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Invited Research Article

An evaluation of human interventions in the anthropogenically disturbed Caribbean Coast of Colombia

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ABSTRACT

Although human interventions have influenced many coastal areas around the world, research has rarely assessed the environmental impacts of these anthropogenic perturbations. To understand the dominant coastal interventions in countries with tropical areas, this study established a baseline along the continental Caribbean coast of Colombia (approximates 1700 km), based on 29 types of human interventions cataloged via Google Earth images. In total, of the 2742 human interventions identified, the most common were low-density-settlements (n = 971), groins (n = 738), and luxury settlements with piers (n = 188). In addition, the study assessed the environmental impact of each type of intervention based on the extent, intensity, reversibility, and persistence of their effect on coastal processes, as well as their frequency of appearance in the study area. The three most impactful types of human intervention were equivalent to those with the highest frequency: a. Low-density settlements; b. Groins/Jetties; c. Luxury settlements with a pier. In addition, the highest values of environmental impact correspond to material extractions and infrastructure assets such as breakwaters and seawalls. None of these anthropogenic disturbances, however, were within the ten most impactful interventions identified in the study area. The socio-natural patterns of coastal development identified by this study can steer integrated environmental management in coastal tropical countries with rapid economic growth, diversity of human interventions and heterogeneous geographical distribution.

1. Introduction

Despite being one of the most biodiverse countries in the world, Colombia exhibits a conventional system for Environmental Impact Assessment (EIA), with equal or even lower robustness than countries with lower natural and cultural richness (Pereira et al., 2018; Toro et al., 2010). This fact is made intricate given the cultural multiplicity of this tropical country (DANE, 2012a). Regarding coastal environments, the impacts of human interventions on natural and cultural heritage have been a concern for decades. For example, in the 1970s, Great Britain's Heritage Coasts Project assessed the effects of recreation facilities, housing, mechanized agriculture, groins, and other interventions impacting their coasts (Williams and Howden, 1979). More recently, the second generation of the issue of integrating the international project of Land–Ocean Interactions in the Coastal Zone (LOICZ) raised the human dimension in the analyses of coastal systems, after being mainly focused on their biogeochemistry (LOICZ, 2005; Ramesh et al., 2015). Nowadays, the LOICZ project has evolved to the Future Earth Coasts project and looks at 'hotspots' of anthropogenically disturbed coasts. One of its themes focuses specifically on human development along the coast, and the constraints thereof (Ramesh et al., 2015).

In general terms, EIA is a process identifying, predicting, evaluating, and designing mitigation measures for any relevant effects of development proposals prior to making a major project decision, particularly regarding biophysical and social aspects (IAIA and IEA, 1999). Despite the worldwide acceptance of this instrument for environmental management, several omissions overshadow its effectiveness. When assessing the potential impacts of a new intervention over an anthropogenic area, the cumulative and synergic effects that former human developments may introduce to the analysis are often overlooked (Folkeson et al., 2013). Hence, the environment's capability of absorbing the combined effects of such perturbations, without losing substantial environmental values, is an effective concept in EIA context (Loro et al., 2014; Santoso et al., 2014). Consequently, this approach requires a baseline of existing human perturbation in natural and

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anthropogenic landscapes, which comes along with an inventory of all works and activities affecting the area of developmental interest.

In coastal areas, partial inventories of human interventions have been conducted in several countries for various purposes (e.g. Coastal management, environmental baselines, etc.). Barragán and de Andrés (2015) analyze several coastal cities and agglomerations and accounted for densely populated human settlements around the world via city population databases and Google Earth imagery. At a regional scale, Dias et al. (2013) canvassed over 60 sites along the coasts of Brazil, Argentina, Spain, and Portugal to analyze the anthropogenic impacts on Iberian and American coastal areas. According to the historical alteration of coastal sites, the authors devised the categorization of six levels of anthropogenic impact related to well-defined activities, such as tourism and salt ponds. At a local level, Ali and El-Magd (2016) identified landform transformations caused by human activities (e.g., urban development and fish farming) to reconstruct the geomorphological evolution of the Nile Delta through the spatial analysis of satellite images, spanning 25 years. Most specifically, Pranzini et al. (2015) inventoried the coastal defense works in 25 European countries, to analyze shore-protection strategies on the continent. Similarly, Bezzi et al. (2018) identified hard and soft interventions within the monitoring platform of littoral cells, to assess the effectiveness of shoreline erosion management in the Veneto Region (northeastern Italy).

In Colombia, the only type of human intervention that is properly inventoried corresponds to shore-protection structures, and it has been recorded at different geographical levels by government institutions and academics (Correa and Vernette, 2004; Gracia et al., 2018; Posada et al., 2009). Although the national environmental authority has developed a database structure for the geographical information of licensing procedures (Solarte, 2017), the information it gathers is restricted to the projects and activities under its national competence; thus, an overall inventory of all interventions affecting the coastal zone has never existed in Colombia. Consequently, the analysis of such anthropogenic patterns at a large geographical scale may strengthen the registry of human interactions with Earth systems for an effective management.

Based on the hypothesis that diversity and amount of interventions are relevant parameters in quantifying anthropogenic impacts, the following questions arise: a. How diverse are human interventions in coastal areas? b. How can an environmental baseline of human interventions be established at a large scale area, such as the Caribbean Coast of Colombia? and c. Which could be the impact of such interventions in terms of type and frequency of occurrence? Therefore, this study seeks three main objectives linked to human-landscape interactions: 1. Identify the anthropogenic disturbances to the coastal areas of a tropical country with rapid demographic and economic growth, such as Colombia; 2. Generate a baseline of the human interventions currently affecting this coastal area; 3. Compare the unitary and total effect of each kind of human intervention on coastal heritage, highlighting those works or activities that should be better regulated.

1.1. Study area

The Continental Caribbean Coast of Colombia (CCCC) is located at the northwestern corner of South America, a region influenced by the subduction of the Nazca and Caribbean plates under the South American plate (Correa and Morton, 2010). The shoreline is 1700 km long and is characterized by an alternation of mountainous areas with deltaic plains from the three major Colombian rivers (Magdalena, Sinú, and Atrato) (Correa and Pereira, 2019; Restrepo and López, 2008). It has been shaped by the formation of thick accretionary prisms with sediment supplied from the erosion of the northern Andes, judging by the estimated rates of river's sediment load (44 Mt/yr) at the Magdalena River (Duque-Caro, 1984; Restrepo et al., 2015). Interactions between geological processes and historical anthropogenic activities in coastal watersheds have resulted in unstable coastal geomorphology with environmental deterioration in several places (Correa and Pereira, 2019). Fig. 1 presents the main characteristics of the coastal morphology of the study area, where deltaic plains are shown as beach-lagoon systems, spits, and sandy barrier islands linked to extensive mangrove swamps.

