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Relationship Between the Map of Bouguer Anomalies and The Geohydrological Characteristics of The Karst Aquifer of Yucatán. A Review on The Water Vulnerability

Batllori-Sampedro EA[1*], Canto-Mendiburu, S.N[2]

[1]IPN Center for Research and Advanced Studies Merida Unit. Department of Human Ecology
[2]Sustainable Management an Impact Assessment, SCP. 17 Street, number 01 x 20 and 18, Suburb Montebello, Merida, Yucatan, Mexico

[*]**Corresponding author:** Batllori-Sampedro E, IPN Center for Research and Advanced Studies Merida Unit. Department of Human Ecology. Email: eduardo.batllori@hotmail.com

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Abstract

Maps of intrinsic vulnerability to contamination are necessary tools for water management, however, for Yucatan state, it is relevant to consider its karst nature when generating them. Therefore, through a in deep review on published information of the Chixchulub multi-ring system gravimetry (density and porosity contrast), the derived analysis of Bouguer anomalies, and the maps of total horizontal gradients obtained were compared with various geohydrological, geochemical, geophysical, stratigraphic studies, and 2 structures were recognized: a) Areas located close to high gravimetric values (> 30 mGal/km), associated with falls of the groundwater table, with predominance of brackish water in a reduced thickness, and b) Areas located at low gravimetric values (< 20 mGal/km), associated with elevations of the water table, and large thicknesses of fresh water, keeping the saline interface at depth. Hence, it is of high relevance to adopt the approach here presented to give precise results on intrinsic vulnerability and groundwater movement, adding to the correct management of the hydric resource.

Keywords: *vulnerability, gravimetry, hydrogeology, permeability, Chicxulub.*

Resumen

Los mapas de vulnerabilidad intrínseca a la contaminación son herramientas necesarias para dirigir acciones de gestión del agua que impulsen su conservación y aprovechamiento adecuado, sin embargo, para el caso del estado de Yucatán, se requiere generar más congruencia con su naturaleza kárstica. Por lo que, a través del reconocimiento del sistema multianillos de un cráter de impacto mediante gravimetría y contraste de densidad (y porosidad), así como los análisis derivados de las anomalías de Bouguer, se obtienen los mapas de gradientes horizontales totales. Esta imagen se coteja con diversos estudios geohidrológicos, geoquímicos, geofísicos, estratigráficos, entre otros, y se reconocen 2 estructuras: a) Áreas que se ubican cercanas a valores altos gravimétricos (> 30 mGal/km), asociados a caídas del nivel del agua subterránea, con predominio de agua salobre en un reducido espesor, b) Áreas que se ubican en valores gravimétricos bajos (< 20 mGal/km), asociados a elevaciones del manto freático, y a grandes espesores de agua dulce, manteniendo la interfase salina a profundidad. De aquí la propuesta de la presente aproximación para generar mayor precisión en la evaluación de la vulnerabilidad intrínseca y del movimiento de agua, sumando al manejo adecuado del recurso hídrico.

Palabras Clave: vulnerabilidad, gravimetría, hidrogeología, permeabilidad, Estado de Yucatán.

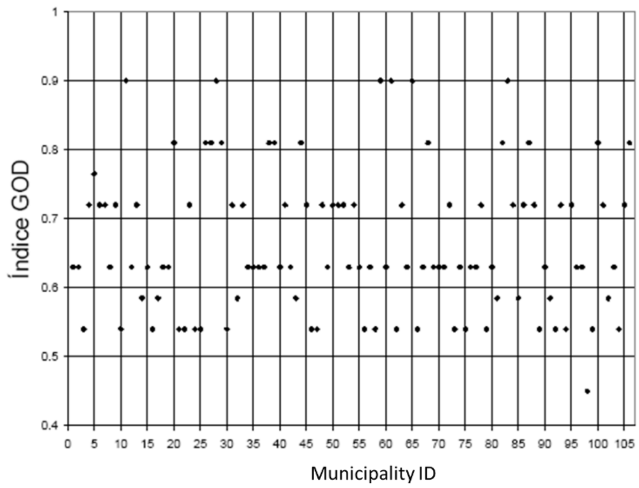
Introduction

The development of maps of intrinsic vulnerability to contamination has been considered a primary need to promote warnings and establish strategies for the conservation and management of aquifers in general, and those of the karst type [1-3]. However, there is a great deal of subjectivity in the various methodologies that tend to bias the expected results when different models are applied in the same area. In the case of the Yucatan aquifer, the results show that the methodologies used are not entirely applicable (DRASTIC and EPIK types) and must be adapted to be congruent with the regional karst characteristics [4-6].

The degree of intrinsic vulnerability can be expressed by means of an index that can be determined through various methodologies such as: The Aquifer Vulnerability Index (AVI), the DRASTIC methodology and the GOD methodology (Groundwater occurrence, Overall aquifer class, Depth to groundwater). The AVI is an index used to quantify the vulnerability of an aquifer, through the hydraulic resistance "c" to the vertical flow of water when passing through the different materials on the ground. This methodology is based on the assumption that the contaminant travels in a vertical direction [7-10]. The methodologies and indices developed to determine vulnerability generally have a hydrogeological approach, and mainly consider parameters such as the depth of the saturated and unsaturated zone, lithology, hydraulic conductivity, net recharge, infiltration, and land slope. Among the most common indices are SINTACS and Pi, which are not specific for karstic aquifers [11].

Bolio Barrios et al, 2011 [12], uses the EPIK method, with an environmental focus, and developed for karstic aquifers. It considers variables such as high permeability in limestone, protective cover (depth of soil), infiltration, and karstic landscape (degree of development). Aguilar-Duarte, Y. et al, 2016 [13], mentions that various studies have recently been reported for Yucatan that would improve the interpretation of the vulnerability of the aquifer to contamination, such as: i) the typology and spatial distribution of karstic depressions in Yucatan (Aguilar et al., 2016) [14]; ii) an approximation of vulnerability according to depressions; iii) mathematical models that estimate environmental functions in soils (Aguilar et al., 2011) [15] and their cartographic representation (Aguilar and Bautista, 2011) [15]; iv) development of Leptosol LP units in the plains (Bautista et al., 2011) [12]; and v) agroclimatic indices that reflect humidity intensity and distribution (Delgado-Carranza et al., 2011) [16]. In his work, a spatial integration of the elements of the environment (relief, soil and climate) was carried out, with the objective of generating and proposing a Vulnerability Index of the Yucatecan Karstic Aquifer (IVAKY) considering the forms of relief, soils and climates to identify different levels of groundwater vulnerability to contamination, as a derivation of the EPIK method. The Atlas of Hazards of the State of Yucatan, from the Mexican Geological Service (2013) [17], offers a lot of information on sinkhole density, soil thickness, faults, fractures, susceptibility to collapse and subsidence, among other documents. Batllori, E. and Canto S. (2022) [18], incorporate the Bouguer Gravimetric Anomalies into the analysis, based on the differentiated density of the rock, which can better describe the multi-ring system linked to the Chicxulub Crater, subjected to different types of climate and important fluctuations in temperature, favoring weathering (Table 1).

Table 1: Intrinsic vulnerability maps to pollution prepared by various authors using different evaluation methods.

Author	Method	Results	Map
Pérez y Pacheco (2004)	AVI	This methodology uses the hydraulic conductivity and the thickness of the layers of different material found above the water level in order to quantify the index. This index is not adequate to calculate the vulnerability of groundwater to contamination since the values used for the calculation are relatively constant for the entire state of Yucatán.	
	GOD	It was observed that two of the three variables (the type of aquifer and the lithology of the cover) were constant for the entire state. The values of the GOD index varied between 0.45 and 0.9; so the index values were due solely to depth to the static level. 	
	DRASTIC	The related variables (depth to the static level, recharge, type of aquifer, type of soil, vadose zone and hydraulic conductivity) corresponding to each one of the municipalities of the state of Yucatán (Pérez, 2003). The values correspond to high, very high and extreme vulnerability on the DRASTIC scale. The author showed that there are only two values; the high vulnerability in most of the state and the extreme vulnerability located mainly in the coastal zone.	

