub-criterion with the least weight is considered non-optimal;

The moderately optimal one(s) will be the other sub-criteria of the criterion.

If the intersection occurs between two sub-criteria classified as *optimal*, its category for zoning purposes is considered to be *suitable*. In the cases in which the intersection is carried out between two sub-criteria classified as *optimal* and *moderately optimal,* its category for zoning purposes is considered *moderately suitable.* In the same way, if the intersection is carried out between two sub-criteria classified as *moderately optimal,* it is considered *moderately suitable* (Table 2).

Table 2. Categorization of the intersections of the sub-criteria of each use/activity.

INTERSECTION	CATEGORY
Optimal ∩ Optimal	Suitable
Optimal ∩ Moderately optimal	Moderately Suitable
Moderately optimal ∩ Moderately optimal	Moderately Suitable

Finally, if there are intersections in pairs between different areas (suitable and/or moderately suitable), the final classification of the resulting intersection will be based on the value of the weighting of each initial intersection; In other words, if, for example, two zones intersect –one suitable (with a weight of 0.35) and one moderately suitable (with a weight of 0.25)– the resulting intersection will be classified as a "Suitable Zone", since the initial suitable intersection has the highest weighted average. Additionally, if there is an area where only suitable sub-criteria intersect, it will be classified as a very suitable area.

Co-location model

For its part, the Co-location Model seeks to establish the location of uses/activities in areas where others already exist (Marine Management Organization, 2013), through the determination of compatibility criteria (Hennessey and Sutinen, 2005), which are defined from a review of the state of the art in relation to the positive and/or adverse effects within each pair of uses, in such a way that the intensity of the conflict is minimized (Afanador *et al*., 2019). For the study area, a hypothetical exercise was carried out in which the proposal for an aquaculture project is evaluated in a location where there are already marinas-piers and a wind farm, taking into account the following stages (Figure 4):

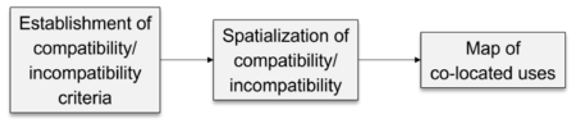

Figure 4. Methodological stages for analyzing the co-location of uses/activities.

Establishment of compatibility/ incompatibility criteria

This analysis is carried out by pairs of uses, building two matrices: the first one contains technical and environmental criteria (established in the allocation analysis with the respective weight of the criteria); and the second considers variables that allow the efficient and effective development of each use.

- Matrix of technical and environmental criteria

  Let U_x be the use for which the co-location analysis is performed.

  Let U_1, U_2, U_3... U_n be all the uses that currently occupy a geographical space.

  For each use, the suitability criteria established in the allocation analysis are taken with their respective weights.

  A matrix of technical and environmental criteria is prepared between U_x and U_n (Table 3) and it is assessed by rows, taking into account the Hennessey and Sutinen scale (Table 4), which establishes whether each sub-criterion of U_x is compatible or incompatible with each sub-criterion of U_n. This is explained in a justification matrix.

Table 3. Matrix of technical and environmental criteria between U_x and U_n.

				U_n							
				$Crit_t1$	$Crit_t2$	$Crit_t3$	$Crit_tn$	$Crit_a1$	$Crit_a2$	$Crit_a3$	$Crit_an$
uso			$W_i\,Crit_i$	W_tCrit_t1	W_tCrit_t2	W_tCrit_t3	W_tCrit_tn	W_aCrit_a1	W_aCrit_a2	W_aCrit_a3	W_aCrit_an
U_x	Criterios Técnicos $(Crit_t)$ $\sum_{t=1}^{n} W_tCrit_t$	$Crit_t1$	$W_t\,Crit_t1$								
		$Crit_t2$	$W_t\,Crit_t2$								
		$Crit_t3$	$W_t\,Crit_t3$								
		$Crit_tn$	$W_t\,Crit_tn$								
	Criterios Ambientales $(Crit_a)$ $\sum_{a=1}^{n} W_aCrit_a$	$Crit_a1$	W_aCrit_a1								
		$Crit_a2$	$W_a\,Crit_a2$								
		$Crit_a3$	$W_a\,Crit_a3$								
		$Crit_an$	W_aCrit_an								

Let $W_i Crit_i$ be the weight of established in the allocation analysis.

Let $\sum_{i=1}^{n} W_i Crit_i$ be the sum of the weights of the technical and environmental criteria of U_x.

Let $W_a\, Crit_a$ be the weight of the environmental criterion a established in the allocation analysis, and $W_t\, Crit_t$ the weight of technical criteria t established in the allocation analysis.

Let $\sum_{a=1}^{n} W_a Crit_a$ be the sum of the weights of the environmental criteria of U_x, and $\sum_{t=1}^{n} W_t Crit_t$ the sum of the weights of the technical criteria of U_x.

To determine the compatibility/incompatibility, whichever of $\sum_{t=1}^{n} W_t Crit_t$ or $\sum_{a=1}^{n} W_a Crit_a$ is higher is chosen (Table 4).

Table 4. Hennessey and Sutinen compatibility/incompatibility scale (2005).

COMPATIBILITY CRITERIA	VALUE	COMPATIBILITY/INCOMPATIBILITY
The two uses enhance each other	1	Compatible
The two uses do not interfere with each other	0.75 - 0.99	Compatible
One use can improve the other	0.5 - 0.749	Conditionally compatible
One of the uses negatively affects the other	0.25 - 0.49	Conditionally incompatible
The two uses affect each other negatively	0 - 0.249	Incompatible

- Efficiency and effectiveness matrix

Let V_x be the efficiency and effectiveness variable for U_x.

