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Identification of Karst Forms Using LiDAR Technology: Cozumel Island, Mexico

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Additional information is available at the end of the chapter

Abstract

Morphological relief analysis allows the identification of geomorphological forms and cartographic-environmental studies make extensive use of the medium (1:50,000) and large scale (1:250,000), where the topographical contrast is evident. However, at a detailed scale (<1:20,000) and for territories where the contrast of relief does not exceed 10 m in height, the morphological analyses must be adapted accordingly, because they contribute information to altimetry studies and to the topographic configuration of units. Thus, through visual interpretation and manipulation of high-resolution topographical LiDAR data from Cozumel Island, a relief analysis is presented at a detailed scale for the purpose of recognizing the geomorphological units of karst origin, using altimetry and slope cartography, digital models of elevation, and shading that permits the identification of 109 new exokarstic doline and uvala formations.

Keywords: GIS, karst, relief, island, Caribbean

1. Introduction

Geologically, the Island of Cozumel's basement is calcareous from the upper Tertiary period and reef from the Holocene period, which, accompanied by tropical climatic elements, give rise to dissolution karst formations. The study uses records of uvalas and cenotes in the area of study, which were obtained through a record from touristic service providers and from the community, as well as from scientific articles [1, 2]; however, there is no updated and complete database. For the purpose of contributing to the identification of karst forms (dolines,

uvalas, and poljes-locally called "cenotes" and "rejolladas"), altitude mapping and digital models of elevation, shading, and slope generated with LiDAR (light detection and ranging) data were used for identification and cartography.

The word LiDAR is an acronym for the term *LIght Detection And Ranging*, that is to say, detection and measurement of light. This technique is currently becoming a basic tool in studies based on topographical analysis and precision of the information base [3–5]. The use of LiDAR products has greatly improved and has a significant influence in the earth science disciplines [6, 7]. Its usefulness is emergent in shallow reliefs and those with little altitudinal difference.
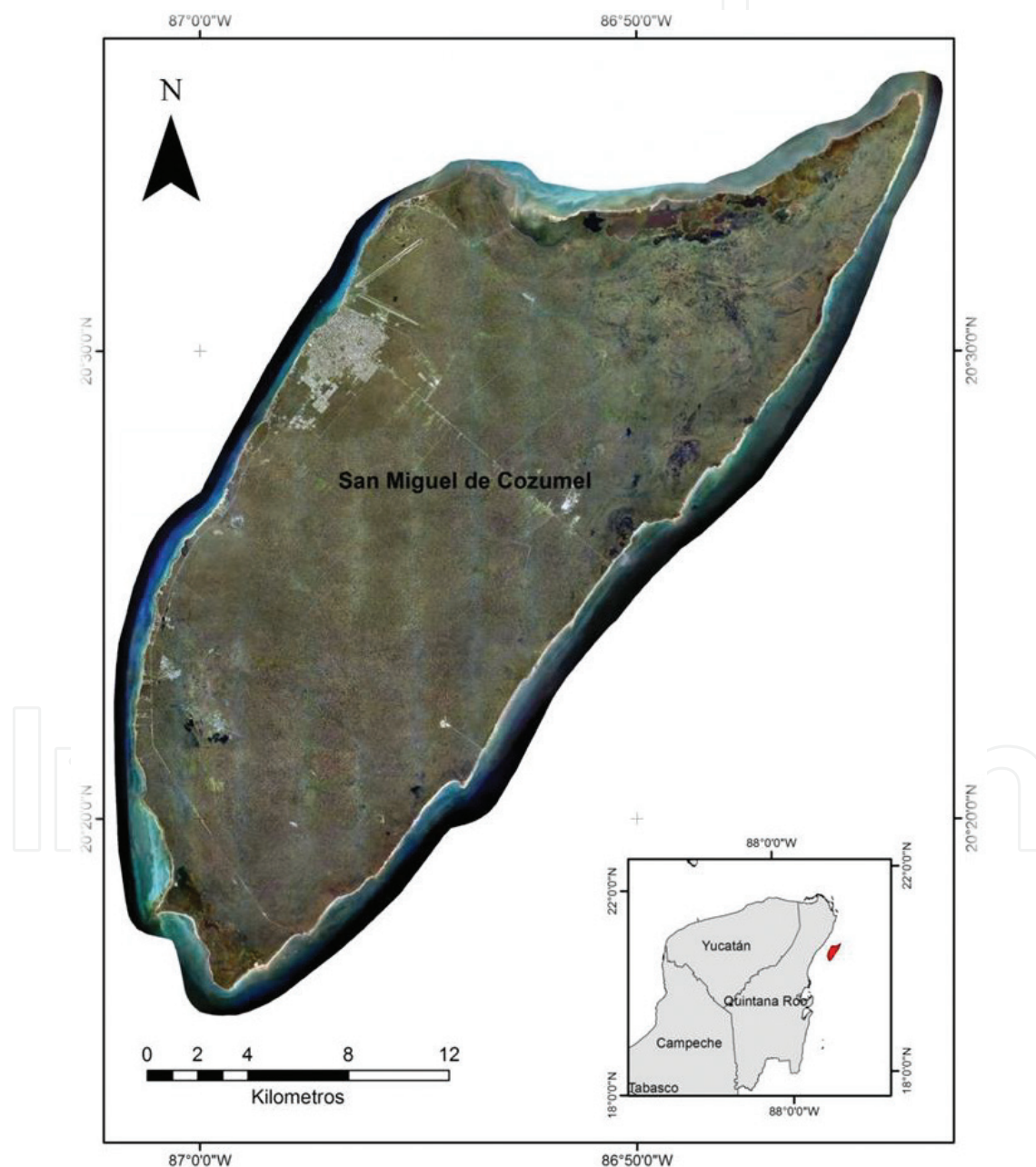
Figure 1. Location of Cozumel Island in Mexico.