As a relevant feature, the southern Caribbean coast is influenced by the mud diapiric phenomenon, a reformative process of marine floors and onshore areas due to buried low-density materials intruding on the surface (Fig. 1). Mud diapirism has profound effects on the coastal geomorphology of the area acting as the main control of the depositional patterns in the area, and as a driving force in the formation of extensive shoals and coralline archipelagos, such as the El Rosario and San Bernardo islands to the south of Cartagena city (Carvajal et al., 2010; Vernette, 1989). As human development spread along the southern Caribbean coast, violent diapiric extrusions and associated effects, such as fires, surface fracturing, and differential vertical movements, are becoming a first-order geological hazard in the area (Mendivelso et al., 2010).

From a socioeconomic framework, the CCCC exhibits higher levels of economic development compared to the coastal zones facing the Pacific Ocean; although, the five most populated cities in the study area (Barranquilla, Cartagena, Santa Marta, Ciénaga, and Riohacha) concentrate only 6.4% of the total national population (DANE, 2012a). The commercial and port activity represented exports for US$ 47.009 million in 2014, being Barranquilla and Cartagena the cities with the biggest port facilities in the Caribbean (CCO, 2017). In addition, the tourist activity in the country, within the '3S' tourism category (sun, sea, and sand; Anfuso et al., 2017), is gathered in Santa Marta, Cartagena, and Coveñas, and generated US$ 4.980 million in 2014 (DANE, 2012b; MINCIT, 2011). Additionally, the primary economic sector (agriculture, livestock, and mining) represents the main activity in five of the eight coastal departments of the study area (Choco, Cordoba, Sucre, Magdalena, Guajira), with very low participation from fisheries (0,17% of gross domestic product; CCO, 2017; DANE, 2012b).

From a geographical perspective, the CCCC was divided by Decree 1120 of 2013 into five Environmental Coastal Units (ECU), according to its socio-naturals features. These ECUs are determined as "(an) *area of the coastal zone defined geographically for its management [. . .], which contains ecosystems with their own and distinctive characteristics, with similar conditions and connectivity in terms of their structural and functional aspects*" (article 2). A summary of the main characteristics of ECUs is gathered in Table 1 and the representation of their boundaries is depicted in Fig. 1. The limits of the ECUs are set inland at 2 km from the shoreline (Decree 1120 of 2013, Article 3, numeral 1c) and the same distance offshore.

2. Methods

The analysis of the environmental impact of human interventions comprises two stages: 1. An inventory of the coastal interventions through the observation of satellite images. 2. An evaluation of the environmental impact of each category of intervention, given their unitary importance and frequency of appearance. The former allowed to build a database of human interventions, while the latter analyzed their effects on environmental features, such as geomorphology and landscape.

2.1. Inventory

To approximate the number of human intervention in the CCCC, an exhaustive list of intervention typologies was compiled using

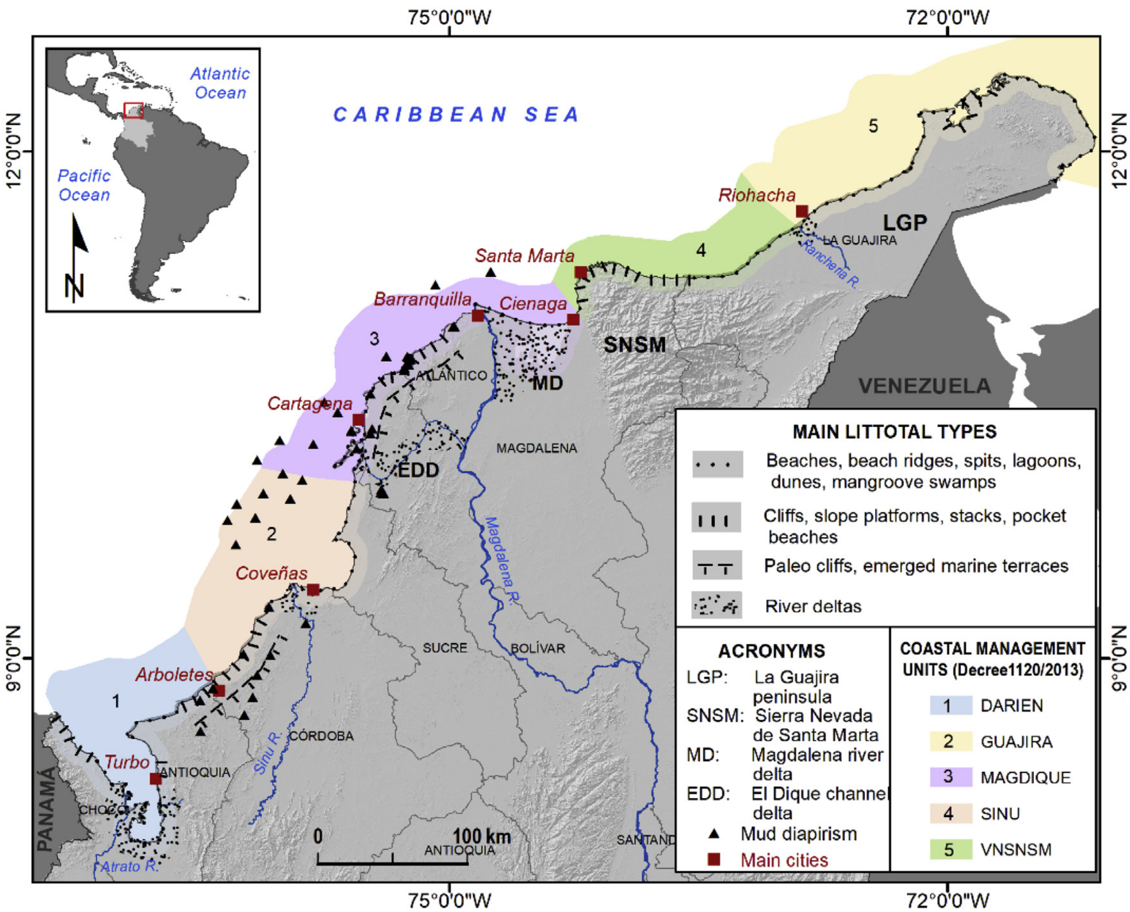

Fig. 1. Location of the study area. Adapted from Correa and Pereira (2019); Carvajal et al. (2010), and Vernette (1989). The acronym MAGDIQUE refers to the unit Magdalena-Canal del Dique and VSNSM to the unit of the northern slope of Sierra Nevada de Santa Marta.

the structure of coastal uses and activities proposed by Botero et al. (2014). This scheme served as a reference to select 29 types of human interventions, in terms of landscape transformation, infrastructure, and joint facilities, whose emplacement within the terrestrial or marine limits of the coastal zone can disturb the natural processes influencing the coastal morphology (Pereira et al., 2018). Although these categories were created for coastal zoning and marine spatial planning, this study adapted them to fit an impact assessment approach (Appendix 1 describes each typology). This approach facilitates the use of a wide list of typologies and their internal consistency, reassuring that each typology is part of a group of interventions without redundancies or gaps, something which is usually not taken into account in previous studies (e.g. Ali and El-Magd, 2016; Bezzi et al., 2018; Dias et al., 2013; Pranzini et al., 2015). Additionally, a code system was established to represent each type of intervention, using six letters and three digits (see codes and coding system in Appendix 1).