Let V_1, V_2, V_3 … V_n be all the efficiency and effectiveness variables for each U_n.

A matrix of efficiency and effectiveness variables is prepared between U_x and U_n (Table 5), and it is assessed by rows taking into account the Hennessey and Sutinen scale (Table 4), which establishes whether each variable of U_x is compatible or incompatible with each variable of U_n. This is explained in a justification matrix (not included in this article).

Table 5. Efficiency and effectiveness matrix between U_x and U_n.

				U_n			
				V_1	V_2	V_3	V_n
USO			$W_i V_i$	$W_X V_1$	$W_X V_2$	$W_X V_3$	$W_X V_x$
U_x	Variables Eficiencia y Eficacia V_n $\sum_{i=1}^{n} V_i W_i$	V_1	$W_X V_1$				
		V_2	$W_X V_2$				
		V_3	$W_X V_3$				
		V_n	$W_X V_4$				

Let $W_i V_i$ be the weight of each efficiency and effectiveness variable established by the bibliographic review where:

$\sum_{v=1}^{n} W_i V_i$ = 100 %

To determine the compatibility/incompatibility, the highest $W_i V_i$ is chosen.

Final compatibility/incompatibility:

To express the final compatibility/incompatibility between U_x and U_n, we can say:

$$\overline{X}_t = \frac{\sum_{t=1}^{n} W_t Crit_t + \sum_{i=1}^{n} W_i V_i}{2}$$

$$\overline{X}_a = \frac{\sum_{a=1}^{n} W_a Crit_a + \sum_{i=1}^{n} W_i V_i}{2}$$

Where $\overline{X}$ is the arithmetic average of the values obtained from compatibility between technical (t) and environmental (a) criteria and the most important efficiency/effectiveness variables. Once the compatibility criteria have been established between each pair of uses/activities, processing is carried out using GIS tools to delimit the area in which the use/activity can be carried out in a way that is compatible with the other uses/activities present in the geographic area.

Results

Assignment Model

To develop this methodology, a bibliographic review was carried out to define the technical and environmental criteria, and thus spatialize suitable and moderately suitable areas for aquaculture, marinas-piers and offshore wind farms.

For this investigation, Dimar selected the technical and environmental criteria depending on the type of maritime activity, and the availability and coverage of the information, taking into account that some criteria do not apply to the evaluated uses. Oceanographic data such as depth and currents correspond to multi-year averages from databases such as GEBCO, HYCOM, among others; however, the model can be applied to different climatic seasons or in specific time periods, and more criteria can be considered in future analyses.

Aquaculture

Suitable areas for the future development of aquaculture were determined using the available oceanographic criteria and data: seabed, wave period, significant wave height, currents and possible effects on sediments (Table 6). In this case, the depth was not taken into account because it varies depending on the species to be cultivated.

Table 6. Technical and environmental criteria used to establish the most suitable areas for aquaculture.

Criteria	Weight of the criteria	Sub-criteria	Weight of the sub-criteria	Category	*Final weighting	Source
Seabed type	0.20	a) Sandy	0.5	Suitable	0.100	Meindl, 1996; Rojo, 2016; Cardia, Ciattaglia & Corner, 2017; Ivars, 2017; Queensland Government, 2019
		b) Rocky	0.35	Moderately Suitable	0.070	
Wave period (T)	0.12	a) 1.9 s < T ≤ 359 s	0.5	Suitable	0.060	Munk, 1950, in Palomino, et al., 2001; Rubino, 2008; Cavia del Olmo, 2009; Kapetsky, Aguilar & Jenness, 2013; COWI & Ernst, 2013; López & Ruiz, 2015
Significant wave height (Hs)	0.13	a) 0.59 m < Hs ≤ 6.9 m	0.5	Suitable	0.065	Munk, 1950, in Palomino, et al., 2001; Rubino, 2008; Cavia del Olmo, 2009; Kapetsky, Aguilar & Jenness, 2013; COWI & Ernst, 2013; López y Ruiz, 2015

Criteria	Weight of the criteria	Sub-criteria	Weight of the sub-criteria	Category	*Final weighting	Source
Speed of current (Wc)	0.25	a) 0.13 m/s < Wc ≤ 1 m/s (Medium)	0.5	Suitable	0.125	Milne, 1976; Carroll et al., 2003; Stigebrandt, 2011; Kapetsky, Aguilar & Jenness, 2013; COWI & Ernst, 2013; López & Ruiz, 2015
		b) 0 m/s ≤ Wc ≤ 0.13 m/s (Slow)	0.35	Moderately Suitable	0.087	
Direct destruction	0.30	a) Sediments	0.4	Suitable	0.120	Handy & Poxton, 1993; Boyd, 1995; FAO, 2006; Perez et al., 2008; Herbeck et al., 2013; Rabasso, 2016

*Final weighting=criterion weight x sub-criterion weight.

Once the different criteria have been spatialized, pairs are intersected and suitable and moderately suitable areas are identified from the weightings of each of them (Figure 5).

