INDEX OF VULNERABILITY TO POLLUTION OF KARSTIC COASTAL AQUIFERS: ANALYSIS OF FACTORS FOR THE URBAN ZONE OF PLAYA DEL CARMEN, MEXICO

WILBERT D. UHU YAM, OSCAR FRAUSTO-MARTÍNEZ,
JOSÉ F. RODRÍGUEZ CASTILLO & ORLANDO COLÍN OLIVARES
Laboratorio de Observación e Investigación Espacial,
Universidad Autónoma del Estado de Quintana Roo, México

ABSTRACT

The present study proposes four factors for the construction of a vulnerability index in relation to the pollution of coastal aquifers in urban karst areas. It considers three environmental factors (climate, relief and rise in sea level) and one anthropogenic (use of land), with greater importance given to the latter, as the intention is to work with the premise of being a built-up area, as is the case with Playa del Carmen, Mexico. For each factor, the following variables were considered: (1) Relief: frequency of depressions and form type, depending on their morphological features; (2) Climate: with the Modified Fournier Index; (3) Rising sea level: with the modelling of sea level rise, potentiometric surface level and distance from the coast; and (4) Use of land: differentiated by the secondary zoning of the urban development program and land population co-efficient of occupation. For the relief factor, the most vulnerable areas were identified at the north and southern extremes of the urban area with a frequency of 30 to 37 depressions and a predominance of sinkholes and sinkholes-uvalas. The Modified Fournier Index is from 198.46 to 200.74, with a distribution of high vulnerability to the south-east; the land use factor shows high to very high vulnerability distributed throughout most of the city. a sea rise projection of 1 to 3 m is identified in the first 2 km with respect to the coastline, at a distance from the coast of 1 to 3 km and a constant potentiometric surface level for the entire study area. Finally, the uses are designated as commercial, residential tourism, high housing and mixed uses.
Keywords: karstic depressions, rainfall, saline intrusion.

1 INTRODUCTION

The development process of man has given the guidelines to properly conceptualise elements linked to his habitat, environment and a possible relationship between these [1], leading to an interest in learning about the vulnerability of ecosystems. The concept of vulnerability to the contamination of groundwater was introduced by Albinet and Margat [2] and began a great interest in this area. The definition of vulnerability to contamination from Zwahlen [3] was taken up again for this study: “Features from hydrogeology, soils, relief, climate and vegetation, inherent to the system as a whole that determine the susceptibility to contamination by anthropic activities”.

Since then, there are currently different models proposed to calculate the vulnerability of aquifers to contamination due to the different ecosystem’s characteristics. The first to appear were DRESTIC, SINTACS and GOD [4]. Emphasis was then placed on indices for karst areas such as EPIK, PI, COPK, KARTIC, RISKE, the Slovenian approach, PaPRIKa, KAVI, LEPT, and APLIE [5]. These models have a hydrogeological approach [6]. While the IVAKY model of Aguilar-Duarte et al. [5] proposes a combination of multiple factors, such as relief, climate and land. However, urban development in karstic coastal areas is a relevant aspect due to population growth, the expansion associated to irregular settlements and the replacement of natural environments it brings which implies a significant land use change [7].

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Thus, it is necessary to consider criteria associated with these problems, so it would be ideal to use the land use criterion as the main factor that directly influences the vulnerability degree to aquifer contamination, since urban infrastructure works as a waterproofing, reducing infiltration and increasing pollutants [8] and has a direct influence on recharge and infiltration [9]. Likewise, it is proposed to consider specific problems for coastal areas, such as climate change [10], [11] and incorporate criteria such as the rise of the sea [12] and the distance respect to the coastline, because of contamination can also occur on a horizontal plane [13], [14].

Based on the above, the objective of this study was to propose factors to design an index for the vulnerability to contamination of karst-coastal aquifers in built-up areas on a small scale and apply it to the coastal city of Playa del Carmen, Mexico.

