



# Is the coastal vulnerability index a suitable index? Review and proposal of alternative indices for coastal vulnerability to sea level rise

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## Abstract

The Coastal Vulnerability Index (CVI) has been widely applied around the world. This study provides a review of the suitability of the variables and mathematical expression of the CVI and proposes a new Integrated Coastal Vulnerability Index (ICVI), comparing both indices for 4 study areas in the southern Caribbean. The ICVI assesses vulnerability to sea level rise by integrating the Environmental Vulnerability Index (EVI) and the Socioeconomic Vulnerability Index (SVI). Regarding the variables that constitute the indices, it is noted that the CVI includes vulnerability and hazard variables and therefore it should be considered a risk index rather than a vulnerability index. The EVI includes geomorphological vulnerability variables, like the CVI, but also ecological ones. Regarding the mathematical expression, the use of the arithmetic mean versus the formula proposed for the CVI is discussed based on the comparison of the results obtained for EVI and SVI in the 4 study areas. In addition, the use of absolute (between 0 and 1) or relative (based on percentiles) limits in these indices, and the use of weights or not, are also discussed. The conclusion is that the use of relative thresholds necessarily forces the identification of very low to very high vulnerability zones for any study, and the use of weights on the variables increases the subjectivity of the assessment, all of which impedes the comparability of the index at a global level. Therefore, the ICVI, with the formula based on the arithmetic mean, with absolute limits between 0 and 1 and without variable weightings, is preferable to the CVI for use at the global level.

## Introduction

Risk analysis is based on the assessment of hazards and vulnerability. Hazards are mainly characterized by the energy or magnitude of the dangerous event, combined with their duration and frequency. Natural hazards include climatic, geological and biological hazards (Bryant 2005). Climate change affects the severity of natural hazards like the occurrence of extreme events in temperatures, hurricanes, rains, storms energy, and sea level rise. Then, the risk of floods

and coastal erosion is increasing due to climate change (IPCC 2007).

Initially, vulnerability has been analyzed from a human and socio-economic point of view, i.e., the possibility of loss of human lives, injury, or economic loss (Gordon 2020). The anthropic pressure over the coastal areas increased significantly in the last century (Small and Nicholls 2003), and consequently increased the socio-economic vulnerability of the coastal areas. The relevance of the natural resources led to the inclusion in the analysis of the ecological or environmental vulnerability (Kaly et al. 2003). In addition, bearing of geological resources led to include the consideration of vulnerability analysis also from a geomorphological perspective, e.g., the vulnerability of dunes, beaches, and cliff to sea level rise (Palmer et al. 2011).

Coastal vulnerability to sea level rise has been analyzed using different methodologies (Thieler and Hammar-Klose 1999; Pendleton et al. 2004; Balica et al. 2012; Pantusa et al. 2018). One of the most widely used is the Coastal Vulnerability Index (CVI) defined by Gornitz (1991). Understanding the term Indices as the signals that measure, simplify and communicate the complex reality of an event (Farrell

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and Hart, 1998, Barnett et al. 2008). In this study, we analyze the suitability of the CVI as an index for measuring coastal vulnerability to sea level rise, particularly their variables and the mathematical expression. We also propose an alternative index (ICVI) that combine the socio-economic (SVI) and environmental vulnerability (EVI).