The Yucatan Peninsula has an area of 39,340 km^2 and is located in southeast Mexico's. The most outstanding structural features of Yucatán are the sinkhole region and the aligned islands of Cozumel and Mujeres. The altitude of Yucatán not exceeding 300 m elevation dominates. Previous studies have recognized that different types of karstic depressions abound in the vast plateaus of the northern and eastern Yucatan Peninsula, and there are also extensive systems of caves and caverns in the entire landscape [8]. Climatic subtypes are warm and humid with summer rains and warm and humid with summer and winter rains [9]. Cozumel is part of the Yucatan peninsula with sedimentary rocks formed on a wide platform. The core drillings indicate that the island is formed from reef sediment with a thickness of 100 m or more, which dates from the Oligocene and Quaternary Epochs [10].

Cozumel Island pertains to the state of Quintana Roo, located at 20° 28′ N, 86° 55′ W (**Figure 1**). Cozumel Island faces the coast of the Yucatan Peninsula in the Caribbean Sea, approximately 16.5 km to the east of the Yucatan Peninsula, in the zone of the Northwest Caribbean [11]. The climate is hot and humid with abundant rainfall in the summer. The average annual temperature is 25.5°C and precipitation reaches 1504 mm per year. Cyclones have an important effect, increasing the amount of rainfall in the summer [12].

The relief of the island does not exceed 15 m of altitude above the sea level and the cartographic representations have been developed with data at 1:75,000 and 1:50,000 scale [1, 13]. The presence of dolines and uvalas with exokarstic forms has been reported, but the majority have been characterized over time, due to the fact that they do not exceed 50 m in diameter [14–16], which makes it necessary to recognize other techniques that aid the identification of exokarstic forms. For that reason, this study employs LiDAR modeling for the purpose of recognizing doline and uvala forms, enriching the list of these relief forms, and indicating the areas with higher density of exokarstic forms.

2. Methodology

To achieve the objectives, the following were necessary (**Figure 2**):

Phase 1. Revision of the inventory of exokarstic forms (caverns, dolines, uvalas, and poljes – "cenotes" and "rejolladas") reported in Cozumel Island [1, 2, 13–17], as well as the reports from the association of speleologists MAYAB AC [18] were consulted, 37 of the reported karst units were recognized in these studies, and a georeferenced database was also generated for the purpose of making the information available for reference.