2 MATERIALS AND METHODS

2.1 Study area

The city of Playa del Carmen, with a land area of 2,205 km^2 and a coastline of 87.20 km, is in the Mexican Caribbean, in the Cancun–Tulum corridor, to the east of the Yucatan peninsula. Specifically, between the extreme geographic coordinates: 20° 45' north and 19° 46' south in latitude and 86° 57' east and 88° 05' west in longitude (Fig. 1). Playa del Carmen is located within the RH33 hydrogeological region, while the rest of the municipality is within the RH32 region. Characterized by the absence of surface rivers but it does have several water systems: lagoons, cenotes, wetlands [15].

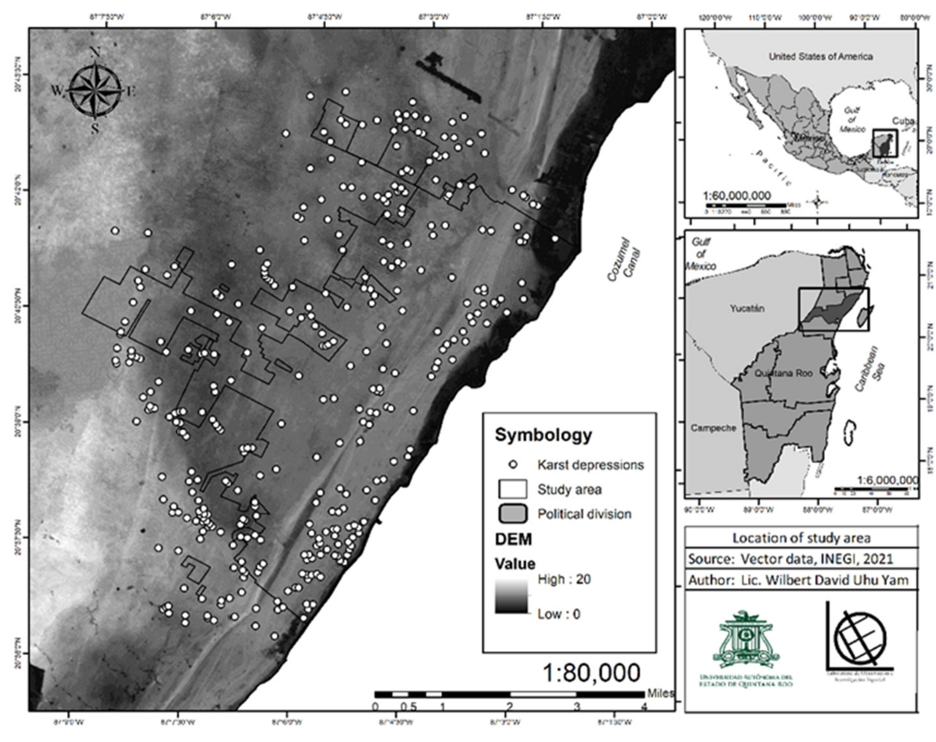

Figure 1: Location of the built-up area of Playa del Carmen.

3 TECHNIQUES AND TOOLS

3.1 Five study phases were established

3.1.1 Phase 1: Relief

For this factor, two indicators were considered: (a) the frequency of topographic depressions, with the karst depressions being identified first by taking the process described by Frausto-Martínez et al. [16] and Colín-Olivares et al. [17] as a reference and processing the 5 m resolution LiDAR data in ASCII/GRID format from INEGI. Subsequently, considering the land use polygons of the secondary zoning of the urban development plan, the frequency of karstic units was calculated; (b) karst depression predominantly by identifying morphometric features according to the proposals by Colín-Olivares et al. [17] and Rodríguez-Castillo et al. [18]; then classifying them into sinkholes, uvalas and poljes, as proposed by Fragoso-Servón et al. [19] and Frausto-Martínez et al. [20]. The frequency of the type of depression by land use was calculated. Finally, a weight was assigned on a scale from 1 to 10, using a hierarchical structure for each indicator, with the aim of homogenizing the data and obtaining a single map for the relief factor.

3.1.2 Phase 2: The Modified Fournier Index (MFI)

Proposed by Arnoldus [21], The Modified Fournier Index was calculated, with monthly precipitation data, in a period of 28 years (1990–2018) from 11 meteorological stations of the National Water Commission. The calculation is monthly, annual and for the observation period according to the suggestion of PHI-LAC [22]. Subsequently, in the ArcGIS v.10.8 software, a spatial analysis and the construction of distribution isolines were performed using the inverse distance weighting (IDW) interpolation technique. Finally, the data was taken only for the study area.

