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Assessment of the Magdalena River delta socio-ecological system through the Circles of Coastal Sustainability framework

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River-mouth systems and deltas are hotspots where many of the coastal syndromes can be found. Moreover, these systems provide essential ecosystem services (e.g., recreation, food provisioning, protection against natural hazards). The present study focuses on the socio-ecological system at the delta of the Magdalena River in the central Caribbean Region in Colombia. This research seeks to assess the multidimensional sustainability of the Magdalena river-mouth system (MRm-SES) to improve the knowledge basis for its integrated management. To do so, an assessment tool named "Circles of Coastal Sustainability" (CCS) was used to evaluate the system splitting it into four domains (environmental, social, economic and governance) that were divided into 5 categories each. These domains were evaluated through a total of 52 indicators distributed like this: 16 for the Environmental domain, 16 for the Economic domain, 12 for the Social and Cultural domain and, 8 for the Governance domain. The results show that the overall sustainability of the MRm-SES is classified as "Satisfactory." None of the domains is in "Excellent" or "Bad" conditions. However, the evaluation of the categories shows that four (4) of them have "Poor" conditions (i.e., Social Benefits, Demographics, Economic Security, and Resources Management). Hence, it is recommended to put those categories at the centre of the discussion to define management strategies (e.g., Preserving and restoring habitats; tackling sources of pollution and excessive sediment; local reduction of net Greenhouse Gas and adaptation to climate change; participation of local communities in the management design and implementation), without disregarding the interrelation with the other categories and dimensions. Finally, it is argued that despite all the improvement opportunities, the CCS is a valuable tool to evaluate and communicate with different stakeholders (academic community, managers and decision-makers, local communities, etc.), to improve the sustainability of coastal systems in Colombia and the world.

KEYWORDS

socio-ecological system, Magdalena River, Caribbean region, indicators, coastal zone management, sustainability assessment

1 Introduction

The ocean and its related habitats, including the coastal areas, provide benefits to the global community (e.g., climate regulation, coastal protection, food, recreation, transport routes). However, those benefits rely on the maintenance of the natural processes, marine species and ecosystem functioning which can be affected by human activities (United Nations, 2021). Coasts are special habitats in the transitional zone between land and sea forming part of a land-ocean continuum system (Crossland, 2005). Due to its variety of landscapes and matching services, coasts have always been places of particular interest for human settlers. According to the United Nations, 2.8 billion people live within 100 km of the coast (Future Ocean, International Ocean Institute, German Marine Research Consortium, mare, 2017). Consequently, coastal systems are subject to multiple syndromes including sediment unbalance, variation in water flows, eutrophication and contamination due to inputs from inland activities (e.g., industry, agriculture), changes in land-use and destruction of natural cover, urban sprawling, loss of biodiversity, exploitation of non-renewable resources and global change (e.g., climate change and sea-level rise) (Newton et al., 2012). All these syndromes can be connected to 5 main drivers of change that affect the ocean's status, for better or for worse, and they are: population growth and demographics, economic activities, technological advances, changing governance structures and geopolitical instability and climate change (United Nations, 2021).

Along the coast is possible to find river-mouth systems and deltas which are hotspots where many of the coastal syndromes can be found (Newton et al., 2012). Historically, these systems have been profoundly influenced by human activities, for example, agriculture and forestry influence the delta growth due to the negative effects in the basin that increase erosion and sediment transport by the rivers. Another example of human-driven changes in deltas is their subsidence due to the extraction of fluids (e.g., water or oil) that leads to the compaction of the sediment layers reducing its volume and contributing to higher relative sea-level rise rates (Davis and FitzGerald, 2020). Increased urbanization and industrialization, changing hydrogeomorphology, large-scale engineering projects and climate change, among others, are also pressures and hazards for these systems (Elliott et al., 2019).

The present study focuses on the socio-ecological system formed at the main river-mouth (i.e., Bocas de Ceniza) of the Magdalena River (henceforth MRm-SES). The Magdalena River basin is the largest watershed in the northern Andes of South America. Along its axis lives approximately 80% of the population in Colombia and houses 80% of the GDP. The sediment yield for this basin is the highest among the rivers draining in the Caribbean coast and the sediment discharges have the same magnitude of rivers with larger basins (e.g., Paraná, and Orinoco) (Restrepo et al., 2017). Both Exogenic Unmanaged Pressures (ExUP) and Endogenic Managed Pressures (EnMP) affect the Magdalena River delta (Elliott et al., 2017). The former, are those outside the study (or managed) area and their causes cannot be directly tackled within that particular system. However, the system still needs to deal with their consequences or state changes, such as sedimentary unbalance, climate change, eustatic sea-level change, soil denudation/erosion in the basin, sea surface temperature change, plastic litter influxes (transported by marine currents and fluvial fluxes), increased flux of contaminants (e.g., litter and toxic substances) and nutrient inputs from the Magdalena river, among others (Restrepo-Ángel, 2008; Restrepo-Ángel et al., 2015; Restrepo et al., 2016; Tejeda-Benítez et al., 2018; Acosta-Coley et al., 2019; Bustos Usta and Torres Parra, 2021). On the other hand, the Endogenic Managed Pressures (EnMP) are those that occur within the study area and can be directly managed. Some examples are littering and waste generation, nutrients and other contaminants inputs, untreated or inadequately treated wastewater disposal to soil and water bodies, deforestation, infrastructure construction, irruption of sediment inputs and the littoral drift, introduction of alien species, among others (Tosic et al., 2018; Rangel-Buitrago et al., 2019; Chacon et al., 2020; Portz et al., 2020; Torres-Bejarano et al., 2020; Villate et al., 2020; Rangel-Buitrago et al., 2021; Ávila and Gallo, 2021).

The starting point of this research was the question: Is the Magdalena River-mouth socio-ecological system sustainable? Other complementary questions emerged from the main one: What indicators can be used/developed to assess the sustainability of the system? What are the categories/domains that require the most attention/action? Can a socio-ecological assessment of the Magdalena river-mouth system help to improve the management of the study area? Hence, the present study is an attempt to understand the main issues hindering the sustainability of the MRm-SES, leaving behind a sectorial view and moving towards a holistic approach that recognizes not only the multiple interactions that occur within the system but also the existent connections with other compartments that have been commonly managed as separate components (e.g., the river basin and the sea) whereas, in reality, they work as whole system interchanging matter and energy. Identifying and understanding the key issues in the different domains of the system and how these interact with each other, is the first step to inform decision-makers and/or to define strategies for tackling the main problems and move towards a sustainable system.

2 Methodology

2.1 Study area

The Magdalena River delta is arcuate and has an estimated area of 1,690 km^2. After passing through Calamar, the Magdalena River splits and most of the flow (i.e., >90%) continues its course to the main mouth at 'Bocas de Ceniza', near the city of Barranquilla. Additionally, the river has a secondary mouth at Cartagena's and Barbacoas' bay where a 10th of the streamflow is discharged through an artificial structure called "Canal del Dique." The waters from this river also represent an important influx of fresh water for the largest and most complex of Colombia's swamp marshes: the "Cienaga Grande de Santa Marta - CGSM" (Restrepo et al., 2016; Ávila and Gallo, 2021) which is connected to the Magdalena River through various canals and, depending on the climate and hydrological conditions (i.e., dry/wet season along the Magdalena basin) and other forcing variables such as tides and wind, the fluxes on some of these canals can come to a halt or even flow in the opposite direction (i.e., from the Cienaga towards the River). Figure 1 provides a simplified graphical representation of the Magdalena River basin and its connection to the Caribbean Sea.

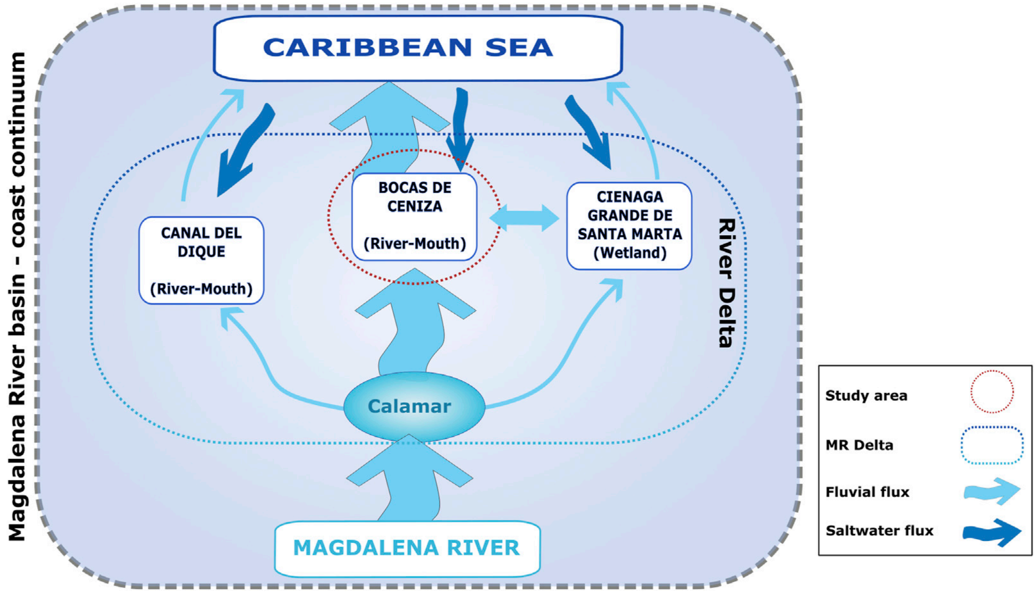

FIGURE 1
The Magdalena River basin—coast continuum. Conceptual diagram.

The delta of the Magdalena River is located in Colombia's central Caribbean region. It is an area of utmost importance for the environmental and socio-economic dynamics of the Caribbean region in Colombia. To illustrate the socio-economic importance of this deltaic system we can consider that the two main cities of the Caribbean region (i.e., Cartagena and Barranquilla Metropolitan Area—BMA) are in this delta. Considering only the population of those two cities (i.e. 3 million people), the Magdalena Delta is home to nearly a quarter of the population in the Caribbean region of Colombia in 2018 (excluding Antioquia) (DANE, 2018). In economic terms, Atlántico and Bolívar produce more than half and nearly 8% of the Colombian Caribbean region and Colombia's GDP during 2018, respectively. (DANE, 2021b).

The present assessment is focused on the socio-ecological system of the Magdalena River delta at 'Bocas de Ceniza', henceforth, referred to as MRm-SES. It covers a stretch of coast which encompasses a 90-km coastline with NE-SW primary orientation and some sectors E-W-oriented (See Figure 2). The study area has an extension of 390,000 ha, 60% corresponds to land and the remaining 40% corresponds to the marine area. Of the total area, a small portion (i.e., 11%) is within the jurisdiction of the Santa Catalina municipality (Bolívar department) whereas most of the study area is located within the administrative boundaries of the Atlántico department. It is important to note that every time a reference to "Study Area" is made in this document, it corresponds to the red polygon in Figure 2 unless otherwise stated.

Delimitation of the study area was, first and foremost, based on environmental aspects, namely, drainage basins discharging its waters to the left margin of the lower Magdalena River (between Calamar and Bocas de Ceniza) and directly to the Caribbean Sea; the continental shelf (i.e., isobath −200 m or 12 nautical miles from the low water line in areas where the continental shelf was very narrow such as in front of 'Bocas de Ceniza'). Further adjustment was done based on administrative aspects (e.g., urban settlements, and municipal and departmental boundaries). In cases where the administrative criteria led to an obvious disruption of a continuous habitat (e.g., "Ciénaga del Totumo" that is shared between the Atlántico and Bolívar departments), preference was given to the environmental criterium.

The Atlántico department is divided into four (4) drainage basins (see Figure 2). The four (4) drainage basins (or hydrographic sub-zones as called by the Institute of Hydrology, Meteorology and Environmental Studies - IDEAM in Colombia) are "Canal del Dique—Right Margin" (Cd-Rm), "Ciénaga de Mallorquin" (CdM), "Direct to the Caribbean" (DtC) and "Western bank of the lower Magdalena" (DtM-LM). A brief description of each of these basins is presented in Table 1.

The present study focuses on the CdM, DtC and DtM-LM drainage basins, considering that the pressures and impacts that are manifested in them can have direct or indirect repercussions on the coastal zone and marine waters. The first basin (i.e., Cd-Rm), in the south of the Atlántico, was excluded since it is part of the "Canal del Dique" subsystem, which is beyond the scope of the present assessment.

