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Chapter

Subterranean waters in Riviera Maya of the Yucatan Peninsula: Vulnerability and the Importance of Monitoring

Luis M. Mejía-Ortíz, Alejandro L. Collantes-Chávez-Costa, Cruz López-Contreras and Oscar Frausto-Martínez

Abstract

The Mexican Caribbean coast has great scenic beauty both on the surface and underwater, which is why it has been a developing area for tourism since the 1970s, establishing sites such as Cancun and Playa del Carmen and empowering others such as Cozumel and Tulum. Their biological richness is enormous, especially in the Mesoamerican Reef of which they are a part. However, this richness and scenic beauty are not possible without the ecological assemblages that exist within these regions' adjacent ecosystems, mainly the surrounding seasonally dry tropical forest and the coastal wetlands that, together with the oceanographic characteristics of the Caribbean Sea, potentiate it, turning the region into the most visited in Latin America. To this end, groundwater plays a very important role in the assemblages of biotic and abiotic elements that are shared with the Caribbean Sea; thus, its constant monitoring allows us to identify how the changes that occur in the tropical forest are producing various changes in the composition and abundance of coastal reef elements. Here, we present results of our study of groundwater conditions (temp, pH, oxygen dissolved, and salinity) in nineteen cenotes and underground rivers of the Riviera Maya and six cenotes of Cozumel. We also profiled the predominant vegetation on the surface of this region, which is a seasonally dry tropical forest, to understand the components and functioning of these subterranean ecosystems to assess their vulnerability and identify their threats from human development (population growth, tourism development, mobility capacity). These threats not only affect the cave and coastal organisms but also the tropical karstic landscapes that are characteristic of these systems.

Keywords: underground, aquatic monitoring, ecological links, vulnerability

1. Introduction

The groundwaters in many places around the world are sources of freshwater for human use [1]. In Mexico, the Yucatan Peninsula is the largest freshwater source in the

region. Its soil is mainly karstic, allowing a high porosity and filtration of rainwater to the underground [2, 3]. Due to this reservoir, the tropical forest is tall and exuberant because the soil layer is thin enough to allow tree roots to reach the aquifer. The extreme hot conditions cause the forest to be dry or semi-dry [4, 5]. Over many years, these conditions have produced thousands of conduits and entrances [6, 7] that reach to coastal areas as subterranean rivers. The richness of the Caribbean Sea establishes important conditions for the proliferation of coral reefs [8]. The terrestrial ecosystems (tropical forest, mangrove, and dune) are connected by underground waters that establish links among the adjacent terrestrial and marine ecosystems (coastal lagoons, sea grass, and coral reefs). However, this role that is important, has been poorly valuation, and the groundwaters has a unique characteristics that produce a special ecosystems [9]. The state of Quintana Roo and its coast have natural attractions with unique scenic beauty, such as Caribbean beaches, reefs, lagoons, and archeological sites, among others. Tourism is based on sun and sand, but there are other tourist attractions that are highly visited, such as nature reserves and cultural areas [10]. This set of attractions motivated the creation of Cancún in 1970, which became the largest and most important tourist destination in Mexico and the Caribbean [11]. Natural attractions also led to the development of the Riviera Maya in the 1990s, which is equally as recognized as Cancun [12]. Together, these locations receive around 12 million visitors per year [13]. Initially, tourists visited for the coastal and marine landscape, but in recent years visitors have become more interested in the cenotes and underground activities. All these, therefore that another human activity such as mobility, pork farms, soil extractions and growing of the cities are the development project that in the next years will produce environmental impacts in special to water [14]. For these reasons, it is important to monitor the water to understand how the ecosystems work.

2. Material and methods

From 2016 to 2020, we profiled 19 cenotes in Riviera Maya and six in Cozumel (**Figure 1**) using the Hydrolab Data Sonde 5 (Hydrolab DS5) to identify the different layers and variations. We recorded dissolved oxygen (± 0.01 mg/l), pH (± 0.01 pH), salinity ($\pm 0.01\%$), and water temperature ($\pm 0.01^\circ\text{C}$). The Hydrolab DS5 was programed to record every 30 seconds and the divers introduce in the cave during one and half hours. At the same time, recording of faunal composition was conducted to identify crustaceans such as isopods, different species of shrimp, amphipods, and remipedes [15, 16, 17]. Divers also recorded tree roots into the aquifer using taxonomic guides [18, 19] and identified the systems with clear water discharges to the Caribbean Sea. We also examined tourism and tourist activities in the Riviera Maya and Cozumel and corroborated this data with vegetation and soil use in the surrounding the cenotes as well as with data reported in the literature.