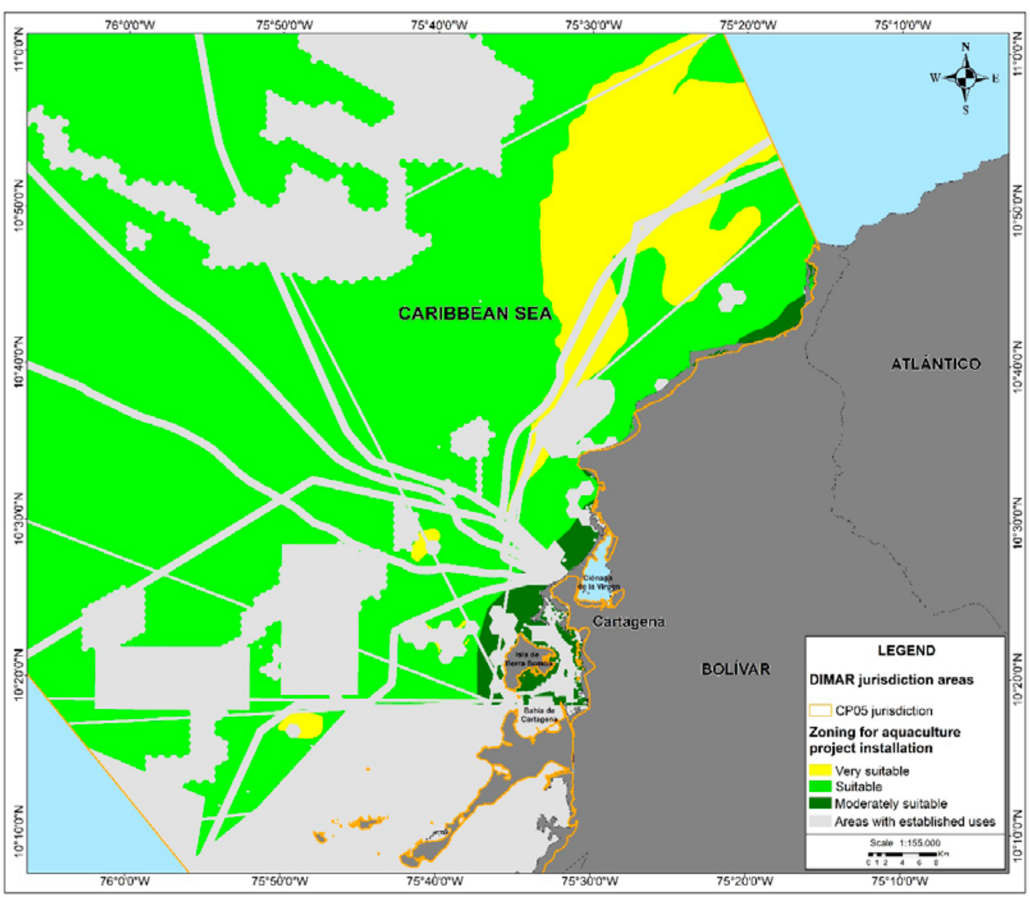

Figure 5. Location map of very suitable, suitable and moderately suitable areas for the development of aquaculture in the study area.

Marinas-piers

For the most optimal location of the marinas-piers, the criteria of wave period, significant wave height, currents, and possible effects on sediments were used (Table 7).

Table 7. Technical and environmental criteria used to establish the most suitable areas for the development of marinas-piers.

Criteria	Weight of the criteria	Sub-criteria	Weight of the sub-criteria	Category	*Final weighting	Source
Wave period (T)	0.15	a) T ≤ 1.9 s	0.5	Suitable	0.075	Munk, 1950, in Palomino, et al., 2001; Cavia del Olmo, 2009; Southern Forrest Products Association, 2014; Ocón, 2014; Bellido & Siesquen, 2018
		b) 1.9 s < T ≤ 359 s	0.35	Moderately Suitable	0.052	
Significant wave height (Hs)	0.20	a) Hs ≤ 0.59 m	0.5	Suitable	0.100	Munk, 1950, in Palomino, et al., 2001; Cavia del Olmo, 2009; Southern Forrest Products Association, 2014; Ocón, 2014; Bellido & Siesquen, 2018
		b) 0.59 m < Hs ≤ 6.9 m	0.35	Moderately Suitable	0.070	
Speed of current (Wc)	0.30	a) 0 m/s ≤ Wc ≤ 0.13 m/s (Slow)	0.5	Suitable	0.150	Kapetsky, Aguilar & Jenness, 2013; Tobiasson & Kollmeyer, 2013; Ocón, 2014
		b) 0.13 m/s < Wc ≤ 1 m/s (Medium)	0.35	Moderately Suitable	0.105	
Direct destruction	0.35	a) Sediments	0.35	Suitable	0.122	Schlacher & Schlacher, 1998; Erftemeijer & Lewis, 2006; Yuk & Aoki, 2007; Dosseto, Buss & Chabaux, 2014

*Final weighting=criterion weight x sub-criterion weight.

Figure 6 shows the suitable and moderately suitable areas for the location of the marinas-piers according to the criteria analyzed.