Data collection and processing was done with Google Earth. This software gathers images from different satellite constellations (e.g. Digital Globe, Astrium), providing easy access to numerous satellite images of the study area with high enough quality to observe the topographic relief and identify geomorphological units (Berry et al., 2014; Harris et al., 2014; Hossain et al., 2016; Magaña et al., 2014). In addition, the image information was also sourced from alternative imagery services such as ©Nokia, ©Bing, and ©ESRI. Where necessary, ArcMap from ESRI or the open source gvSIG were used to alternative imagery inputs.

Among the tools of Google Earth, position marks and its editing options, historical imagery and street view were used. Almost 4000 position marks were placed over Google Earth imagery to represent punctual, linear, and surface shape interventions within the 29 identified typologies (see the kml files of the supplementary material). Historical imagery allowed us to recognize and differentiate the types of interventions by comparing images from

Table 1
Main characteristics of the ECUs in the CCCC.

ECU	Coastal geomorphology	River deltas	Coastal lagoons	Coastal cities
GUAJIRA	Flat coast (beaches, low hills)	Rancheria River	None	Riohacha
VNSNSM	Rocky coast (Cliffs, high mountain)		Los Flamencos lagoon	Santa Marta
MAGDIQUE	Flat coast (beaches, low hills, diapirism)	Magdalena River	Cienaga Grande de Santa Marta swamp, La Virgen swamp	Ciénaga, Barranquilla, Cartagena
SINU		Sinu River	La Caimanera swamp	Coveñas
DARIEN	Mixed coast (beaches, cliffs, low hills, diapirism)	Atrato River	None	Arboletes, Turbo

different times. Ultimately, the street view was used as a discriminating tool in areas with roads and streets, as it provided further details of the height and material of built structures around streets and roads. These details helped in differentiating one type of intervention from another.

Although the image resolution of Google Earth was mostly appropriate for the observation scale, high degrees of cloudiness on a few sectors of the GUAJIRA, SINU, and DARIEN units made it difficult to identify the interventions. In these cases, alternative imagery services were used to mark the interventions obscured by clouds, and their geographic reference was then marked in Google Earth to keep all data in a single repository. In the case of the DARIEN unit, the high-resolution images of the spatial geodatabase developed by Prüssmann and Correa (2012) were also used, comprising the littoral geomorphology of the Urabá Gulf. Finally, the source data used for the identification of each intervention, together with the respective intervention typology code and additional observations were recorded in MS Excel ® worksheets.

2.2. Environmental impact estimation

To quantify the overall impact of human interventions, Unitary Environmental Impact (UEI) and Total Environmental Impact (TEI) were calculated for each one of the twenty-nine types. The UEI refers to the effect of a type of intervention (e.g. ports, luxury settlements or roads), meanwhile the TEI refers to the effect of all interventions identified on the study area within each typology. The calculation was based on the equation proposed by Conesa (2006) and adapted in Eq. (1) and (2), which are influenced by four attributes (Table 2): extension (EXT), intensity (INT), reversibility (REV), and persistence (PER). In addition, α refers to the maximum value possible from the total sum of the attributes. Therefore, Eq. (2) introduced the frequency (Frq) as a multiplier of the UEI to calculate the Total Environmental Impact (TEI) by type of coastal intervention. The values of UEI and TEI are dimensionless because they express the estimation of environmental impact, rather than a measurement.

The conceptualization of coastal processes was used as a reference to differentiate the scale and/or dimension of the attributes in the assessment of each typology, particularly for EXT and INT attributes (Appendix 2). Such conceptual framework is consistent with a novel approach of impact assessments, in which the analysis of natural flows within a given kind of environment is closer to the character of the impact than the conventional analysis of segmented components (Pereira et al., 2018).

$$UEI = (EXT + INT + REV + PER)/\alpha \tag{1}$$

$$TEI = Frq\ (EXT + INT + REV + PER)/\alpha \tag{2}$$

The overall assessment was complemented by the application of descriptive statistics to the calculated values of TEI for each environmental unit and the entire study area. It was supported by the incompatibility principle, which states that simple aggregation operators favor significance rather than precision (Toro et al., 2012; Zadeh, 1973). Therefore, graphical representation of data distribution, quartiles, and interquartile ranges were used to refine data and highlight the concentration and magnitudes of the environmental impact due to coastal interventions. In addition, box plot analyses and Tukey tests were performed to identify extreme and mild outliers.

3. Results

3.1. Coastal interventions in the CCCC

Among the over 50 types of works and activities which might affect the coastal zone proposed by Botero et al. (2014), only twenty-nine were identified in the study area (see appendix 1). The geographic distribution of coastal interventions in the study area is presented in Fig. 2, wherein a pie chart shows their relative frequencies for each ECU. As a first evaluation, the gross-level pie chart reveals that 60% of the interventions were concentrated in the SINU and MAGDIQUE units, which relates to coastal length and morphology because the probability of having human interventions is higher in longer and sandy coasts than that in mountainous and rocky littorals.

Concerning typologies, Fig. 2 illustrates that low-density settlements and groins are the only interventions that are frequently observed in the majority of coastal units (>15%). In addition, sixteen typologies are shown in the figure, meanwhile the rest of typologies they comprised <1% in all ECUs. Therefore, the label 'other' grouped those categories with low values. Fig. 3 shows examples of the six most common intervention types.

Regarding geographical representation, the MAGDIQUE unit has the highest diversity of intervention typologies (93%) from the 29 identified, followed by SINU (72%), VNSNSM (79%), DARIEN (55%) and finally GUAJIRA (41%). The distribution of interventions in the mountainous units shows that VNSNSM comprises three gross typologies, covering 68% of the interventions, the majority of which belong to low-density-settlements and tourism and recreation. Another 22% is almost evenly distributed among luxury settlements, 3S tourism, basic activities, maritime transport, and road infrastructure. The remaining 10% is distributed into 14 types within the categories of human settlements, infrastructure on shore, railway infrastructure, industrial typologies, maritime trade facilities, and tourism and recreation. Regarding the partially mountainous DARIEN unit, the two predominant intervention typologies of most units (low-density settlements and groins) comprise 77% of the unit's account, with a relation

Table 2
Attributes to calculate the importance of the impact of every type of coastal intervention (Based on Conesa, 2006 and Toro et al., 2013).