3. Results

3.1 Environmental conditions

After checking the profiles of twenty-four underground systems, it was possible to recognize three main ecosystems. The first is a freshwater ecosystem that is not stratified and that has similar conditions of oxygen, temperature, and pH in superficial

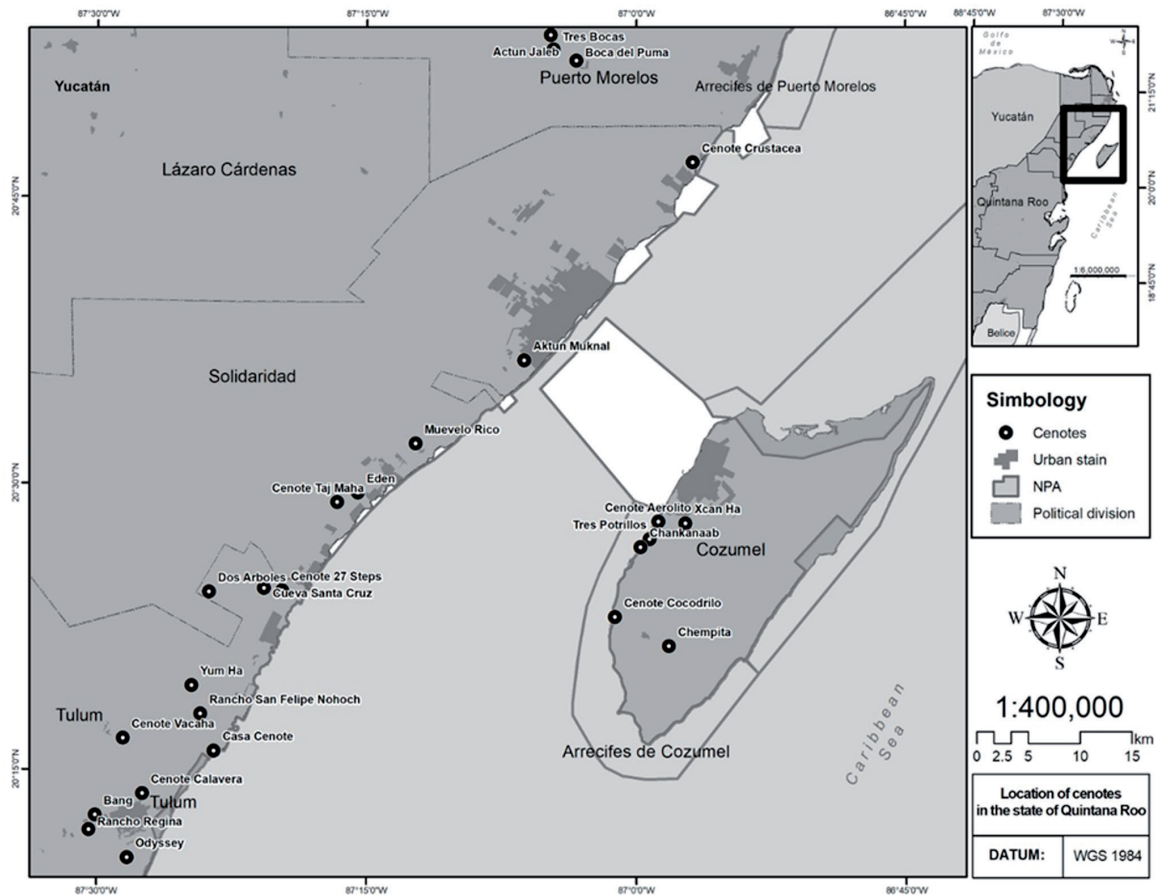


Figure 1.
 Location of the different cenotes in the Riviera Maya and Cozumel.

and bottom areas. We recorded 10 sites in freshwater ecosystems (**Table 1**), some of which are shallow ponds and some of which are 15 meters deep.

In these profiles, the water column is not stratified accordingly with the salinity content. The temperature and oxygen dissolved have a negative relationship with the depth because both variables decrease as depth increases. However, pH values are more independent and showed variations, possibly due to the biochemical karst process, as has been reported for other systems [20] (**Figure 2**).