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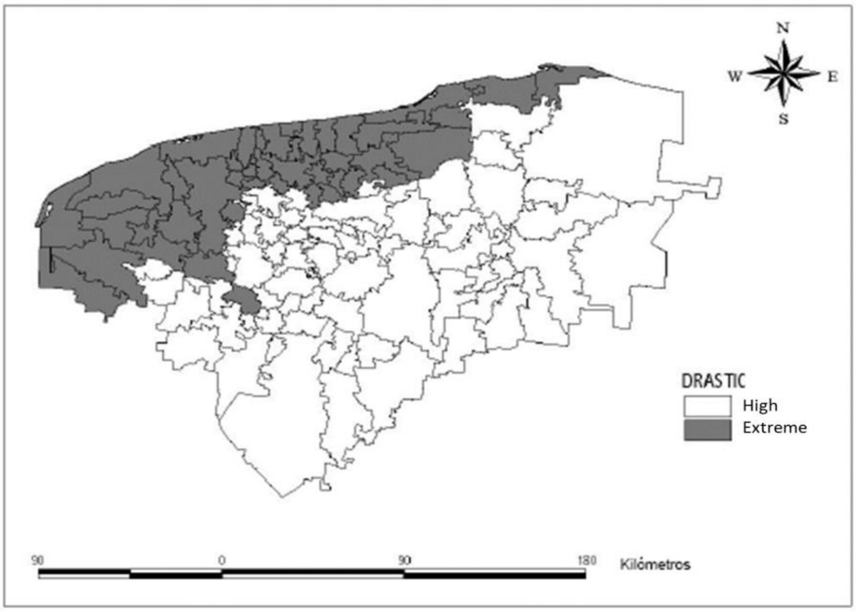
<tr><td></td><td></td><td>
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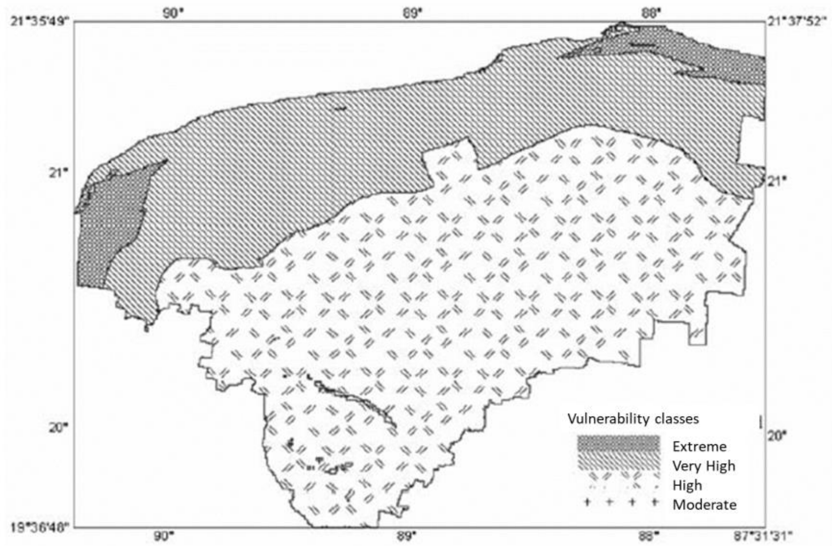
<tr><td>Rosela Pérez-Ceballos, Julia Pacheco-Ávila y Jorge Euán-Ávila, en 2002</td><td>DRASTIC</td><td>The results showed that the vulnerability index ranged from 157.6 to 207.8; these index values were classified resulting in 4 classes: moderate, high, very high and extreme. Likewise, the results indicated that only 0.2 % of the total area is in the moderate category, while 61 % is assigned to the high category, 33.8 % to the very high category, and 5 % is in the extreme category.

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<tr><td>Albornoz Euán Beth sua Iztaccihuatl; González Herrera Roger Amílcar; Pacheco Ávila Julia Guadalupe; y Zetina Moguel Carlos, 2015</td><td>DRSTIL modified from DRASTIC</td><td>A modification of the DRASTIC methodology, the DRSTIL, was implemented, in which the aquifer factor (A) and hydraulic conductivity (C) are not included because they do not present great variations for the study area. The L factor (Land use) was added to reflect the impacts that the various activities that take place on the soil surface have on the quality of groundwater. The results of vulnerability to groundwater contamination using the DRSTIL index differ from those obtained in other works implementing the DRASTIC index or a modification of it. On the map, the areas classified with minimum vulnerability occupy 1.23 % of the total area of the entity and are located in the Sierra de Ticul. The low vulnerability classification occupies 37.95 %, it is distributed in the southern region, in some areas of the eastern, northeastern region and on the coastal coastline in its western and central part. The vulnerability classification with the</td></tr>
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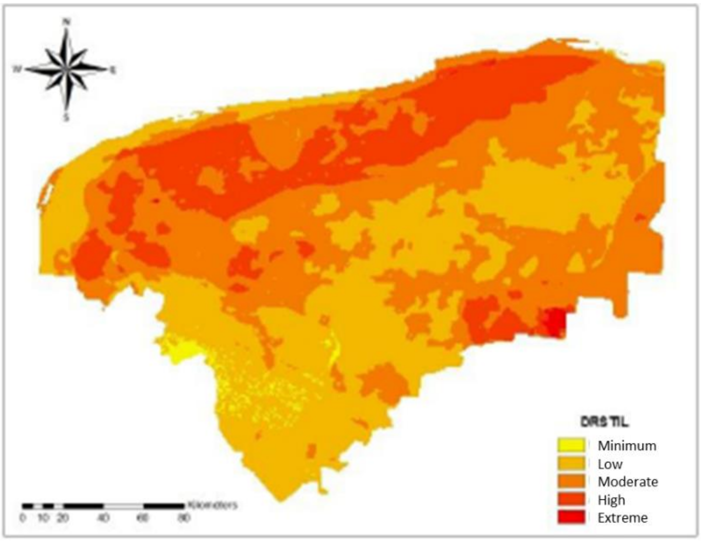
<tr><td></td><td></td><td>highest coverage in the State of Yucatán was moderate with 42.51 % of the total area. These areas are found mainly in the southern part of the eastern, northeastern, central, central coastal, western, and western regions of the state. Areas classified as highly vulnerable occupy 18 % of the total area. They are found mainly in the central part of the western, central and northeastern coast regions, and in some areas of the east and west. The Extreme classification occurred in 0.31 % of the area located in the southern part of the eastern region of the State.

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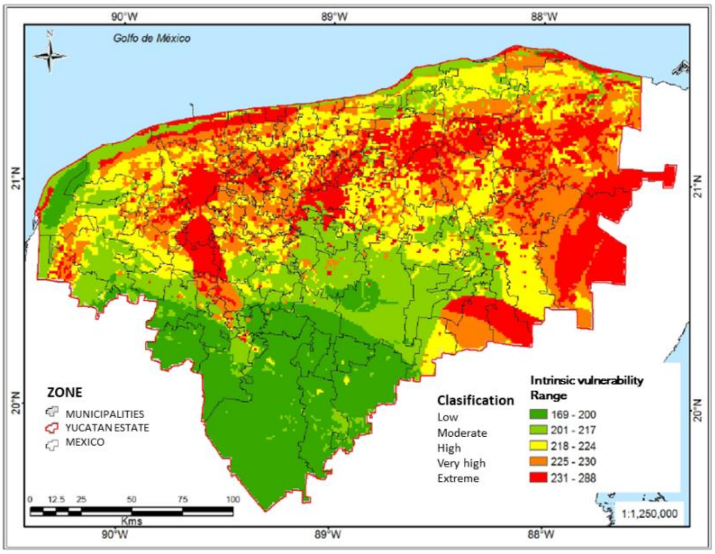
<tr><td>Flor Arcega F. (2018)</td><td>DRASTIC</td><td>Using the results generated for the DRASTIC model, the intrinsic vulnerability map was generated, which shows that taking all these characteristics, more than 50 % of the State is in a vulnerability between high, very high and extreme (19, 20 and 21 %, respectively). Medium and low vulnerability contribute with 20 % equally.

