

A PROBABILISTIC APPROACH TO A COASTAL VULNERABILITY INDEX: A TOOL FOR COASTAL MANAGERS

Canul Turriza Román¹, Mendoza Edgar¹, Silva Rodolfo¹

Vulnerability assessment is invaluable information for coastal managers to develop better coastal development plans. Two approaches to do so are presented here: one evaluates vulnerability from a deterministic view applying the analytical hierarchy process (AHP); the second uses a probabilistic approach based on the Latin Hypercube and Monte Carlo modeling, therefore it considers the probability distribution functions of the variables under analysis. The results show that a probabilistic approach is more suitable for the assessment of coastal vulnerability.

Keywords: coastal vulnerability, probabilistic index, coastal management

INTRODUCTION

Presently, there is not a universally accepted method to assess coastal vulnerability. Among the several existent methods, most are based on the combined use of physical and social data, together with simple numerical models. In turn, most of the available research relies on deterministic approaches, where arbitrary weights are assigned to the variables involved and almost no information is given on uncertainty (Ma et al., 2010). Therefore, accurate and reliable data on coastal vulnerability is hard to obtain.

In general, it is difficult to study vulnerability assessment, deterministic approaches can quantify low levels of vulnerability, while probabilistic ones must simulate the real behavior of the random values of the variables under analysis. Here we present a vulnerability assessment using a deterministic approach and a probabilistic approach applied to the state of Campeche, with the main objective that the results provide more robust knowledge about the most vulnerable coastal sector and be a useful tool for stakeholders and plans coastal development.

The state of Campeche (Fig. 1) is located in the Yucatan Peninsula, Mexico. Its coast is 520 km long, and formed mainly by sandy and rocky beaches. San Francisco de Campeche and Ciudad del Carmen are the most important coastal cities and have the largest populations within the state corresponding to 20.60% and 26.79%, respectively (INEGI, 2010). Isla Arena is located in the Los Petenes Biosphere Reserve and Ciudad del Carmen in Laguna de Terminos Flora and Fauna Protection Area (Nava et al., 2018).



Figure 1. Location of the study area.

¹ Engineering Institute, National Autonomous University of Mexico, Circuito Escolar s/n, Edif. 17, Ciudad Universitaria, Coyoacán, CDMX, 04510, México

METHODOLOGY

Two methodologies were applied to assess the vulnerability of the Campeche coast; based on two approaches: a deterministic assessment (static) with analytical hierarchy process (AHP) applied to the entire coast of the state and a probabilistic computation (dynamic) applied in 3 coastal areas of the state of Campeche: Isla Arena in the north, San Francisco de Campeche in the center and Ciudad del Carmen in the south (see Fig. 1). Both processes are described next.

Coastal vulnerability with analytical hierarchy process (AHP)

Here the vulnerability is defined as the level at which the human population and ecosystems are subject to damage or hazards due to social and biophysical factors (Ávila 2007). The vulnerability assessment of the coastal region must consider physical and socioeconomic variables, to generate information for decision making for sustainable development and reduce the risk of disasters.

The index proposed here considers 5 groups of variables (physical and socioeconomic), each with its respective classification (see Fig. 2).