The second type of ecosystem is a brackish/marine water ecosystem. In these ecosystems the marine entrance has a direct connection with the sea. As such, some marine animals such as echinoderms and some species of fish live in caves. In these systems the mixing zone between freshwater and marine water is all time and only in some season is possible identify stratification in the water column. We recorded two systems in this study (**Figure 3** and **Table 2**).

The third type of ecosystem is an anchialine pool, which is a subterranean estuary containing freshwater and marine water separated by a mixing zone called the halocline. Anchialine pools can be found at different depths according to their distance from the sea. In this study, we recorded thirteen of these systems in the Riviera Maya and Cozumel. In these ecosystems, the stratified water column is due to the salinity changes that produce similar conditions of temperature, pH, and oxygen dissolved. It is interesting that in these environments the most rich species were found just past the halocline in the marine layer.

In anchialine ecosystems the temperature and oxygen dissolved decrease as depth increases, and both have a direct relationship with the halocline at different depths.

Systems	Salinity	Environmental conditions	Organisms recorded
Boca del Puma	Freshwater	The water profile is not stratified with similar values of temperature and pH; decreasing a little for oxygen dissolved	<i>Typhlatya mitchelli</i> ; <i>Creaseriella anops</i> ; <i>Creaseria morleyi</i> <i>Antromysis cenotensis</i>
Tres Bocas	Freshwater		<i>Typhlatya mitchelli</i> ; <i>C. anops</i> ; <i>Creaseria morleyi</i> <i>A. cenotensis</i>
Actun Jaleb	Freshwater		<i>Typhlatya mitchelli</i> ; <i>C. anops</i> ; <i>Creaseria morleyi</i> <i>A. cenotensis</i>
Muevelo Rico	Freshwater		<i>Typhlatya mitchelli</i> ; <i>C. anops</i> ; <i>Creaseria morleyi</i> <i>A. cenotensis</i>
Aktun Muknal	Freshwater		<i>Typhlatya mitchelli</i> ; <i>C. anops</i> ; <i>Creaseria morleyi</i> <i>A. cenotensis</i>
Vacaha	Freshwater		<i>Typhlatya mitchelli</i> ; <i>C. anops</i> ; <i>Creaseria morleyi</i> <i>A. cenotensis</i> <i>Stygomysis holthuisi</i>
Cueva Santa Cruz	Freshwater		<i>Typhlatya mitchelli</i> ; <i>C. anops</i> ; <i>Creaseria morleyi</i> <i>A. cenotensis</i>
Dos Arboles	Freshwater		<i>Typhlatya mitchelli</i> ; <i>C. anops</i> ; <i>Creaseria morleyi</i> <i>A. cenotensis</i>
San Felipe Nohoch	Freshwater		<i>Typhlatya mitchelli</i> ; <i>C. anops</i> ; <i>Creaseria morleyi</i>
Yum Ha	Freshwater	<i>Typhlatya mitchelli</i> ; <i>C. anops</i> ; <i>Creaseria morleyi</i> <i>A. cenotensis</i>	

Table 1.

Record of freshwater subterranean ecosystems with environmental conditions and fauna registered.