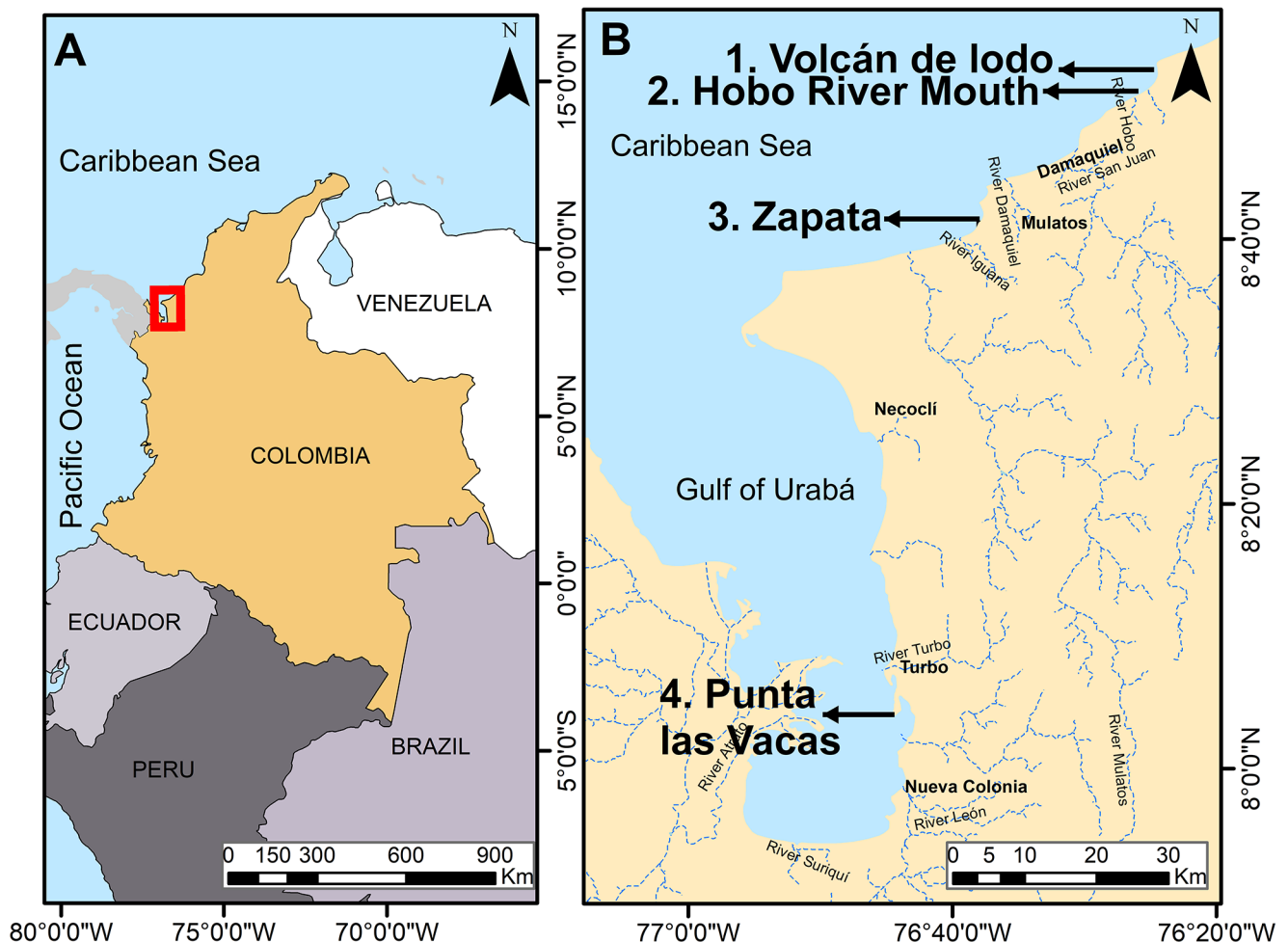
## Methodology

### Study area

Four coastal sites from the southernmost part of the Colombian Caribbean have been chosen to assess their vulnerability to sea level rise (Fig. 1). The climate of the region is controlled by the oscillation of the Intertropical Convergence Zone, which determines the occurrence of two seasons (rainy and dry) that control the wave and wind regimes (Toro et al. 2019). Tides are mixed and semi-diurnal, with

a micro-tidal range of approximately 0.5 m. and a sea level rise of approximately 3 to 3.6 mm/year (Gallego 2021).

Volcán de Lodo and the mouth of Hobo River are located in the Arboletes municipality. Mudstone terraces of 5 to 10 m in height on both coastal strips currently show accelerated erosion, mainly due to wave impact combined with clay contraction and expansion (García-Echavarría et al. 2022). The Volcán de Lodo strip contains, backshore above the marine terrace, an active mud diapir about 15 m high and ranging in diameter from 200 m at the base to 55 m at the top of the crater. The mouth of the Hobo River is located 1 km southwest of the urban centre of the municipality. In the rainy season, the river flows directly into the Caribbean Sea, while in the dry season the river mouth is often closed by a sand barrier. The NE bank of the Hobo River mouth has the terraces described above, while on the SW bank a beach and mangrove swamp have developed. In the coastal strip of Zapata (Municipality of Necoclí), the mouth of the Zapata River is located on the SW margin, with a similar pattern to the Hobo River mouth; in the central sector there



**Fig. 1** Study area: Location of the Southernmost Colombian Caribbean (A) and the four study places (B): (1) Volcán de Lodo, (2) Hobo River mouth, (3) Zapata, and (4) Punta Las Vacas spit

are coastal defence structures; and the NE margin is occupied by marine terraces of about 3 to 8 m in height. Punta Las Vacas (Municipality of Turbo) is a spit 3 km long and 90 m wide on average. It has been severely impacted by coastal erosion in recent decades, caused by anthropogenic alterations including river diversion, intensive agriculture and cattle ranching, sand extraction and construction of coastal defence structures without prior planning, disturbing the vegetal cover and sedimentary dynamics (Correa et al. 2005; Alcántara-Carrió et al. 2019). Present cliff retreat of the four study places is high, reaching up to 4 m/yr to Volcán de Lodo, Hobo River and Zapata, and even 9.8 m/yr in Punta Las Vacas spit (García-Echavarría et al. 2022).

### Coastal vulnerability index faced to sea level rise risk

The coastal vulnerability faced to sea level rise was determined, dividing the coastal strip in  $100 \times 100 \text{ m}^2$  cells, through the use of the Integrated Coastal Vulnerability Index (ICVI), which was defined as the average of the Environmental Vulnerability Index (EVI) and the Socioeconomic Vulnerability Index (SVI), with their respective variables. All the variables and both indices are same pondered.