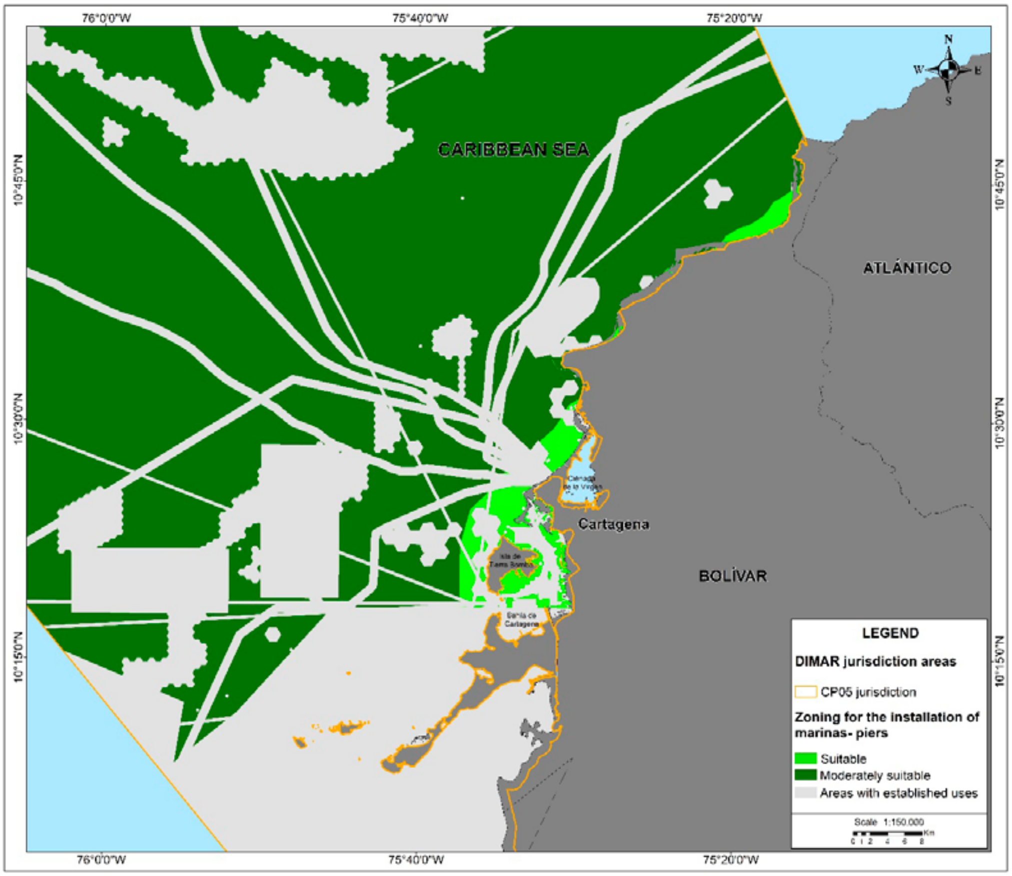

Figure 6. Location map of suitable and moderately suitable areas for the development of marinas-piers in the study area.

Wind farms

The criteria used for the most optimal location of wind farms were depth, currents, significant wave height, wind speed at a height of 150 m, seabed type and slope, in addition to possible effects on sediments (Table 8).

Table 8. Technical and environmental criteria used to establish the most suitable areas for the development of wind farms.

Criteria	Weight of the criteria	Sub-criteria	Weight of the sub-criteria	Category	*Final weighting	Source
Depth (P)	0.25	a) 0 m - 60 m	0.7	Suitable	0.175	Usón, 2014; Fugro Marine GeoServices Inc. 2017; Vagiona & Kamilakis, 2018
		b) > 60 m	0.3	Moderately Suitable	0.075	

Criteria	Weight of the criteria	Sub-criteria	Weight of the sub-criteria	Category	*Final weighting	Source
Seabed type	0.12	a) Sandy	0.5	Suitable	0.060	Boehlert & Gill, 2010; Prado, 2018; Xu et al., 2020
		b) Muddy and silty	0.35	Moderately Suitable	0.042	
Seabed slope (Pf)	0.11	a) 0 % - 3 %	0.5	Suitable	0.055	Resolución MinAmbiente N° 2965, 1995; Malhotra, 2010; Xu et al., 2020
		b) 3 % < x ≤12 %	0.35	Moderately Suitable	0.038	
Speed of current (Wc)	0.03	a) 0 – 1.75 m/s	0.7	Suitable	0.021	Kapetsky, Aguilar & Jenness, 2013; González, 2007; Esteban, 2009; Loughney et al. 2021
		b) > 1.75 m/s	0.3	Moderately Suitable	0.009	
Significant wave height (Hs)	0.04	a) 0 – 5 m	0.5	Suitable	0.020	Loughney et al. 2021
		b) 5 m < Hs ≤ 8 m	0.35	Moderately Suitable	0.014	
Wind speed (V)	0.28	a) >8 m/s	0.8	Suitable	0.224	Baban & Parry 2001; Sesma, 2020
Direct destruction	0.09	a) Sediments	0.5	Suitable	0.045	Mariyasu, 2004; Inger et al, 2009; Wilhelmsson, 2010
Sediment plume generation	0.08	a) Sands	0.6	Suitable	0.048	NOAA, 2007; Vaselli et al, 2008

*Final weighting=criterion weight x sub-criterion weight.

The suitable and moderately suitable areas for the location of wind farms according to the analyzed criteria are shown in Figure 7.