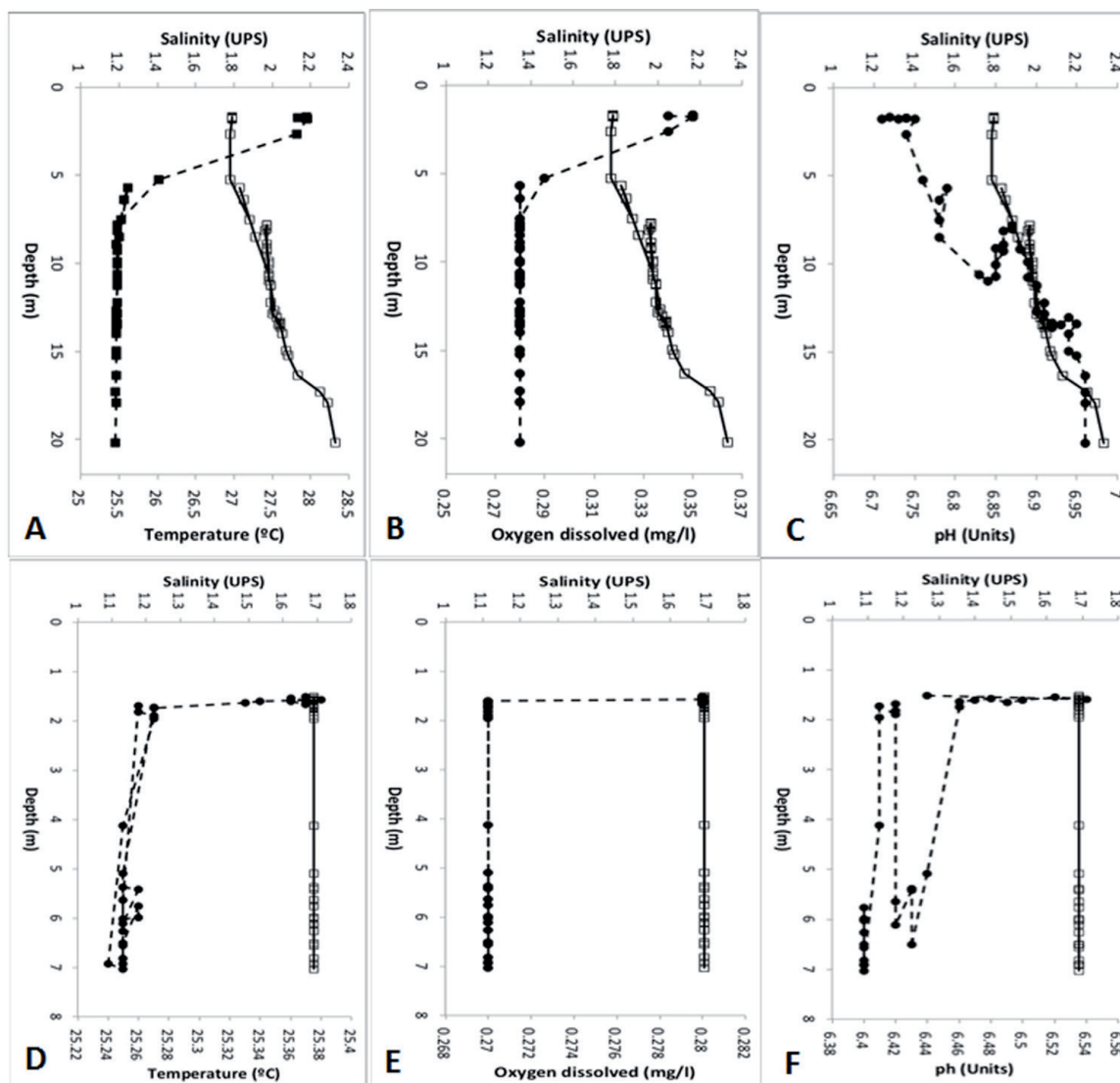


Figure 2. Examples of profiles according to the depth of freshwater ecosystems. A, B, and C graphs are for the Santa Cruz system, and D, E, and F graphs are for the Vaca ha system. Salinity is represented by continuum lines with \square , and temperature, oxygen dissolved, and pH are represented by dashed lines with \bullet .

However, in the case of Cenote Calavera, the temperature increases at same time that the marine layer is present. In contrast, the pH values in all cenotes are higher in comparison with the superficial layer due to the alkalinity value of the marine layer (Figure 4).

These three main ecosystems exist in different places according with several factors such as surrounding vegetation but mainly with the depth when the subterranean branch cave reaches, but also is relationship with the distance from the coast that the cenote (entrance) is located because the incorporation of the marine layer is most important in the those systems close to the coastal area but far away to the coastal line the freshwater lenses is more wider whilst that the marine layer is found to deeper area (Figure 5).

3.2 Surrounding vegetation to the aquifer

The semi-evergreen seasonal forest is the dominant tropical forest in the study area, and in the state of Quintana Roo [21, 22]. In Mexico, this kind of seasonal