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<tr><td>Emilio Rodrigo Bolio Barrios, Santos Armando Cabrera Sansores, Francisco Bautista Zúñiga y Julia Guadalupe Pacheco Ávila, en 2011</td><td>EPIK</td><td>The EPIK methodology was developed for karstic aquifers and takes into account variables such as high permeability in limestone, protective cover (soil depth), infiltration, and karst landscape (degree of development). The authors considered only the following geoforms to study: 1) coastal plain, 2) low subhorizontal karst plain; 3) grouped sinkholes, located in the geohydrological zone called semicircle of cenotes, 4) undulating karstic plain with deep cenotes; and 5) medium subhorizontal karstic plain, corresponds to the geohydrological zone known as interior plain. The geomorphological landscape of grouped sinkholes corresponded to the most vulnerable category. Most of the landscapes were classified as very vulnerable;</td></tr>
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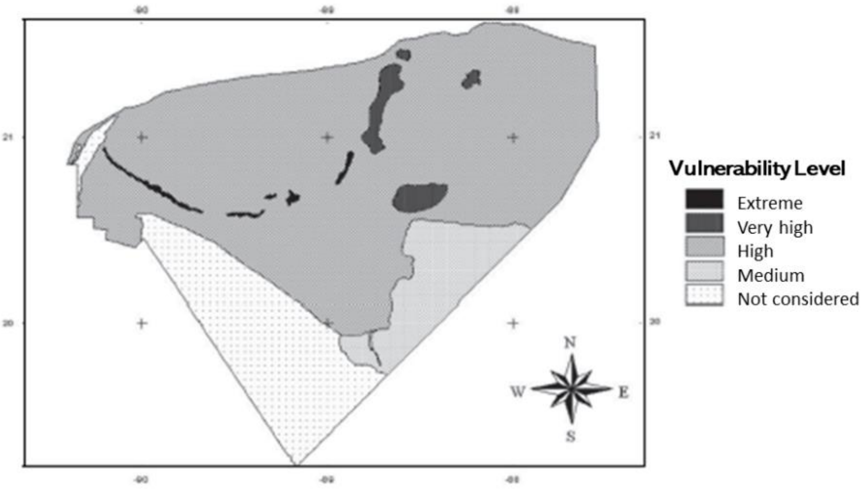
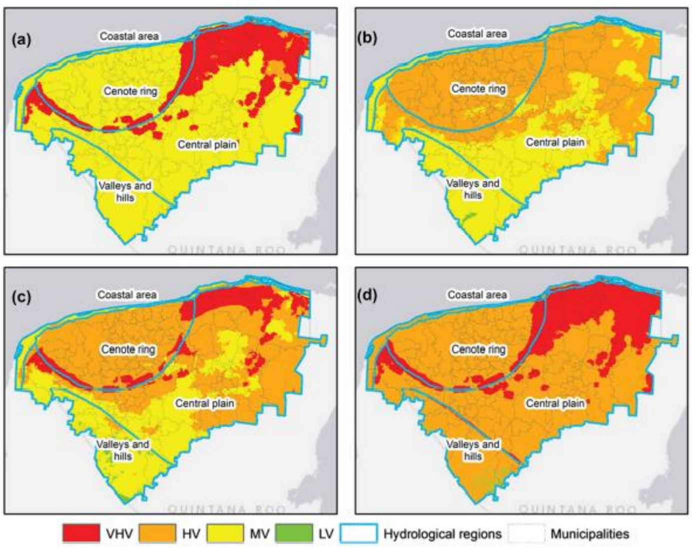
		however, with the breakdown of the index it was possible to observe that the values of the EPIK parameters are not identical, and that the combination of these produces similar results. 
Miguel Moreno-Gómez, Julia Pacheco, Rudolf Liedl y Catalin Stefan, en 2018,	4 European methods (EPIK, PI, COP, and PaPRIKa) applied to Yucatecan karst	Study on the applicability of European methods for vulnerability assessment. There is great subjectivity in the various methodologies that tend to bias the expected results when different models are applied in the same area. The interpretation of the data, the weight of the factors and the vulnerability rates, vary between the different methods, displaying different spatial results when applied to the same site. Similar vulnerabilities were identified in more than 52 % of the spatial arrays among the maps generated using the COP, PI, and EPIK methods. However, these methodologies do not achieve congruence with the regional characteristics, since the authors mention that in the European methods applied the vulnerability classes are not congruent with the regional intrinsic characteristics. The results show that the methodologies used are not applicable and must be adapted to be consistent with regional characteristics, such as shallow waters and diffuse regional infiltration. The average class percentages between the PI and COP methodologies are very important, differing only by the very high vulnerability class, related to the surface karst characteristics according to the COP method. On the other hand, the EPIK and PaPRIKa method show very similar values for the very high vulnerability class, associated with areas of very high karstification. Vulnerability classes in relation to the surface of the state of Yucatan. a.- EPIK, b.- PI, c.- COP, d.- PaPRIKa 

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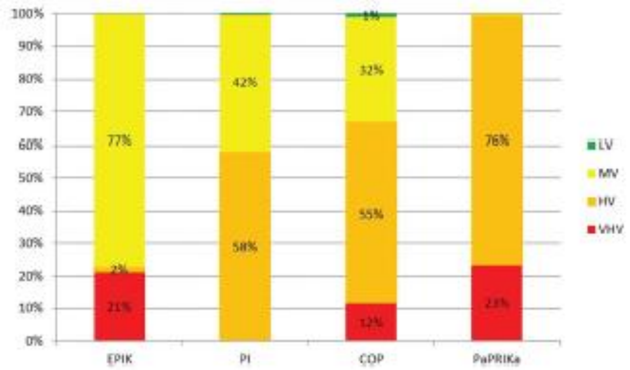
<tr><td></td><td></td><td>
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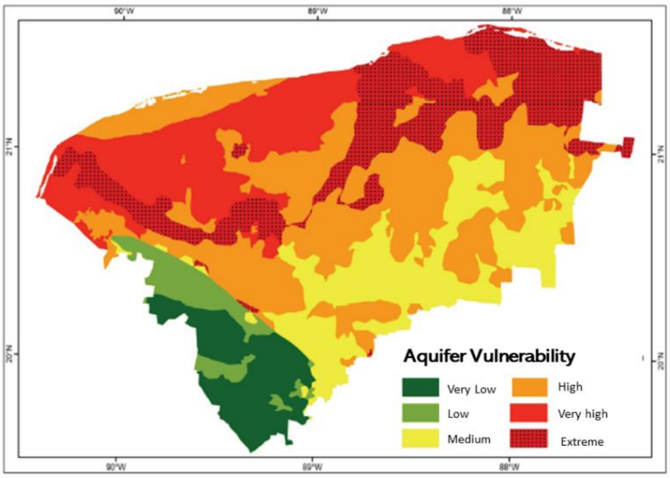
<tr><td>Yameli Aguilar-Duarte, F. Bautista, M. E. Mendoza, O. Frausto, T. Ihl, y C. Delgado, en 2016</td><td>IVAKI</td><td>It was built based on a 1:50,000 scale geomorphopedological map, which contains the density and typology of karstic depressions and edaphic associations in each geomorphopedological unit. The climate factor is included through the length of the rainy period that considers quantity, distribution and intensity of the rain. The three factors (relief, soils, and climate) were weighted with the Analysis Hierarchy Process (AHP) using ArcGis 9.1. The result is a map with six vulnerability classes. a) The class of extreme vulnerability corresponds to the Ring of Cenotes and continues towards the northeast, with 19 % of the state surface. b) The class of very high vulnerability located in the low karstic plain (less than 10 m) inside the Ring of Cenotes, with 19 % of the state surface. c) The class of high vulnerability in the coastal plain and the karstic plains (20 and 30 m of altitude), presented greater surface (33 % of the state surface). d) The medium vulnerability class located in the karstic plain of 40 m altitude to the south and southeast of the state of Yucatan, with high rainfall, occupies 17 % of the state surface. e) The class of low vulnerability located in the interior plains with low infiltration soils; the hills and the mountains, which are the highest parts of the territory, correspond to 4 % of the state surface). f) The class of very low vulnerability located in the south of the state in the hills with very low infiltration soils, occupies 8 % of the state surface.