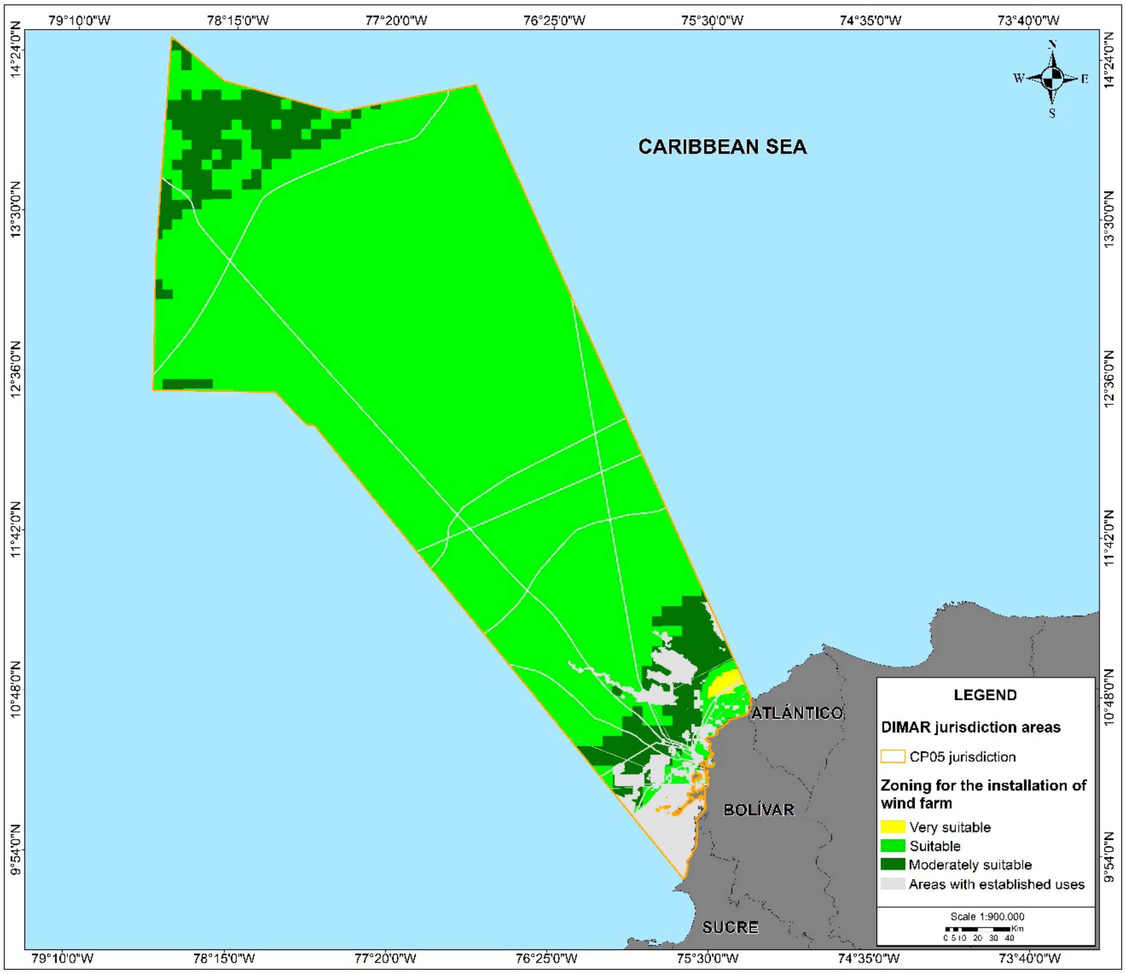

Figure 7. Location map of very suitable, suitable and moderately suitable areas for the development of wind farms in the study area.

Co-location model

The co-location methodology was applied with a hypothetical exercise, in which an aquaculture project was located in an area categorized as suitable for this activity and where there is a marina-pier and wind farm. Taking into account the above, the technical and environmental criteria (designated in the allocation model) were evaluated, and the efficiency and effectiveness variables were defined (proximity to the coast, water quality and use by tourists) between pairs of uses to obtain the expression of compatibility and incompatibility between them (Figure 8).