The EVI was calculated by the arithmetic mean of its variables (Eq. 1), and alternatively by a geometric expression (Eq. 2), proposed by Gornitz (1991), considering 3 geomorphological and 3 ecological variables: geomorphological features (a), slope (b), shoreline migration rate (c), ecosystem type (d), environmental conservancy measures (e), and presence of interest species (f). The variables assessment was carried out through fieldwork and interpretation of both Landsat 7 (Enhanced Thematic Mapper+ sensor) and Landsat 8 (Operational Land Imager sensor) satellite images from 1996 and 2018, respectively, as well as orthophotos taken with a drone in 2018. Besides, the slope was obtained through a Digital Elevation Model developed with GDAL tool in ArcGIS; and the shoreline migration rate was calculated by the End Point Rate (EPR) of the DSAS tool (Thieler et al. 2009; Koroglu et al. 2019). The characterization of ecosystem type and presence of interest species was based on Blanco-Libreros et al. (2015) and Blanco-Libreros (2017). The geomorphological variables were classified after Hammar-Klose et al. (2003) and Ojeda et al. (2009).

$$EVI = \frac{a + b + c + d + e + f}{6} \quad (1)$$

$$EVI = \sqrt{\frac{a * b * c * d * e * f}{6}} \quad (2)$$

The SVI was calculated by the arithmetic mean of its variables (Eq. 3), and alternatively by a geometric expression (Eq. 4), based on Gornitz (1991), considering as variables: use of the territory (g), building coast ratio (h), population density (i), economic activity (j), economic value (k) and sociocultural heritage (l). The use of the territory and the building coast ratio (Rangel-Buitrago and Posada-Posada 2013) were obtained by analysis of aerial photographs. The population density (people/10,000 m<sup>2</sup>) in 2018 was obtained from the National Administrative Department of Statistics of Colombia. Tourist activity and economic value were obtained from Vargas et al. (2021). Certification of the presence of sociocultural heritage assets was requested from the Colombian Ministry of Culture, the Colombian Ministry of the Interior and the Colombian Institute of Anthropology and History. Vulnerability for all variables ranges between 0 and 1. The criteria of classification of the environmental and socio-economic variables are in Table I and II of the Suppl. Material).

$$SVI = \frac{g + h + i + j + k + l}{6} \quad (3)$$

$$SVI = \sqrt{\frac{g * h * i * j * k * l}{6}} \quad (4)$$

Taken into consideration the maximum (absolute) range of possible values for the vulnerability of the variables, the EVI (Eq. 1), SVI (Eq. 3), and ICVI (average of EVI and SVI) indices also range between 0 and 1, which is in accordance with Varnes (1984) and Barnett et al. (2008). However, this is not the case when the geometric formulas are considered to obtain EVI (Eq. 2) and SVI (Eq. 4), neither for absolute range of possible values or considering the 20%, 40%, 60% and 80% percentiles of the particular set of values of EVI or SVI obtained in the study area, in accordance with the suggestion of Gornitz (1991) and Gornitz et al. (1994) (Table III of Suppl. Material).

## Results

### Comparison of the calculation methods

Environmental vulnerability (EVI) and socioeconomic vulnerability (SVI) result very different according to the calculation method and classification criteria used. Thus, considering absolute values to classify the EVI and SVI (Table III of the Suppl. Material), the results based on the geometric formulas (Eq. 2 and 4) generate lower vulnerability values than those based on the arithmetic mean formulas (Eq. 1 and 3). On the other hand, if the percentiles of the

range of values obtained in the study area are used, using the geometric formulas (Eq. 2 and 4), vulnerability values from very high to very low are obtained (Fig. 2).