2.2 Socio-ecological assessment framework

There are different frameworks for the assessment of socio-ecological systems. However, they are usually focused on either the social domain (e.g., How's Life? The safe and just space for humanity) (OECD, 2020); the environmental domain (e.g., Planetary Boundaries, Ocean Health Index) (Steffen et al., 2015; Halpern, 2020); or in evaluating the causes and responses to particular problems or ecosystem services (e.g., DPSIR, DAPSIWRM and Ecosystem Services Approach) (Patrício et al., 2016; Elliott et al., 2017).

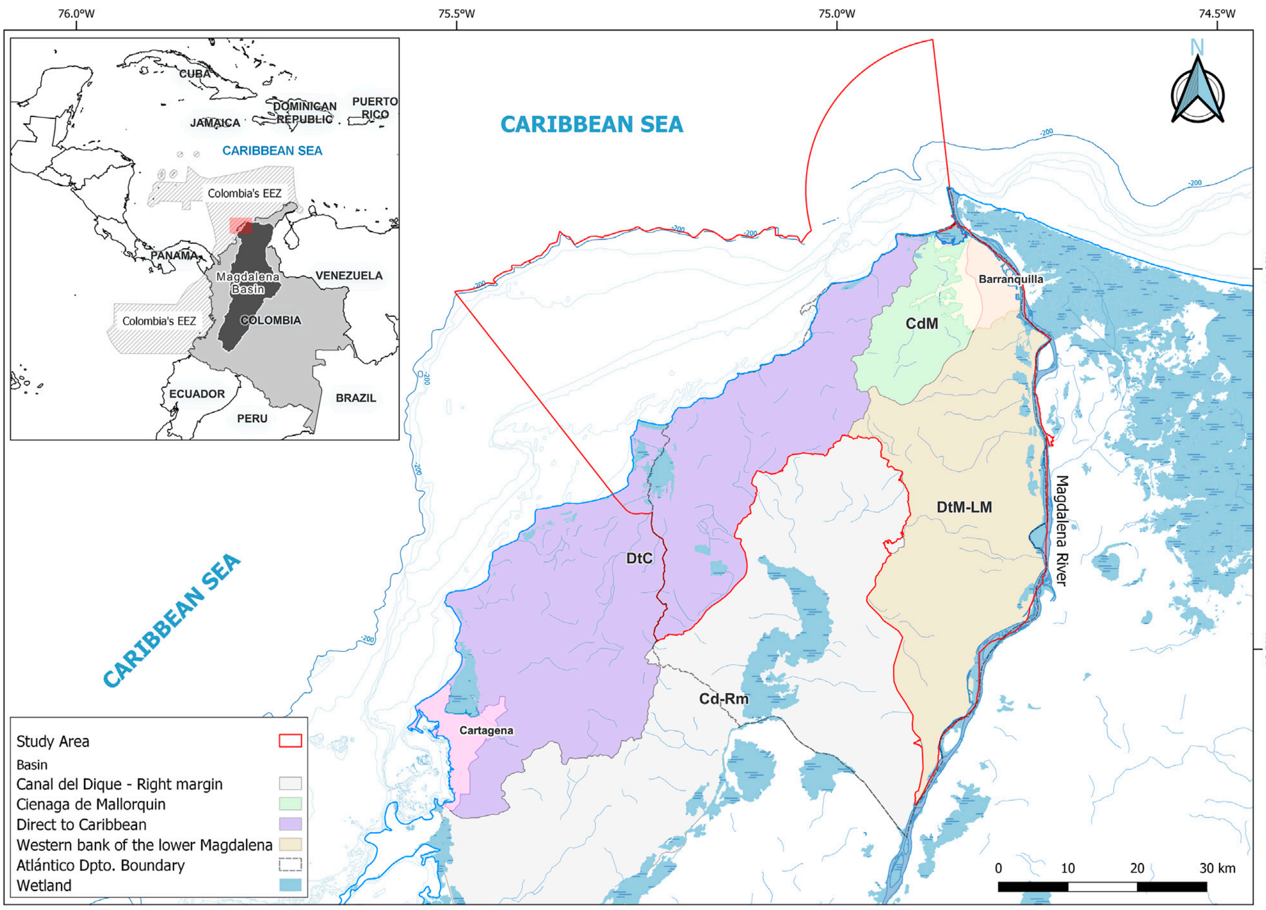

FIGURE 2
Location of the study area (Coordinate Reference System EPSG 4326—WGS 84).

TABLE 1 Drainage basins in the Atlántico department.

Name	Brief description	IDEAM code	Abbreviation in this study
Ciénaga de Mallorquín	The area is 26,000 ha approx. The main watercourse is “Arroyo Grande” whose main tributaries are “Arroyo Granada” and “Arroyo Hondo.” The municipalities of Puerto Colombia, Barranquilla, Galapa, Baranoa, Soledad and Tubará are part of this basin. “Arroyo Hondo” and “Arroyo Santo Domingo” watercourses receive the stormwater and treated wastewater from Barranquilla. Three swamps are in this basin: “Ciénaga de Mallorquín,” “Lago del Cisne” and “Ciénaga de Manatíes”	SZH: 2909	CdM
Direct to Caribbean	Located in the north-western part of the study area it covers eight municipalities of the Atlántico and other municipalities of Bolívar department among which there is Santa Catalina (included in this study). Its total extension is 187,000 ha approx., however, only 82,000 ha (i.e., 44%) are within the study area. This basin contains more than fifteen creeks, and the main swamps are: “Ciénaga del Totumo,” “Ciénaga de Balboa,” “Ciénaga La Redonda,” “Ciénaga El Rodeo,” “Ciénaga Uvero,” “Cienaga de Luruaco,” “Laguna de Puerto Colombia,” among others	SZH: 1206	DtC
Western bank of the lower Magdalena	With an area of 115,000 ha approx. In this basin there are more than eleven swamps and twelve creeks. The main creek in this basin is the “Arroyo Grande.” Most of the creeks in this area drain its waters to any of the swamps that form a wetland complex which is composed for the following water bodies: “Complejo Lagunar de Malambo,” “La Bahía’ swamp, “Ciénaga Grande de Malambo,” “Ciénaga El Convento,” “Ciénaga de Santo Tomás,” “Ciénaga de Sabanagrande,” among others	SZH: 2904	DtM-LM
Canal del Dique	It has an area of 404,000 ha approx. and covers three departments and twenty-five municipalities. Its water drains to Cartagena Bay through an artificial channel named “Canal del Dique”. Important: This basin is out of the scope of the present study	SZH: 2903	CD-RM

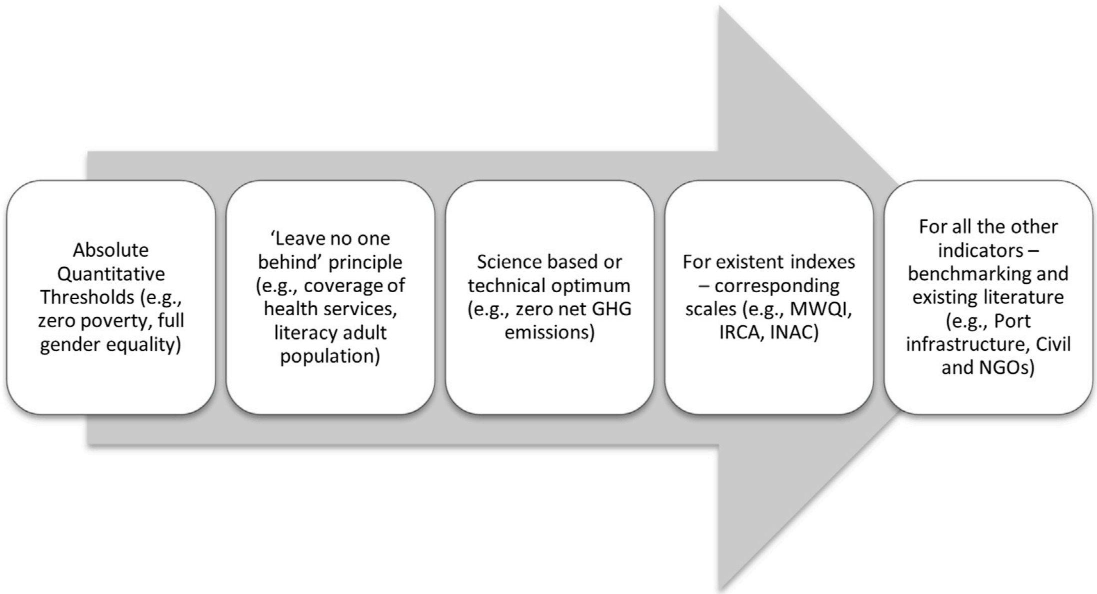

FIGURE 3
Decision tree to define thresholds (upper and lower boundaries) for the indicators. Source: adapted from Sachs et al. (2021).

In other cases, a more holistic approach has been considered (e.g., Circles of Sustainability) (James, 2015). However, that framework was developed for urban environments and does not take into consideration the particularities of the coastal areas which include, among others: natural habitats and their functionality are more relevant in a coastal setting (where both urban and natural areas interact) than it is in an urban area; Hydrodynamics play an important role in shaping the coast; Economic activities at coastal zones are strongly linked to the ocean (i.e., Blue Economy); the fact that coastal zones intrinsically represent the interaction with river basins and the ocean, requires management that goes beyond the traditional administrative or geographic boundaries (e.g., management of fisheries usually requires a regional rather than a local approach). Hence, this study uses an adaptation of the Circles of Coastal Sustainability (CCS) which was developed with the idea of having a multidimensional approach to evaluating coastal systems (de Alencar et al., 2020).

The CCS was developed to assess the "*critical processes that facilitate/constrain sustainability of the world's coastal zones. The (. . .) framework can support management by identifying key features that influence environmental sustainability and human wellbeing*" (P. de Alencar et al., 2020). To achieve this, the CCS relies on a transdisciplinary approach that involves four (4) domains: Environment, Society and Culture, Economy, and Governance. Those domains are divided into five (5) categories and, each category can be divided into different sub-categories allowing the assessment to account for the distinct levels of resilience, resistance, and hysteresis of local conditions (de Alencar et al., 2020).

The CCS was constructed in a way where domains and categories should remain invariable to avoid "*reductionist efforts focused on individual components that can overlook critical interactions.*" That is, the four (4) domains and the five (5) categories within each domain should be kept for all cases were CCS is used to evaluate the sustainability of a coastal system. However, subcategories and their indicators can be selected or created upon local specificity and data availability which allows its adaptation to different coastal areas of the world, even though the framework was developed and first applied in the context of a developed country of the European Union (de Alencar et al., 2020). In other words, some of the indicators used in the present study might not be applicable to other systems either because there are different biophysical characteristics (e.g., "Tropical Dry Forest cover change" is not and useful indicator in middle-latitudes systems) or because the information is not available (e.g., "Livelihood diversification Index" might no be used in other systems).

In this adaptation for the Magdalena delta, a semi-quantitative approach is used to assign the scores for most of the indicators with the purpose of reducing the bias that comes from scoring them based on expert qualitative judgement (i.e., four of them were scored based on expert judgement). Specifically, in this study, preponderance is given to less subjective criteria, favouring reference values which are defined following the decision tree shown in Figure 3 where the Absolute Quantitative Thresholds are preferred (e.g., zero poverty) to benchmarking or qualitative comparison against existing literature or based on expert judgement (e.g., Port Infrastructure) which is the last resource to use in absence of adequate quantitative indicators.

Additionally, the idea of establishing categorical values for the chosen indicators guarantees that the application of this framework in similar systems (i.e., given the same or similar indicators can be used) can be conducted by different subjects/organizations leading to the same or very similar results.

2.2.1 Subcategories and indicators for the MRm-SES

The CCS framework allows the selection of sub-categories and indicators that are adapted to the local context. A list with

TABLE 2 Indicators used for the present assessment with their corresponding data sources. Note: colours indicate the different domains as follows: Environmental (Green), Social and cultural (Blue), Economy (Orange) and, Governance (Yellow). The colour coding is kept throughout the document.