Intensity (INT)		Extension (EXT)	
Incidence of the action on the environmental factor		Area affected by the impact in relation to the total area of the surroundings	
Low	1	Isolated	1
Medium	2	Partial	2
High	4	Widespread	4
Very high	8	Total	8
Total	12	Critical	+4
Reversibility (REV)		**Persistence (PER)**	
Natural recovery of the environmental factor to its initial state before the impact		Permanence of the impact from the time of its appearance until when the environmental factor returns to its initial state.	
Short-term (<1 year)	1	Fleeting (<1 year)	1
Medium-term (1–5 years)	2	Temporary (1–10 years)	2
Irreversible	4	Permanent (>10 years)	4

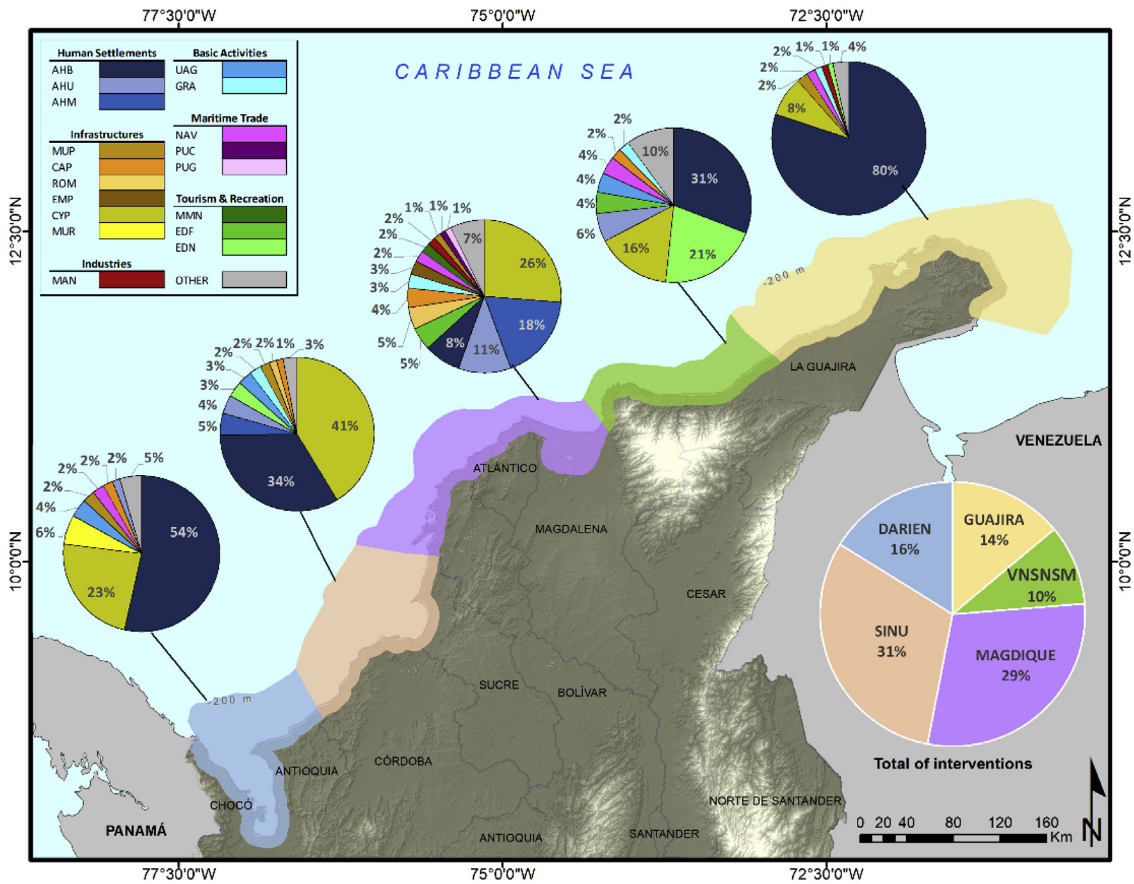

Fig. 2. Intervention's distribution according to Environmental Coastal Units in the Colombian continental Caribbean (acronyms are described in Appendix 1).

close to 2:1. Another 18% is distributed among four typologies related to agriculture, infrastructure, maritime trade, and human settlement. The remaining 5% is distributed among the categories of human settlements, basic activities, industry, maritime trade, and tourism.

The distribution of interventions in the flattest units shows that MAGDIQUE has a longer list of typologies, the majority of them (55%) relies on shore-protection infrastructure and luxury settlements, with and without piers. Another 37% is distributed among the categories of human settlements, tourism and recreation, infrastructure, maritime trade, industry, and basic activities. The remaining 7% gathers 12 typologies of human settlements, infrastructure on the shore, mining, basic activity, industry, and, particularly, tourism and recreation. Regarding the SINU unit, the majority of identified interventions (75%) are distributed among human settlement and shore-protection infrastructure. Another 22% is distributed among basic activities, human settlements, tourism, and infrastructure. The remaining 3% is spread in 11 typologies of the following categories: infrastructure, human settlements, the remaining basic activity, industries, maritime trade, and, particularly, tourism and recreation. Finally, intervention diversity in GUAJIRA is restricted to 20%, half of which deals with infrastructure that is perpendicularly attached to the shore (e.g., groins, navigation channels). Another 6% is distributed among a human settlement and facilities for the activities of maritime trade, industry, and tourism. The remaining 4%" deals with five types of interventions in the categories of infrastructure, basic activities, and maritime trade.

Referring to the concentration of interventions, Table 3 summarizes the 14 typologies whose appearance in a single unit is more than 50% of the total count within all ECUs. These values complement the data represented in Fig. 2, where MAGDIQUE appears as the most diverse unit because it also holds the highest concentration of interventions by typology, comprising 79% of the interventions on Table 3. In contrast, GUAJIRA unit registers the lowest amounts of interventions, either within the highly concentrated typologies (3%) or by the total of intervention typology represented among the 29 identified in the study (41%).

MAGDIQUE also concentrates the industrial and commercial activity in the study area because it comprises 61% of the interventions in the typologies manufacture and ports. MAGDIQUE has the biggest concentration of tourism-related interventions, not only for the 3S tourism and marinas but also for two interventions attributed to second residences (luxury settlements). Within the same category of tourism and recreation, the VNSNSM unit precedes having one highly concentrated intervention (nature tourism) that is accounting 57% of the occurrences. Finally, GUAJIRA is the only unit where none of the invention types is particularly concentrated, but where low-density settlements are abundant (Table 3).