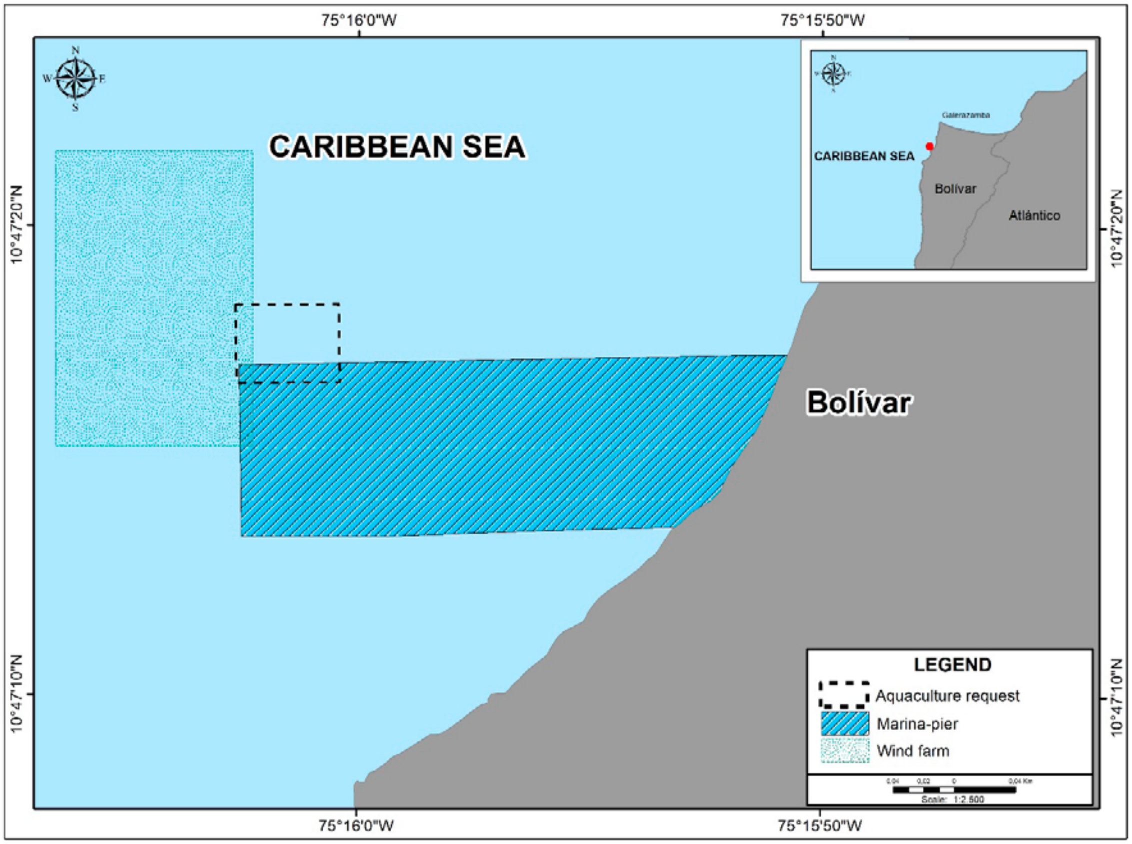

Figure 8. Location map of the (hypothetical) aquaculture project application.

For this analysis, the compatibility criteria were established according to Hennessey and Sutinen (2005) (Table 4) and then, using expert judgment, it was defined: firstly, if there is compatibility/incompatibility between the minimum requirements that are needed for the projects to be developed; and secondly, whether there any positive or negative impacts on the activities of the three uses, by evaluating the efficiency and effectiveness variables between each pair of uses (Table 9).

Table 9. Analysis of the compatibility level of the evaluated uses.

Uses	Compatibility/incompatibility value			Compatibility/ incompatibility
	Technical and environmental sub-criteria	Efficiency and effectiveness variables	Average	
Aquaculture *vs.* Marinas-piers	0	0.25	0.125	Incompatible
Aquaculture *vs.* Wind farms	0	0.75	0.375	Conditionally incompatible
Marinas-piers *vs.* Wind farms	0	0.75	0.375	Conditionally incompatible
Aquaculture *vs.* Marinas-piers *vs.* Wind farms	0	0.58	0.292	Conditionally incompatible

From Table 9 it can be deduced that aquaculture is incompatible with marinas-piers and conditionally incompatible with wind farms. For their part, marinas-piers are conditionally incompatible with wind farms. The intersection of the three uses leads to a conditionally incompatible situation (Figure 9).

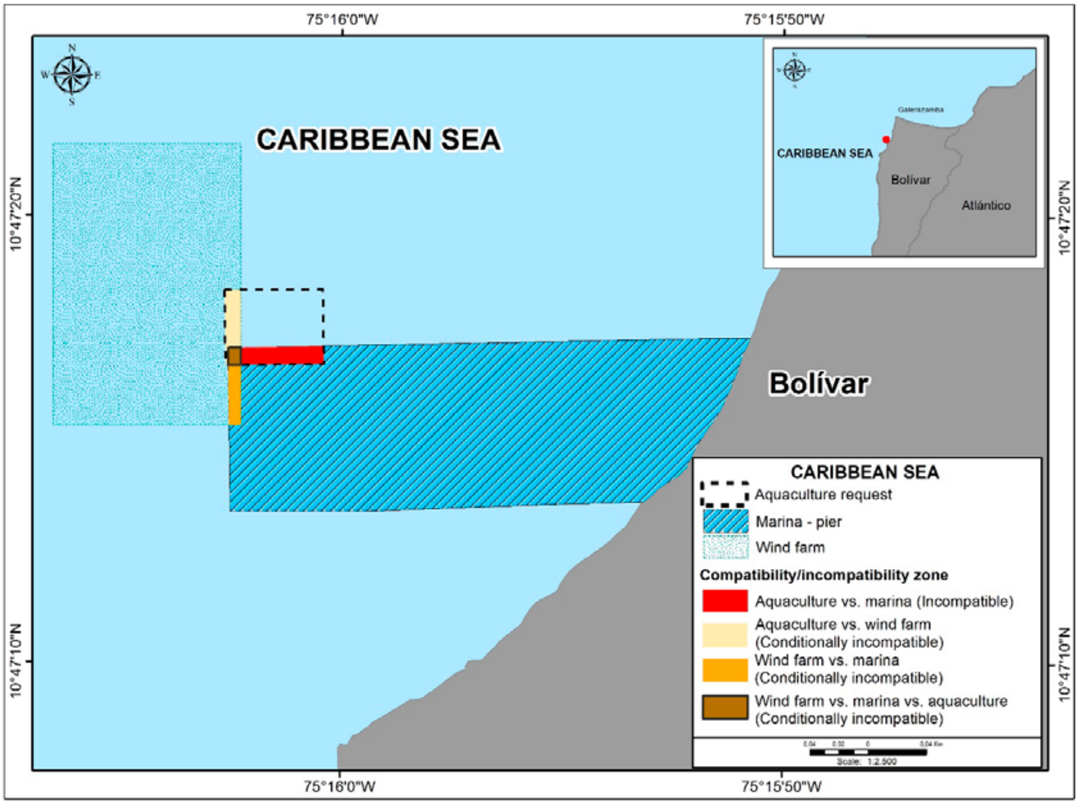

Figure 9. Map of compatible and incompatible zones for the aquaculture project.