Category	Sub-category	Indicators	References and data sources
1. Alterations of landscapes	Land	Land cover change (%) (i.e., Tropical Dry Forest—TDF)	Schubert et al., 2018; Aldana-Domínguez et al., 2019
	Shoreline	Shoreline hardening (or armouring)	Rangel-Buitrago et al. (2018)
2. Ecosystem function	Biodiversity loss	Proportion of threatened species	Minambiente, 2017; OHI, 2022
	Ecosystem services	Natural hazard regulation	Halpern et al., 2012; OHI, 2022
	Biodiversity protection	Share of protected areas	CBD (2012)
3. Global environmental change	Climate change: SLR	Sea-level change	IDEAM, PNUD, MADS, DNP, Cancillería (2017)
	Climate change: SST	Sea surface temperature change	COLOMBIA. Ministerio de Ambiente y Desarrollo Sostenible, 2015; IDEAM, PNUD, MADS, DNP, Cancillería, 2017; Bindoff et al., 2019
	Climate change: Atmospheric temperature change	Atmospheric temperature change	COLOMBIA. Ministerio de Ambiente y Desarrollo Sostenible, 2015; IDEAM, PNUD, MADS, DNP, Cancillería, 2017; Bindoff et al., 2019
	Climate change: Precipitation change	Precipitation changes	; Bindoff et al., 2019
	Climate change: GHG	Per Capita Net Greenhouse Gas (GHG) emissions per year	IDEAM, PNUD, MADS, DNP, Cancillería, 2016; DANE, 2018; UNEP, 2021
	Natural change	Frequency of extreme events	COLOMBIA. Ministerio de Ambiente y Desarrollo Sostenible, 2015; IDEAM, IAvH, IGAC, INVEMAR, Minambiente, 2017
4. Shifts in hydrodynamics	Waves	Absolute Wave Energy Flux change	Orejarena-Rondón et al. (2022)
5. Biogeochemical and physical flows	Freshwater contaminants	Freshwater Suspended Sediment Load (SSL)	Restrepo et al., 2017; Restrepo-Ángel et al., 2018
	Water quality status	Marine Water Quality Index (MWQI)	INVEMAR (2021)
	Freshwater cycles	Water Regulation Index (WRI)	IDEAM (2019)
	Sediment cycles	Erosion/accretion rates	INVEMAR, 2017; Rangel-Buitrago et al., 2017
1. Societal benefits	Goods and services	Fish stock under the status of "Collapsed" and "Over-exploited"	Page et al., 2020; OHI, 2022
2. Demographics	Population growth	Coastal population growth rate	DANE (2018)
	Social class	Incidence of income poverty	DANE (2022)
3. Social wellbeing	Subjective wellbeing	Subjective wellbeing	DANE (2019)
	Food security	Prevalence of food insecurity	UNAL, INS, ICBF (2020)
	Water security	Water Quality for Human Consumption Risk Index—IRCA	Minsalud (2020)
	Health	Coverage of essential health services	DANE (2019)
4. Identity	Sense of self	Inter-census change in the ethnic population	DANE (2021a)
	Sense of place	Lasting special places/traditions	CITUR, 2012, 2014; OHI, 2022
5. Social resilience	Education	Literacy rate of adult population	DANE (2019)
	Climate Change Adaptation	Relative Effort Indicator—IER	DNP (2021)
	Risk Management	Preventive risk management investement	DNP (2021)
1. Security	Livelihoods	Relative change of ocean-related activities' GDP	DANE, 2021b; OHI, 2022
	Income Gender Gap	Gender wage gap	DNP, 2019; ONU Mujeres, DANE, CPEM, 2020
	Employment patterns	Unemployment rate	DANE (2022)

(Continued on following page)

TABLE 2 (*Continued*) Indicators used for the present assessment with their corresponding data sources. Note: colours indicate the different domains as follows: Environmental (Green), Social and cultural (Blue), Economy (Orange) and, Governance (Yellow). The colour coding is kept throughout the document.

Category	Sub-category	Indicators	References and data sources
2. Infrastructure	Energy supply	Share of electricity generated from renewable sources AND Share of households with access to electricity	DANE, 2018; UPME, 2019; IEA, 2021
	Tourism	Relative change in occupancy rate in commercial accommodation	MinCIT (2021)
	Transport	Percentage of goods transported by transport mode	COLOMBIA. Ministerio de Ambiente y Desarrollo Sostenible (2015)
	Access	Port infrastructure ANDQuality of roads	SuperTransporte, 2019; Patiño M., 2019; Gobernación del Atlántico, 2020; Puerto de Barranquilla, 2021; INVIAS, 2022
3. Economic wellbeing	Equality	GINI Index	DANE (2018)
	Housing	House affordability	Torres Ramírez, 2012; DANE, 2017; OECD, 2020
4. Industry	Renewable	Percentage of GVA generated by activities/sectors relying on Renewable resources	DANE (2021b)
	Extractive	Ratio Extractive/Renewable activities AND Relative change in GVA from "Agriculture, livestock and fishing"	DANE (2021b)
5. Dependency	Resource	Relative change of overall workforce within blue economy	DANE (2021b)
	Diversity	Livelihood diversification in small-scale fishing households	Maldonado et al. (2022)
1. Organisation	Civil and NGOs	Civil and NGOs number	CRA, 2014; CRA and ASOCARS, 2014; CRA, 2015; ANT, 2021; Mintic, 2022
2. Law and justice	Law and justice	Existence of and Integrated Coastal Zone Management (ICZM)	Botero et al., 2020; CRA, 2020
	Norms	Existence of norms regarding ICM	Botero et al., 2020; CRA, 2020
3. Representation and power	Participation in elections	Voter turnout	Registraduría Nacional del Estado Civil, 2022; MOE, 2019
	Women representation	Percentage of women in politics	MOE, 2018; Vicepresidencia de la República, 2022
4. Legitimacy and accountability	Corruption	National Anticorruption Index (INAC)	Secretaria de Transparencia (2022)
5. Resource management	Management plans	Existence operative instruments for the management of natural resources	CRA, 2016; COLOMBIA. Minambiente, 17/April/2017, CRA, 2020
	Decentralization of power	Decentralization and existence of public competencies	Botero et al. (2020)

52 indicators (i.e., 16 for the environmental domain, 12 for the social domain, 16 for the economy domain and, 8 for the governance domain) was chosen for the Magdalena River mouth (see Table 2) more information can be found in the Supplementary Material (Table 2 - CCS Magdalena River-mouth Summary).

Where possible, the chosen indicators correspond to those officially used at the national or international level (e.g., OECD or SDG indicators). Where insufficient data was available for an official indicator, or to close data gaps, other metrics from secondary and unofficial providers were selected. *"The selection criteria included the practicability of each indicator, the availability of data to support them, and the communicability of the information conveyed by them to managers and other stakeholders"* (de Alencar et al., 2020).

2.3 Sustainability score: Defining thresholds, normalization, weighting, and aggregation

Sustainability scores or levels for each indicator range from one (1) to five (5) where the lowest score represents the worst condition and is described as "Bad" and the highest score is obtained when the system presents optimal conditions and is considered 'Excellent', in-between is possible to find the "Poor" (Score = 2), "Satisfactory" (Score = 3) and "Good" (Score = 4) levels. Calculating a sustainability score for the domains, categories and indicators involves the following steps: (i) establishing sustainable or performance thresholds; (ii) rescale the data to ensure comparability across indicators (normalization); (iii) aggregating the indicators within subcategories and categories.

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TABLE 3 Categorical scales to normalize the scores from the quantitative indicators of all domains. Notes: NA is written in those indicators that were evaluated using a qualitative approach. In cases where values can be either positive or negative, they are related to "gain" or "losses," respectively. For instance, a value of—0.5%/y in the "Land-cover change" indicates a yearly reduction of Tropical Dry Forest with respect to a reference condition.

Indicator	Measurement unit	Justification upper or lower bounds	Worst (Lower bound)	Best (optimum)	Bad	Poor	Satisfactory	Good	Excellent
Land cover change (i.e., TDF)	%/y	SDG Target	−1.5	0.5	x < −0.5	−0.5 < x ≤ - 0.05	−0.05 < x < 0.05	0.05 ≤ x < 0.275	x ≥ 0.275
Shoreline hardening (or armouring)	%	Technical optimum	100	0	x ≥ 70	50 < x ≤ 70	30 < x ≤ 50	10 < x ≤ 30	x ≤ 10
Proportion of threatened species	%	Technical optimum	75	0	x ≥ 55	35 < x ≤ 55	15 < x ≤ 35	5 < x ≤ 15	x < 5
Natural Hazard Regulation	%	Technical optimum	0	100	x ≤ 30	30 < x ≤ 50	50 < x ≤ 70	70 < x ≤ 90	x > 90
Protected areas	%	Adapted Aichi targets	0	30	x ≤ 5	5 < x ≤ 10	10 < x ≤ 15	15 < x ≤ 20	x > 20
Sea-level change rate compared to global average	%	Adapted from IPCC Sixth Assessment Report	100	0	x > 50	30 < x ≤ 50	10 < x ≤ 30	0 < x ≤ 10	x < 0
Sea surface temperature change	°C	Adapted from IPCC Sixth Assessment Report	3	0	x > 2.0	1.5 < x ≤ 2.0	1.0 < x ≤ 1.5	0.5 < x ≤ 1.0	x ≤ 0.5
Atmospheric temperature change	°C	Paris Agreement	2	0	x > 2.0	1.5 < x ≤ 2.0	1.0 < x ≤ 1.5	0.5 < x ≤ 1.0	x ≤ 0.5
Rainfall change	%	Adapted from TCNCC	50	0	$\lvert x \rvert > 40$	$20 < \lvert x \rvert \le 40$	$10 < \lvert x \rvert \le 20$	$5 < \lvert x \rvert \le 10$	$\lvert x \rvert \le 5$
Net GHG emissions per year	ton CO2e/capita	Technical optimum	20	0	x > 4	3 < x ≤ 4	2 < x ≤ 3	0 < x ≤ 2	x ≤ 0
Extreme events trends (slope)	Dimensionless	Arbitrary value	1	0	NA	x > 0.5	−0.5 < x ≤ 0.5	x < −0.5	NA
Wave Energy Flux	%	Arbitrary value	50	0	$\lvert x \rvert > 40$	$20 < \lvert x \rvert \le 40$	$10 < \lvert x \rvert \le 20$	$5 < \lvert x \rvert \le 10$	$\lvert x \rvert \le 5$
Freshwater Suspended Sediment Load	%	Arbitrary value	50	0	$\lvert x \rvert > 40$	$20 < \lvert x \rvert \le 40$	$10 < \lvert x \rvert \le 20$	$5 < \lvert x \rvert \le 10$	$\lvert x \rvert \le 5$
Marine Water Quality Index	Dimensionless	Index scale	0	100	x ≤ 25	25 < x ≤ 50	50 < x ≤ 70	70 < x ≤ 90	x > 90
Freshwater streamflow variability	Dimensionless	Index scale	0	1	x ≤ 0.50	0.50 < x ≤ 0.65	0.65 < x ≤ 0.75	0.75 < x ≤ 0.85	x > 0.85
Erosion/accretion rates	m/y	Benchmarking	−1.5	1.5	x ≤ −1.5	−1.5 < x ≤ - 0.2	−0.2 < x < 0.2	0.02 ≤ x < 1.5	x ≥ 1.5
Catch by stock status	%	Technical optimum	100	0	x > 50	35 < x ≤ 50	20 < x ≤ 35	5 < x ≤ 20	x ≤ 5
Coastal population growth rate	%/y	Arbitrary value	5	0	x > 1.5	1.0 < x ≤ 1.5	0.5 < x ≤ 1.0	0.1 < x ≤ 0.5	0 < x ≤ 0.1
Incidence of income poverty	%	SDG Target	30	0	x ≥ 20	20 > x ≥ 15	15 > x ≥ 10	10 > x > 5	x ≤ 5
Subjective wellbeing	Dimensionless	Index scale	0	10	x < 2.5	2.5 < x < 5.0	5.0 < x < 7.0	7.0 < x < 9.0	x > 9.0
Prevalence of food insecurity	%	Leave no one behind	100	0	x ≥ 50	30 < x ≤ 50	15 < x ≤ 30	5 < x ≤ 15	x ≤ 5
Water Quality for Human Consumption Risk Index - IRCA	Dimensionless	Index scale	100	0	80.1 ≤ x ≤ 100.0	35.1 ≤ x ≤ 80.0	14.1 ≤ x ≤ 35.0	5.1 ≤ x ≤ 14.0	x ≤ 5.0
Coverage of essential health services	%	Leave no one behind	0	100	x ≤ 50	50 < x ≤ 65	65 < x ≤ 80	80 < x ≤ 95	x > 95
Inter-census change in the ethnic population	p.p	Arbitrary value	−5	NA	x< − 2.0	−2.0 < x ≤ −0.5	−0.5 < x ≤ 0.0	0.0 < x ≤ 0.5	x > 0.5

(Continued on following page)

TABLE 3 (*Continued*) Categorical scales to normalize the scores from the quantitative indicators of all domains. Notes: NA is written in those indicators that were evaluated using a qualitative approach. In cases where values can be either positive or negative, they are related to "gain" or "losses," respectively. For instance, a value of—0.5%/y in the "Land-cover change" indicates a yearly reduction of Tropical Dry Forest with respect to a reference condition.