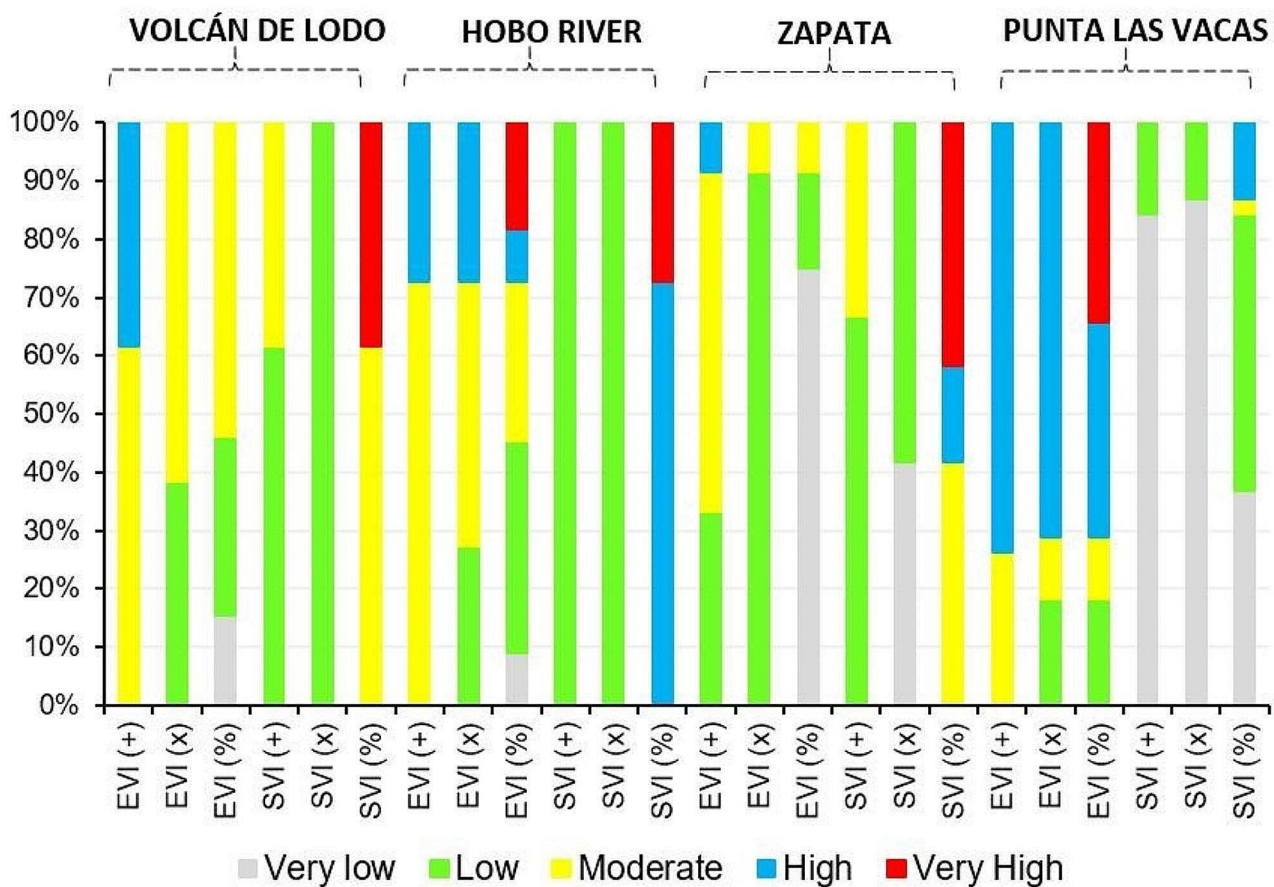
**Environmental, socioeconomic, and total vulnerability after the arithmetic mean method**

Of the set of environmental variables analyzed, the vulnerability associated with species of interest, changes in the coastline, and geomorphological characteristics of the coast stand out. The areas with mangrove cover are home to endangered species such as the blue crab *Cardisoma guanhumi* and manatee *Trichechus manatus*, as well as some endemic birds such as *Chauna chavaria* and *Bucco noanamae*, with high or very high vulnerability values in 83.78% of the coastline. Shoreline change rates in the Punta Las Vacas spit reach  $-9$  m/yr, while in Volcán de lodo, Hobo River mouth and Zapata reach up to  $-4$  m/yr, assigning high or very high vulnerability to 62.16% of the coast. Most of the coast is occupied by beaches (66.22%), with

high vulnerability, while the rest of the area contain cliffs (33.78%) with moderate vulnerability.

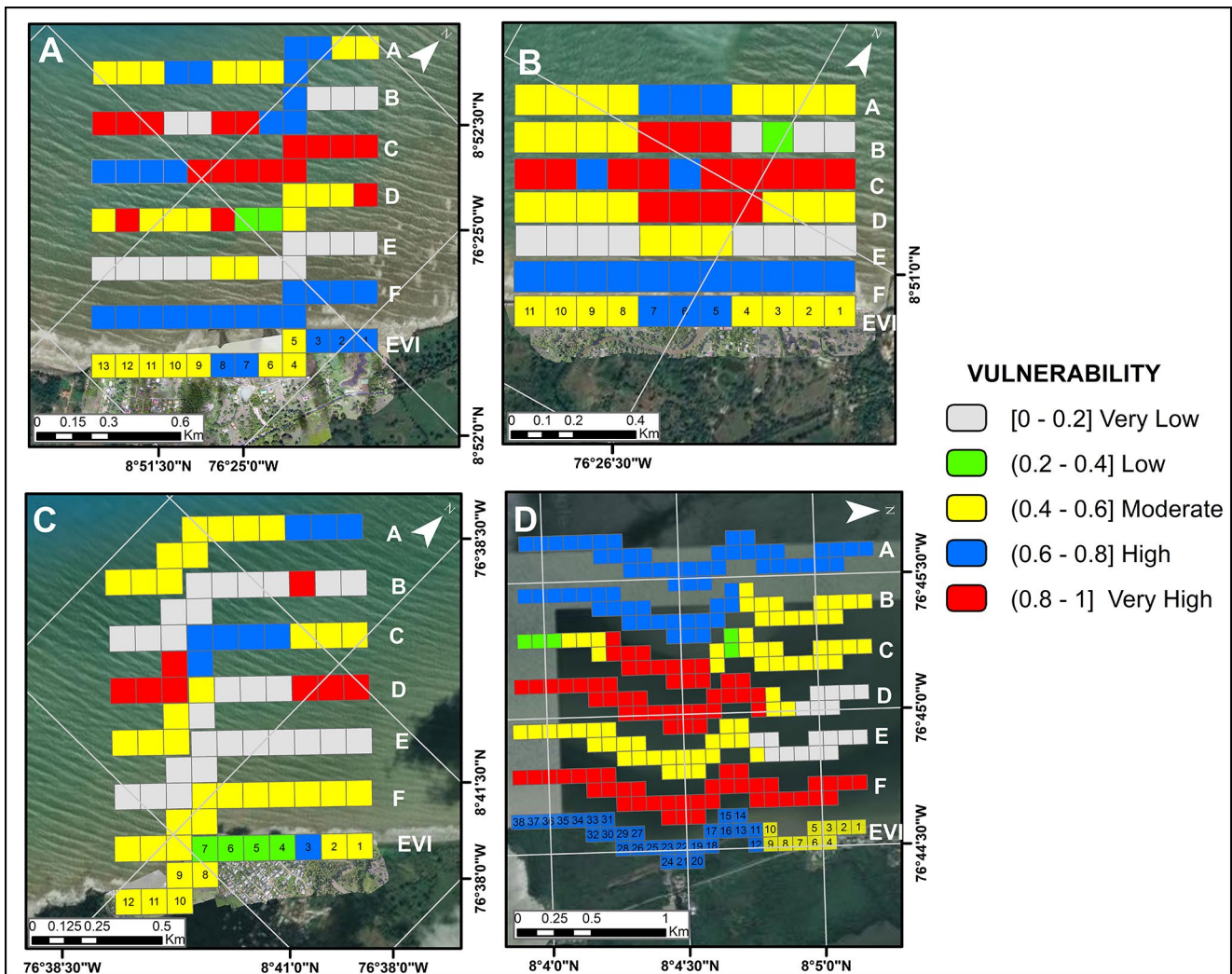
Environmental vulnerability is high in 50.00% of the coastal strip studied, which corresponds to river mouths or areas with mangrove cover, due to moderate, high or very high vulnerability values for the variables geomorphological features (a), shoreline migration rate (c), ecosystem types (d), and presence of species of interest (f). Another 44.59% of the coast presents moderate vulnerability, with vulnerability according to the different variables ranging from very high to very low. The remaining 5.40%, which corresponds to the stretch with coastal protection works in Zapata, has low vulnerability (Fig. 3).