The compatibility/incompatibility (Table 9) defined by expert judgment is calculated as the average between the compatibility values of the sub-criteria and the variables (established in the table of Hennessey and Sutinen, 2005), and indicate that the technical and environmental sub-criteria that are needed to perform a use are not the same ones needed for the other two uses, while some of the efficacy and efficacy variables are compatible or conditionally incompatible.

The MAYC model is already proposed for the uses of aquaculture, marinas-piers and offshore wind farms with the respective allocation and co-location analysis; however, a new expert judgment must be carried out in the event that more information on technical-environmental criteria and the efficiency-effectiveness variables is integrated, as well as when including other uses/activities to be analyzed.

Discussion

The planning of marine-coastal spaces requires us to connect different spatial/temporal factors and scenarios that enable the allocation and co-location analysis of the future location of maritime activities in such a way that social, economic, regulatory, technical and environmental aspects are integrated (Ehler, 2008; Ehler and Douvere, 2009; Coccolli *et al*., 2018; Afanador *et al*., 2019).

In accordance with this, the Colombian Maritime Authority, as part of its methodology, analyzed only the technical and environmental criteria related to the physical conditions for the selection of the most suitable site for aquaculture, marinas-piers and wind farms, taking into account that this methodology in the future may include more economic, regulatory and social criteria and aspects related to the activities analyzed. It also evaluates efficiency and effectiveness variables that allow the compatibility and incompatibility between these uses to be established. Although these activities are not currently carried out in these areas, it cannot be ruled out that in the future this type of proposal may be made and users, depending on their needs and capacities, must estimate the costs of operation and logistics.

Different authors have proposed methodologies that seek to assign the best space for the performance and productivity of maritime activities. Currently, the fastest growing food sector is aquaculture: the world demand for seafood is increasing and this is driving research into it, bearing in mind that there are more than 200 species that can be farmed (Calado *et al*., 2010; FAO, 2015; Lovatelli, Aguilar and Soto, 2013; Rubino, 2008). For example, Gentry *et al*., 2016 propose an evaluation of a variety of criteria, including water depth, exposure to waves and jurisdictional limits, to define the planning of this use, depending on the diversity of the species farmed and the environmental conditions of the area (Holmer, 2010; Kapetsky *et al*., 2013; Rubino, 2008). The use of GIS in the field of aquaculture began at the end of the eighties (Kapetsky, 1989; Stelzenmüller, Gimpel, Gopnik and Gee, 2017); since then, analyses have been made to find suitable locations for aquaculture facilities, taking into account a series of physical and chemical parameters, such as salinity, depth, temperature, dissolved oxygen and ammonia, in addition to factors such as proximity to brackish water, communication routes, suppliers, welfare level, land/vegetation use and electric power, among others, which can be specific for each species (Díaz and López, 2000; Hernández, 2017; Ramadhan et. al., 2021).

In the case of aquaculture in the study area, taking into account the evaluated criteria, the suitable areas were found far from the coast, where the currents, wave period and significant wave height are moderate, as this facilitates the exchange of water and fish growth (Carroll *et al*., 2003; Stigebrandt, 2011; Kapetsky, Aguilar and Jenness, 2013; Saling *et al*., 2020, López and Ruiz, 2015). Likewise, the sandy bottom facilitates the installation and stability of the required infrastructure (Cardia, Ciattaglia and Corner, 2017). In environmental terms, this activity generates large accumulations of organic matter as a consequence of the urine and feces of the species, causing changes in the sedimentary chemistry and in the water column (due to the presence of ammonia, sulfides and methane), which affects the physiology of the benthic communities (Handy and Poxton, 1993; Boyd, 1995; FAO, 2006).

Regarding the marinas, based on the criteria analyzed, it was found that their optimal location is close to the coast because there are currents, significant wave height and slow wave periods that help to keep the pier structures stable, and facilitate the entry and docking of boats and their mooring systems (Southern Forrest Products Association, 2014; Bellido and Siesquen, 2018). The possible effects on the environment can be attributed to dredging, coastal fills and the construction of infrastructure, as well as the operation of boats and dredgers that cause small spills of gasoline, oil and petroleum that constitute a source of chemical contamination of the different ecosystems (Schlacher and Schlacher, 1998).

Different authors have taken into account a selection of criteria for this type of construction, such as proximity to a metropolitan area, access to transportation, physical description of the area (topography, vegetation, water depths, contiguous uses, site zoning) and oceanographic factors (Tobiasson and Kollmeyer, 2013; Ocón, 2014; Southern Forrest Products Association, 2014; Bellido and Siesquen, 2018).

The selection of the most suitable areas for wind farms is determined by dynamic conditions that enable the cost of the installation to be established, along with the mooring, anchoring and wiring systems that will be used (Usón, 2014; Vagiona and Kamilakis 2018). One of the most important criteria is the wind speed and direction, as this will enable the turbines to provide electrical energy (Baban and Parry, 2001; Sesma, 2020; Bastidas-Salamanca and Rueda-Bayona, 2021; The Renewables Consulting Group and ERM, 2022). Potential environmental effects are caused by submerged parts of offshore wind substructures causing changes that can have lasting effects on seabed sediments (Mariyasu, 2004). Sands are suitable for constructing wind farms, because when they suffer any physical alteration, they generally recover in days or weeks due to the action of waves and currents (Carter and Lewis, 1995; NOAA, 2007).