Phase 2. Construction of a unified LiDAR mosaic of the terrain of Cozumel Island. To do so, the data from point clouds in 32 TIFF information files generated by the ALS 40 system and an information area of 62,556.27 km^2 [19] were revised and corrected; the data resolution is 5 m for the X and Y axes and 15–20 cm for the Z axis. The resolution scale is 1:10,000 for each cartographic model.

Phase 3. The application of filters for the elaboration of morphometric digital models of elevation, slope, and shadows. The digital model of elevation was derived from the simple method
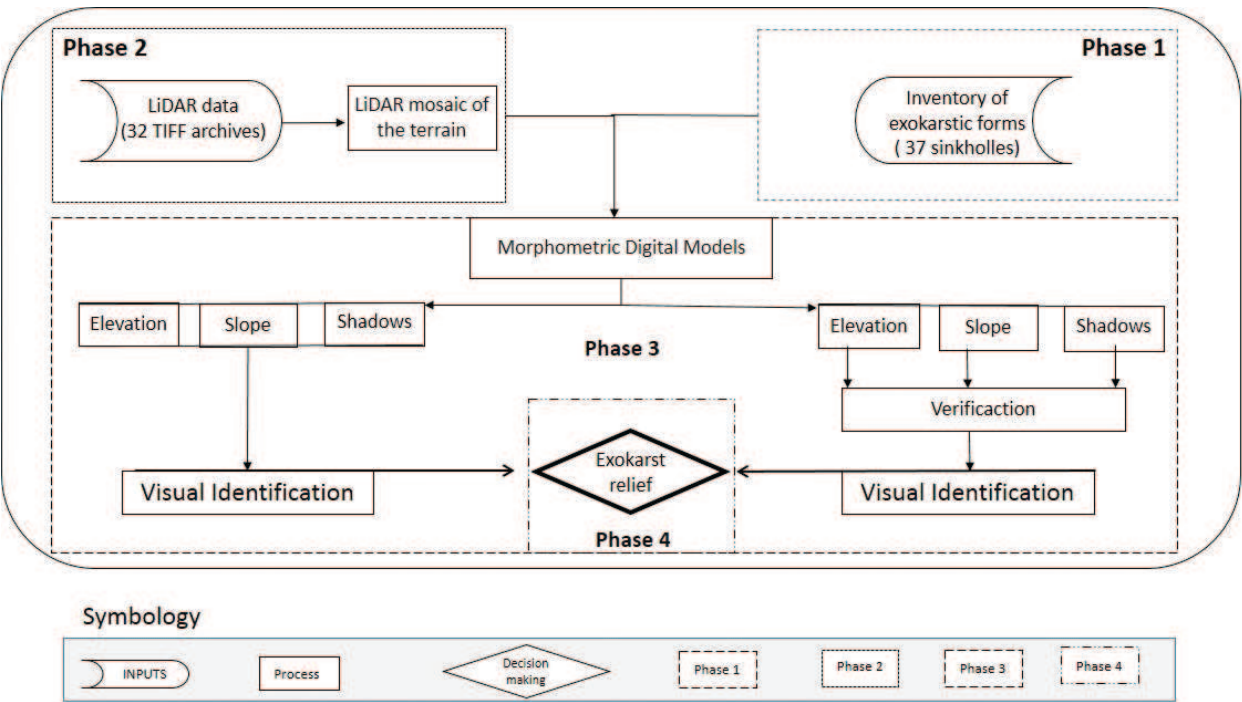
Figure 2. Flow diagram of the methodology.

of nearest neighbor interpolation, rated at 0.05 cm elevation, recognizing up to 16 m of altitude in the area of study [20]. For the terrain shading method, an azimuth of 272° and an elevation of 30° was used, and for the slope map, eight categories of classification were set manually, where the highest category is >40° [21].