Socioeconomic vulnerability is moderate in 12.16% of the coast, where Volcán de Lodo and Zapata Village are located, with greater vulnerability associated with the use of the territory (g), building coast ratio (h), and economic activity (j). In another 44.59%, vulnerability is low and in the remaining 43.24% of the coast, which corresponds to the Punta Las Vacas spit, it is very low (Fig. 4).



**Fig. 2** Frequency (%) of the five vulnerability classes (very low to very high) for each study site. The values of the Environmental Vulnerability Index (EVI) and the Socioeconomic Vulnerability Index (SVI) were obtained after both arithmetic (+) and geometric (X) equations

(Eq. 1 to 4) and classified after the absolute (maximum) range of possible values. In addition, the values obtained by the geometric equations are also classified after the percentiles (%) of the local range of values (Table III of the Suppl. Material)



**Fig. 3** Vulnerability to sea level rise after the environmental variables (a to f) and Environmental Vulnerability Index (EVI) obtained considering Eq. 1. and classified after the absolute range of values (Table III).

(A) Volcán de Lodo, (B) Hobo River mouth, (C) Zapata, (D) Punta Las Vacas spit (see Fig. 1 for location)

Vulnerability is higher for environmental aspects than for socioeconomic ones. Total coastal vulnerability (ICVI) to sea level rise, averaging the values of EVI (Eq. 1) and SVI (Eq. 3), is moderate in the 52.70% of the coast, which corresponds to river mouths, mangrove areas and most of the Volcán de Lodo coast; the remaining 47.30% of the coast presents low vulnerability (Fig. 5).