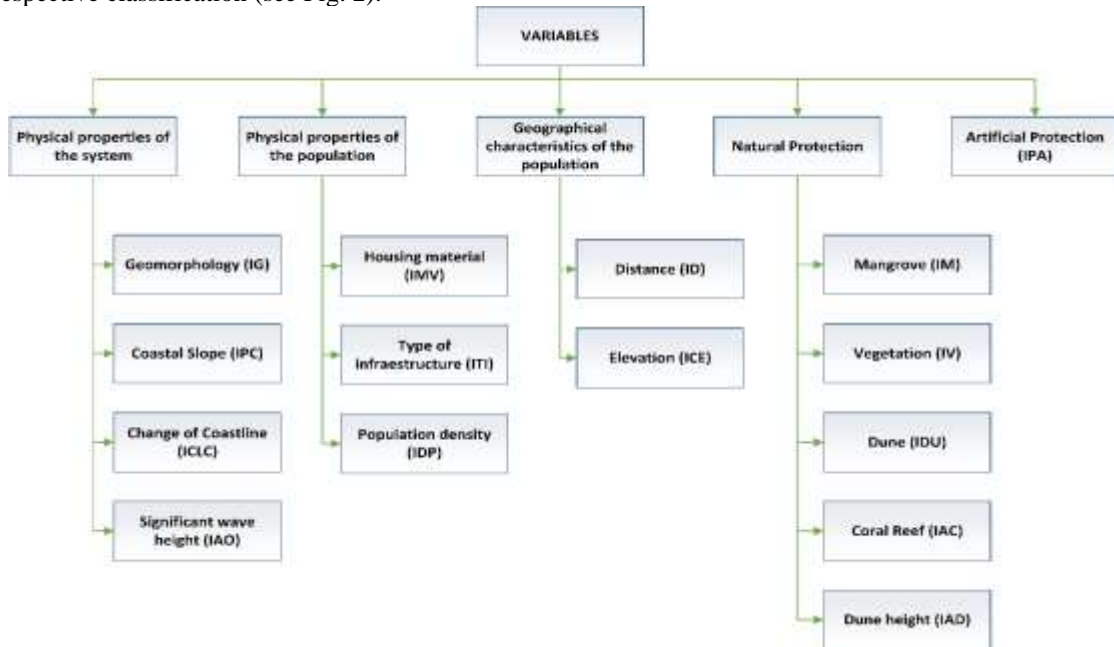


Figure 2. Variables used for the coastal vulnerability index (CVI) assessment.

Each variable is assigned a value from 1 to 5 according to its contribution to vulnerability and related to measurable properties (see Table 1); 1 represents the lowest contribution and 5 the highest (see Table 1). For variables which only presence or absence may be evaluated, 1 and 5 were set, respectively.

To divide the coastal zone into sectors we considered the basic geostatistical areas (AGEB, in Spanish), that are geographical areas occupied by a set of blocks perfectly delimited by streets, avenues, walkers or any other feature to easy identification in the land and whose use of land it is mainly housing, industrial, services, commercial, and others. The areas of the AGEB located at an elevation level below 10 m were projected perpendicular to the coast to obtain the coastal sector under analysis.

The AHP is a method that solves decision – making problem by ranking possible alternatives according to several criteria (Saaty 1977; Saaty and Vargas 1991). Was developed to calculate the needed weighting factors with the help of a preference matrix, where all identified relevant criteria are compared against each other with reproducible preference factors. AHP selects the best alternatives by considering both the objective and subjective factors.

The AHP method was applied to derive the relative weights for a set of criteria incorporating expert judgement. Firstly, pairwise comparisons are carried out for all the parameters involved, and the matrix is completed by using scores based on their relative importance.

To obtain the ranking of the variables, a survey was applied to a group of experts from different research areas. The information was compiled and analyzed, finally a comparison matrix was built.

For the construction of a pairwise comparison matrix, each factor is rated against every other factor and the method employs an underlying linear scale with values from 1 to 9 to assign a relative dominant value within the pair of criteria (Saaty, 1980; Saaty, 1977).

Once the comparison matrix was obtained, a priority vector is calculated which is the normalized eigenvector of the matrix. This done by dividing each of the columns by the corresponding sum. In the next step, the average values of each row are computed and these are used as weights in the objective hierarchy.