3.1.3 Phase 3: Sea level rise

Rise of the sea was analysed from three indicators: (a) Sea level rise considering the projections made for Mexico of 1 and 3 m [15] using the digital elevation model (MDE) created from the digitization of the contour lines and interpolation of the altitude data with ArcGIS v.10.8 software tools; (b) Piezometric level, calculated from the IDW interpolation of 22 sampling wells located in the municipality of Solidaridad; and (c) Distance from the coast–inland, using the technique of area of influence at each kilometre with respect to the coast. Subsequently, a weight was assigned to each indicator on a scale of 1 to 10, using a hierarchical structure and, finally, a summative analysis of the weights of each indicator was applied, with the aim of homogenizing the data and obtaining a single map to this factor.

3.1.4 Phase 4: Land uses

considering that it is an urbanized area, were analysed based on the differentiation designated by the secondary zoning of the land uses of the Urban Development Program (PDU) of the Playa Del Carmen population centre, Solidaridad Municipality 2010–2050 available at http://www.ccpy.gob.mx/archivos/documentos-agendas/tmp_201509113740.pdf. Based on the available Shapefile, a new one was created to group them into 10 land uses according to the permitted activities and the highest category proposed by the same PDU. Subsequently, the degree of vulnerability was assigned to each one according to the considerations of Pousa et al. [8] and Carretero and Kruse [23], as well as the relationship with the land occupation coefficient (LOC), this indicates the total area that can be occupied to build.

3.1.5 Phase 5

With the results obtained from each variable (relief, climate, rise of the sea and land use) the minimum and maximum data were taken to divide them into five quantiles equivalent to each of the five vulnerability categories (very low, low, medium, high and very high). Subsequently, the Analytic Hierarchy Process (AHP) method, proposed by Thomas Saaty in 1980, was applied to obtain priority scales based on expert judgements through pairwise comparisons using a preference scale. Once the weight of each variable was obtained, the following formula was used for each factor:

$$(V1 \times p) + (V2 \times p) + (V3 \times p) = \text{Degree of vulnerability},$$

where:
V: is the variable;
p: is the weight obtained.

Finally, all the information obtained for each factor was imported into ArcGIS 10.8 software, in order to obtain a geographic information system to create the raster models for each factor.

4 RESULTS

The results are presented according to the analysis criteria.

The weights assigned for each variable were: relief; for the frequency of depression 0.75, being the most important variable and 0.25 for the predominance by type of depression. As the climate factor was analysed with only one variable, it was not necessary to apply this method. Similarly, sea level rise was not applied, as the piezometric level is homogeneous for the whole area and sea level rise projections were only included in the very high category, due to the difference in the unit of measurement compared to the distance from the coastline. And finally, for land use, a higher weight (0.83) was given to the permitted uses in each zone and the land occupancy coefficient was given a weight of 0.17.

4.1 Relief

Using remote sensing inputs, a total of 364 karst depressions located in the urban area of Playa del Carmen were identified. According to the elongation index, 23.90% correspond to sinkholes, 43.13% to sinkholes-uvalas, uvalas represent 12.63% and poljes represent 20.23%. With the frequency of units and type of depressions, the most vulnerable areas were identified in the northern and southern limits of the urban area, where residential and mixed tourist land use predominates, which are classified as areas of urban growth, with a frequency from 29 to 37 sinkholes and sinkholes-uvalas type depressions (see Fig. 2 and Table 1).