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<tr><td>Batllori E., y Canto S. 2022</td><td>Bouguer anomalies with DRASTIC and EPIK</td><td>To prepare the intrinsic vulnerability map, the DRASTIC methodology and variables derived from the EPIK method were used. The results obtained show that low vulnerability corresponds to the southern portion of the state of Yucatan, with 14 % of the total state area. The average vulnerability occurs in the southeast-northwest axis with an area of 28 %. High vulnerability is widely distributed in the eastern region, in the largest zone of punctual infiltration in the State, with 28 % of the state surface. The very high vulnerability is associated with the multi-ring system derived from the Chicxulub Crater due to differences in rock densities and hydraulic</td></tr>
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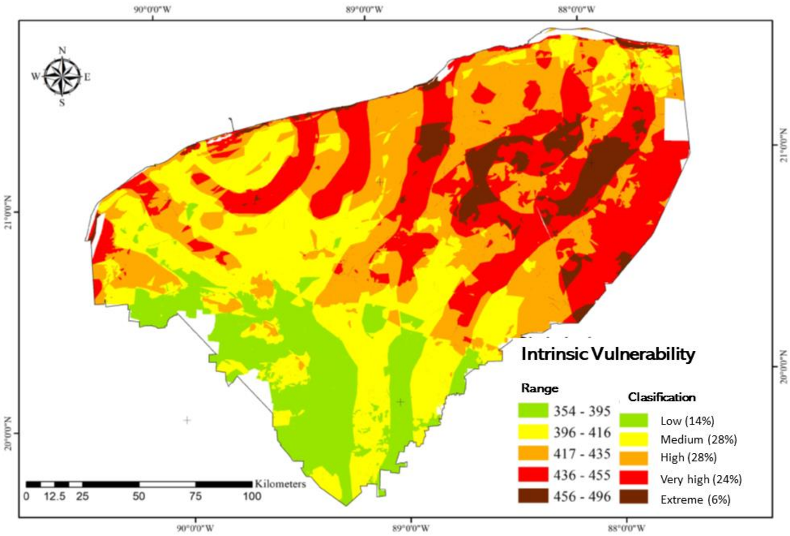
<td>conductivity. This radial zone extends over 24 % of the state territory. Finally, extreme vulnerability occurs in the form of patches in the eastern part of the State, linked to the greater permeability of the territory, derived from a significant presence of cenotes, sinkhole density, fractures, faults, and a type of climate where it occurs the highest rainfall (1,000 – 1,200 mm/year), generating very dynamic karstic processes. It extends over 6 % of the state territory.



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The present proposal seeks to achieve a greater congruence with the regional karst characteristics, so it explores, with strong indirect evidence, the relationship between the various geohydrological and stratigraphic studies that have been developed in the area in different years and by various researchers, with the results of the studies on gravimetry and the gravitational anomalies of Bouguer presented by Sharpton et al (1993) [19] and analyzed by Arellano-Catalán, O. (2017) [20], as well as the variations of the Total Horizontal Gradient (see Arellano-Catalán 2017), as shown in Figure 1.

Objective

This study performs an exploratory analysis of the indirect gravimetric and hydrogeological evidence to define behavior patterns of the Yucatan karst aquifer. The hypothesis is that the structure of the calcareous rock is related to the movement and storage of water, through specific infiltration zones or diffuse infiltration areas, and through preferential groundwater conduits. The information generated will be useful as an input for the elaboration of the maps of intrinsic vulnerability to the contamination of the aquifer, as a characteristic representation of the Yucatan karst.

Materials and Methods

An exhaustive bibliographic review on the Yucatán karst geology and its characteristics was done to collect all the indirect evidence that could be indicating a relation between the structure of the calcareous rock and groundwater hydrodynamic and types of infiltration (Figure 2).

Characteristics of limestone. Density, porosity, permeability

The characteristics of limestone, density, porosity, and permeability that in turn give the gravity anomalies, were obtained from Cásares-Salazar et al. (2006) [21] (Table 1). Gravity anomalies result from the difference in density (or density contrast), between a body of rock and its surroundings. Density is related to the nature of their constituents and the existence of empty spaces between them (porosity) and is defined as mass per unit volume (kg/m^3 o g/cm^3). Porosity is a property that is of great interest in the characterization of rocks, since it is related to their capacity to absorb water. It is related to the storage function, since the interstices can be occupied by water or air, but this does not indicate how much water can be extracted from it considering the depletion (Custodio E., and M.R. Llamas, 1996) [22]. The variation in porosity is the main cause of density variation in sedimentary rocks.

A material is permeable when it has the capacity to be crossed by a considerable fluid during a specific time. For a material to be permeable, it must possess porosity characteristics, so the primary porosity and permeability of the aquifer depends on its lithology; its values are high in the strata constituted by shells and skeletons of organisms and low in the massive limestone and clay strata (Casáres Salazar. R., 2006) [21]. In reality, what makes clays impermeable is their capillary potential, since they reach up to 50 % porosity even though the pores are so small, so the capillary potential can be infinite, and the movement of fluids is null. Over time, these original characteristics can be notably modified by fracture, dissolution, and abrasion, giving rise to secondary porosity and permeability, which vary within a wide range of high values (20 to 40 %) and present a very irregular distribution, due to the erratic course and varied size of the dissolution pipes (Table 2).

Table 2: Permeability indicators in the detritus of the drilling of various wells in the Yucatán coastal plain.

Presence of clays	Clays reduce permeability	
Texture	Smooth	Indicates low primary permeability.
	Porous	Indicates some primary permeability.
Roundness	Angular	Indicates low primary permeability
	Rounded	Indicates some primary permeability
Fragment size	Small	Indicates low primary permeability
	Large	Indicates some primary and / or secondary permeability
Signs of karsticity	Dissolving cavities	Master secondary permeability
	Calcium carbonate and iron oxide redeposition footprints	
	Lack of material recovery, indicating the presence of a cavern	
	Shell fragments	
	Fossils (shell footprints)	
	Remains of reefs	
Hardness	Hard	Indicates low primary permeability
	Soft	Indicates some primary permeability

Source: Casáres Salazar. R., 2006

Results

Arellano-Catalán (2017) [20] made an analysis of the gravimetric data obtained by Sharpton et al (1993) [19], by vectorizing their results. Bouguer gravimetric anomaly (BGA) presents three main features positioned in a radial way, the first circular feature has a radius of 20 km, and the anomaly values are 14 mGal (BGA), that area is surrounded by a low gravimetric with values up to -10 mGal (BGA). The second circular feature has a radius of approximately 60 km with a gravimetric field value of 10 mGal (BGA). The third concentric ring-shaped feature has a radius of about 95 km. However, the Arellano-Catalan (2017) [20] total horizontal gradient (THG) emphasizes the effect of lateral density changes and suppresses regional gradients masking the gravimetric signature originated by the impact lithologies. In the map of the horizontal gradient of the Bouguer anomaly, it is also possible to appreciate the circular arrangement of the sources dominating the gravimetric expression in the study area (Figure 1). The structures in this map seem to be more regular, with the maximum being located 90 km radius from the center of the crater, coinciding with the cenotes ring and better defined over 50 mGal/km (THG).