Phase 4. Analysis of the distribution of units in the inventory and their contrast with the new models of identified forms. In each one of the models, 109 dolines and uvalas were visually identified, using the high resolution models and the contrast of the altimetric data, slope, and shading. Likewise, the information was contrasted with the 37 units reported in the previous studies. Furthermore, field trips were carried out during the months of June and July 2014 to confirm the occurrence of the dolines and uvalas, where the cartographic prospection at 1:10,000 scale was verified.

3. Results and discussions

In the identification of the exokarstic forms, the primary input used was a mosaic of LiDAR images of terrain with a resolution of 5 horizontal m and 0.50 vertical cm, to which later a shade filter with azimuth 272° and height 30° is added (**Figure 3**). Here, dolines and uvalas with diameters between 20 and 125 m and up to 9 m of depth can be identified, as well as basic linear details of the relief. In the mosaic, one can see the geological structure of the quaternary period (old coastal mountain ranges, dunes, and marine terraces).

By applying an altimetric filter with a vertical difference of 0.50 cm, karstic formations are distinguishable. For said identification, the distribution of pixels based on their altitude values
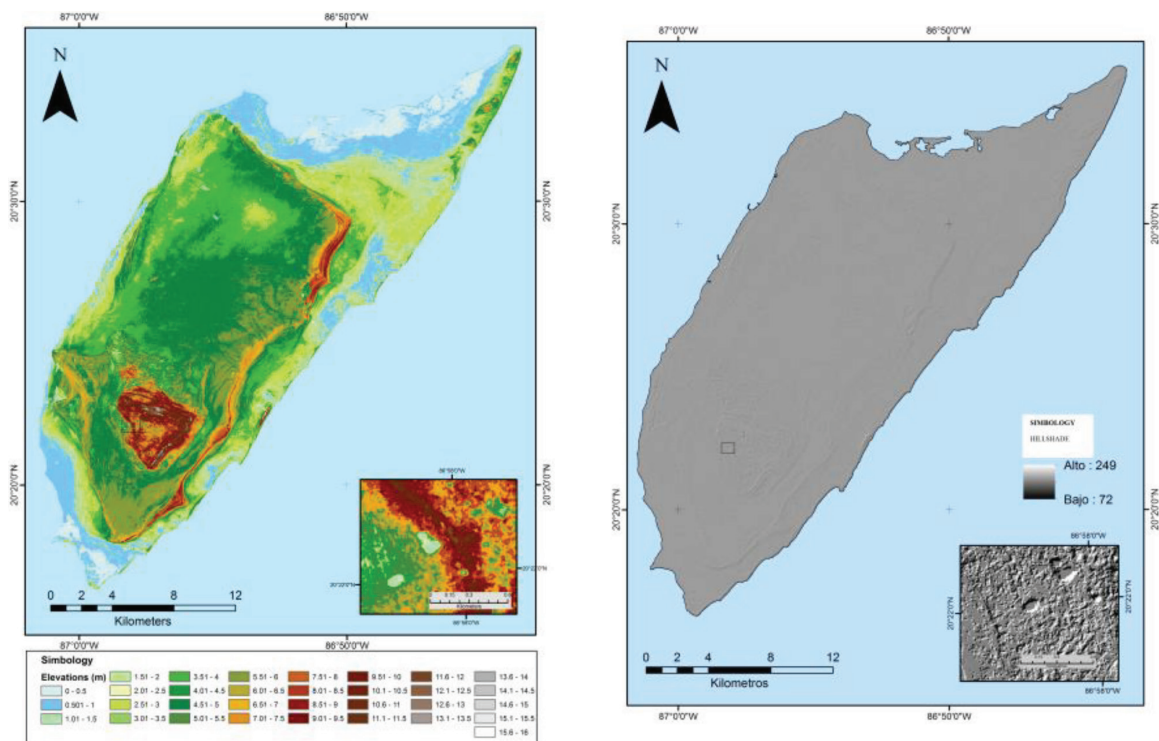
Figure 3. Elevation map with a vertical difference of 0.50 cm and terrain shading model (azimuth 227° and elevation 30°) with details about the known karst formations. Prepared by author based on LiDAR data [8].

was taken into account; groups that presented values in ascending order from the center to the shores were sought out, since this characteristic indicates that there are depressions. Furthermore, a visual interpretation was done in which the identification criteria was the geometric form of said groups. In this case, the semicircular form is associated with the dolines and the irregular forms with processes of the formation of uvalas. The dimensions are congruent with that which was identified in the shading model.