3.2. Environmental impact of interventions

The most relevant interventions in terms of frequency of appearance, the estimated UEI, and the corresponding TEI show clear spatial patterns. Initially, the groins typology is one of the variants of the hard shore-protection structures that comprises over a third of the overall TEI in the study area (36%). When combined, the values of groins with low-density settlements have a TEI of more than half of the overall impact estimated for the study

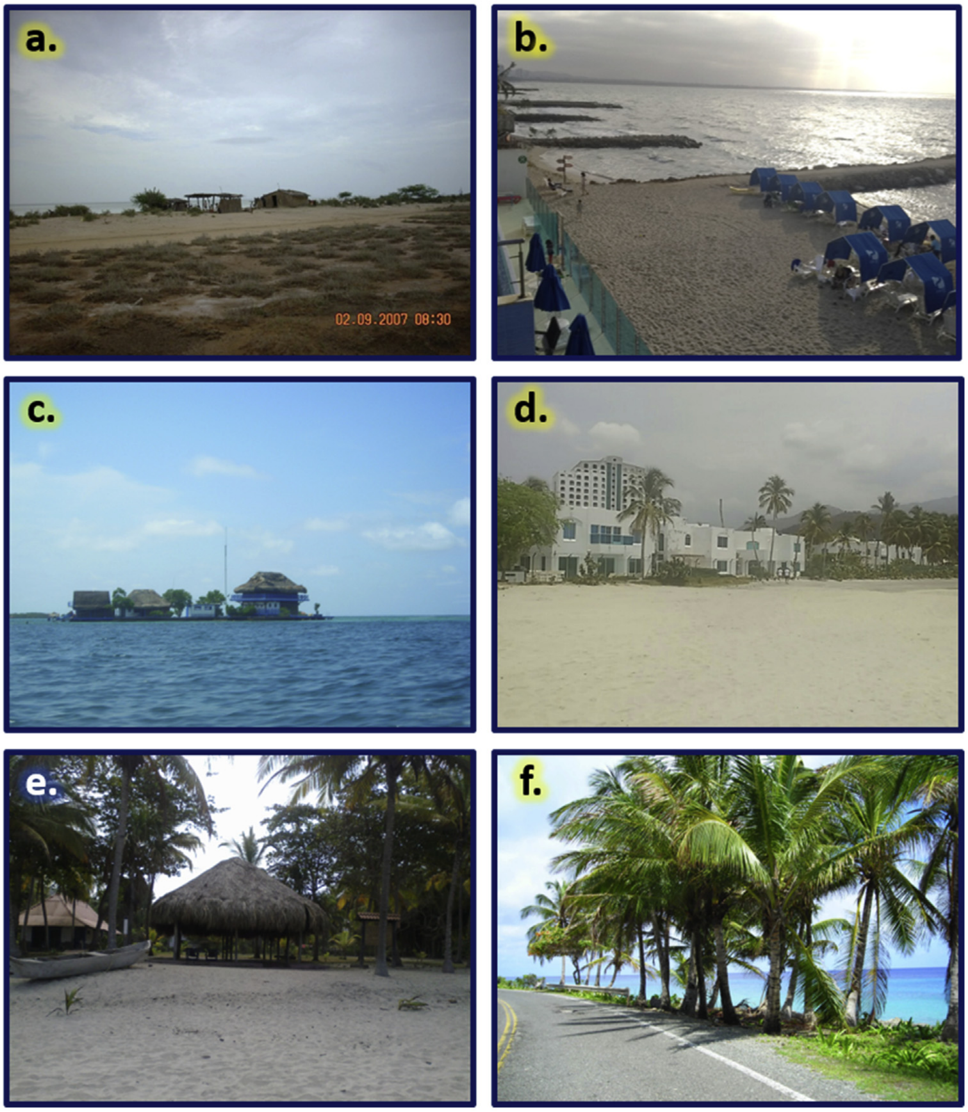

Fig. 3. Most common coastal intervention types in the Colombian continental Caribbean (a. Low-density settlements (AHB); b. Groins (CYP); c. Luxury settlement with a pier (AHM); d. Luxury settlements (AHU); e. Nature Tourism (EDN); f. Road infrastructure (CAP).

Table 3
Number and ranking of occurrences of the highly concentrated types of interventions in the study area (the highest value for each category is shown in bold).

TYPOLOGY		ECUs					TOTAL	FREQ RANK
CODE	NAME	GUAJIRA	VNSNSM	MAGDIQUE	SINU	DARIEN		
AHA	High density settlements	0	5	**10**	2	1	**18**	*13th**
AHU	Luxury settlement	0	16	**89**	33	7	**145**	*4th*
AHM	Luxury settlement with pier	0	3	**146**	39	0	**188**	*3rd*
CAP	Road infrastructure	3	6	**33**	12	9	**63**	*6th*
ROM	Breakwaters	0	1	**37**	13	5	**56**	*8th*
EMP	Inlet navigation channels	3	0	**23**	4	0	**30**	*10th*
CYP	Groins	32	42	211	**349**	104	**738**	*2nd*
MUR	Seawalls	2	1	**9**	2	27	**41**	*9th*
MAN	Manufacture	5	4	**14**	2	2	**27**	*11th*
PUC	Deep water ports without shelter	0	2	**10**	0	0	**12**	*14th*
PUG	Shallow water ports without shelter	3	1	**11**	1	2	**18**	*13th**
MMN	Marinas	0	1	**17**	1	0	**19**	*12th*
EDF	3S Tourism (sea, sand, sun)	0	12	**39**	4	2	**57**	*7th*
EDN	Nature Tourism	4	**56**	9	28	2	**99**	*5th*
SUM (28 types)		**52**	**150**	**658**	**490**	**161**	**1511**	
AHB	Low density settlements	**306**	83	62	283	237	**971**	*1st*
SUM (all types)		**382**	**269**	**803**	**845**	**443**	**2742**	

area (54%). The majority of the overall TEI (85%) is attributed to only ten types of interventions, eight of them are among the most frequently occurring. The eighth and ninth intervention positions within the top ten of TEI correspond to inlet navigation channels and seawalls, which represent together 5% of TEI. These types of interventions are variants of shore-protection structures, together with another two interventions in the top ten (groins and breakwaters), which are under the regional and national competence for environmental licensing in Colombia (Pereira et al., 2018).

Considering the overall values of TEI by type of intervention as a descriptive statistic, the data distribution allowed a filtering analysis, depicted in Fig. 4. The box plot of the TEI value for all 29 intervention typologies indicates that data distribution is asymmetrical (refer to scenario A). A Tukey test revealed the presence of three extreme atypical values, corresponding to the typologies groins, low-density settlements, and luxury settlements with pier; they exceed three times the upper limit of the interquartile range (1.87 units of TEI). The box plot of the analysis without the extreme outliers (scenario A') confirms the presence of a mild atypical value, corresponding to the typology luxury settlements, which exceeded the upper limit of 1.5 times the interquartile range. The dominant interventions types were removed from the analysis in scenario B.