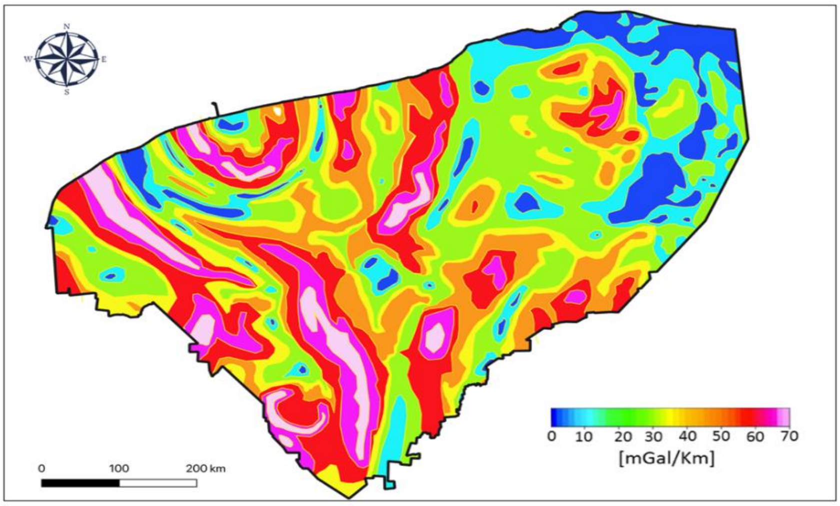


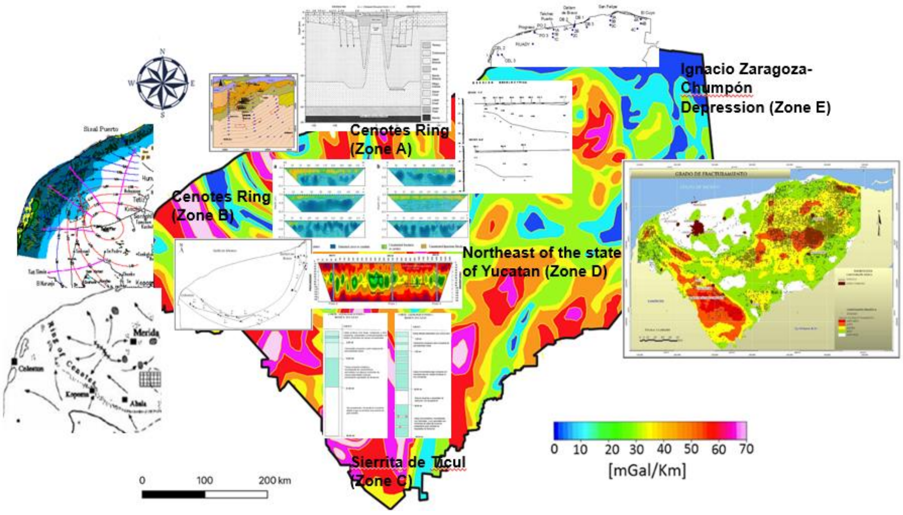
Figure 1: Map of Total Horizontal Gradient (THG). Source: Modified from Arellano-Catalán (2017).

G.L. Christeson, et al (2018) [23], by excavating well M0077A, in the marine part of the impact ring crest, measured through the border between the post-impact sedimentary rock and the sequence of breccias and melt material a drop in density and an increase in porosity, with values from 2.06 to 2.37 g/cm^3 and from 20 to 35 % respectively. The thin layer (25 m) of the impact melt unit below the breccia sequence has densities of 2.26 to 2.37 g/cm^3 and porosities of 19 to 22 %. The authors associate the low density and high porosity of the breccia sequence and melt material with rapid emplacement, hydrothermal disturbance products and the observation of pore spaces and vesicles. Granite materials elevated at the crater rim have densities of 2.39 to 2.44 g/cm^3 and porosities of 8 to 13 %, which differ significantly from a typical undisturbed granite material, which has higher densities and lower porosities. This shows considerable damage to the rock, as it was the most heavily impacted area in the impact basin.

The relationship between the rings of the Chicxulub crater and the cenotes ring is evident on the surface of the terrain by a semi-circular, low-amplitude topographic depression that can be observed by high-resolution interferometric radar satellite images (Hernández, L.; et al, 2011) [24]. The structural rim of the buried crater is marked on the surface because of the differential compaction of almost 5 m of the breccias and fracturing within the crater and favored by dissolution processes through the faults and fractures in the carbonate terrain (Guilick et al., 2013) [25]. Eventually, the dissolution of limestone is accelerated by the presence of saline intrusion, which plays a fundamental role, since the dissolution of limestone occurs on a horizontal plane, associated with the saline interface, the product of the action of astronomical tides and the stratification of water. The Yucatan Peninsula experienced periods of rising and falling sea levels in its recent geological past, as evidenced by the presence of speleothems in some of the currently flooded caves. These periods of rising sea levels probably also played an important role in the formation of the cenotes ring (Van Hengstum et al. 2011) [26].

Derived from the analysis of the previous studies information, it is possible to contribute to achieve greater congruence with the regional karst characteristics, where the presence of a multi-ring type impact crater has been demonstrated. These rings have a radius of approximately 20, 60 and 90 km and the relationship between the rings of the Chicxulub crater and the cenotes rings in the northern part of the Yucatan Peninsula, whose gravimetric values are greater than 30 mGal/km (THG), was corroborated.

By analyzing the fracture map (Yucatan Risk Atlas 2013) and considering the fracture density, fracture length and fracture intersection per unit area, we could determine areas where guidelines appear related to some of the major geomorphological features and that could function as areas or conduits of groundwater with great susceptibility to collapse. The southern zone is the most representative fractured zone and is related to the topographically highest land, which in turn is limited to the east by the Ticul Fault. The highest concentration of dolines is in the northeastern part of the state territory, mainly in the municipalities of Calotmul, Temozón, Sucilá, Espita and Tizimín, where there can be up to 15 dolines per square kilometer, The gravimetric value (THG) here es over 30 mGal/km. The concentration of dolines in the center and some small areas in the northwest are related to the ring of cenotes, on the edge of the Crater of Chicxulub. The zone with relatively less concentration of dolines appears in the north of the State, distributed in the central part of the ring of cenotes, inside the Crater of Chicxulub which works as a geographic limit with the other zones. Then, from the distribution and disposition of the lineages from the Mexican Geological Survey (2013) [17] they determine five zones as follows: Ring of Cenotes (RC) interior zone (Zone A), RC (Zone B); Sierrita de Ticul (Zone C); Northeast of the state of Yucatan (Zone D) and finally the Ignacio Zaragoza-Chumpón Depression (Zone E), each of them with unique geomorphological features that affect groundwater flow (Figure 2).



Source: 1. Urrutia-Fucugauchi et al. (2011) [27]; 2. Andrade-Gómez et al. (2019) [28]; 3. Perez-Ceballos (2011) [29]; 4. CNA (2002) [30]; 5. Casares-Salazar (2006) [21]; 6. Drinking Water Consultants, Sewerage, Geohydrology & Coastal Hydraulics (2008) [31]; 7. Mexican Geological Service (2103) [17]; 8. Faculty of Engineering of the Autonomous University of Yucatan (Anonymous, 1988) [32]; 9. Escolero et al (2005) [33]; 10. Environmental Engineering and Consulting Services SCP (2017) [34].

Figure 2: Map of Total Horizontal Gradient and several studies mentioned here. Source: Modified from Arellano-Catalan (2017).

This is also mentioned by Andrade-Gómez et al. (2019) [28], who found in the RC clear differences between the saturated and unsaturated freshwater layer, based on resistivity profiles, resulting in a two-layer model for the upper part of the aquifer: a vadose or unsaturated zone (300-25,000 Ωm) over a phreatic zone (3-250 Ωm). Valle-Levinson et al. (2011) [35] observed fractures in the matrix grid can vary from microfractures (less than 1 m) to ducts several meters wide. The entire aquifer is connected through this matrix to the sea. The fresh water that constitutes the aquifer flows over the seawater intrusion that penetrates up to more than 90 kilometers inland.