Indicator	Measurement unit	Justification upper or lower bounds	Worst (Lower bound)	Best (optimum)	Bad	Poor	Satisfactory	Good	Excellent
Lasting special places/traditions	NA	NA - Qualitative	NA	NA	NA	NA	NA	NA	NA
Literacy rate of adult population	%	Leave no one behind	0	100	$x \le 50$	$50 < x \le 65$	$65 < x \le 80$	$80 < x \le 95$	$x > 95$
Relative Effort Indicator - IER	Dimensionless	Technical optimum	0	1	$x \le 0.40$	$0.40 < x \le 0.6$	$0.6 < x \le 0.8$	$0.8 < x \le 1$	$x > 1$
Preventive risk management investment	%	Arbitrary value	0	60	$x < 15$	$15 < x \le 30$	$30 < x \le 45$	$45 < x \le 60$	$x > 60$
Relative change of ocean-related activities' GDP	Dimensionless	Adapted from OHI	0	1	$x < 0.50$	$0.50 < x \le 0.70$	$0.70 < x \le 0.85$	$0.85 < x \le 0.95$	$x > 0.95$
Gender wage gap	p.p	Technical optimum	40	0	$x > 20$	$14 < x \le 20$	$8 < x \le 14$	$0 < x \le 8$	$x = 0$
Unemployment rate	%	Adapted SDG Index	26	0.5	$x > 10$	$7.5 < x \le 10$	$5 < x \le 7.5$	$2.5 < x \le 5$	$x \le 2.5$
Access to electricity	%	Leave no one behind	0	100	$x \le 20$	$20 < x \le 40$	$40 < x \le 60$	$60 < x \le 80$	$x > 80$
Share of energy generated from renewable sources	%	WEO 2021—NZE	20	88	$x \le 20$	$20 < x \le 40$	$40 < x \le 60$	$60 < x \le 80$	$x > 80$
Relative change in occupancy rate in commercial accommodation	p.p	Adapted from EC ETIS 2016	50	0	$\|x\| > 50$	$30 < \|x\| \le 50$	$15 < \|x\| \le 30$	$5 < \|x\| \le 15$	$\|x\| \le 5$
Percentage of goods transported by transport mode	NA	NA - Qualitative	NA	NA	NA	NA	NA	NA	NA
Port infrastructure	NA	NA - Qualitative	NA	NA	NA	NA	NA	NA	NA
Quality of roads	%	Technical optimum	0	100	$x \le 30$	$30 < x \le 50$	$50 < x \le 70$	$70 < x \le 90$	$x > 90$
GINI Index	Dimensionless	Benchmarking	0.7	0.25	$x \ge 0.55$	$0.45 < x \le 0.55$	$0.35 < x \le 0.45$	$0.25 < x \le 0.35$	$x \le 0.25$
Household income devoted to housing costs	%	Benchmarking	70	20	$x > 40$	$30 < x \le 40$	$20 < x \le 30$	$15 < x \le 20$	$x < 15$
Percentage of GVA generated by activities/ sectors relying on Renewable resources	%	Arbitrary value	0	70	$x < 25$	$25 < x \le 45$	$45 < x \le 65$	$65 < x \le 75$	$x > 75$
Ratio Extractive/Renewable activities	Dimensionless	Arbitrary value	2	0.2	$x > 1.75$	$1.25 < x \le 1.75$	$0.75 < x \le 1.25$	$0.25 < x \le 0.75$	$x < 0.25$
Relative change in GVA from 'Agriculture, livestock and fishing'	Dimensionless	Adapted from OHI	0	1	$x < 0.50$	$0.50 < x \le 0.70$	$0.70 < x \le 0.85$	$0.85 < x \le 0.95$	$x > 0.95$
Relative change of overall workforce within blue economy	Dimensionless	Adapted from OHI	0	1	$x < 0.50$	$0.50 < x \le 0.70$	$0.70 < x \le 0.85$	$0.85 < x \le 0.95$	$x > 0.95$
Livelihood diversification in small-scale fishing households	Dimensionless	Technical optimum	0	1	$x < 0.15$	$0.15 < x \le 0.30$	$0.30 < x \le 0.45$	$0.45 < x \le 0.60$	$x \ge 0.60$
Civil and NGOs number	Dimensionless	NA - Qualitative	NA	NA	NA	NA	NA	NA	NA

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TABLE 3 (*Continued*) Categorical scales to normalize the scores from the quantitative indicators of all domains. Notes: NA is written in those indicators that were evaluated using a qualitative approach. In cases where values can be either positive or negative, they are related to "gain" or "losses," respectively. For instance, a value of—0.5%/y in the "Land-cover change" indicates a yearly reduction of Tropical Dry Forest with respect to a reference condition.

Indicator	Measurement unit	Justification upper or lower bounds	Worst (Lower bound)	Best (optimum)	Bad	Poor	Satisfactory	Good	Excellent
Existence of policy and norms regarding ICZM	Dimensionless	Benchmarking	0	5	x = 1	x = 2	x = 3	x = 4	x = 5
Voter turnout	%	Leave no one behind	0	100	x ≤ 20	20 < x ≤ 40	40 < x ≤ 60	60 < x ≤ 80	x > 80
Percentage of women in politics	%	SDG Target	0	50	x ≤ 15	15 < x ≤ 25	25 < x ≤ 35	35 < x ≤ 45	45 < x ≤ 55
National Anticorruption Index (INAC)	Dimensionless	Index scale	0	100	x ≤ 25	25 < x ≤ 50	50 < x ≤ 75	75 < x ≤ 95	x > 95
Existence operative instruments for the management of natural resources	%	Leave no one behind	0	100	x ≤ 25	25 < x ≤ 50	50 < x ≤ 75	75 < x ≤ 95	x > 95
Decentralization and existence of public competencies	Dimensionless	Benchmarking	0	5	x = 1	x = 2	x = 3	x = 4	x = 5

2.3.1 Establishing sustainability thresholds

The upper boundary or ideal conditions for each indicator were determined using a decision tree based on the methodology from Sachs et al. (2021) (see Figure 3). Each indicator distribution was censored so that all values exceeding the upper bound scored five (5), and values below the lower bound scored one (1).

It was difficult to define a quantitative scale and ranges for the discretization for four (4) of the indicators. Therefore, a set of conditions based on available literature and expert judgment were used to assign the score. Due to the high uncertainty and subjectivity of this qualitative approach, the indicators using that scoring method were only assessed within the intermediate categories (i.e., Poor, Satisfactory and Good). In other words, they could not achieve an "Excellent" or "Bad" status.

2.3.2 Normalization

To make the data comparable across indicators, "Categorical scales" were defined for the majority of the indicators (OECD and JRC, 2008). Ranges of values were established (i.e., brackets) within the upper and lower limits of each variable/indicator that correspond to a score on the CCS framework scale that goes from one (1) to five (5) as explained above. The categorical ranges defined for each of the quantitative variables are shown in Table 3.

For those indicators where "leave no one behind" (UN Sustainable Development Group, 2022) was chosen as an optimum, a categorical scale was established based on an adaptation from Sachs et al. (2021). Not all indicators received the same brackets division but, the divisions were established in a way that rewards the best performing system and penalises the worst.

Only a few indicators did not require any normalization because in their original source they were already scored from 1 to 5 (i.e., Existence of policy and norms regarding ICZM; Decentralization and existence of public competencies) or because they were scored qualitatively (i.e., "Lasting special places/traditions"; "Percentage of goods transported by transport mode"; "Port infrastructure" and "Quality of roads'; and "Civil and NGOs").

2.3.3 Weighting

The general idea behind the CCS framework is that every category and domain is equally important. Therefore, it would not be necessary to assign weights to the different variables, that is, all categories and domains have the same weight (i.e., 0.2 each of the categories within the domains and 0.25 for each of the domains).

Despite of this, in terms of scale and availability of information in the system, there are some differences. For this reason, a method of weighting the scores according to the area within each administrative division and the population was adopted. In other words, in those cases where the information available is disaggregated at the municipal or department level, those jurisdictions with a larger area or population will have more weight in the final score.

2.3.4 Aggregation

To define sustainability in its different domains, the framework relies on a bottom-up approach where the sustainability score is first assigned to the indicators from each subcategory. The score of each subcategory is calculated as the 'median' of its composing indicators

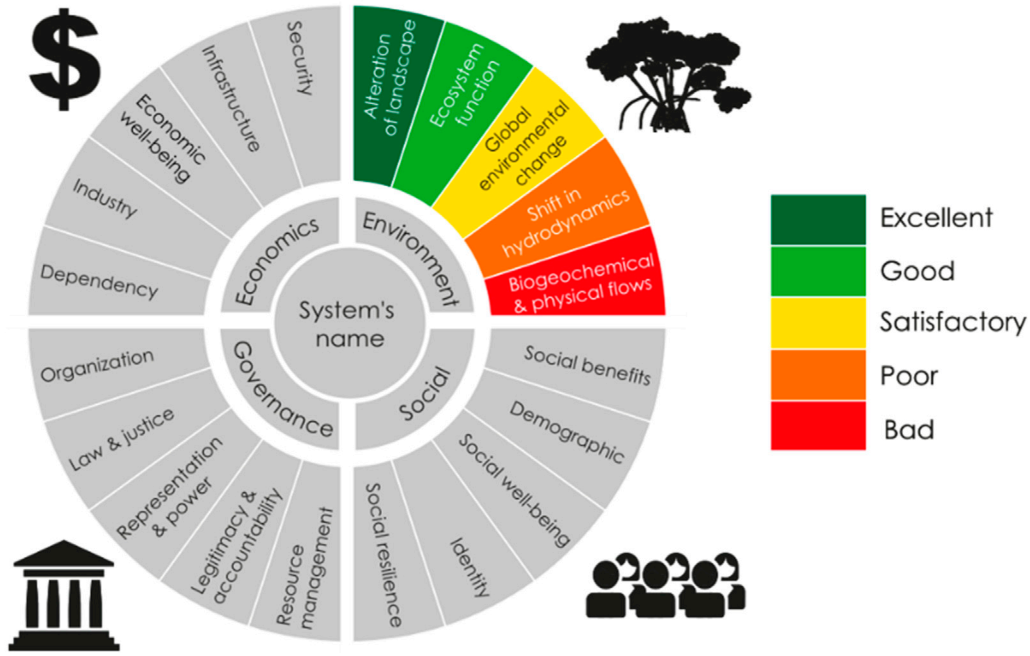

FIGURE 4
Graphical representation of the CCS framework showing the four (4) domains with their respective categories (5).

and so on. This means each domain will have a sustainability score calculated as the 'median' of the five categories that belong to it.

Unlike what was proposed by P. de Alencar et al. (2020), an overall score for the system was defined for the present case study. Now, understanding that none of the domains is superior or inferior to the others, the final score of the system corresponds to the lowest score within its four domains. For example, if the "Economy," 'Socio-cultural' and 'Environmental' domains were scored five (5), but the "Governance" received a score of two (2), then the overall sustainability for the system would be two (2).

2.3.5 Communication

For science communication with stakeholders from different levels and contexts (e.g., decision-makers, academy, public in general) the sustainability score from each category, domain, and system, in general, is represented in a bull-eye-like figure using a different colour matching each level of sustainability as shown in Figure 4.

3 Results

For the assessment of the Magdalena River mouth, a total of fifty-two indicators were chosen. Their distribution among the four domains of the CCS framework is represented in Figure 5. The 'Economy' and "Environmental" domains have the highest number of indicators, both with sixteen (16), followed by the "Society" domain comprising twelve (12) indicators. Finally, the complexity of defining quantitative measures for "Governance" is reflected in the small number of indicators (i.e., only 8).

Using the information presented for each indicator (see Table 4) and taking as a reference the categorical scales defined in the methodology (see Table 3), a sustainability score was assigned to all the indicators. Then they were aggregated by subcategory and, subsequently, by category to obtain the results shown in Table 5. An extended version of this table, with a brief description of the results for each indicator and its corresponding score, is presented as an appendix (see Supplementary Material).