Finally, with the contrast of the slope (see **Figure 4**), where the association of the semicircular forms and forms with a gradient greater than 25° – corresponding, in the majority of cases, to the borders of the uvalas or collapse cenotes – the altimetric difference was up to 8 m of depth. The units with lower gradients (<25°) and altitude contrast (up to 1 m in height) are related to dissolution dolines.

In the records of dolines and uvalas in the region of study, the existence of 37 karstic forms are reported, all of which have been reported as points (with latitude and longitude coordinates), the majority of which measure less than 10 m in diameter [1, 17]; with the interpretation of the models derived from the LiDAR data, 109 forms were able to be identified, with their diameter and depth. The cartography of all of the sites is shown in **Figure 5**.

Furthermore, the density of dolines and uvalas in square kilometers is shown in **Figure 6**. The concentration can be explained by the fact that the area of the highest relief (>10 masl), which corresponds to a marine terrace in which the karstification processes are more evident than in the periphery as well as other morphological genesis (dunes, coastal mountain ranges, lagoons, and shoals), located along the coast and the north of the island, and whose formations can be buried or subterranean (such as caverns and grottoes).
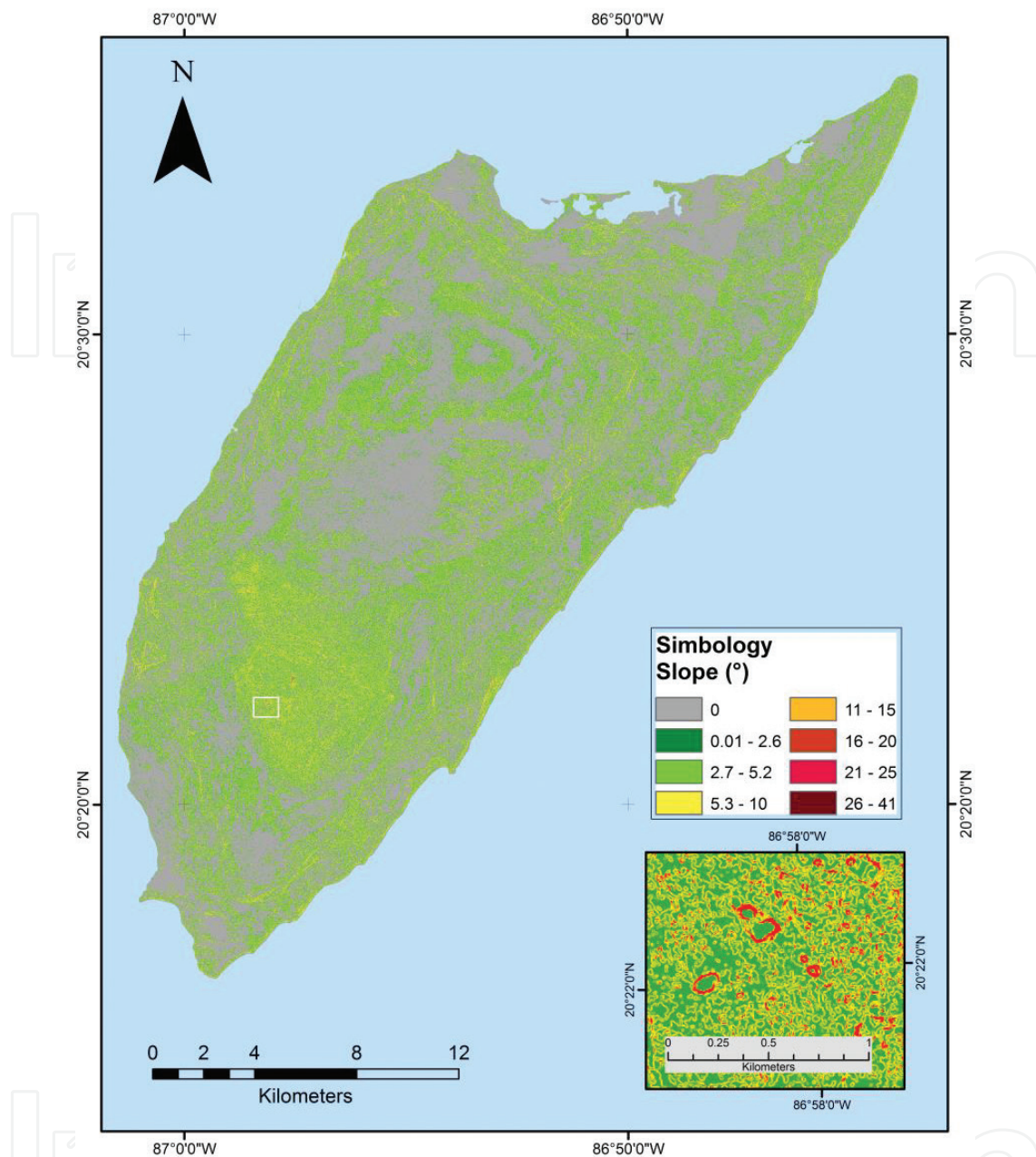
Figure 4. Slope map with six gradient categories. Prepared by author based on LiDAR data [8].