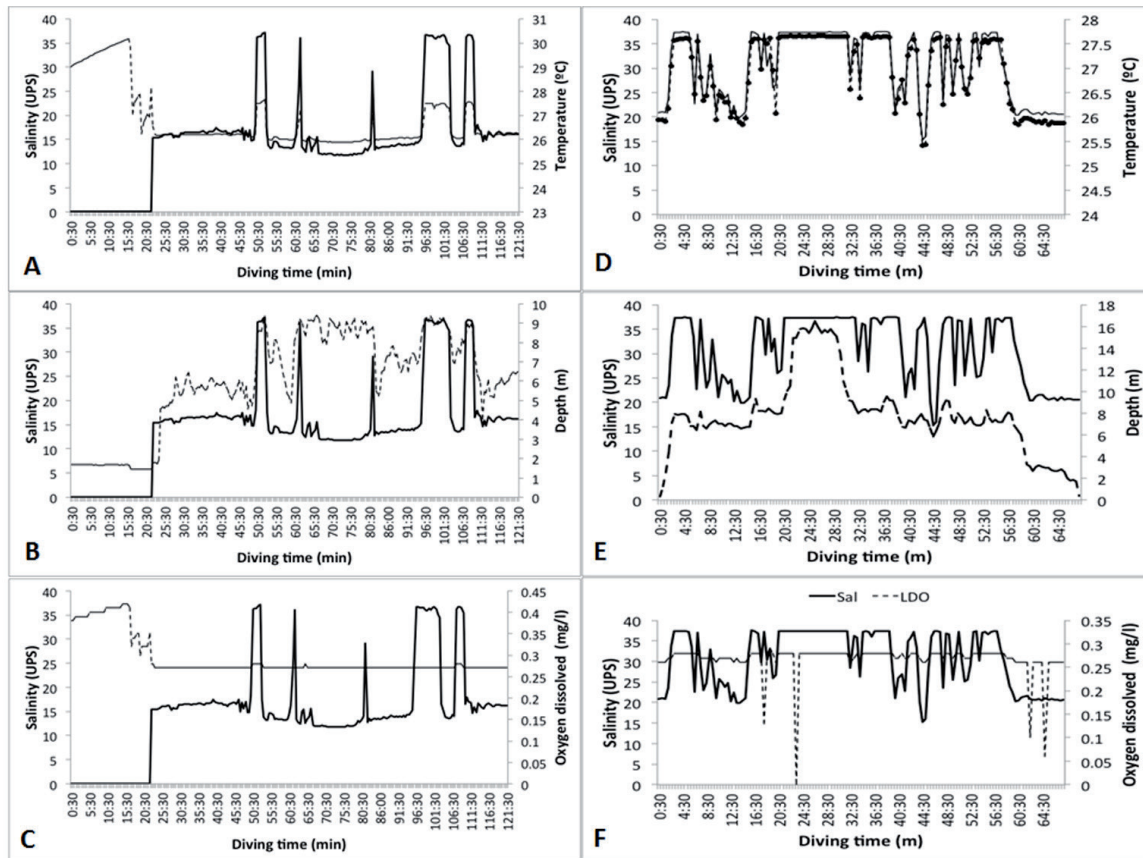


Figure 3. Examples of profiles of brackish/marine ecosystems according to diving time. A, B, and C graphs are for casa cenote from the Actun ha system, and D, E, and F graphs are for cenote Aerolito in Cozumel. Salinity is represented by continuum lines, and temperature, oxygen dissolved, and pH are represented by dashed lines with •.

Systems	Salinity	Environmental conditions	Organisms recorded
Casa Cenote	Brackish/Marine water	The water profile is not stratified; just the mixing zone; and the temperature, oxygen dissolved, and pH showed values similar in the superficial and deeper layers	<i>Typhlatya pearsei</i> ; <i>Metacrirolana mayana</i>
Aerolito	Brackish/Marine water		<i>Procaris mexicana</i> ; <i>Metacrirolana mayana</i> ; <i>Xibalbanus cozumelensis</i> ; <i>Copidaster cavernicola</i> ; <i>Ophionereis conmutabilis</i>

Table 2. Record of brackish/marine water subterranean ecosystems with environmental conditions and fauna registered.

tropical forest is known as a tropical evergreen forest [23] or medium semi-evergreen forest [24]. This vegetation develops in the Aw climate [25], characterized by a short but well-marked dry season, which in the area extends from November to May, during which short, sporadic, and infrequent rains may occur (191 mm in average), in addition to a rainy season the rest of the year, with rainfall around 1000 mm and an average annual temperature between 20 and 25°C. A semi-evergreen seasonal tropical forest grows on mainly flat terrain with shallow soils (20 or 35 cm deep), generally of the Rendzina type, and with outcrops of limestone [4].