GIS tools and multicriteria analysis have been widely used around the world to decide the location of wind farms, taking into account technical, spatial, economic, social and environmental criteria, which may vary depending on the study area, and the availability and quality of information (Chaouachi, Covrig and Ardelean, 2017; Díaz *et al*., 2000; Gavériaux *et al*., 2019; Loughney *et al*., 2020; Bastidas-Salamanca and Rueda-Bayona, 2021; The Renewables Consulting Group and ERM, 2022). In Colombia, different studies have analyzed the potential of wind energy in the country, considering, in addition to technical criteria, variables such as topography, proximity to urban centers, ports and protected areas, agreeing that the Colombian Caribbean Sea, mainly the central-northern region, has characteristics suitable for the development of this type of project (Guerrero-Hoyos *et al*., 2019; Pabón, 2019; Carvajal *et al*., 2019; Bastidas-Salamanca and Rueda-Bayona, 2021). Likewise, the World Bank Group set out a roadmap that establishes the areas of interest for the exploration and estimation of wind capacity in the Colombian Caribbean (The Renewables Consulting Group and ERM, 2022). These areas were evaluated by DIMAR using the methodology of the MAYC model and, in coordination with the Ministry of Mines and Energy, the central Caribbean area was nominated for the development of wind farms through Resolution 40284 of 2022.

Additionally, in the co-location analysis, the efficiency and effectiveness variable of proximity to the coast is necessary for the uses of aquaculture and marinas-piers, since it facilitates their operation and economic development through the exchange of goods and services using roads, airports and ports (Benetti *et al*., 2010; Kapetsky, Aguilar and Jenness, 2013; López and Ruiz, 2015; FAO, 2019). In contrast, offshore wind farms can be located far from the coast, to avoid interfering with maritime traffic routes, strategic naval facilities and spaces of ecological interest, among other uses/activities (WWEA, 2017).

The increase in maritime uses favors the development of methodologies for the co-location of activities based mainly on the use of GIS (Yates *et al*., 2015). Different authors have used these tools to find the best spatial distribution and compatibility among different activities such as fishing, aquaculture and renewable energy, among others, in order to facilitate decision-making focused on management and planning (Yates *et al*., 2015; Di Tullio *et al*., 2018; Kyvelou and Lerapetritis, 2020).

The MAYC methodology is a management instrument in which the establishment of suitable areas is a starting point that will allow decision makers to take advantage of the potential of Colombia’s marine-coastal zones by integrating technical and environmental variables (established in the methodology proposed here) with regulatory, economic and social aspects (to be defined in the future by the decision makers, and which may be included in the model), in order to minimize existing conflicts to the lowest possible level and optimally assign the location of the uses/activities within a geographic space. Due to the above, it is important to take into account that the model must be integrated with different territorial planning tools, such as Local Territorial Ordering Plans, Hydrographic Basin Ordering and Management Plans, Departmental Ordering Plan, among others, and it is therefore necessary to establish links with different stakeholders (public entities, research centers, private companies and academia, among others) who can provide information and feedback for the marine planning process that seeks to turn the country into a bioceanic power (DNP, 2020; Afanador *et al*., 2020).

Conclusions

This methodology was applied in the zones free of uses/activities that represent 93 % of the study area, allowing the identification, based on the criteria analyzed, of the suitable and moderately suitable zones for the location of the aquaculture, marinas-piers and wind farms, while also establishing whether these three activities can be carried out in the same geographical space, through multi-criteria analysis, and the use of GIS-based analytical tools, considering different technical and environmental criteria, as well as efficiency and effectiveness variables.

In the case of aquaculture, it is the use with the greatest future growth trend at a global and national level, due to the projected increases in the production and consumption of fishery products. Taking this into account, it is possible to locate new aquaculture projects in 90.23 % of the study area. The suitable areas are mainly far from the coast, where this activity is facilitated by the currents, wave periods and significant wave heights, and their possible variations depending on the climatic seasons of the Colombian Caribbean.

Currently, worldwide and in Colombia, the aim is to reduce greenhouse gas emissions through the implementation of non-conventional renewable electricity generation. In this regard, 84.18 % of the study area meets the technical and environmental criteria for the installation and operation of offshore wind farm projects.

For its part, 0.39 % of the study area meets the minimum requirements for the installation of marinas/piers, which facilitates that this activity, which is expected to grow in Colombia by approximately 42 % by the year 2028 due to the projected increase in tourism, can be located in an optimal and sustainable way. This is mainly in areas near the coast, where the currents, significant wave heights and slow wave periods allow the construction and maintenance of its infrastructure, as well as the transit of boats.

The MAYC Model was applied with technical-environmental criteria and specific efficiency-effectiveness variables in this study; however, it is possible to carry out other analyses in which more information is updated and integrated.

In the hypothetical exercise of the co-location model, the differences between the technical and environmental criteria analyzed for the uses/activities of aquaculture, marinas-piers and wind farms established that they are not compatible, and therefore cannot be developed within the same geographical space, according to the established methodology.

Finally, the MAYC Model is a tool for the ordering of marine-coastal space by the Colombian Maritime Authority. In this sense, the information obtained is an input to be complemented and integrated into the territorial management processes carried out by the different national, regional and local entities that are related to the coasts and marine areas of the country.

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