Table 1. Synthesis of variables, classification and ranking.					
Parameter	Coastal vulnerability ranking				
	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
Elevation	NA	> 10 m	> 4m and ≤ 10m	> 1m and ≤ 4m	≥ 1 m
Dune	NA	dune with vegetation	with dune	without dune	NA
Dune height	NA	> 5 m	> 2 m and ≤ 5 m	≤ 2 m	NA
Geomorphology	NA	cliff or rocky beach	sandy or gravel beach	mud coast	NA
Coastal slope	> 1.0	0.50 – 1.0	0.10 – 0.50	0.05 – 0.10	< 0.05
Significant wave height	< 0.55 m	0.55m – 0.85m	0.85m – 1.05m	1.05m – 1.25m	> 1.25
Change of coastline	> 2.0 m	1.0m to 2.0m	-1.0m to 1.0m	-2.0m to -1.0m	< -2.0m
Mangrove	with mangrove	NA	NA	NA	without mangrove
Vegetation different to mangrove	with vegetation	NA	NA	NA	without vegetation
Coral reef	with reef	NA	NA	NA	without reef
Distance to coast	NA	> 4 km			≤ 500m
Population density	dispersed	NA	NA	NA	concentrated
Housing material	concrete	NA	NA	NA	wood and others
Artificial protection	with protection	NA	NA	NA	without protection
Type of infrastructure	rural	NA	NA	NA	urban

The matrix must be coherent, therefore, a consistency index known as consistency ratio CR, must be computed in the AHP synthesis process (Saaty, 1977). If $CR < 0.10$, the matrix is consistent, otherwise if $CR > 0.10$ we need to re – evaluate the pairwise comparisons and test again the consistency by AHP.

The weights derived using AHP are used for calculating the CVI. The CVI is estimating according to the formula:

$$CVI = \sum_{i=1}^n W_i * V_i \quad (1)$$

where CVI is the vulnerability index for a given area; W_i is the weight of criterion i ; V_i is the vulnerability score under criterion i and n is the total number of criteria.

Coastal vulnerability with probabilistic approach

Deterministic methods are usually applied to vulnerability evaluation in most situations. Although adhering to the limits specified by deterministic methods can facilitate an acceptable low level of vulnerability, the deterministic methods do not quantify uncertainties in the systems. Therefore, the information regarding how low or how high the system vulnerability can hardly be obtained. It is required to develop a probabilistic method for evaluating the system vulnerability (Ma et al., 2010).

The probabilistic approach combined with different models has been applied in several studies. Here, qualitative and quantitative variables are analyzed; the former are evaluated as discrete variables with a discrete distribution of uniform whole type, and the latter as continuous variables with a normal distribution (see Fig. 3).

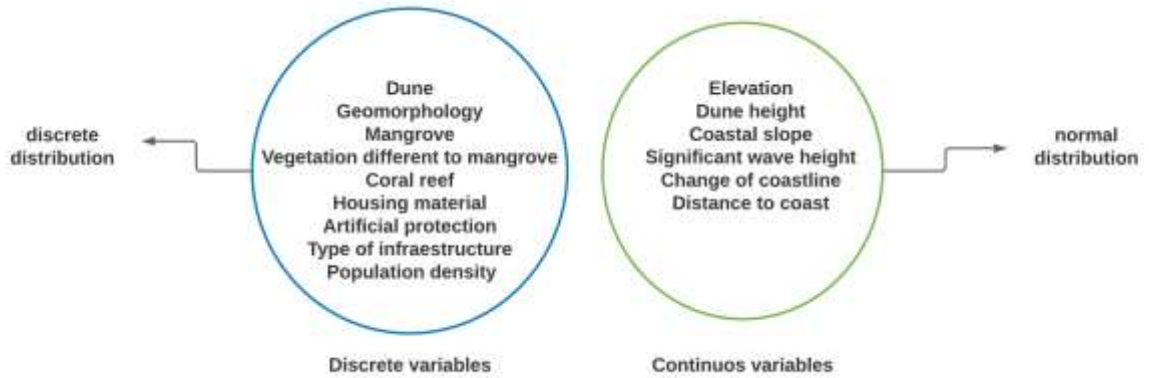


Figure 3. Classification of variables into continuous and discrete.

Each variable is considered probabilistic and a probability distribution is attributed to it based on the limit values of each variable. Subsequently, a Monte Carlo and Latin Hypercube analysis were applied to calculate the possible values of the CVI (probabilistic), as a result we obtain the distribution of the function.