The domain with the higher number of indicators scoring "Bad" was the Environmental domain with four out of 16 (i.e., Land Cover Change, Protected areas, Atmospheric temperature change and Freshwater suspended sediment load) followed by the Socio-cultural domain with three indicators in the same sustainability level (i.e., Incidence of Income poverty, Prevalence of food insecurity and Relative Effort towards climate change adaptation). On the contrary, the Economy domain presented only one indicator scoring "Bad" (i.e., Gender wage gap) while having the most indicators in the "Excellent" sustainability level, a total of 5 out of 16 (i.e., Relative change of ocean-related activities; Access to electricity; Relative change in occupancy rate in commercial accommodation; Relative change in GVA from "Agriculture, livestock and fishing"; Relative change of overall workforce within the blue economy). Finally, most of the indicators from the Governance domain stayed in the middle scores of the sustainability scale, namely, five out of 8 scores 'Satisfactory'. Only one of the indicators in this domain (i.e., Operative instruments for natural resources management) was scored as "Bad." Overall, the highest proportion of the indicators (i.e., 16 out of 52 - equivalent to 31%) received a "Satisfactory" score, while the lowest proportion correspond to the indicators that scored 'Excellent' (i.e., 8 out of 52 - equivalent to 15%) (see Figure 6).

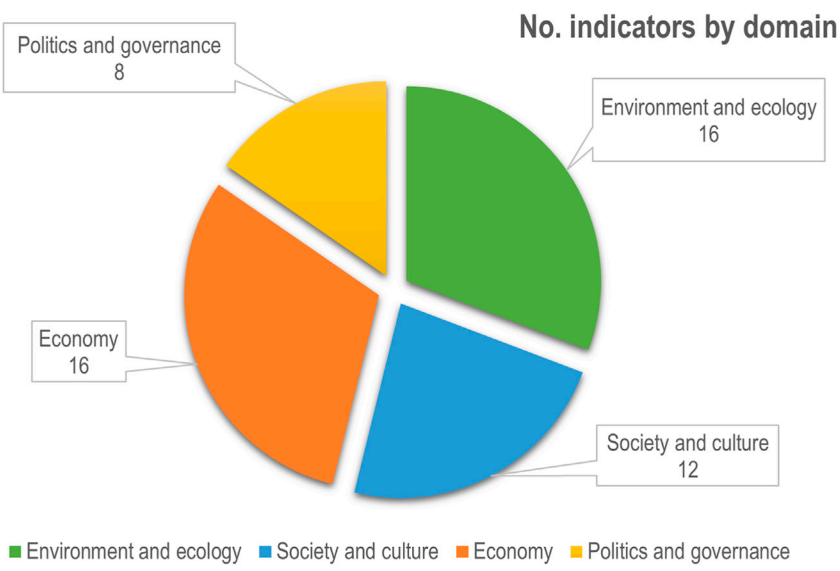

FIGURE 5
Number of indicators by domain.

Regarding the categories, only the "infrastructure" received the highest sustainability score (i.e., "Excellent—5"). None of them reached the lower extreme of the sustainability scale (i.e., "Bad—1"). After "Infrastructure," the categories with the highest sustainability level are "Social wellbeing," "Identity" and "Social resilience" from the social domain and "Dependency" in the economic domain. The three of them received a score of "Good—4." More than half of the categories (i.e., eleven categories) received a "Satisfactory—3' score. Finally, the categories that received the lowest score are those with a "Poor—2" level of sustainability. They correspond to 'Societal benefits' and 'Demographics' in the social domain; "Resource management" from the governance domain and, 'Security' within the economy domain. The predominance of medium scores within categories is reflected in the scores of the domains that were evaluated as "Satisfactory," except for the "Social" domain that exhibits a "Good" level of sustainability. In consequence, the MRm-SES was found to have a "Satisfactory" condition (see Figure 7).

4 Discussion

4.1 The Magdalena River-mouth sustainability issues

It is important to stress that CCS framework focuses on a category-by-category analysis, however, looking at the results of the lower divisions (i.e., sub-categories and indicators) or "de-constructing the score" (OECD and JRC, 2008) has the advantage of providing a deeper understanding of what elements of the system have driven it to the current state.

Nevertheless, this "deconstruction" should be done with caution, without losing sight of the fact that the assessment of indicators and subcategories is only an intermediate step that does not speak to the sustainability of the system in the way the CCS framework conceive it (i.e., through categories and domains). In other words, it may happen that in domains such as the Economic domain, where 16 indicators were selected in total, there is a high number of indicators with a high rating (i.e., 50% of the indicators were assessed as 4- Good or 5-Excellent), however, this does not necessarily imply that the final rating of the domain will be Good or Excellent, the rating of the domain will depend on: (i) How the rating of the indicators that make up the same subcategory is balanced and, (ii) How the ratings of the different subcategories that make up a category are balanced.

4.1.1 Environmental domain

The five categories in this domain have "Satisfactory" conditions. However, these outcomes should be analysed with caution. When looking at the subcategories and indicators nearly half of the indicators (i.e., 7 out of 16 or 44%) were assigned a "Bad" or "Poor" level. These indicators were distributed in four (4) of the five (5) categories. Among the seven indicators more than half are associated with ExUP (i.e., Atmospheric temperature change, Trends in extreme events, Freshwater and SSL, and erosion/accretion rates) while only the three remaining can be managed within the study area, namely, they are EnMP (i.e., Land cover change, protected areas and net GHG emissions per year).

Looking at the above, clues begin to emerge as to what strategies could be pursued to improve the sustainability of the system. Regarding temperature increase, there are no exclusive local measures that can be effective in stopping temperature change given it is associated with GHG emissions on the global scale. Therefore, a greater and immediate commitment to reduce GHG (especially methane) is required from the world's main generators through their Nationally Determined Contributions (NDC) that, so far, are not enough to limit temperature rise below 1.5°C by the end of the century (Shukla et al., 2022).

TABLE 4 Data for the assessment of each indicator.

Indicator	Data
Land cover change (%) (i.e., Tropical Dry Forest—TDF)	Data from the BMA showed an average loss of −124.3 ha/year (i.e., −1.87%/year, using 1986 as References year)
Shoreline hardening (or armouring)	The total length of the hard protection structures corresponds to nearly 6% (i.e., 4.2 km approx.) of the total shoreline length in the MRm-SES (i.e., approx. 71 Km)
Proportion of threatened species	In the study area, until 2021, there are observations from 2325 different species (110 in Santa Catalina - Bolivar and 2215 in Atlántico). From those, 30 species (1.26%) are listed as threatened in the Resolution 1912/2017
Natural hazard regulation	Current natural hazard regulation services associated to mangrove cover are only 60% of what it used to be in 1985
Share of protected areas	Only 4,861 Ha are under some category of protection within the study area meaning that less than 3% of the land is protected
Sea-level change	SLR rate Atlántico: 8.47 ± 0.58 mm/yr. SLR rate Bolivar: 8.33 ± 0.59 mm/yr. In both cases: period 2071–2100, scenario RCP 4.5 If compared to the global average rate in 2100 for the RCP 4.5 scenario (i.e., 7 mm/yr), the local rates are 20% higher
Sea surface temperature change	According to the projections from the TCNCC, the central Caribbean SST could experience an increase around 0.5, 0.9°C and 1.4°C by 2040, 2070 and 2100, respectively, under the RCP 4.5 scenario
Atmospheric temperature change	According to the evaluated scenarios, the atmospheric temperature in the study area could increase in 1.1°C by 2040 and, by the end of the XXI century, it could be 2.2°C higher
Precipitation change	In terms of rainfall, the climate change scenarios suggest that average precipitation in the Atlántico can be reduced in −7.39% between 2011–2040, −9.52% between 2041–2070 and can be −11.26% by the end of the XXI century
Per Capita Net Greenhouse Gas (GHG) emissions per year	Net GHG emissions = 7,342,000 ton CO2e Net CO2 emissions = 6,179,027 ton CO2 Atlántico's population in 2012: 2,315,361 inhabitants Net GHG emissions (*per capita*): 3.2 ton CO2e Net CO2 emissions (*per capita*): 2.7 ton CO2
Frequency of extreme events	Between 1901 and 2015, in the Atlántico there have been 1,135 hydro-meteorological extreme events. A big proportion of them corresponded to Flooding (54%), Windstorms (23%) and Landslides (7%). The remaining 16% involve events such as wildfires, storms, swells, droughts, torrential floods, among others It can be said with a high degree of uncertainty, that extreme events had a rising tendency between 1980 and 2015
Absolute Wave Energy Flux change	Annual wave energy exhibited two different behaviours: Overall for the Caribbean, increasing (1958–1987) and decreasing (1989–2017). Total decreased in front of Barranquilla 11%–12% Annual decreasing rate in front of Barranquilla 0.15%–0.20%
Freshwater Suspended Sediment Load (SSL)	Sediment load displayed an increase of 48% when comparing the mean load of 16,153 t/d during the 1984–2000 period with the observed inter-annual mean of 23,906 t/d for the 2005–2010 period. Overall, between 2005 and 2011, there was an increase of 44 Mt/y of SSL
Marine Water Quality Index (MWQI)	ICAM dry season: Acceptable (51.8) ICAM wet season: Acceptable (65.9)
Water Regulation Index (WRI)	Between 2000–2010 the average streamflow of the Magdalena river has increased more than 20% compared to average streamflow from 1941–2010. Overall, the Water Regulation Index - IRH in the study area is 0.77 (High) according to ENA 2018
Erosion/accretion rates	Average shoreline evolution: 0.65 m/yr (1986–2016) Proportion of coast per evolution category: High erosion (>−1.5 m/y): 39% Erosion (−0.2 to −1.5 m/yr): 21% Stability (−0.2 to +0.2 m/yr): 19% Accretion (>0.2 m/yr): 21%
Fish stock under the status of “Collapsed” and “Over-exploited”	Catch by stock status in 2018: Collapsed—69.9% Over-exploited - 0% Exploited—0% Developing - 0% Rebuilding—30.1%
Coastal population growth rate	Period 1985–2005: increased in more than 800,000 people reaching a total number of 2.17 million inhabitants by 2005, representing an increasing rate of approximately 41,000 people per year. Period 2005 and 2018: slower increasing trends with an average increment of 28,000 people per year. Between those years the population increased approximately a 17% corresponding to more than 371,000 inhabitants, reaching a total of 2.5 million inhabitants (i.e., 1.3%/yr.)
Incidence of income poverty	

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TABLE 4 (*Continued*) **Data for the assessment of each indicator.**