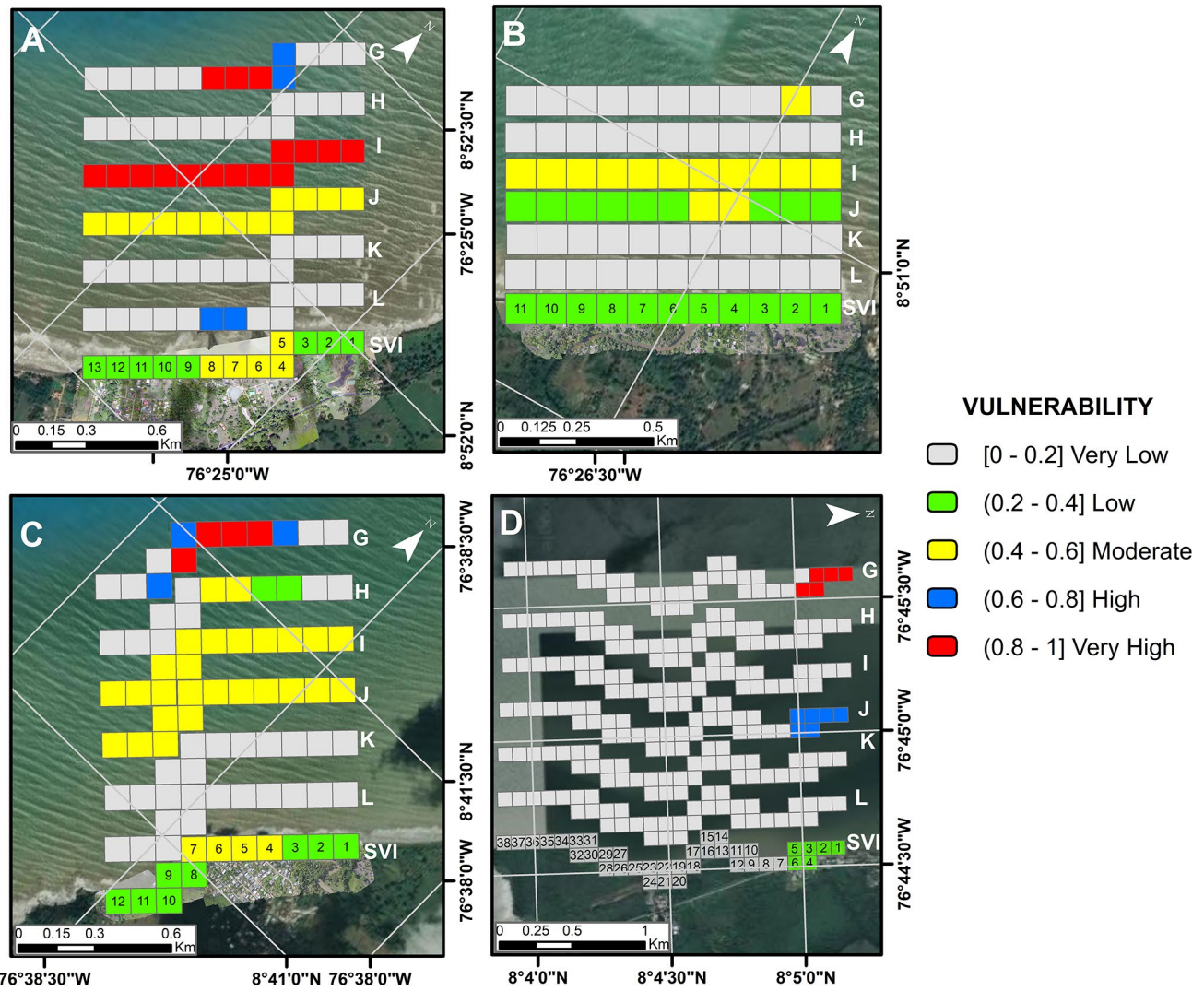
## Discussion

### Conceptual review of the CVI

The CVI was defined by Gornitz (1991) to determine coastal vulnerability to sea level rise. However, three of the variables considered are related to the energy of the processes affecting the coastline, i.e., they are indicators of hazards

(wave height, rate of sea level rise, and tidal range) instead of vulnerability. The other four variables (relief, rock type, landform, and shoreline migration rate) describe the vulnerability or fragility of the territory only from a purely geomorphological point of view. It could even be considered that shoreline migration rates are actually a measure of risk or even disaster, i.e., a catastrophic phenomenon that is already occurring, rather than a vulnerability variable. Gornitz et al. (1994) included in the CVI six additional variables relate to tropical storms and hurricanes, which actually are again indicator of hazards rather than vulnerability.

Regarding these physical variables, the tidal range has been widely debated for its role in coastal risk assessment, as one of the roles played by the astronomical tide is the daily modulation of the hazard (waves and mean sea level rise). For this reason, we consider that it is not strictly considered a vulnerability variable, but a hazard variable, and therefore



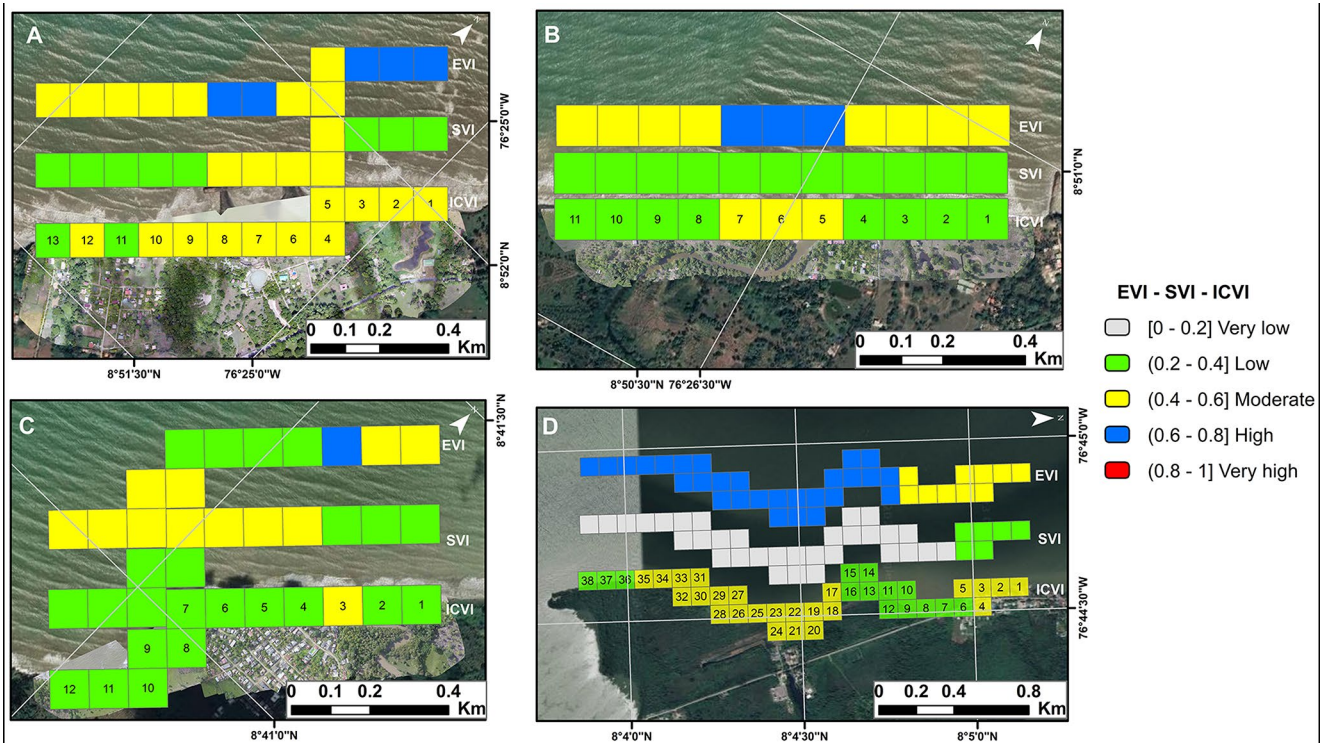
**Fig. 4** Vulnerability to sea level rise after the socio-economic variables (g to l) and Socio-economic Vulnerability Index (SVI) obtained considering Eq. 3. and classified after the absolute range of values. (A)