4.2 Climate

The minimum historical annual regional rainfall was recorded at the Centro Vallarta station, with 67.3 mm and the maximum at Playa del Carmen with 2,790.4 mm. The average 28-year Modified Fournier Index ranged from 130.7 to 224.1. The highest value was at the Cancun station, which was classified within the very high rainfall category, according to the PHI-LAC classification [22]; and the minimum value was recorded at Centro Vallarta, classified in the high category. For the urban area of Playa del Carmen, the values range from 185.02 to 200.74, according to interpolation data mainly from the only meteorological station within

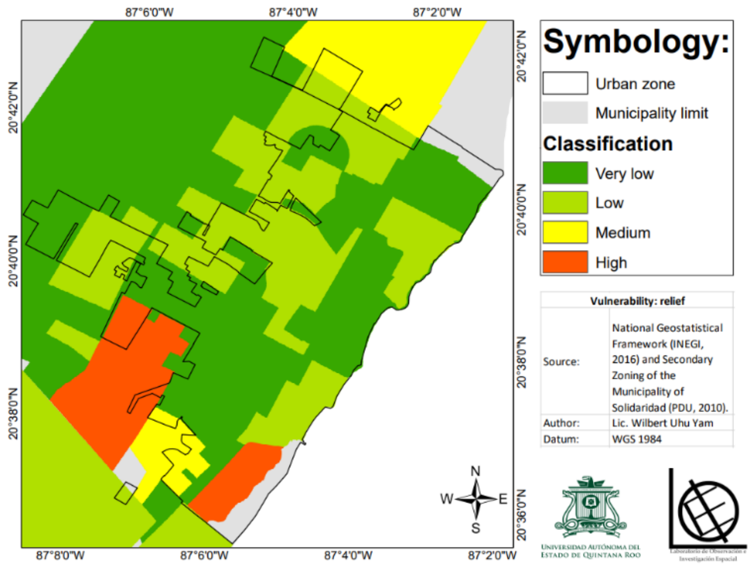

Figure 2: Vulnerability map by factors: relief.

Table 1: Description of the vulnerability categories.

	Description				
	Relief		*Climate*	*Sea level rise*	
Category	Frequency	Predominantly	MFI	Distance from the coast (km)	Rise in sea level (m)
Very low	<7	sinkholes, sinkholes-uvala	185.02–189.58	7–9	–
Low	8–19	sinkholes, sinkholes-uvala, poljes and uvalas	189.59–192.97	6–7	–
Medium	20–27	sinkholes-uvala	192.98–195.87	5–6	–
High	28–27	sinkholes-uvala	195.88–198.46	3–5	–
Very high	–	–	198.47–200.74	1–3	1–5

the study area and the closest stations (Cozumel and Centro Vallarta). Identifying a greater vulnerability to the southeast of the urban area with values of the Modified Fournier index from 198.46 to 200.74 (see Fig. 3 and Table 1).

4.3 Sea level rise

Considering that the groundwater is found a few meters deep and that the altitude in the urban area does not exceed 11 m above sea level, the projections of the increase in sea level for the year 2100, which are from 1 to 5 m, were considered. Specifically, 57.96% of the karstic depressions would be affected. At the potentiometric surface level, 22 wells ranging from

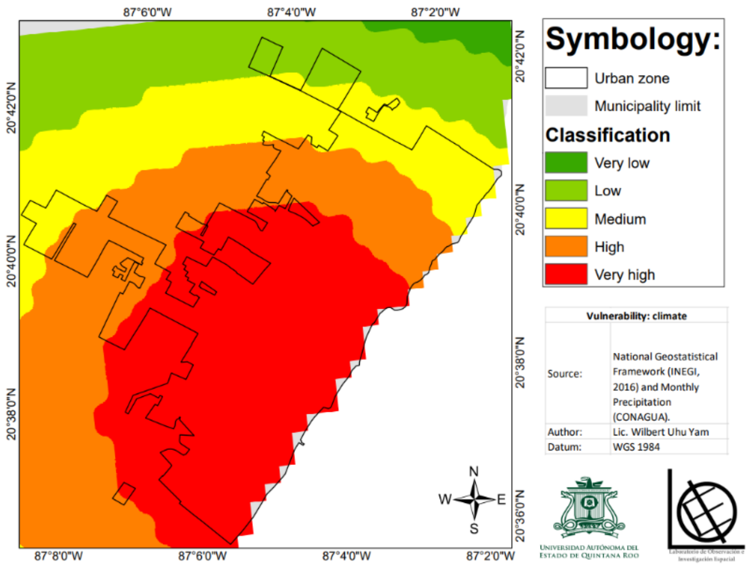

Figure 3: Vulnerability map by factors: climate.