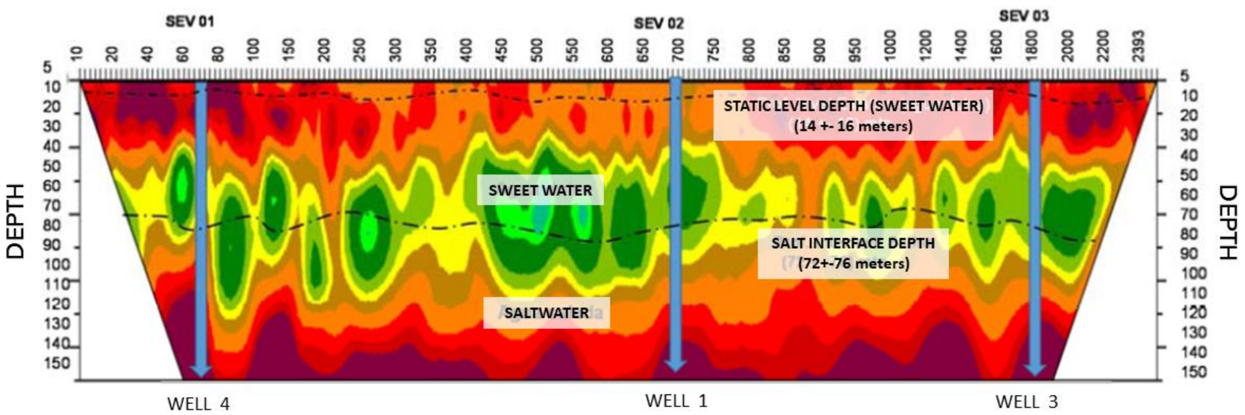
It can be seen how the water levels of the phreatic layer decrease in the areas of the ring of cenotes and the direction of the dominant flows are towards this dump, implying an increase in hydraulic conductivity in these sections (Marín, 1990, 1988) [36,37]. Perry et al. (2002) [38] and Pérez-Ceballos (2011) [29], showed that along the coast, from Celestún (to the west) to El

Cuyo (to the east), associations are observed between the values of the Total Horizontal Gradient and the characteristics of the rock and the aquifer clearly, and present a conceptual model, based on geochemistry and the circulation of groundwater along the cenotes ring. This model proposes the existence of a waterway in the area between Telchaquillo and Tekit; it also postulates a recharge area to the southeast, towards Sotuta. It is worth mentioning that this description considers the recharge zones at a local level, since it does not consider the model proposed by the National Water Commission (CONAGUA), which is a model at a regional level.

According to Perez-Ceballos, R.Y. (2011) [29], in this Cenotes Ring, the processes of dissolution and precipitation of minerals were different with respect to the climatic season. Thus, in rains and “Nortes” (winter) the dominant processes were the dissolution of calcite, the precipitation of dolomite and the gasification of carbon dioxide, with an increase in the magnitude of these chemical processes being noted during the rains. However, during the dry season the dominant chemical processes were calcite precipitation, dolomite dissolution and carbon dioxide degasification. In the rainy and northern seasons, this dissolution of the minerals, when transported to the coastal zone, generates an oversaturation in the water so that it precipitates, favoring the increase of minerals that reach the coastal zone. Similarly, an increase in electrical conductivity (EC) was observed, the concentrations of Na+ and Cl- at the ends of the Cenote Ring, attributing it to the effect that this climatic season has on the sea, the wetland, and the coastal aquifer, causing a push force of the sea water inland from the Yucatan aquifer. The results of the reverse hydrogeochemical modeling also corroborated the entrance to the cenotes ring of groundwater to the west, from the southern Yucatan State, with the presence of sulfur; and to the east side (in Dzilam) another entrance of groundwater to the cenotes ring was identified whose origin is different from that entering the cenotes of the west.

The Technical Committee on Groundwater of the Cenotes Ring Geohydrological Zone (COTASMEY), and the Secretariat of Urban Development and Environment, administration 2012 - 2018, presented the document "Groundwater Balance in the Cenotes Ring Geohydrological State Reserve Zone", and the company Environmental Engineering and Consulting Services SCP prepared in year 2017 the "Geohydrological Study of the Eastern Area of Homún, Yucatán”, where four wells were drilled on the site to depths of about 40 m. They mention that in the aquifer of the Ring of Cenotes Geohydrological State Reserve, the transmissivity was of the order of 7.90 m^2/s, with a general hydraulic conductivity of the area of 11,376.00 m/day, and with flows of 10.07 m^3/day/m.

The lithological cuts of the exploratory wells made at the center of the State Geohydrological Reserve show limestones of greater to lesser compaction with alterations by intercalations or clay nodules. There are also caves and large cavities at depths of more than 20 m and with thicknesses that vary from 13 to more than 30 meters (Figure 3).



Source: Environmental Engineering and Consulting Services SCP 2017 [34].

Figure 3: Lithologic cuts of exploratory wells 1 and 3. Geoelectric section of the central zone of Natural Protected Area of the Ring of Cenotes.

Despite this general characteristic, there are particular effects on changes in the hydraulic gradient in these highly fractured and porous areas. The low hydraulic conductivity of some areas (clayey soils, as in well 3) is reflected in high hydraulic gradients (0.000035 m/m), which correspond to the energy loss suffered by the water due to friction during its journey through the clayey geological material. At these sites, hydraulic conductivity of 4,796.13 m/d and transmissibility of 3.33 m^2/s is observed.

On the contrary, in lands where the hydraulic conductivity is high (such as well 1 in karstic aquifers), the water levels reflect hydraulic gradients of low magnitude (0.00000674 m/m), a hydraulic conductivity of 24,925.74 m^2/day is observed, with a transmissibility of 17.30 m^2/s. So, it can be established that for a constant flow (10.07 m^3/day/m), if the hydraulic conductivity decreases, the hydraulic gradient will have to increase, and viceversa.

According to the results of the geoelectrical section of the lithology, the saline interface is located between 72 and 76 m deep, and the freshwater zone is mainly made up of microcrystalline or recrystallized limestone with very high porosity and very permeable, with a thickness of 60 m.

In 2008, the company Drinking Water Consultants, Sewerage, Geohydrology & Coastal Hydraulics, I.C., conducted a Geohydrological study to define the contact of the semi-confined caliche layer (aquitard) in the southern area of the port of Progreso, Yucatán. In the coastal area, contact of the semi-confinant caliche layer (aquitard) was identified by means of underground probes at a depth of 15 meters. A layer of compact limestone was identified with thicknesses between 0.5 and 2.90 m and which, according to the variations in level observed during its drilling, corresponds to an aquitard and effectively acts as a confining layer of the aquifer. This aquitard has a lateral extension towards the south of the town of Flamboyanes. Further south, the compact surface layer changes to an altered limestone with the presence of dissolution and fossil features corresponding to limestones of the upper Miocene (Carrillo Puerto formation) Pliocene, so it is assumed that the contact between these and the upper Pleistocene limestones (aquitard) takes place at this point, 8 km to the coast. Taking as reference the hydraulic potential and its distance from the coast, it can be observed that there is a change in the slope or hydraulic gradient when changing the aquifer from unconfined to confined conditions; that is, the hydraulic gradient is higher in the unconfined aquifer and lower in the confined aquifer. The porosity of the denser parts of the caliche near the surface of the land is 1% or less, in marked contrast to the rock 1.5 m or more below the surface, whose porosity is about 15%. Because of the low porosity of caliche, rainwater remains stagnant at the surface for a long period of time; this also indicates that the degree of fracture is very small, if not in some areas [39].

However, the hydraulic conductivity of the aquifer in the southern portion of this coastal zone of Progreso is 21,500 m/d, in the limestones of the Upper Miocene - Pliocene, with the presence of an unconfined aquifer, which is directly related to the effective porosity of the medium analyzed, for karstic limestones and sandy limestones (Sascab) with values between 0.20 and 0.30. Towards the north in the coastal floodable zone, the hydraulic conductivity values decrease to 1,700 m/d, this is evidence that the aquifer is confined or semi-confined. It is observed that on average 7 m^3 per day flow in each linear meter of aquifer.