Volcán de Lodo, (B) Hobo River mouth, (C) Zapata, (D) Punta Las Vacas spit (see Fig. 1 for location)

it is not considered within the proposed index (ICVI). Furthermore, several authors such as Gornitz (1991), Shawn et al. (1998) and Rangel-Buitrago and Posada-Posada (2013) consider that macrotidal zones are more vulnerable to sea level rise, but on the contrast, authors such as Thieler and Hammar-Klose (2000), Pendleton et al. (2004), Ojeda et al. (2009) consider that a wide tidal range implies less vulnerability.

Other geomorphological variables have been used to define the CVI, as is the case of Ramadhan et al. (2022), who considered coastal material, grain size, exposure, foreshore landform, backshore landform, vegetation density and shoreline slope of the Bugel Coast (Indonesia). Vieira et al. (2018) included variables such as land cover and anthropogenic activities in Cananéia-Iguape coast (Brazil), while Sekovski et al. 2020 considered as variables the elevation,

dune coverage, shoreline covered by artificial, recent shoreline change and land cover to assess the vulnerability of the Ravenna province (Italy). In any case, the CVI defined by Gornitz et al. (1994) or these authors only consider geomorphological aspects, and it must be combined with the analysis of ecological and socio-economic aspects to determine the total coastal vulnerability to sea level rise. Thus, other authors included similar index to determine the social vulnerability and economic vulnerability, combining them with the CVI (McLaughlin and Cooper 2010; El-Zein et al. 2021; Ramakrishnan et al. 2023), in addition to considering different climatic scenarios (Snoussi et al. 2008).



**Fig. 5** Vulnerability to sea level rise after the Environmental Vulnerability Index (EVI), Socio-economic Vulnerability Index (SVI) and Integrated Coastal Vulnerability Index (ICVI). EVI and SVI are obtained by the arithmetic mean formulas (Eq. 1 and 3). The ICVI is

calculated as the average of the EVI and the SVI. EVI, SVI and ICVI are classified after the absolute ranges of values (Table III). (A) Volcán de Lodo, (B) Hobo River mouth, (C) Zapata, (D) Punta Las Vacas spit (see Fig. 1 for location)

### Mathematical review of the CVI

The CVI defined by Gornitz et al. (1994) has been widely used (Shaw et al. 1998; Thieler and Hammer-Klose 2000; Pendleton et al. 2004; Boruff et al. 2005). Gornitz et al. (1994) argued that the arithmetic mean formula shows less sensitivity to misclassification errors and missing data. However, there are doubts about their formula. Gibb et al. (1992) showed deficiencies in the use of this calculation, including a tendency to distort the output range and distribution of the final index. They argued that it yields an index that does not accurately represent the ranking of the variables and consequently, the distribution of CVI values should be sorted into vulnerability categories by dividing the data into percentiles.