Therefore, to identify interventions underestimated by the importance of extreme and mild outliers, Fig. 5 expands the values of UEI and TEI in the five units of the study area through two scenarios: A. All typologies, and B. Typologies without outliers. The first column gathers the UEI values with a coded color, according to their respective quartiles (Q1=blue, Q2=green, Q3=yellow, Q4=red), and the bars on the following columns represent their TEI values. The last column represents the proportion of the overall TEI attributed to each intervention's typology, with the same coded color aforementioned. The last row in each scenario represents the percentage of TEI in each ECU according to the respective scenario. A special analysis was done in scenario B, where the penultimate row represents the percentage of TEI after extracting the interventions with atypical values but according to the totals of scenario A. Therefore, last two rows of scenario B allow to identify the masking effect caused by the outlier typologies.

The results show that 31% of the overall TEI in the study area corresponds to the 25 types of interventions. The other 69% is attributed to only four typologies (CYP, AHB, AHM, and AHU), which produces a shadow effect on the other 25 interventions. This is the case for: seawalls in DARIEN; aquaculture, farming and livestock, breakwaters, road infrastructure and public docks in SINU; nature tourism in VNSNSM; public docks, aquaculture, and inlet navigation channels in GUAJIRA. The filtered representation of scenario B demonstrates how MAGDIQUE has the same tendency of the TEI as the entire study area. Although SINU has a higher proportion of interventions compared to MAGDIQUE, the interventions in the latter region have a higher overall environmental impact. This particularly clear in Fig. 5B, where the outliers are removed from the analyses.

Finally, over one-third of the overall TEI in the area is attributed to groins, not only because its UEI value is moderate-to-high (Q3), but also because it exhibits the second highest frequency of occurrence in the area. The other three typologies comprising the atypical values of TEI belong to the category of human settlements, with the isolated populated areas holding the second position in TEI rank, despite having a low UEI (Q1). The remaining two types are luxury housing, with and without private pier, whose values are rather similar with a joint representation of ̃15% on the overall TEI of the study area. In this case, the frequency cannot be solely responsible because the UEI value of luxury settlements is medium-to-low (Q2), while the case of these settlements with a private pier lies in Q3, due to their direct effect on coastal morphology.

4. Discussion

4.1. Coastal intervention's patterns

Some socio-natural patterns can be extracted from the results reached, which poses useful lessons for coastal tropical countries with rapid economic growth, such as in Colombia. Low-density settlements were the most representative typology, probably because of spreading of human population over the territory. Although human settlements fail to represent a classic subject of environmental licensing, they encompass joint facilities and land transformations, which contribute to a territorial approximation of the environmental state. In fact, low-density settlements represent are not highly concentrated in any particular unit, they still represent over 80% and 53% of the intervention counted in GUAJIRA and DARIEN, respectively. Another exceptional case is presented in

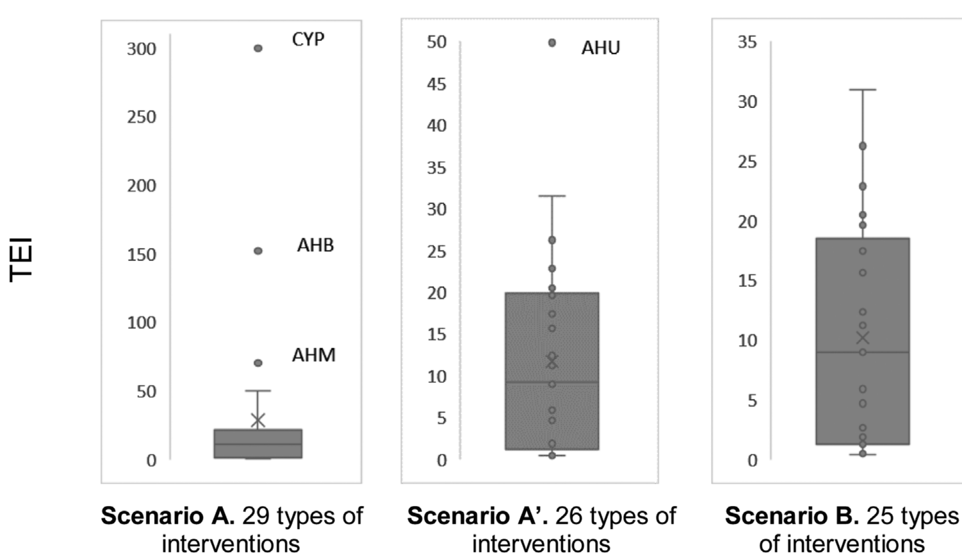

Fig. 4. Box plots for the overall TEI values, representing the asymmetric distribution of data (A), the distribution without extreme outliers (A'), and the distribution without extreme and mild outliers (B).

Scenario A.: 29 types of interventions

TYPE	UEI	DARIEN TEI	SINU TEI	MAGDIQUE TEI	VNSNSM TEI	GUAJIRA TEI	% of overal TEI
EMP	0,688	0	2,75	15,8125	0	2,0625	2,5%
AHA	0,625	0,625	1,25	6,25	3,125	0	1,4%
DMI	0,625	0	0	1,25	0	0	0,2%
CAP	0,500	4,5	6	16,5	3	1,5	3,8%
MUR	0,500	13,5	1	4,5	0,5	1	2,5%
MMN	0,500	0	0,5	8,5	0,5	0	1,1%
PUG	0,500	1	0,5	5,5	0,5	1,5	1,1%
PUC	0,500	0	0	5	1	0	0,7%
VFE	0,500	0	0	0	0,5	0	0,1%
ROM	0,469	2,34375	6,09375	17,34375	0,46875	0	3,2%
EDM	0,469	0	1,875	2,8125	0	0	0,6%
MCR	0,438	0	0	0,4375	0	0	0,1%
CYP	0,406	42,25	141,78125	85,71875	17,0625	13	36,3%
AHM	0,375	0	14,625	54,75	1,125	0	8,5%
GRA	0,375	1,5	7,875	9	2,25	2,25	2,8%
PYC	0,375	0	0,375	1,125	1,125	0	0,3%
AHU	0,344	2,40625	11,34375	30,59375	5,5	0	6,0%
EDF	0,344	0,6875	1,375	13,40625	4,125	0	2,4%
MUP	0,313	3,4375	5,3125	3,4375	0,625	2,8125	1,9%
INA	0,313	0,625	0	0,9375	0,3125	0	0,2%
UAG	0,281	4,78125	7,03125	1,96875	3,09375	0,5625	2,1%
GRM	0,281	0	0,28125	0,28125	0	0	0,1%
AHP	0,281	0	0	0,5625	0	0	0,1%
NAV	0,250	2,75	0,75	4,75	2,5	1,75	1,5%
ESH	0,250	0	0	1	0,25	0	0,2%
TYS	0,250	0	0	0,25	0,25	0,25	0,1%
MAN	0,219	0,4375	0,4375	3,0625	0,875	1,09375	0,7%
AHB	0,156	37,03125	44,21875	9,6875	12,96875	47,8125	18,4%
EDN	0,125	0,25	3,5	1,125	7	0,5	1,5%
% of overall TEI		14%	31%	37%	8%	9%	100%