In the zone where the aquifer is unconfined, the discharge is 12.96 m^3/d/m; however, towards the North-Northeast zone of the Progreso area, due to the decrease in hydraulic conductivity, there is a significant decrease in the amount of groundwater that flows towards that zone, compared to those observed in the West zone.

Casares Salazar. R., 2006 [21], presents his hydrogeological results derived from well drilling as shown Figure 2, along the coastal zone of Yucatan, from Celestún (to the west) to El Cuyo (to the east), associations can be observed between the values of the Total Horizontal Gradient and the characteristics of the rock and the aquifer.

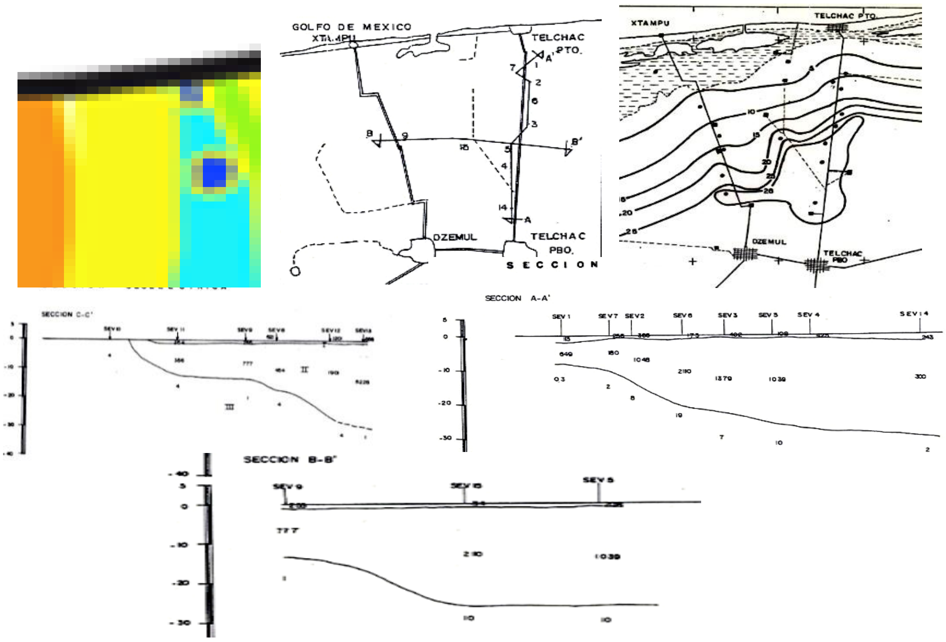
In Celestún, Dzilám de Bravo (inside the cenotes ring), and the area of San Felipe, limestone and calcarenite rocks predominate with shells of high primary and secondary permeability in the first, in Dzilám it is presented with elements of higher primary and secondary permeability, like coquinas and recrystallized limestone rocks and with fossil shells, in San Felipe a semi-impermeable caliche stratum can be observed at depth (with the presence of fossils, which gives it some secondary permeability). The superficial caliche is observed, although with the presence of fossils. All these wells evaluated are located near high gravimetric values (greater than 30 mGal/km THG).

On the other hand, in the case of Progreso, Telchac Puerto, and the Cuyo, to the east, a permeable stratum is being confined by two impermeable layers of caliche (recrystallized limestone) in the first meters of depth, followed by low permeability calcarenites, this in the three cases, and only in the case of Telchac Puerto, below them there are cavities and dissolution voids. The wells are in low gravimetric values (less than 20 mGal/km THG).

Escolero et al (2005) [33], conducted a hydrogeochemical study in the northwestern portion of the cenotes ring, by means of a census in year 2000 of 24 wells or cenotes, during the dry season, and distributed in their greatest proportion, inside the cenotes ring, complementing information on the area of Sisal, Hunucmá Kinchil and Umán. In 2002, following Hurricane Isidoro, the National Water Commission (CNA, 2002) [30] carried out a census of underground hydraulic uses in the most northwestern portion of the ring, where it reported 30 existing wells (many of them outside the cenotes ring). The lithological cuts correspond to fractured limestone with color variations between white, cream, and light brown, as well as altered limestone in its fractured crystalline and creosote or clayey variations. From the results obtained, the configuration of the SO4/Cl ratio indicates the mixture of fresh waters with a ratio corresponding to the influence of contacts and dissolution of evaporites and are located to the west and south of the study zone. Interestingly, low calcite saturation rates are located outside the inner part of the cenotes ring, this may be due to the cenotes ring that isolates the eastern portion of the study zone. The central area of the northwestern part of the state of Yucatan is defined as having a low concentration of ions in the water and is proposed as a hydraulic reserve, since in the central portion the water flows radially. This corresponds to a great thickness of water, more than 30 meters, with an important elevation of the static level. This situation could refer to the hypothesis of slow flows with high hydraulic gradients and low conductivity. This area is in low gravimetric values (less than 20 mGal/km THG).

Escolero et al (2000) [33] also highlight the fact that there is an area with raised hydraulic heads (confirming the previous data) that forms a dividing line for the groundwater with a radial type of flow. The differences in the hydraulic heads between the center of this radial pattern and Mérida and Kopomá are of the order of 23 and 25 cm, respectively, and are located between 35 and 45 km from the coast, in the town of Umán, forming a cross section between the coast and Kopomá. Thus, the contamination produced by the city of Merida does not reach this area, which is why it has been proposed as a hydraulic reserve [33]. This area is in low gravimetric values (less than 20 mGal/km THG).

The Faculty of Engineering of the Autonomous University of Yucatan (Anonymous, 1988) [32] carried out studies during November 1988, after Hurricane Gilberto, to March 1989, with the objective of determining the most suitable place to drill wells for the supply of good quality water, for use as drinking water, in the area of Telchac Pueblo, Dzemul and Telchac Puerto. It carried out a census and leveling of 47 wells and cenotes between Xtamphu and the population of Telchac Puerto and between Telchac Pueblo and Dzemul, measuring the electrical conductivity of the water as well as other hydrogeochemical data (Figure 4).



Source: Anonymous, 1988 [32].

Figure 4: Census and leveling of wells and cenotes in Dzemul, Xtamphu, Telchac Pueblo and Telchac Puerto and Location of the Geoelectric Sections (right) that offer a conceptual model of the depths to the salt interface and comparative with THG.

The presence of two layers of hard and fractured rock is evident at depths of 14 and 17 m. In the central portion, starting at 10 m depth, the exploratory drill hole crossed a sequence of three layers of hard and thin limestone, inter-layered with thin conductive layers, located at depths of 11, 13 and 15 m. In the west, hard and thin limestone (one meter thick) is interspersed between 7 and 15 m, while in the east, the resistivity curves reveal the presence of a 6 m thick conductive layer, from 7 to 13 m deep, which is associated with the stratification of total dissolved solids in water and the existence of rock with secondary porosity.

In this way, the document presents the conceptual model of the depths to the saline interface. To the south, 7.5 km away, the freshwater lens increases from almost 10 meters in Dzemul to more than 30 meters in Telchac Puerto and Sinanché (Figure 4).

To the west (Dzemul to Xtamphu), limestone saturated with brackish water can be seen almost 5 km inland from the coast, promoting a large blanch with strong crystallization of salt and mangrove with strong physiological problems in the coastal area. The wells located in this area are close to high gravimetric values (greater than 30 mGal/km THG).

While for the east (Telchac Pueblo - Telchac Puerto), the limestone with brackish water is not present near the coast, so the presence of a layer of fresh water 5 meters thick extends to the east, where mangrove forests abound with a large presence of emergence. The great thickness of fresh water in the central-eastern portion of the area (more than 30 meters) is therefore notorious, constituting a hydraulic reserve for the population of Telchac Puerto, Telchac Pueblo and Dzemul. The wells are in low gravimetric values (less than 20 mGal/km THG).