Although there is a new distribution model of dolines and uvalas, as well a proposal for density of karstic forms, it must be considered that in this study, the interpretation and identification of exokarstic forms follows a traditional process of relief form analysis [3, 5], based on the visual morphological differences (crests, slopes, surface, and background), known for their morphometric elements (height, slope, and depth).

The advantage of using LiDAR models, which are free for the public to access through the National Institute of Statistics, Geography and Informatics of Mexico, allows the processing of detailed data at a detailed horizontal scale (5 × 5 m) and at 0.05 cm of vertical height. The aforementioned was not possible until the year 2010, when LiDAR flights were carried out in
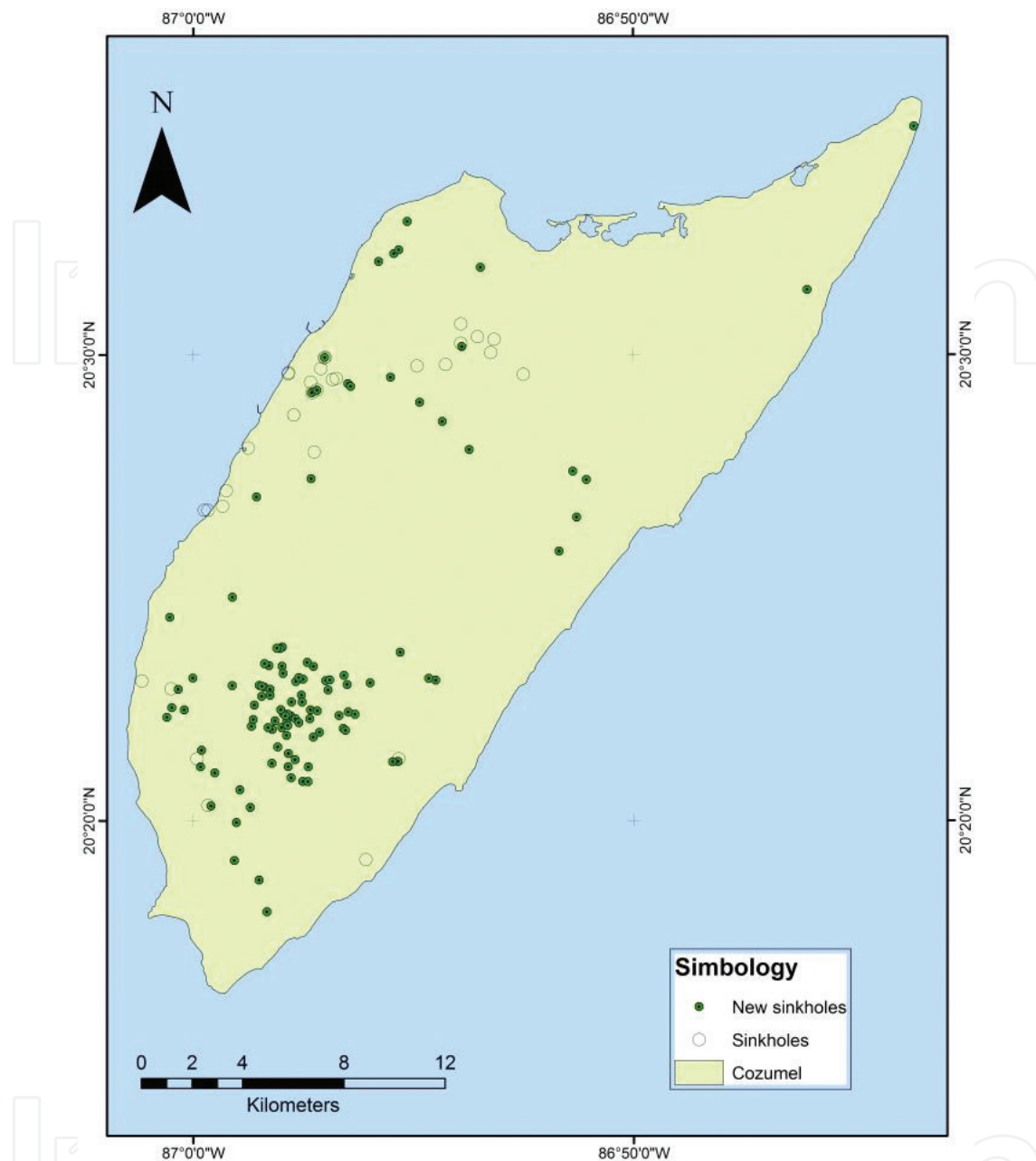
Figure 5. Map of point distribution of the karst forms in Cozumel Island. Prepared by author based on data reported [12–19] and this study.

this area of study, characterized by low altimetric contrast (<10 m) and by a base cartography at 1:50,000 scale. For this reason, it is not possible to identify karstic forms with dimensions less than 50 m, where the cost would be excessive, as pointed out by others authors [10, 14, 19].