2.15 to 19.11 m obtained a constant potentiometric surface level of 6.40 m for the city with the interpolation analysis, with the distance from the coast divided into kilometres. The areas with greater vulnerability were found within the first 3 km of coastline (see Fig. 4 and Table 1).

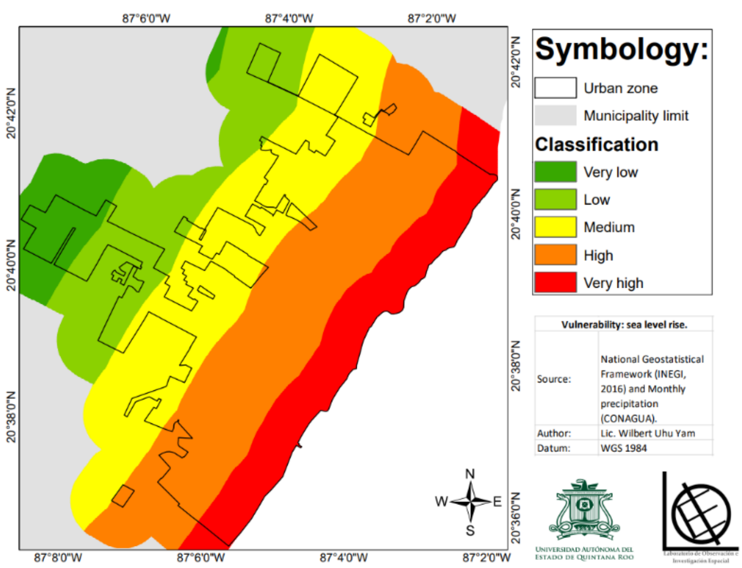

Figure 4: Vulnerability map by factors: sea level rise.

4.4 Land use

There were 24 uses identified, classified into 11 groups, according to the activities allowed in the urban development plan. A high to very high vulnerability was attributed for most of the city, for mixed use, growth, high rise residential, low intensity industrial and commercial. Within the city, protection zones associated with karst depressions, mangroves and jungle zones were identified (see Fig. 5 and Table 2).

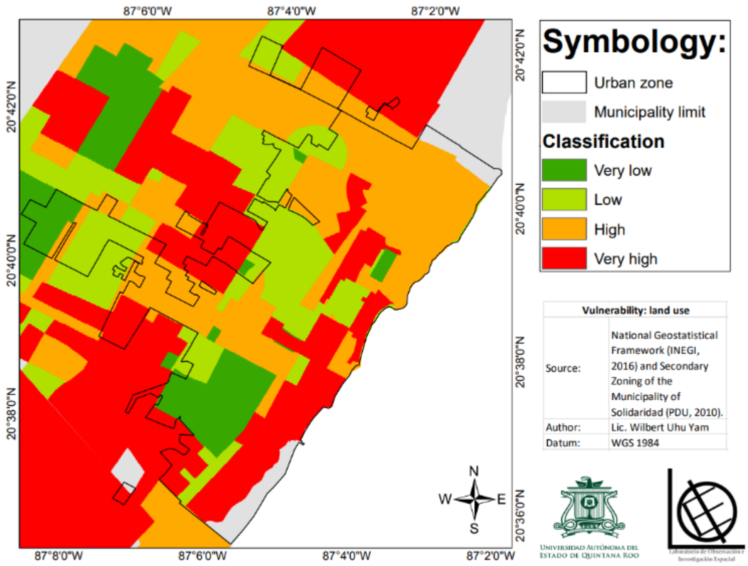

Figure 5: Vulnerability map by factors: sea level rise.

5 DISCUSSION

The growth of cities in the coastal areas of the north-east of the Yucatan Peninsula is one of the most significant aspects, with very high population growth and expansion rates, associated with the development of irregular settlements, a lack of urban planning and wastewater treatment services, coupled with the impact on highly sensitive natural environments, such as caves, caverns, and cenotes [21].

This type of urban growth in karstic areas affects the quality of the water systems, since manufacturing, storage and transportation activities that contain potential substances for the contamination of groundwater are carried out in them. Likewise, this factor plays an important role since it affects the recharge of aquifers in two ways: (a) it potentiates it due to the reduction of the impermeable cover, urban runoff from dry wells and their subsequent infiltration, sewage exfiltration and water pipes and excessive irrigation; and (b) recharge decreases, due to impermeable surfaces, the capture of water by the pluvial network and the extraction of water [24].