RESULTS

Coastal vulnerability with analytical hierarchy process (AHP)

We have obtained the consistency ratio less than 0.1 ($CR < 0.1$) and it can be considered for further calculation. A representative minimum value of 1.42 and a maximum of 4.76 was obtained, the calculated CVI values are ranking into five categories, similarly to the ranking of each criteria, to highlight the different levels of vulnerability: very low, low, moderate, high and very high, as seen in Table 2:

Value	Categories
1.42 – 2.09	Very low
2.09 – 2.75	Low
2.75 – 3.42	Moderate
3.42 – 4.09	High
4.09 – 4.76	Very high

From the results of the AHP, it was obtained that the most important variable for the vulnerability analysis is geomorphology and the least important is artificial protection.

Finally, the data was processed in a GIS and a coastal vulnerability map was developed. Figure 4 represents a synthesis of the vulnerability of the coast of Campeche. The southern area of the state shows high vulnerability, the central zone is characterized by moderate vulnerability and the northern zone show low, moderate and high vulnerability.

Only four coastal sectors present low vulnerability, while the interior of the Laguna de Terminos presents moderate vulnerability. Similarly, it is observed that the main coastal urban centers are classified as highly vulnerable.



Figure 4. Coastal vulnerability of state of Campeche.

Coastal vulnerability with probabilistic approach

We obtained nine variables analyzed with discrete distribution and six variables analyzed with normal distribution. In the latter, the data series allow us to know the temporal variability of the variables. In Table 3, the constant values of the variables used in the deterministic approach and the mean and standard deviation used in the probabilistic approach are presented for the 3 zones.

Variable	Isla Arena			San Francisco de Campeche			Ciudad del Carmen		
	Deterministic value	Mean	St Dev	Deterministic value	Mean	St Dev	Deterministic value	Mean	St Dev
Elevation	1	1	0.70	5	4.3	0.71	0	0.5	0.72
Dune height	1.48	1.4	0.812	0	0.5	0.71	1.96	1.5	0.912
Significant wave height	1.07	1	0.619	1.06	1	0.519	1.06	1.05	0.609
Change of coastline	3.56	0	0.74	1	0.1	0.667	0	-1	0.664
Distance to coast	54	1.5	0.3850	200	4	0.258	95	2	0.285
Coastal Slope	0.03	0	0.11	0.06	-0.15	0.12	0	0.01	0.14

For each sampling type, 100 000 iterations were carried out in order to have a better convergence of the results. An iteration is a smaller unit within a simulation. At each iteration, a new set of random numbers is extracted for the distribution functions of the model, recalculating and storing the values of all the designated outputs. And the convergence was defined as the number of iterations required such that statistic of interest stays within 0.5% of the results, selecting the 90th percentile as the base; noting that more iterations are required as the base percentile increases. So, we can affirm that we have a 95% confidence. Although the literature identifies 10 000 iterations as the benchmark for a “sufficient” value of convergence (Morgan & Henrion, 1990; Garvey, 2000), here we take 100 000 iterations since as we take more iterations, the sample mean approaches the population mean, and the sample variance approximates the population variance.

For Isla Arena, the Latin Hypercube sampling presents a lower standard deviation than the Monte Carlo sampling; in both cases, the average value of the vulnerability is 3.63, classified as high vulnerability according to the classification in Table 2. Likewise, it is observed that with the Latin

Hypercube the values tend towards the average value. Figure 5 shows that 90% of the vulnerability of the area ranges from moderate to very high vulnerability and there is only a 5% probability that the area will have low vulnerability.