New dolines and cenotes have been identified, along with the areas of greater density. However, an accurate characterization of each identified unit is needed to increase the understanding of the types of dolines (dissolution, collapse, and suffusion) and uvalas (first, second or third generation), their relation with the creation (structural or climatic) and with the type and intensity of the process of karstification.
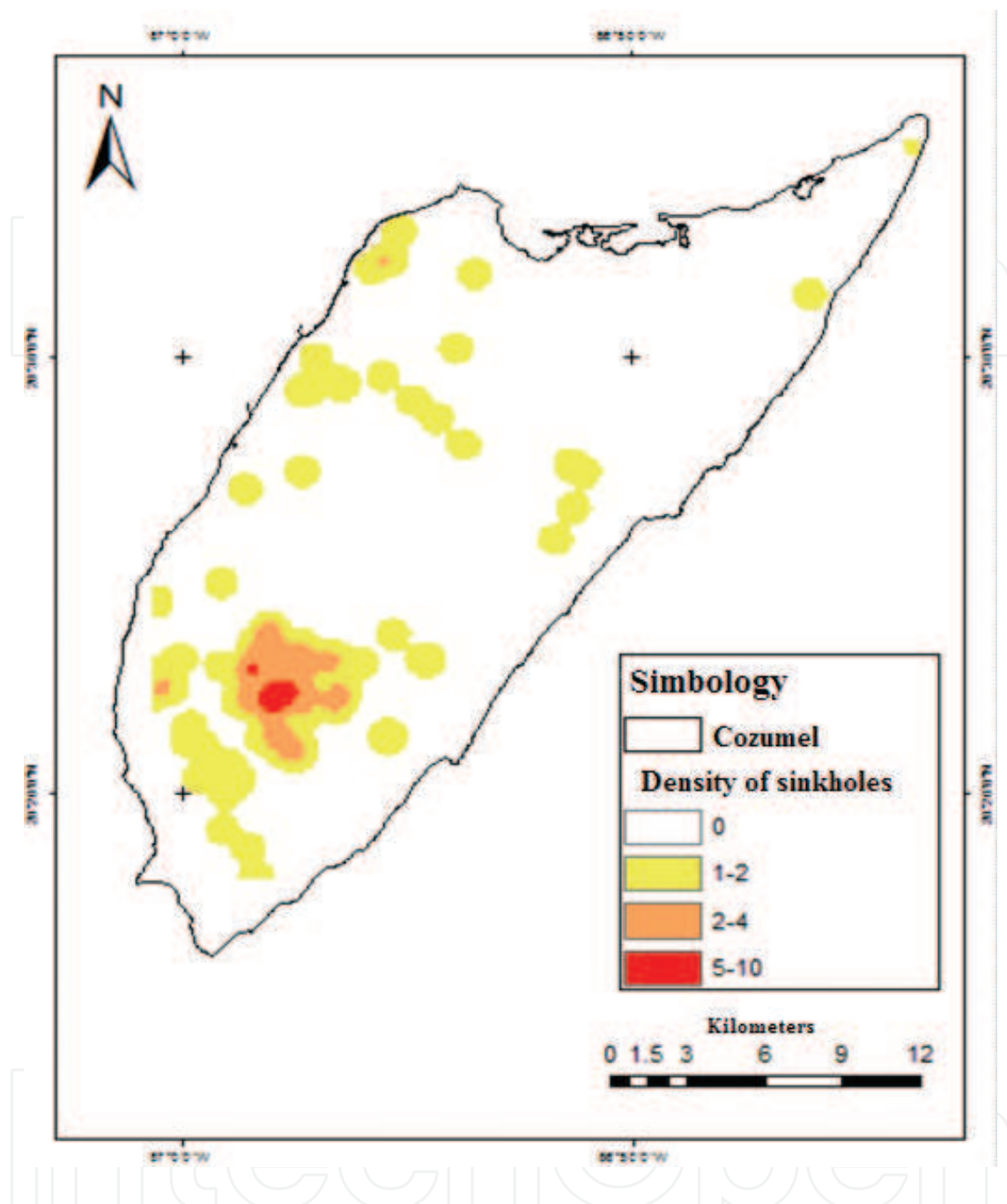
Figure 6. Density model of karstic forms by km² in Cozumel. Prepared by author based on the identification of dolines and uvalas using the LiDAR model [8].

4. Conclusions

The use of LiDAR data is not new to the study of karstic reliefs in tropical areas, where data has been manipulated by filters to highlight forms in the relief; among the most common are the hypsometric models, field studies, and slope.

In the area of study, there are no reports about the use of LiDAR technology for the recognition of dolines and uvalas, and consequently the use of LiDAR data is a proposal to identify and

enrich the doline and uvala inventories in karst areas with little altimetry contrast. Even though in this study, new dolines and uvalas are reported, it lacks the complete verification and error estimation in the data interpretation and its concurrence with the reports in the literature.

The density map of dolines and uvalas have a resolution of 5 × 5 m, being a detailed-scale map which serves to orientate new searches for the calibration of LiDAR data and to be able to orientate its use in the entirety of the northeastern zone of the Yucatan Peninsula, where LiDAR data are open and free to access for scientific and academic study, with the potential for application to and studies about quaternary geology, the evolution of the landscape, the evidence of the coastal dynamic, and the transformation of the landscape in the area inhabited by the Maya of the Yucatan.

Acknowledgements

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