Scenario B.: 25 types of interventions (without CYP, AHB, AHM, and AHU)

TYPE	UEI	DARIEN TEI	SINU TEI	MAGDIQUE TEI	VNSNSM TEI	GUAJIRA TEI	% of overal TEI
EMP	0,688	0	2,75	15,8125	0	2,0625	2,5%
AHA	0,625	0,625	1,25	6,25	3,125	0	1,4%
DMI	0,625	0	0	1,25	0	0	0,2%
CAP	0,500	4,5	6	16,5	3	1,5	3,8%
MUR	0,500	13,5	1	4,5	0,5	1	2,5%
MMN	0,500	0	0,5	8,5	0,5	0	1,1%
PUG	0,500	1	0,5	5,5	0,5	1,5	1,1%
PUC	0,500	0	0	5	1	0	0,7%
VFE	0,500	0	0	0	0,5	0	0,1%
ROM	0,469	2,34375	6,09375	17,34375	0,46875	0	3,2%
EDM	0,469	0	1,875	2,8125	0	0	0,6%
MCR	0,438	0	0	0,4375	0	0	0,1%
GRA	0,375	1,5	7,875	9	2,25	2,25	2,8%
PYC	0,375	0	0,375	1,125	1,125	0	0,3%
EDF	0,344	0,6875	1,375	13,40625	4,125	0	2,4%
MUP	0,313	3,4375	5,3125	3,4375	0,625	2,8125	1,9%
INA	0,313	0,625	0	0,9375	0,3125	0	0,2%
UAG	0,281	4,78125	7,03125	1,96875	3,09375	0,5625	2,1%
GRM	0,281	0	0,28125	0,28125	0	0	0,1%
AHP	0,281	0	0	0,5625	0	0	0,1%
NAV	0,250	2,75	0,75	4,75	2,5	1,75	1,5%
ESH	0,250	0	0	1	0,25	0	0,2%
TYS	0,250	0	0	0,25	0,25	0,25	0,1%
MAN	0,219	0,4375	0,4375	3,0625	0,875	1,09375	0,7%
EDN	0,125	0,25	3,5	1,125	7	0,5	1,5%
% of overall TEI (within outliers)		4%	6%	15%	4%	2%	31%
% of overall TEI (without outliers)		14%	18%	49%	13%	6%	100%

Fig. 5. Values of the unitary (UEI) and total (TEI) environmental impacts estimated for the CCCC. Scenario A: all 29 identified intervention typologies; Scenario B: intervention typologies without atypical values. Distribution of data in quartiles: Q1 in blue, Q2 in green, Q3 in yellow, and Q4 in red.

the MAGDIQUE unit, where the Barú peninsula figures as a hotspot for coastal interventions, particularly luxury settlements that operate as second residences, due to the landscape value of the tourist beaches in the area (Rangel-Buitrago et al., 2013; Williams et al., 2016). Luxury settlements represent a type of infrastructure linked to a non-permanent population that coincides with tourist seasons on coastal zones (Barragán and de Andrés, 2015). Lastly, the dominance of nature tourism in VNSNSM (57% occurrences) may be attributed to the presence of three natural parks in this unit: Sierra Nevada de Santa Marta, Tayrona, and Los Flamencos, the last two being directly on the littoral.

The typology 'groins' is the most popular infrastructure type determined along the extent of the study area, with representative percentages of appearances among all interventions in each ECU. Conversely, SINU concentrates almost half of all groins identified in all five units (47%), making it one of the few interventions whose highest concentration is not in MAGDIQUE. This rigid structure has been responsible for the instability of several kilometers of coast in the Colombian Caribbean littoral as a collateral effect of localized interventions to counteract coastal erosion (Correa et al., 2005; Rangel-Buitrago et al., 2015). It is worth noting the high level of littoral armoring in SINU and DARIEN, given their low infrastructure and economic development, which do not justify the high level of hard structures. One explanation is based on Rangel-Buitrago et al. (2018b), who state that most of the protective works were carried out as private efforts to protect tourism-related infrastructure, farming lands, and luxury rural housing. Indeed, analysis of coastal erosion in this area pinpoints a proliferation and ineffectiveness of shore-protection works, judging by the rising erosion rates, approximating 3 m/yr (Correa et al., 2005; Paniagua-Arroyave et al., 2018; Prüssmann, 2011; Rangel-Buitrago et al., 2015). Correa and Vernette (2004) reported that out of the 150 rigid shore-protection structures in this area, only ten have proven effective, while the remaining was useless and even induced an accelerated erosion. Overall, these situations suggest that Colombian regulations differ from the good practices of countries with broader tracking in coastal management (e.g., Cuba) that recognize hard shore-protection structures as an environmental violation (Pereira et al., 2018).

The effectiveness of hard structures for mitigating littoral erosion is widely debated (Botero et al., 2013; Correa and Gonzalez, 2000; Pranzini et al., 2015; Williams et al., 2018). Within the alternative measures to counteract shore erosion, the relocation of existing infrastructure and human values, also known as managed realignment, is gaining acceptance (Rangel-Buitrago et al., 2018a; Williams et al., 2018). This kind of alternative management options has lower environmental impacts that shore-protection infrastructures. Given the geomorphological instability of the Colombian Caribbean and projections of at least 1 m sea level rise in the following 100 years (IPCC, 2014), immediate or programmed retreat figures as a pertinent strategy in territorial planning and environmental management.

Regarding geographical patterns, MAGDIQUE concentrates industrial and commercial activity, which is consistent with the socioeconomic character of the study area. This ECU contains three of the five most populated cities of the Colombian Caribbean (Barranquilla, Cartagena, and Ciénaga), as well as two harbor and industry hotspots related to the current operational facilities of the region (DANE, 2012a,2012b). It is worth mentioning that three maritime trade and joint infrastructure facilities are projected with approved environmental licenses in DARIEN. Conversely, despite exhibiting a medium-high typology diversity, VNSNSM contains the lowest total amount of interventions identified in the gross study area. This is probably due to its shorter extent of coastal plains with respect to other ECUs (Correa and Morton, 2010). Lastly, GUAJIRA probably has the lowest amount of interventions because almost half of its territory is a desert with an indigenous population (DIMAR-CIOH, 2013).