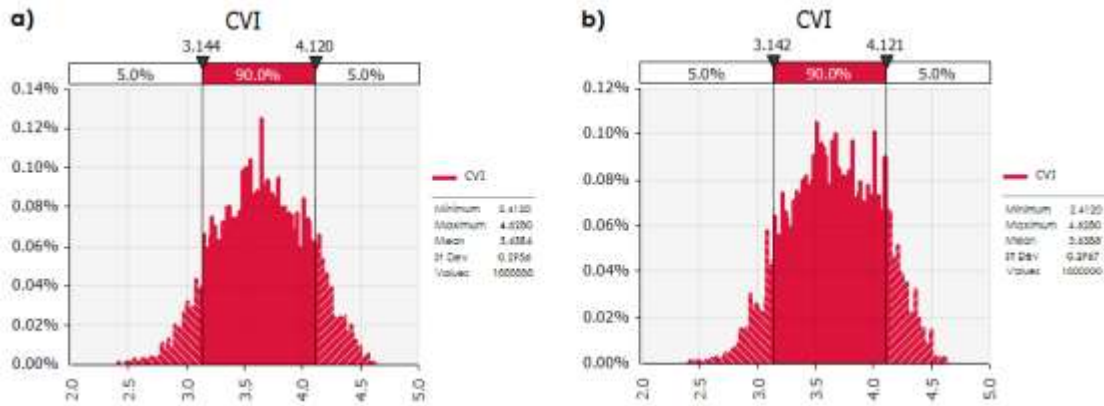


Figure 5. Coastal vulnerability of Isla Aguada. a) Latin Hypercube; b) Monte Carlo.

For San Francisco de Campeche, the Monte Carlo sampling have a lower standard deviation than Latin Hypercube sampling. In the Latin Hypercube, the values tend towards a leptokurtic distribution, while for Monte Carlo sampling the distribution is slightly mesokurtic. According to the vulnerability classification in Table 2, 90% of vulnerability can range from moderate to high vulnerability; while low and very high vulnerabilities each only have 5% probability of being present (see Fig. 6).

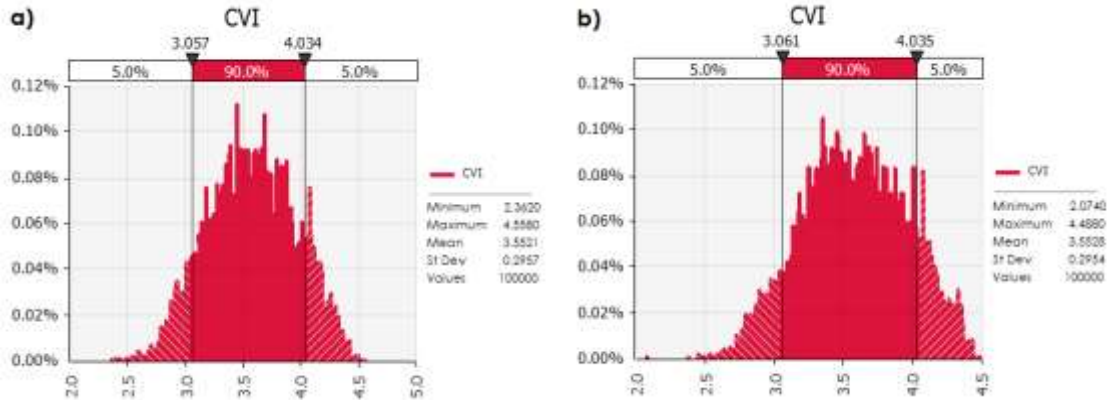


Figure 6. Coastal vulnerability of San Francisco de Campeche. a) Latin Hypercube; b) Monte Carlo.

For Ciudad del Carmen, the results of both estimations are very similar, in both the value of the standard deviation is 0.299; while the value of the mean is 3.74. According to Table 2, the mean value can be classified as high. Figure 7 shows that 90% of the CVI values are in the numerical range of 3.239 / 3.243 to 4.228 / 4.230 (Latin Hypercube / Monte Carlo), being classified from moderate to very high vulnerability; it is also shown that 5% of the vulnerability can take values lower than 3.24 to 2.47, presenting a low vulnerability and 5% can take values greater than 4.23 to 4.75, being classified as very high vulnerability. In this case, the curve of the graph shows an inclination to the right, that is, towards the representative values of a very high vulnerability.