Derived from the documentary review presented, it is possible to contribute to the map of intrinsic vulnerability to groundwater contamination of the State of Yucatan, a proposal to achieve greater congruence with the regional karst characteristics, where the presence of a multi-ring type impact crater has been demonstrated., whose gravimetric values are greater than 30 mGal/km, is corroborated. The density of the rock allows us to identify the location and configuration of certain karst patterns linked to the movement and storage of water, depending on the porosity of the medium.

Final reflection

From the review of the lithological sections, the geohydrological studies, with piezometry and hydrochemistry, we can conclude the characterization of 2 main structures:

a) Sites where calcarenites and limestone rocks with shells of high primary and secondary permeability predominate, with elements of higher primary and secondary permeability, such as coquinas and limestone rocks recrystallized with shells and fossils, with semi-impermeable strata of caliche at depth but with the presence of fossils, which gives it some secondary permeability in the form of cavities and caverns. The superficial caliche is also observed, although with the presence of fossils. All these evaluated wells are located near high gravimetric values (greater than 30 mGal/km THG), and are associated with falls of the groundwater table, with elevations of the saline interface, which is why brackish water predominates in a reduced thickness, particularly in areas near the coast, through a hard and fractured limestone, interstratified with conductive layers, denoting rock with secondary porosity, with low gradients and high hydraulic conductivity (in the figure 1 of the Total Horizontal Gradient they are presented in violet, red and yellow). Some sites are associated with Celestún, Dzilám de Bravo and San Felipe, as well as the outer and inner cenotes ring (90 and 20 km).

b) Sites where permeable strata predominate and are being confined by two impermeable layers of caliche (recrystallized limestone) in the first meters of depth, followed by low permeability calcarenites. In some cases, cavities and dissolution voids can be found below them. The wells are located in low gravimetric values (less than 20 mGal/km THG) and have been associated with elevations of the water table, and large thicknesses of fresh water, maintaining the saline interface at depth. They are also hard and fractured limestones with large gradients and low hydraulic conductivity (in the figure of the Total Horizontal Gradient they are presented in green, light blue and dark blue). Some associated sites are Progreso, Cuyo, and the proposed hydraulic reserves for Celestún, and the western zone of Hunucmá and Umán, and the center of Telchac Puerto - Telchac Pueblo.

Therefore, the presented review showed that the structure of the calcareous rock is related to the movement and storage of water. Then, it is highly recommendable to use a map of Bouguer Anomalies and match them with the geohydrological characteristics of karst aquifer as an input for the elaboration of the map of intrinsic vulnerability to the contamination in any given karstic aquifer to give precise results on groundwater movement for a sustainable management (Figure 5).

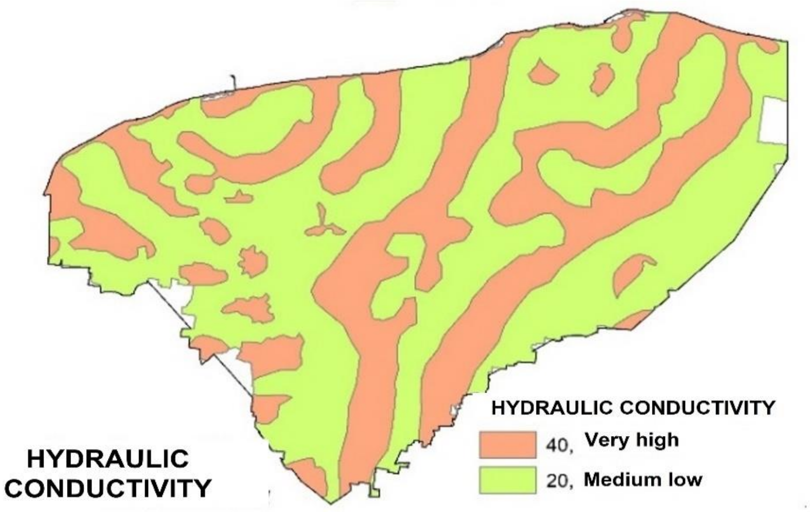


Figure 5: Variations in the values of gravimetry and representation of hydraulic conductivity related to THG and the porosity of the medium.

Hence, the results produced by the different methods used for the state of Yucatán in recent years are not homogeneous, there is great variability as shown in Table 3.

Table 3: The percentages of the surfaces defined by a specific vulnerability class for all the reviewed methods are presented.

Method	**Vulnerability % State surface**						**Author**
	Extreme high	**Very high**	**High**	**Moderate**	**Low**	**Very low**	
DRASTIC	40		60				Rosela (2004)
DRASTIC	5	33.8	61	0.2			Rosela (2014
DRASTL	0.31		18	42.51	37.95	1.23	Albornoz (2015)
DSTI	48.54		35.98	15.48			Guijón (2007)
DRASTIC	19	20	21	20	20		Arcega (2018)
EPIK							Bolio (2011)
EPIK		21	2	77			Moreno (2018)
PI			58	42			Moreno (2018)
COP		12	55	32	1		Moreno (2018)
PaPRIKa		23	76	1			Moreno (2018)
IVAKY	19	19	33	17	4	8	Aguilar (2016)
Total	**131.85**	**128.8**	**419.98**	**227.19**	**62.95**	**9.23**	
Frequency	**6**	**6**	**10**	**9**	**4**	**2**	
Average	**21.97**	**21.46**	**41.99**	**27.46**	**15.73**	**4.16**	
Max/Min	**48.54/0.31**	**33.8/12**	**76/2**	**77/0.2**	**42.95/1**	**8/1.23**	
Bouguer anomalies	6	24	28	28	14		Batllori (2022) [18]

The presence or use of 6 vulnerability classes is observed: extreme high, very high, high, moderate, low and very low. It is observed that the high Vulnerability class occurs in 10 of the 11 reviewed methods, it has an average of 41.99 % of the state surface. It is followed in importance by the class of Moderate Vulnerability in 9 of the 11 methods with an average state area of 27.46 %. In both cases, the discrepancies between methods are very important, associated with areas of very high kastification. Another characteristic is the bias towards the very high and extreme high Vulnerability classes, observed in 6 of the 11 study cases, with a spatial occupation of approximately 21.5 % each, derived from the karstic relief and the presence of sinkholes. Finally, the low and very low Vulnerability classes are scarce among the cases studied, the discrepancies between methods are very low, however, their greatest presence is in the south of the state, with surfaces of 15% and 4% respectively.

According to Batllori E, and Canto S, (2022) [18], the inclusion of the Bouguer gravimetric anomaly map, as a factor of hydraulic conductivity and differences in density of the rock through which water transits underground, as well as the type of climate that characterizes the humidity and temperature regime, the thickness of the soil and of course the presence of faults, fractures and sinkholes, promotes the very high and extreme vulnerability class in the territory to develop in the state of Yucatán coming from the southeast and going northwest, and this is consistent with the DRASTIC method applied by Arcega, 2018 [40]. Similarly, the reflection of the karstic characterization linked to areas of high hydraulic flow through preferential channels described in the IVAKY method (Aguilar et al 2016) [13] as grouped sinkholes, referring to the Anillo de Cenotes, is related to the gravimetric method to define and detail this context. Due to the multi-ring system of the Chicxulub Crater and other karstic processes, they appear as concentric waves of very high and extreme vulnerability in the southeast-northwest direction, aligned with differential rock densities and preferential flows. These concentric waves of very high and extreme vulnerability extend over a gradient that goes from extreme vulnerability in the southeast of the state to very high, high, and medium vulnerability in the northwest, covering very well the edaphic, soil moisture, and climatic factors, mainly described in the IVAKY method.

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The role played by each co-author to be declared
Author: Description and analysis of all information.
Co-author: Elaboration of cartography

Source of funding and payment of staff to be included
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