In the method described by Gornitz (1991), the ranges of values of each variable vary between 1 and 5, and therefore the CVI can theoretically vary between 0.4082 and 51.0310. However, the range of CVI values obtained for each study are divided by the 25%, 50% and 75% percentiles into the low, moderate, high, and very high vulnerability classes. Therefore, this method always will identify sectors with low to high vulnerability for each study, i.e. the assignment of vulnerability for each particular place is clearly relative to the combination of places considered for

each study. Therefore, the vulnerability values obtained cannot be compared with the results obtained for other studies, even if the same method has been applied. Index-based methods should offer a clear comparability of vulnerability between different areas (Balica et al. 2012), but vulnerability class obtained from percentiles only permit to compare among the considered places for the own study, not with other study areas. Furthermore, not all coasts in the world need to have areas from very low to very high vulnerability. Despite this, Cogswell et al. (2018) indicate that 30% of the works on coastal vulnerability during the period 2014 to 2017 used the method of Gornitz (1991). A detailed review of other index is show by Simac et al. (2023). What most of the papers do agree on, included Gornitz (1991), but not Gornitz et al. (1994), is that all variables are equally important and therefore do not use weighted values. The CVI in the study area (four locations in the Colombian Caribbean), applying the methodology of Gornitz et al. (1994), range between 7.07 and 28.86 Vulnerability classification based on percentiles force to identify sectors with very low to very high vulnerability, while absolute ranges of classifications identify an 85% of the coastline with high or very high vulnerability (García-Echavarría et al. 2022).

The well-known studies by Varnes (1984) and Barnett et al. (2008) indicate that vulnerability should vary between

0 and 1. Likewise, it is interesting that the hazard values vary between 0 and 1 so that the risk values, calculated as the multiplication of vulnerability by hazard, again vary between 0 and 1. Taken into consideration the arithmetic mean equations, the EVI (Eq. 1), SVI (Eq. 3) and ICVI vary between 0 and 1; their vulnerability classes have been defined considering the absolute (maximum) possible range of results, rather than percentiles (Table III of Supplementary Material). Therefore, these indices and classifications have global application.

The EVI results, using a geometric formula (Eq. 2) equal to that proposed for the CVI, and the absolute range of possible values (Table III of Suppl. Material) are clearly lower than when an arithmetic mean formula (Eq. 1) is used (Fig. 2). The differences are even greater if the values of the geometric formula are classified considering percentiles, as suggested by Gornitz et al. (1994), because using percentiles forces the identification of areas from very low to very high vulnerability, which clearly conditions the validity of the result (Fig. 1).

Risk is calculated by multiplying hazard by vulnerability, which means that if vulnerability is high but there is no hazard, then there is no risk. However, to determine vulnerability to each hazard, if there is no vulnerability according to one variable (e.g., slope), it does not imply that the total vulnerability is zero, but that there may be vulnerability according to other variables. Therefore, it is not logical to use formulas based on multiplication to calculate vulnerability. The arithmetic mean formula (Eq. 1 for EVI and Eq. 3 for SVI) and the use of the maximum possible range of values for their classification (0 to 1, Table III) results in a much more adequate method than the method proposed by Gornitz et al. (1994).

## Conclusions

The CVI considers vulnerability and hazards variables (wave height, sea level rise), so it is a coastal risk index rather than a vulnerability one. The CVI only consider the physical/geomorphological aspects of the coastal vulnerability. A suitable coastal vulnerability index should consider the environmental and socioeconomic vulnerability, whit both the geomorphological and ecological vulnerability combined on the environmental vulnerability, but never variables related to hazards.

It is recommended that vulnerability indices vary between 0 and 1, and likewise the vulnerability after each variable should range between 0 and 1. Arithmetic mean formulas should apply to obtain the vulnerability indices. The results should be classified considering the absolute (maximum) range of possible values, in order to be a classification with

global application and not forced to identify areas with very low to very high vulnerability to sea level rise in any study area. Vulnerability classifications based on percentiles force to identify sectors with very low to very high vulnerability for any study area, which is not objective. Not every coast in the world needs to have areas from very low to very high vulnerability.

The use of arithmetic mean formulas allows the number of variables to be increased, if considered necessary. Weighted arithmetic mean formulas are not recommended, because the weighting is often subjective, it means that weighting criteria would change depending on each site and each author, and therefore, the results would lose the spatial comparability. However, if the objective of a study were to assess the evolution of vulnerability over time for a particular study site, weighting may be important for the sake of adaptability of the index to site-specific conditions at the expense of global comparability, which in our view is the objective of the proposed ICVI. It is recommended that such weighting be carried out by an interdisciplinary team of experts with specific knowledge of the locality to be assessed.

When the absolute range of possible values is considered to classify vulnerability indices, the geometric expression, as considered for the CVI, underestimate vulnerability compared to arithmetic mean formulas. Arithmetic mean formula for the vulnerability indices (EVI, SVI, ICVI), with vulnerability variability ranging from 0 to 1, and vulnerability indices ranked after the absolute (maximum) range of possible values is the most accurate mathematical method.

The four places analyzed show higher environmental vulnerability (mainly moderate or high) than socioeconomic vulnerability (mainly low or very low). The total vulnerability (ICVI) of the study area to sea level rise, combining environmental and socioeconomic aspects, is moderate (52.70%) or low (47.30%).

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**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests. All authors contributed to the study conception and design. Material preparation was performed by the three authors. Data collection was performed by Luz Marleny García Echavarría and Alfredo Jaramillo-Vélez. Data analyses were performed by Luz Marleny García Echavarría and Javier Alcántara Carrió. The first draft of the manuscript was written by Javier Alcántara Carrió and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. The authors declare non-financial interests, directly or indirectly related to the work submitted for publication.

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