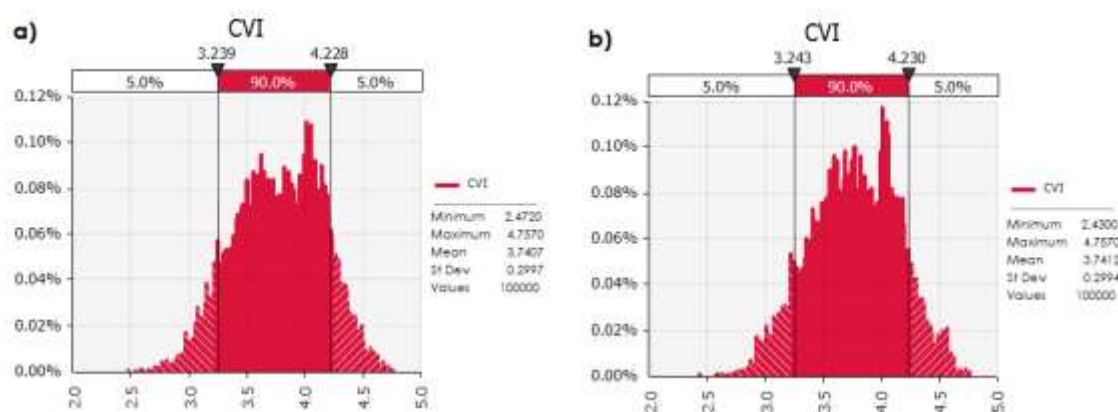


Figure 7. Coastal vulnerability of Ciudad del Carmen. a) Latin Hypercube; b) Monte Carlo.

CONCLUSIONS

The application of the AHP approach generates a more robust result when considering the opinion of experts in the weighting of the variables.

The probabilistic approach makes it possible to identify the minimum and maximum levels at which the vulnerability of an area can fluctuate. This means, on the one hand, that vulnerability is dynamic, since vulnerability will change depending on the conditions that arise in time and space; for example, in dry season, a lower wave height will imply a lower vulnerability than in the storm season with a higher wave height. And on the other hand, that we can know what is the range of vulnerability values that can occur in an area, when performing an intervention action for benefit or harm, which modifies the conditions of any of the variables under analysis, for example the coastal slope.

In general, for Campeche, Latin Hypercube sample has the lowest standard deviation compared to the Monte Carlo sample; so Latin Hypercube better represents realistic variations of vulnerability.

In more robust analysis, the distribution for each variable should be considered without adjusting to a normal distribution.

REFERENCES

- Ávila García, P. 2007. Las cuencas hidrológicas de México y su vulnerabilidad socioambiental por el agua. In M.A. Porrúa (Ed.), *Políticas de desarrollo regional. Agenda para el desarrollo*, México, DF, Universidad Nacional Autónoma de México, 133 – 161 pp.
- Garvey, P. 2000. Probability methods for cost uncertainty analysis: a system engineering perspective.
- INEGI. 2010. Principales resultados por localidad 2010.
- Ma, J., Huang, Z., Wong, P.C., Ferrymant, T., & Northwest, P. 2010. Probabilistic vulnerability assessment based on power flow and voltage distribution. In *IEEE PES T&D 2010*, 1-8 pp., <https://doi.org/10.1109/TDC.2010.5484304>.
- Morgan M.G., Henrion M. 1990. Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis.
- Nava Fuentes, J.C., Arenas Granados, P., & Cardoso Martins, F. 2018. Integrated coastal management in Campeche, Mexico; a review after the Mexican marine and coastal national policy. *Ocean & Coastal Management*, 154, 34 – 45 pp.
- Saaty, T.L. 1977. A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology*, 15(3), 234 – 281. [https://doi.org/10.1016/0022-2496\(77\)90033-5](https://doi.org/10.1016/0022-2496(77)90033-5)
- Saaty, T.L. 1980. *The Analytic Hierarchy Process*. New York, McGraw – Hill.
- Saaty, T. L., & Vargas, L. G. (1991). *Prediction, projection, and forecasting: applications of the analytic hierarchy process in economics, finance, politics, games, and sports*. Boston: *Kluwer Academic Publishers*.