In the context of the environmental impact estimation, the novel application of Eq. (1) and (2) on coastal environments demonstrated that the four types of interventions having the highest frequency coincide with those having the highest TEI, although their respective order is slightly different. However, among the ten most frequent typologies, only two are in the top ten interventions with the higher UEI. For example, low-density settlements exhibit the highest frequency, while ranking at the penultimate position of unitary impact. However, the total impact attributed to this typology ranks second among all identified typologies. Although low-density-settlements depicts an exceptional case, other typologies support the premise that numerous occurrences of interventions with medium-to-low unitary impact can magnify the environmental effect (e.g., nature tourism, 3S tourism, aquaculture and luxury settlements with pier), being an analysis rarely done in previous assessments (e.g. (Ali and El-Magd, 2016; Barragán and de Andrés, 2015; Dias et al., 2013; Pranzini et al., 2015).

Furthermore, the consideration of both scenarios (A and B) leads to a better understanding of the behavior of TEI values among all the intervention typologies, by removing the shadowing effect of the atypical values. As an example, the outlier analysis highlighted that luxury settlements (with and without piers) are highly impactful interventions, but they are currently not considered in the environmental licensing procedure of several countries (Pereira et al., 2018). These typologies are commonly regulated by municipal land-use plans, which are the official urban planning instruments in many countries, such as Colombia. The regulation of these kinds of interventions by local administrations could be hampered, because of the political and economic power of their owners (Neal et al., 2018). Apart from sociopolitical factors, the complementary role between environmental impact assessment and land-use planning is clearly demonstrated.

Finally, analysis of outliers suggests the importance to assess both UEI and TEI. While MAGDIQUE and SINU hold over one-third of the overall TEI, MAGDIQUE accounts for almost half of the overall TEI and SINU drops to less than the fifth part when the four dominant intervention categories are included. Judging by the high concentration of the groins typology in SINU, most of the impact is derived from hard shore-protection structures. Conversely, the increased representation of MAGDIQUE is attributed to a combination of interventions with UEI values in the third and fourth quartiles. Therefore, the importance to regulate the environmental impact of the vast majority of human interventions is also demonstrated, even when they may have a relatively low frequency of appearance on the territory.

4.2. Limitations of coastal interventions inventories from remote sensing

Despite the wealth of information gathered, data collection from optical remote sensing images has limitations when identifying activities lacking a distinctive shape or requiring temporal analysis. Some intervention typologies cannot be easily discerned from an aerial perspective; such is the case for underground conduits (e.g., water conductions and pipelines), irrigation infrastructure, or beach nourishment, which are included among the long list of coastal uses and activities proposed by Botero et al. (2014). The mentioned interventions are an example of the kind of intervention that requires a time-series analysis for proper recognition.

Another type of intervention that cannot be easily identified is submarine sewage disposal. This kind of intervention has been recognized in the marine strategy of the European Directive 2008/56. Conversely, human interventions associated with drainage basin alterations and extensive land-use and livestock are not often associated with the coastal zone because they transcend their conceptual boundaries. However, they might have important implications on the coastal morphology by changing sediment supply (Correa and Restrepo, 2002; LOICZ, 2005; Restrepo et al., 2016). Although the scope of the inventory was narrowed down to the legal definition of the coastal zone in Colombia, and to the parameters at the temporal and spatial resolution of the available inputs, the interventions linked from the upstream drainage areas need to be included in further studies (Milanes et al., 2017).

Last but not least, sources of information, such as historical documents and narratives, inhabitants' testimonies, and time-series of remote sensing data, may be incorporated as a relevant data source. Studies on the Colombian coastline (e.g. Botero et al., 2013; Rangel-Buitrago et al., 2018b) confirm that an important, but undefined, number of rigid coastal structures (particularly groins) built at the beginning of the twentieth century, have been destroyed. Little evidence of this situation is recorded in an inventory based on a single satellite images' set, as shore erosion rapidly reconfigures the aerial view of coastline profiles; as such, historical reports could greatly complement the data gathered by remote sensing.

5. Conclusions

The exhaustive inventory of interventions in the Caribbean Coast of Colombia shows heterogeneous socio-natural patterns that can steer integrated environmental management in tropical countries. Based on the hypothesis that diversity and amount of interventions are relevant parameters in quantifying anthropogenic impacts in coastal areas, this analysis allowed to determine how diverse are those human interventions, how many of them could be affecting a large scale area, and which could be the impact of such interventions in terms of type and frequency of occurrence. Initially, the results show a moderate diversity of human intervention types, and spatial variation in anthropogenic disturbances to the coastal zone. Within the five environmental coastal units, the MAGDIQUE unit has the most diverse set of coastal interventions, although the SINU unit represents the majority of interventions. Conversely, GUAJIRA has the lowest diversity of interventions, which are highly concentrated in low-density human settlements. These findings confirm the strong relationship between urban development and the diversity of the economic activities on the coast.

Secondly, the high occurrence of relatively small human settlements and shore-protection structures, compared with larger interventions such as ports or aquaculture ponds, demonstrates the importance of accounting for the frequency and distribution of small intervention types, due to their synergic effect on the total environmental impact. In other words, the quantity of human interventions is not enough as a parameter by it-self to establish a baseline of the anthropogenic disturbance at a large scale area, but it gains relevance when complemented with the diversity of interventions. Nevertheless, further research should include *in situ* field work to reinforce the hypotheses about the repercussions of human perturbation on the morphological evolution of the Earth's surface, perhaps within global projects such as Future Earth.

Finally, this study demonstrated the importance of evaluating the unitary environmental impact (UEI), as well as the sum of the impacts of the same kind of intervention (TEI) to overcome the limitations of generic EIA. Although this research comprehends an extensive coastal area, it could also be applied to smaller areas, as long as the analysis is done at sub-national scales. Moreover, the box plot analysis demonstrated that extreme and mild outliers in the data can minimize the real effect of the majority of coastal interventions, which forces misevaluations of their real environmental impact. Therefore, the findings of this study stress the need to control the geographical distribution of coastal interventions, and the importance to develop alternative approaches of EIA based on socio-natural processes. Last, but no least, the worldwide significance of the findings of this study, regarding human-impacted coasts, relies on two methodological contributions: 1) the identification and cataloging of human interventions in tropical coast through free-access imagery sources, and 2) the generation of a baseline of the environmental impacts at a regional scale.

Declaration of Competing Interest

Nothing declared.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ancene.2019.100215.

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