Indicator	Data
	In 2018 the Poverty Income Threshold for the Atlántico and Bolivar departments were USD $96 (3.2 USD/day) and USD $88 (2.9 USD/day) current prices, respectively. With those thresholds, the incidence of income poverty was estimated in 24.2% for the Atlántico and 36.2% in Bolivar, while the national average was 27.0%
Subjective wellbeing	Life satisfaction score: Atlántico (8.32 points) Bolívar (7.95 points) Caribbean region (8.24 points) Colombia (8.26 points)
Prevalence of food insecurity	The prevalence of food insecurity in the Caribbean region is the highest in Colombia being 10.8 p.p. (i.e., 65.0%) higher than the National average (i.e. 54.2%). More specifically, in the departments of Atlántico and Bolívar this figure corresponded to 58.8% and 68.5% for the same year
Water Quality for Human Consumption Risk Index—IRCA	Out of 20 municipalities: 14 in the Atlántico (70%) presented “No Risk” 1 in the Atlántico (5%) presented “Low risk” 4 in the Atlántico (20%) presented “Medium risk” 0 presented “High Risk” 1 in Bolívar (5%) presented “Sanitarily unviable”
Coverage of essential health services	Atlántico: Affiliated (91.6%), Non-affiliated (8.3%), No answer (0.2%) - Contributive (44.3%) and Subsidized (55.5%) Bolívar: Affiliated (93.5%), Non-affiliated (6.3%), No answer (0.3%)—Contributive (26.7%) and Subsidized (73.2%)
Inter-census change in the ethnic population	The percentage point (pp) change in the proportion of indigenous and NARP peoples between 2005 and 2018 shows a decrease in the representation of NARP people and an increase in the proportion of indigenous people. Specifically, the NARP population had a change of −0.6 pp and −0.8 pp in Atlántico and Bolívar, respectively. In the case of indigenous people, the change was 0.4 pp and 0.2 pp, respectively
Lasting special places/traditions	For Atlántico, in 2011 there were a total of 407 attractions (i.e. 57% material tourist attractions, 21% festivities and events, 16% natural sites and 6% intangible heritage) with the city of Barranquilla having the largest number. In the case of Santa Catalina (Bolivar), the main sites of interest are the Totumo volcano, Cocos Island, the swamps of La Redonda and El Totumo, the beaches of Galerazamba and Loma Arena, the salt flats of Galerazamba, among others, for a total of 10 tourist attractions
Literacy rate of adult population	The percentage of the population aged 15 years or over who can read was 96.4% in the Atlántico and 92.2% in Bolívar
Relative Effort Indicator—IER	IER Atlántico (2018) = 0.4 IER Bolivar (2018) = 2.2
Preventive risk management investment	Overall, in the Atlántico and Santa Catalina $6.4 USD million (i.e., 46.9% of the total) of the risk management funds were used in preventive strategies
Relative change of ocean-related activities’ GDP	The ratio between the Gross Domestic Product—GDP of 2016 and the 5-year average GDP (i.e., 2011–2015) for the coastal-related activities shows values above 1 (i.e., all activities and both departments)
Gender wage gap	Barranquilla: women earned 76.9% of the men’s average income during 2018, in other words, the gender gap was 23.1 pp (Score = 1) Cartagena: women earned 81.2% of the men’s average income during 2018. In other words, the gender gap was 18.8 pp (Score = 2) Note: average value. If analysed by educational level, gaps can be as high as 37.5 pp
Unemployment rate	Overall Participation Rate—TGP (2018) = 63.3% AVG TGP (2001–2018) = 58.2% Employment rate—TO (2018) = 58.4% AVG TO (2001–2018) = 52.1% Unemployment rate—TD (2018) = 7.7% AVG TD (2001–2018) = 10.5%
Share of electricity generated from renewable sources AND Share of households with access to electricity	Up to 2018, 68% of the electricity in Colombia was generated by hydroelectric plants. Less than 1% corresponded to non-conventional renewable energy sources. (Score = 4) By 2018: 85.8% of the total households has access to electricity (Score = 5)
Relative change in occupancy rate in commercial accommodation	Avg Hotel Occupancy in 2017: 51.41% Avg Hotel Occupancy in 2018: 53.90% Relative change in pp = 2.5 pp
Percentage of goods transported by transport mode	Cargo: Plane (0.11%), Road (62%), Inland waterways (14.78%) and Maritime transport (23%) Passengers: Plane (16.94%) and Road (83.06%)
Port infrastructure AND Quality of roads	Sub-indicator 1: Port infrastructure (Score: 4) Sub-indicator 2: Roads in Good or Excellent conditions: 65% Bad and poor conditions: 35% (Score: 4)
GINI Index	GINI Coefficient (2018): Atlántico - 0.443 Bolivar - 0.472
House affordability	Household income devoted to housing costs (2017): Barranquilla: 31.4% Cartagena: 30.8% National: 28.7%
Percentage of GVA generated by activities/sectors relying on Renewable resources	

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TABLE 4 (*Continued*) **Data for the assessment of each indicator.**

Indicator	Data
	32.6% of Atlántico's GVA during 2018 came from activities that rely (or have the potential to) on renewable resources
Ratio Extractive/Renewable activities AND Relative change in GVA from "Agriculture, livestock and fishing"	The ratio of Extractive GVA between Sustainable GVA is 1.08 or, in other words, the GVA from extractive industries is nearly 10% more than the one produced by sustainable activities (Score = 3) When dividing the GVA from the ALF activities in 2018 (i.e. 133,000 USD) by the 5-year average value between 2013 and 2017 (i.e.,117,000 USD) the ratio was 1.14 (Score = 5)
Relative change of overall workforce within blue economy	Relative change of overall workforce within blue economy - Atlántico: 1.05 - (Score = 5) Relative change of overall workforce within blue economy - Bolivar: 1.01 - (Score = 5)
Livelihood diversification in small-scale fishing households	Simpson Diversity Index Non-fishing (0.370) and Fishing (0.459)
Civil and NGOs number	Local community councils - 545 Ethnic communities - 2 NGOs - 305 Public educational institutions - 291 Civil associations - 167
Existence of and Integrated Coastal Zone Management (ICZM)	Colombia has a public policy represented in the PNAOCI and the PNOEC, however, they mention that its implementation is in the early stages and that there are no evaluation and monitoring mechanisms in place for those responsible from executing the policy
Existence of norms regarding ICM	Colombian regulatory framework has an integrated sectoral approach and recognises the differences that exist in the coastal zone, but clarify that the current regulations are not specifically oriented towards the "management of the coastal/maritime public domain"
Voter turnout	National elections (2018): Senate (60.0%), Chamber (60.4%) and President (46.7%) Local elections (2019): Governor (74.6%) and Mayor (74.8%)
Percentage of women in politics	Percentage of women governors between 2000–2020 (14.3%) Percentage of female mayors in 2019 (17.4%) Percentage of women elected in the House of Representatives 2018 (42.8%)
National Anticorruption Index (INAC)	INAC Barranquilla: 77.6 (2019) and 82.36 (2020) INAC Atlántico: 74.2 (2019) and 70.4 (2020)
Existence operative instruments for the management of natural resources	Up to 2020, less than (20%) of the natural resources had management instruments implemented within the CRA jurisdiction
Decentralization and existence of public competencies	Colombia has "an ICM-oriented public responsibility distribution scheme with coordination mechanisms" Score = 3/5

Despite absolute GHG emissions being significantly lower than other areas in the region and the world, this does not mean that GHG emissions in the study area should not be considered for management. Compared to emissions in South America and the Caribbean (i.e., 9.2 t CO2e), emissions in the study area are lower but not ideal. The ideal sustainability scenario will be one in which net GHG emissions are zero by mid-century and to achieve this goal radical transitions need to be implemented including reduction of the overall fossil fuel use, the deployment of low-emission energy sources, switching to alternative energy carriers, and energy efficiency and conservation (Shukla et al., 2022). Better yet, the positive effects could spill over or depend on other categories (e.g., reducing the use of fossil fuels requires an electricity grid that is dependable, resilient and relies little on fossil fuels, which would be reflected in the "Infrastructure" category). In addition, investment in energy transition projects could create job opportunities to replace jobs in the oil and gas industry that could reach a global peak by 2028 (Rifkin, 2019).

At this point, it is important to note that Colombia has an energy matrix with a good level of sustainability (almost 70% is generated from renewable sources) (Paniagua and Duarte, 2021) that can become more resilient with the promotion and development of non-conventional renewable energies such solar, hydrogen and onshore and offshore windfarms (UPME, 2019; Renewables Consulting Group, 2022). However, Colombia's main challenge is therefore how to adapt and/or build new infrastructure to allow an energy transition for the transport and industry sectors, which are the main consumers of fossil fuels in the country (UPME, 2019).

4.1.2 Social and cultural domain

In the "Society and Culture" domain there were two categories whose score was 'Poor': The "Social benefits" and the "Demographics." The former is composed of the "Goods and Services" subcategory, evaluated through the "Catch by fish stock status" indicator which showed that nearly three-quarters of the catch came from species that are under the status of Collapsed or Over-exploited. The stocks have reached this status due to the mismanagement of both artisan and industrial fisheries, pollution and climate change (WWF, 2020). For this reason, marine management measures such as the creation of protected areas and/or special management areas are required, but above all the participation of the communities in the formulation of management measures and the appropriation of the governance of the resources is

TABLE 5 CCS scores by category and domain for the Magdalena River-mouth. Note: as explained in the methodology, the score for each domain is calculated as the 'Median' of the corresponding 5 categories.

Domain	Score	Label	Category	Score
Environment and Ecology	3	Satisfactory	1. Alterations of landscapes	3
			2. Ecosystem function	3
			3. Global environmental change	3
			4. Shifts in hydrodynamics	3
			5. Biogeochemical and physical flows	3
Society and culture	4	Good	1. Societal benefits	2
			2. Demographics	2
			3. Social wellbeing	4
			4. Identity	4
			5. Social resilience	4
Economy	3	Satisfactory	1. Security	2
			2. Infrastructure	5
			3. Economic wellbeing	3
			4. Industry	3
			5. Dependency	4
Politics and governance	3	Satisfactory	1. Organisation	3
			2. Law and justice	3
			3. Representation and power	3
			4. Legitimacy and accountability	3
			5. Resource management	2

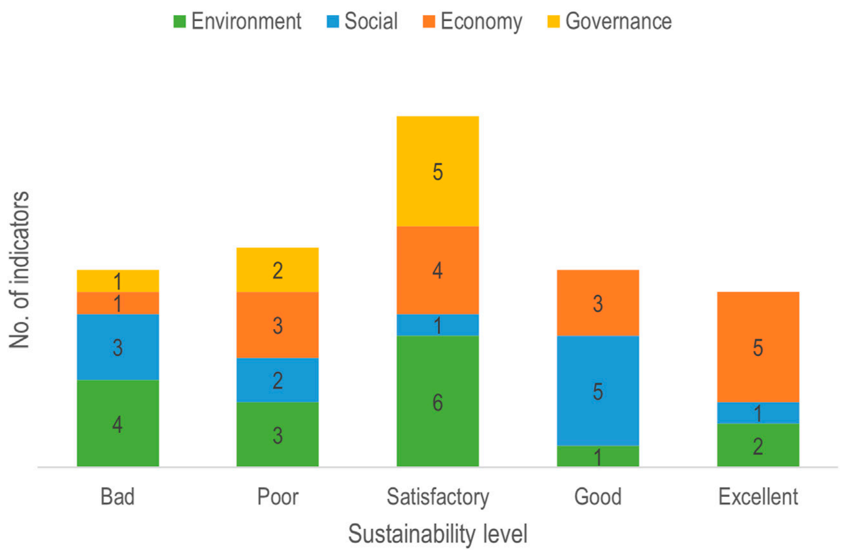

FIGURE 6
Number of indicators by sustainability level.

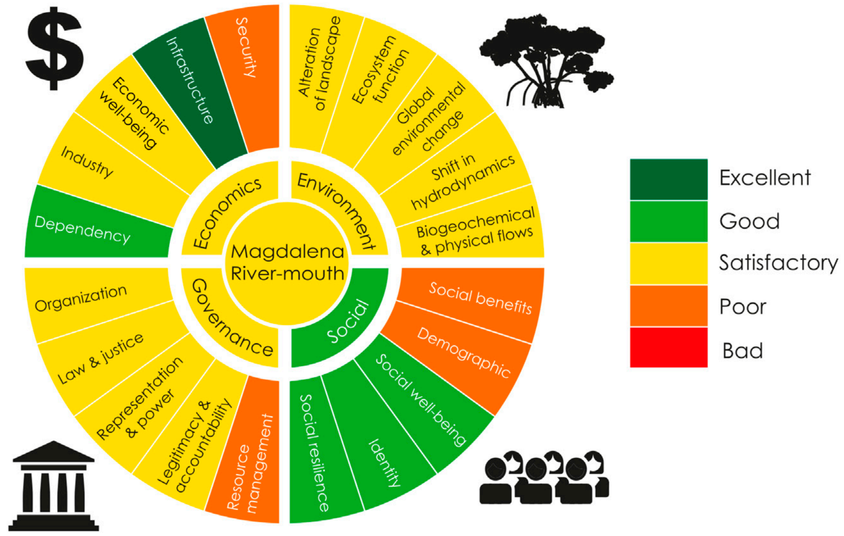

FIGURE 7
CCS score for the Magdalena River-mouth socio-ecological system.

required (WWF, 2020; Future Ocean, International Ocean Institute, German Marine Research Consortium, mare, 2021). Precisely as a response to this need for management that involves the communities, in Colombia, the formulation of "Consensual Fisheries Management Agreements—ACMP" is being carried out with 9 pilot communities along the Caribbean coast (Saavedra-Díaz et al., 2015). Therefore, it is expected that there will be a monitoring of the compliance and effectiveness of these agreements to know their effects in the short and medium term and to evaluate their replicability with the other fishing communities including those within the study area.