Due to these properties, studies such as those by Howard and Gerber [24] and Serra et al. [25], have considered the uses of land and soil for the study of groundwater contamination, while Heiß et al. [26] has annexed this factor together with the analysis of the DRASTIC index and González-Herrera et al. [27] modified this same index, adding the use of land.

Table 2: Vulnerability categories according to land use.

Category	Land use	Description
Very low	Protection	They are intended for the conservation of wells and wetlands, in these areas building of any kind is not allowed
Low	Equipment, urban parks and country tourism	They are intended for public administration buildings and services such as sports centers, schools, etc.
Medium	Low intensity housing	The construction of 20 houses with a frequency of 72 people per hectare is allowed
High	Commercial, residential tourism and industrial	The construction of 40 houses per hectare is allowed and can be used for markets, canteens, vehicle workshops, gas stations and restaurants. The construction of 25 houses or 50 rooms per hectare and should not exceed four levels. Is intended for the light industry such as storage and packaging of lubricants, storage of products that do not imply high risk and gas distribution
Very high	High intensity housing and mixed	The construction of 60 houses with a frequency of 216 people per hectare is allowed. In addition to the construction of 60 homes per hectare and can be used for commercial, residential, equipment and industrial activities

Due to the advanced process of urbanization in the coastal zone, it is necessary to consider the effects of climate change that favour the acceleration of sea level rise, affecting ecosystems. This increase can affect the total submergence or an increase in coastal flooding, loss or changes in habitats (including islands), coastal erosion and saline water intrusion into surface waters and aquifers [28] and the presence of extreme events such as cyclones, rainfall and floods [29]. The study by Ruiz-Ramírez et al. [15] shows the sea rise scenarios for Playa del Carmen, highlighting the damage caused by the rise of the sea, since it estimates an affectation of 90,895 m^2 with a rise of 3 m.

The relief and climate factors were considered in the vulnerability index of Aguilar-Duarte et al. [5] for the Yucatan aquifer. However, the relief factor was not given the same degree of importance here, as this index proposal was focused on urban areas. Despite this, a morphometric analysis of the karst units was performed on a detailed scale (1:10 000) with the help of relatively new methodologies [16]–[18]. The climate factor can be analysed with different indexes, such as the annual rainfall amount and intensity used in the COP model or the spatial distribution of the duration of the rainy period used in the IVAKY model [5]. However, it was decided to use a simple option for calculation, based on the information available, using rain erosion from the Modified Fournier Index, as it complies with the functionality of indicating the areas of greatest rainfall intensity. Thus, the greater this is, the greater the infiltration of water and contaminants, with the water operating as a transport medium for contaminants towards the aquifer [30].

Regarding the vulnerability results by factor, it is observed that the climate behaves inversely to the results reported for the state of Yucatan with the IVAKY model, where the greatest vulnerability is found in the centre of Yucatan and thus the coast decreases [5]; in the relief factor a more homogeneous distribution is distributed and with a tendency to a high and very high vulnerability for both studies; for sea level rise, the highest vulnerability is found in areas very close to the coast, coinciding with the studies by Chachadi and Lobo-Ferreira [13] and Blanco de la Paz et al. [14].

6 CONCLUSIONS

Pollution vulnerability indices are of great importance for territorial management. However, the proposals to calculate it have been modified according to the needs and characteristics of each area studied. The proposal of this study incorporates the land use factor and the rise in sea level as central elements as it is an urbanized coastal area. These factors had not been taken into consideration when developing vulnerability indices for the Yucatan Peninsula. The methods used to analyse the land use and relief factors allowed us to work at a detailed scale (1:10,000). However, due to the climate factor, it was not possible to generate information with a degree of detail less than 1:50,000 due to the dispersion of local meteorological stations. For the sea rise factor, the records on the piezometric level are scarce. It contributes to define an approach to the analysis of vulnerability to contamination of coastal karstic aquifers in urban areas on a scale and a change of traditional approach where only the natural characteristics of the ecosystem are considered.

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