It should be noted that in common-pool resources management, the same as in the case of climate change, measures must go beyond the local scale to reach a regional or even global scale. For the MRm-SES, this implies the management and governance of the Caribbean Large Marine Ecosystem (CLME). To this end, regional and sub-regional agreements have been worked out to develop an integrated regional approach to governing shared Living Marine Resources (sLMR) of the CLME and Adjacent Regions (known as CLME+). However, the implementation of these programmes, projects and initiatives, during 5 years, has not been exempt from challenges such as institutional capacity; lack of capacity building, leadership and awareness; inexistence of legal, political and social capital; abundance of socio-cultural constraints, among others (Fanning et al., 2021). Again, it would be necessary to monitor the implementation of the SAP to evaluate its effects on the fish stocks in the CLME+ region.

The second category is formed by the "Population growth" and the "Social class" subcategories, which received a score of "Poor—2" and "Bad—1," respectively. There is a common consensus that increasing population could impose higher pressures on the Earth's and, therefore, coastal habitats. However, this is not the only nor the most crucial factor. For example, in some cases, rising living standards have been considered equally or even more important than population growth in terms of environmental impacts (i.e., consumption and production patterns will be responsible for a 70% increase in consumption *per capita* while only 30% will be attributable to population growth) (UN-DESA, 2021). Hence, what a priory seems to be a straightforward assessment where population growth stabilization (i.e., net growth = 0) is the optimal condition, becomes a more complex situation.

One thing is sure: *"population growth is a major driver of the increasing demand for food"* and the current food production is not sustainable. Therefore, to avoid the impacts of a growing population it is paramount to move to sustainable practices (UN-DESA, 2021).

Looking at Income Poverty, the results for the study area are "Bad-1." In the department of Atlántico one (1) out of five (5) people are in monetary poverty and in Bolívar this figure is about one (1) out of three (3) people. These social and economic problems have direct consequences on the sustainability and management of the resources because people who strongly rely on extractive activities such as fishing have no choice but to keep fishing, even beyond the sustainable thresholds, to survive (Future Ocean, International Ocean Institute, German Marine Research Consortium, mare, 2021). In the end, they are doing it to satisfy their most basic needs and, as Maslow suggested in 1943 and 1970, "*one must satisfy the lower-level deficit needs before progressing on to meet higher level growth needs*" (Elliott et al., 2017). Hence, alternative sources of income and incentives for habitat preservation and recuperation could improve ecosystem health while providing alternative livelihood opportunities. An example of the application of these strategies can be found in the Cispatá Bay in Colombia where the conservation of eleven (11) thousand hectares of mangrove is helping to tackle climate change while providing alternative sources of income for the locals. It is expected that "*For the 12,000 people who depend on the mangroves for food, firewood and livelihoods, the sale of carbon offsets will provide a degree of financial security as well as the initial funding needed to develop a sustainable ecotourism program and improve fishing practices in the region*" (Conservation International, 2022).

In the MRM-SES these strategies could be implemented in areas such as Ciénaga de Mallorquín and Ciénaga del Tótumo. Thus, if we assume an optimistic scenario in which 1 ha of mangrove could provide a direct livelihood for at least 1 person, and if we consider that recovery of up to 90% of the original mangrove cover in the study area (i.e., which is the minimum percentage required to reach an 'Excellent' condition according to Table 3), the mangrove forests within the MRm-SES could be a source of income for around 720 people (i.e. 720 ha out of a baseline of 800). This is without considering the indirect benefits that could be obtained in the future from activities such as ecotourism or better fishing yields. While these assumptions are optimistic and oversimplify economic dynamics that are not necessarily linear (i.e., it is possible that 1 ha is not sufficient to provide income for one person), they serve to illustrate the fact that habitat restoration, a measure of the environmental domain, could have positive effects on the socio-cultural domain.

4.1.3 Economic domain

The worst category in this domain was the "Security" that was found to have a "Poor" condition. The category was divided into three subcategories (i.e., livelihoods, gender, and employment patterns). The main issue in this category is the high rates of unemployment and the disparities in the gender wage gap which received a score of 1 and 2 meaning 'Bad' and "Poor" conditions, respectively. Unemployment can put a strain on the household and public finances, additionally, it can impact individuals and diminish their career prospects. The unemployment rates in the study area are high compared to other countries (e.g., Czech Republic, Iceland and Japan with figures lower than 3%) (OECD, 2022). However, they are considered among the lowest compared to other cities in Colombia (Galvis-Aponte et al., 2019). The unemployment rates in the study area have decreased in the last years due to a lower participation rate, an increase in occupation or both. One aspect that is not considered in the present assessment is the informality of the jobs, which is associated with the quality of the employment (Galvis-Aponte et al., 2019).

In the case of the Gender Wage Gap, it has been associated with multiple factors: economies incapable of generating enough formal jobs, the women's dominant role in domestic jobs and caregiving, the maternity wage penalty, the presence of gender norms limiting women's employment, discrimination and poor working conditions for women (ONU Mujeres, DANE, CPEM, 2020; Iregui-Bohórquez et al., 2021).

4.1.4 Governance domain

In the "Politics and governance" domain the "Resource management" subcategory received a "Poor—2" score, mainly due to the inexistence of key instruments for the management of natural resources being the POMIUAC—RM the most important among them.

The lack of an integrative plan for the use of the resources from the different stakeholders present in the coastal zone hampers its sustainable development because, in the best-case scenario, promotes a sectorial view where each individual/stakeholder seeks to maximise their benefit without considering the implications it can have for other actors, for the environment and even for themselves eventually.

Despite presenting poor conditions, it is expected that once the final version of the POMIUAC-RM is formulated (i.e., after the revisions or adjustments that could derive from the "Prior Consultation" process) and the implementation phase begins, it will lead to an improvement of the system. Monitoring of the implementation process (i.e., activities conducted, resources assigned, among others) and a constant evaluation of the system's evolution, for example, by using some of the indicators presented in this assessment, will be required to identify, since the very early stages of implementation, the positiveness of the outcomes and/or which adjustments are required to make the POMIUAC more effective in achieving its goal.

4.2 Management application of the CCS

The score received by each category serves as an element to prioritise and understand the type of management actions required for the study area such that those categories, where the score was "Bad" or "Poor" require urgent attention and greater efforts for recovery/improvement. Categories with a "Satisfactory" status are those with favourable conditions for achieving a higher level of sustainability through the application of prevention strategies and/or where less effort can lead to greater improvement of the system. Finally, categories with a "Good" or "Excellent" status do not require any immediate action other than preventing deteriorating conditions.

Despite the above, from a management point of view, one should not be drawn into the sectoral approach that has proven to be ineffective in resolving the problems of complex systems such as those found in the coastal zone (Future Ocean, International Ocean Institute, German Marine Research Consortium, mare, 2021). Although the graphic representation of the CCS makes it possible to easily identify those categories with the worst performance, it is necessary to establish the interactions that exist among them to foresee changes (both positive and negative) that would result from an alteration in the status of one or more of the categories. For example, the category of 'Ecosystem function' is composed of three subcategories: (i) Biodiversity Loss (ii) Services and (iii) Biodiversity protection. What would happen if the existing relicts of Mangrove along the study area were lost? Directly this would imply a loss of Natural Hazard Protection. However, indirectly this change would be reflected in other categories, for example, in a Business As Usual scenario, the likely compensation strategy for this loss of protection would be the construction of rigid coastal protection works (Rangel-Buitrago et al., 2018), i.e., there would be coastal rigidification that would affect the landscape and sediment transport dynamics. Furthermore, mangroves are nurseries for many species of fish, and their loss could be reflected in a reduction of the fishing stocks affecting the livelihoods of a vulnerable portion of the population (i.e., the artisan fishers). Also, a natural attraction that serves to invite tourism and is related to the 'Sense of Place' would be lost, and further connections and consequences could be established. So, what initially was a change related to the status of the Environmental domain, ends up extending to the 'Socio-cultural' and "Economic" domains.

Despite those connections that could multiply the effects of a negative impact, they also can be used to design measures that contribute to improving various aspects of the system. For example, mangrove restoration and preservation and the definition of protection status and strategies for the areas where these ecosystems are located, bring multiple benefits. In total, those two measures could have a potential impact (i.e., direct, or indirect) on, at least, a quarter of the indicators. In practical terms, whether that positive impact is strong enough to produce a significant change in the sustainability of the system as measured in the CCS (i.e., indicator, subcategory, categories) will depend on the scale at which the measures are applied as well as their scope (i.e., integral measures can tackle more aspects than those with a sectorial approach).

4.2.1 Managing ExUP and EnMP

The implementation of measures to tackle ExUP is not the responsibility of local managers and institutions in all cases, but the MRm-SES would benefit from their implementation. What is expected is a willingness to participate on the part of decision-makers, the community, and other stakeholders.

- Investment in climate change adaptation measures
- Local strategies to reduce the net GHG contribution in the area, could be through the recovery and preservation of ecosystems that serve as carbon sinks (e.g., mangroves and tropical dry forests), coupled with improved energy efficiency and promoting a more diverse energy matrix that is less dependent on fossil fuels (e.g., reducing incentives or tax exemptions for hydrocarbon exploration and exploitation and instead redirecting this money to renewable energy).
- At the level of the Magdalena River Basin, a coordination mechanism is required between the different CARs with jurisdiction in the Magdalena River Basin so that they can act jointly to solve problems such as deforestation and pollution.

On the other hand, some measures to tackle the EnMP are.

- Designation of new conservation areas under a concept that does not necessarily prohibit their use but promotes a more responsible approach that preserves biodiversity and important habitats.
- Involve the opinions and ancestral knowledge of the communities located within the study area when designing and implementing management measures.
- Work towards the early formulation, updating and/or implementation of the POMIUAC-RM or other strategic plans for resource management in the study area.

The above list is not considered exhaustive, and it is suggested that complementary tools such as the DPSIR framework to define the linkages among categories which can be used to establish tailored measures for the system at a later stage (Gallo Velez et al., 2022).

4.3 The CCS framework: Opportunities for improvement

The CCS framework and representation aim at being a tool for policy analysis and public communication but, moreover, to be an effective call for action. Perhaps one of the advantages of the chosen graphical representations is that, up to a certain extent, it deals with one of the major issues from composite indicators which is mascaraing some issues that draw a simplistic analysis and leads to wrong conclusions (OECD and JRC, 2008). This is done by showing the overall score for the system and each domain while maintaining and showing the results for each category. In this way, is possible to identify what are those aspects that need to be at the centre of the discussion because more effectiveness and actions are required to improve their sustainability.

One aspect that differentiates this study from the one from P. de Alencar et al. (2020) is the attempt to include a semi-quantitative approach to score the sustainability of each category, reducing the bias that comes from an application of qualitative criteria which can be interpreted in different ways by different evaluators, coastal managers, decision-makers, etc. Additionally, the graphical representation suffered major transformations such as the inclusion of the domains and system within the graphic, as well as the use of a more widespread and intuitive colour scale (i.e., traffic-light colours rather than the EU water framework directive colours). Finally, the original framework was tested in Spain but, its application in this study shows that it can be adapted to other latitudes with differences that involve not only geography (and its different habitats, ecosystems, and biomes) but also culture, society, and policy (governance).

Complementarily, the idea behind establishing upper and lower bounds and their respective categorical scales (i.e., ranges within which an indicator receives a certain sustainability score) helps to ensure that the application of this framework in the same socio-ecological system (at different times or by different people) or even in similar systems (i.e., where the same indicators can be used), is based on the same criteria and results in consistent values that do not depend on the view of a particular evaluator. In other words, that the assessment made by two different people/organisations at the same point in time results in very similar levels of sustainability (i.e., taking into account the variability associated with the fact that there are still indicators that are assessed qualitatively). Or, in the case of assessments at different times, the results are truly a reflection of changes in the system and not of changes in assessment criteria.

Despite its advantages, there are still aspects that could improve the reliability of the results and some questions that arise after the application of the CCS framework in the MRm-SES:

- The CCS framework fundamentally relies on secondary information; therefore, it is important to define the degree of confidence of the information presented for each indicator. That is adopting a similar system as the one used in the IPCC or the IPBES reports (IPBES, 2018) (e.g., medium confidence, very likely, high confidence, high confidence, etc.). This degree of confidence should consider not only the quality of the sources employed but also the spatial scale of the information concerning the system being evaluated (i.e., municipal level is more accurate than national level).

To improve the utility of the results by drawing more accurate conclusions, it would be necessary to explore the implication of the different normalization, weighting and aggregation methods for the indicators (for instance, using linear aggregation methods such as arithmetical average or median; or other non-compensatory aggregation methods such as geometric average)

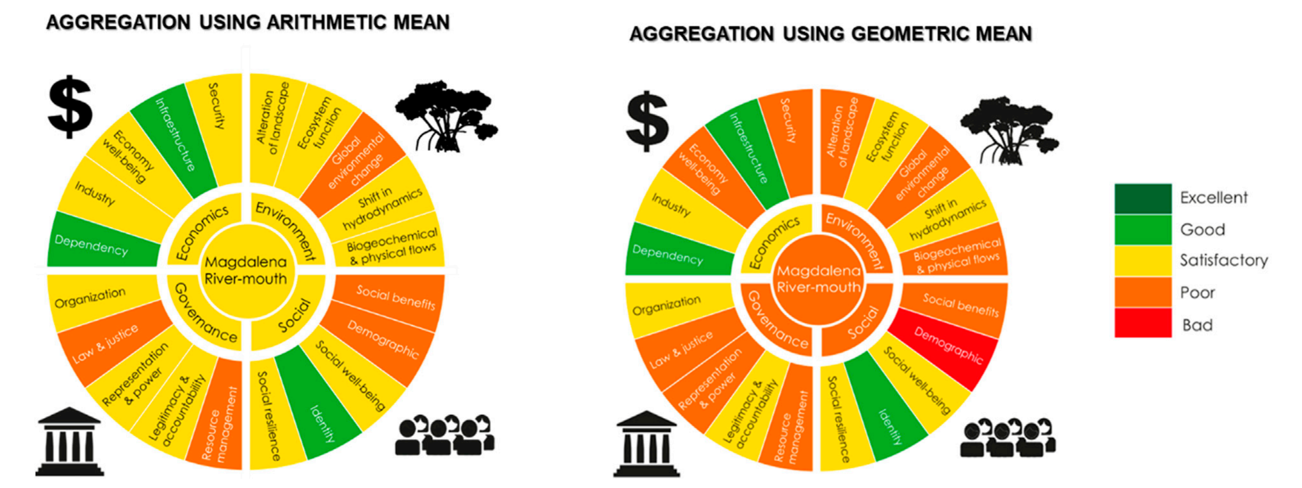

FIGURE 8
Comparison of the CCS results using different aggregation methods (i.e., arithmetic mean—left and geometric mean—right) for the Magdalena River-mouth system.

(s; Papadimitriou et al., 2019). Would it be worth assigning weights within the indicator and subcategory levels? These are aspects whose implications remain to be explored and further analysed through simulations and statistical analyses. The importance of this point can be illustrated by comparing the results of the Magdalena River-mouth using the arithmetic and geometric means for the aggregation. With the geometric mean, results show a system with apparent worse conditions for three of the four domains even though the scores of the individual indicators remained unchanged (See Figure 8). This may seem like a numerical triviality, but its implications from a management point of view can be important. An aggregation method that allows the compensation of low scores with high scores could lead to masking problems within the different categories of each dimension, giving the erroneous idea that none of the categories requires immediate attention and that the current management is giving results, if not good, at least satisfactory. On the contrary, an aggregation method that overly penalizes all categories, resulting in very low levels of sustainability for many of them, could prevent the clear identification of those areas where intervention is truly needed. In other words, it would not help in the prioritization of management measures and resources. Moreover, it could even lead to inaction.

- What will or could happen in the future? Or how is the system compared to previous states? Is it better/worse? Is there an identifiable trend that suggests the system is improving? Could other socio-ecological tools help foresee changes in some of the categories and domains (e.g., "Future Analysis") (Biggs et al., 2022).

This assessment was applied to the main mouth of the Magdalena River in Bocas de Ceniza and can provide a general picture of the sustainability of Colombia's main river delta. However, it is important to investigate what could be the implications of including the other two compartments of the Magdalena River deltaic system such as "Canal del Dique" and "Cienaga Grande de Santa Marta."

4.4 Application of the CCS around the world

Despite being a recently developed framework, efforts have been made to test its application in coastal systems with different characteristics (e.g., geography, scale, socio-economic conditions, cultural aspects, among others) and using adaptations in the methodology (e.g., qualitative, and semi-quantitative).

The first application of CCS was at the national level and used a qualitative approach to assess the coastal zone of Spain as a whole. In this study, it was identified that over-limitations of biophysical barriers have led to a loss of coastal provisioning services which, in turn, is reflected in impacts on the human wellbeing of the communities that depend on them (de Alencar et al., 2020).

In contrast to this first case study, subsequent case studies, including this one, have focused on more narrowly defined social-ecological systems, such as the Chesapeake Bay—United States (Leyva Ollivier, 2022), Cork Harbour—Ireland (Wint Mon Swe, 2022) and the Sundarbans area—India (Deb, 2022). This has provided more detailed information leading to the identification of more specific strengths, problems, and solutions. For example, Leyva Ollivier (2022) identified that the main problems in Chesapeake Bay are the eutrophication, overexploitation of natural resources and the industrial and human development; while Deb (2022) mentions that for the Sundarbans delta (transboundary region) there is inefficiency and lack of accountability of the government, intensification of cyclones, sea level rise, coastal erosion, and delta subsidence besides the socio-economic pressures which include high poverty levels and persistent lack of basic services and, he also mentions the "need for joint action between their governments for a sustainable future". Moreover, Wint Mon Swe (2022) suggests that CCS could be used to evaluate not only sustainability but the resilience of a system against climate change.

All of the above points out that CCS is a framework that can be adapted for the assessment and comparison of very diverse coastal systems ranging from bays and estuaries in developed mid-latitude countries (de Alencar et al., 2020; Leyva Ollivier, 2022), to tropical deltas in developing countries, accounting for long-standing (e.g., land cover/use change) and/or recently developed issues in a system (e.g., plastic and novel substances pollution).

However, something briefly mentioned here and agreed by other authors is the need to use other tools to better understand the "system's structure" (Leyva Ollivier, 2022) and the interconnections that exist between the different elements of the socio-ecological system (Deb, 2022), which in the specific case of CCS, are represented by the Categories. This can help to understand why and how the changes in one category can affect the score for other categories, either for the same or a different domain. For instance, in which way the actualization and execution of current resource management plans in the study area could halt land cover change and/or prevent land-based contamination? What is driving the system to its current state and what can be done to tackle the cause rather than the symptoms?

On the other hand, the application of the different case studies has allowed us to identify possible improvements that have been discussed in this paper and others that are mentioned by other authors. For example, the need to reduce the subjectivity associated with a qualitative assessment of indicators, based purely on discussion with other researchers or experts (Deb, 2022; Leyva Ollivier, 2022; Wint Mon Swe, 2022). Precisely, the adaptation carried out in this study constitutes a step forward in the search for alternatives to reduce such subjectivity.

5 Conclusion

Overall, the sustainability of the Magdalena River-mouth SES can be classified as "Satisfactory." The "Environmental and Ecological" domain exhibited "Satisfactory" conditions. In the case of the "Social and Cultural" domain, three categories (i.e., "Social wellbeing," "Identity" and 'Social resilience') were rated as having 'Good' conditions, and the rest of the categories were rated as "Poor." The "Economic" domain was the only one where a category reached an "Excellent" status. Finally, none of the "Governance" categories exceeded the "Satisfactory" level and the "Resource management" category had "Poor" conditions.

A total of fifty-two indicators, distributed into twenty categories and four domains, were chosen to evaluate the sustainability of the system. The indicators were distributed like this: sixteen (16) indicators each for the Environment and Economic domains, twelve (12) indicators in the Social domain and eight (8) indicators to evaluate the Governance domain. The categories that presented the worst conditions from each domain were: "Social Benefits" and "Demographics" in the Social domain; "Security" in the Economy domain and Resource Management in the Governance domain.

Based on the sustainability score received by the indicators and the categories, some management measures can be considered. In general terms, they involve: Preserving and restoring habitats; tackling sources of pollution and excessive sediment; local contributions to curve climate change through reduction of net GHG and adaptation measures to climate change; participation of local communities in the management design and implementation.

The main advantage of using the CCS framework to assess coastal socio-ecological systems is that it provides a holistic view of the conditions in the system. Moreover, it gives equal weight to the four (4) dimensions of sustainability reinforcing the concept that a truly sustainable system can only be achieved when all the domains present the same level of sustainability. The graphical representation is another strong aspect of this framework because it allows the communication of the results with stakeholders from different spheres (academia, politics, community, organizations, etc.).

Among the drawbacks of the framework, it is possible to mention the necessity of much different information that, most of the time, is dispersed and has to be collected from different institutions. Moreover, sometimes information is available, but it is not easily accessible. Another inconvenience of this framework is the fact of being currently in its development changes, which means that some aspects of the methodology can change in the future. Finally, a critical aspect for the application of the CCS is the selection of the set of indicators which, could be subject to bias if the selection is done by an individual and not by a multidisciplinary group.

This assessment can be complemented and improved by defining the uncertainty of the information used; reviewing the normalization and aggregation methods; using complementary socio-ecological methods/tools like "future analysis" and DPSIR to define tailored measures for the system. Finally, it is suggested to include the other compartments (i.e., CGSM and Canal del Dique) of the Magdalena River delta.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

DG-V: Conceptualization, Formal analysis, Investigation, Writing—Original draft. JR: Conceptualization, Resources, Writing—Review and Editing, Supervision. AN: Conceptualization, Resources, Writing—Review and Editing, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2023.1058122/full#supplementary-material

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Glossary

ACMP	Consensual fisheries management agreements
AMSL	Above Mean Sea Level
BECO	Colombian Energy Balance
BMA	Barranquilla Metropolitan Area
CAR	Corporación Autónoma Regional
CARDIQUE	Corporación Autónoma Regional del Canal del Dique
CCS	Circles of Coastal Sustainability
CEDAW	Convention on the Elimination of All Forms of Discrimination against Women
CEPAL	Economic Commission for Latin America
CGSM	Ciénaga Grande de Santa Marta
CITURCLC	Corine Land Cover
CLME	Caribbean Large Marine Ecosystem
CLME+	CLME and Adjacent regions
CONPES	National Council for Economic and Social Policy
CRA	Corporación Autónoma Regional del Atlántico
DANE	Departamento Administrativo Nacional de Estadística
ECV	National Survey on Quality of Life
ENA	National Study of Water
EnMP	Endogenic Managed Pressures
ENSIN	Nutritional Status National Survey
ETIS	European Tourism Indicator System
EU	European Union
ExUP	Exogenic Unmanage Pressures
FNCE	Non-conventional renewable energy sources
GDP	Gross Domestic Product
GHG	Greenhouse gasses
GMS	Global Mean Sea Level
GVA	Gross Value Added
ICZM	Integrated Coastal Zone Management
IDEAM	Instituto de Hidrología, Meteorología y Estudios Ambientales
IEA	International Energy Agency
IER	Relative Effort Indicator
INAC	National Anti-Corruption Index
INVEMAR	Instituto de Investigaciones Marinas y Costeras José Benito Vives de Andréis
INVIAS	National Roads Institute
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRCA	Water Quality for Human Consumption Risk Index
IUCN	International Union for Conservation of Nature
MR or RM	Magdalena River
MRm-SES	Magdalena River-mouth Socio-ecological System
MRV	Measuring, reporting, and verifying system for climate finance
MWQI	Marine Water Quality Index
NARP	Black, Afro-Colombian, Raizal and Palenquero
NDC	Nationally Determined Contributions
NGO	Non-governmental organization
OECD	Organisation for Economic Co-operation and Development
OHI	Ocean Health Index
PCERM	Per Capita Expenditure on Risk Management
PNAOCI	National Environmental Policy towards Sustainable Development of Oceanic Spaces, Coastal and Island Regions of Colombia
PNOEC	National Ocean and Coastal Spaces Polic
PNUD	United Nations Development Programme
POMIUAC	Integrated Management Plan for the Coastal Environmental Unit
RCP	Representative Concentration Pathways
SDG	Sustainable Development Goal
SGSSS	General System of Social Security in Health
SIN	National Interconnected System
SISCLIMA	Sistema Nacional de Cambio Climático
sLMR	shared Living Marine Resources
SLR	Sea-level rise
SSL	Suspended Sediment Load
SST	Sea surface temperature
SZH	Hydrographic Subzone
TCNCC	Third National Communication on Climate Change
TDF	Tropical Dry Forest
TCNCC	Third National Communication on Climate Change
TDF	Tropical Dry Forest
UAC	Coastal Environmental Unit
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UPME	Mining and Energy Planning Unit
WCR	Wide Caribbean Region
WEF	Wave Energy Flux
WEO	World Energy Outlook
WOA	World Ocean Assessment
WOR	World Ocean Review
WRI	Water Regulation Index