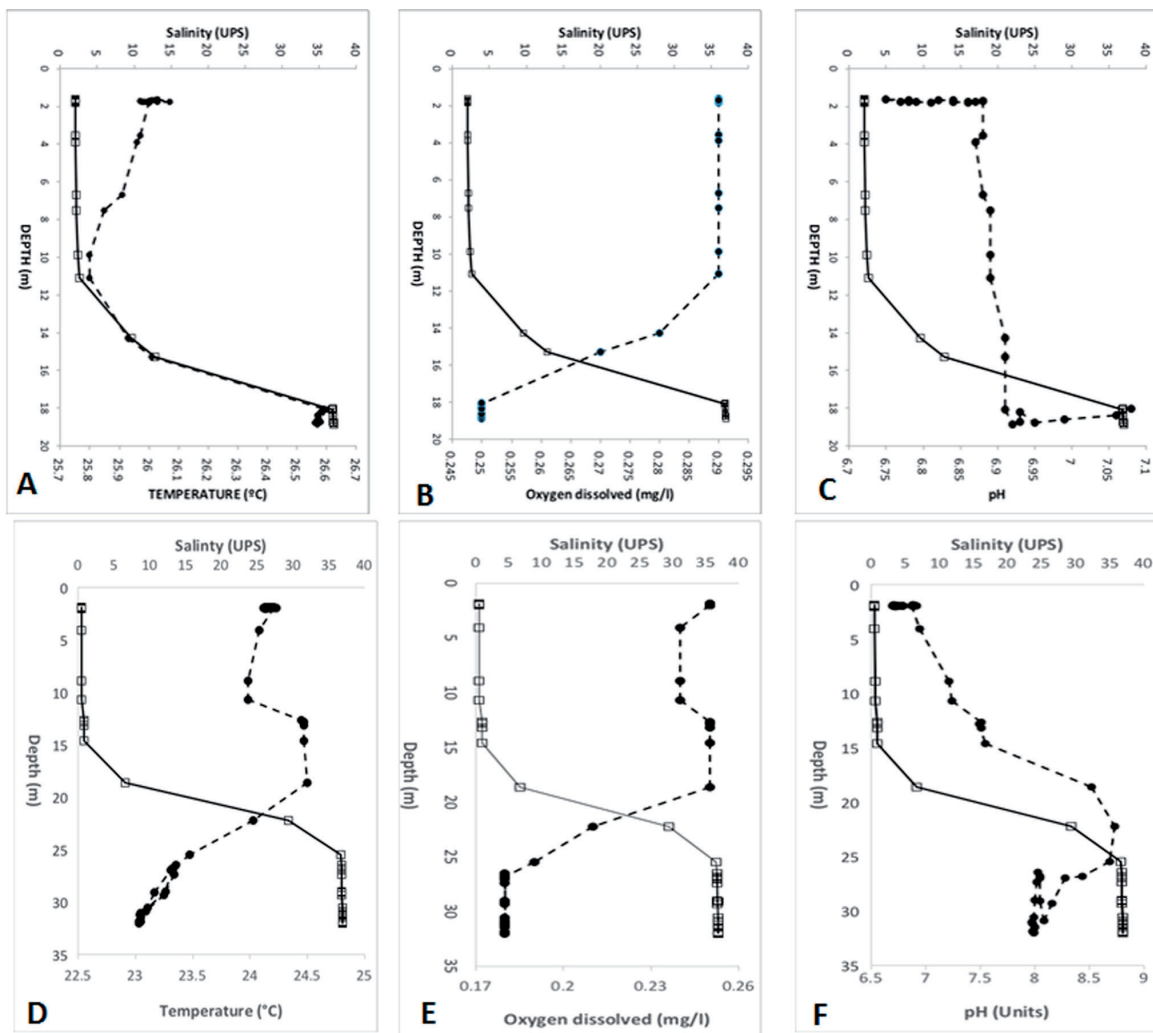


Figure 4. Examples of profiles according to the depth of the water column of anchialine ecosystems. A, B, and C graphs are for cenote Calavera, and D, E, and F graphs are for cenote Chempita in Cozumel. Salinity is represented by continuum lines with □, and temperature, oxygen dissolved, and pH are represented by dashed lines with ●.

Although a large area of this tropical seasonal forest is currently secondary, relics of the original forest can still be found [26]. Several tree strata define its vertical structure with the abundant presence of climbers and epiphytes and a well-developed shrub layer as well as an herbaceous layer composed of seedlings from the species at the upper strata [18]. The characteristic tree species are *Bursera simaruba* (L.) Sarg., *Metopium rownii* (Jacq.) Urb., *Vitex gaumeri* Greenm., *Brosimum alicastrum* Sw., *Manilkara zapota* (L.) P. Royen, and *Psidium sartorianum* (O.Berg) Nied. Among the most frequent shrubs are *Acacia collinsi* Saff., *Bauhinia jenningsii* P. Wilson, and *Eugenia acapulcensis* Steud. To name a few. In the epiphytic stratum, there are species such as *Brassavola nodosa* (L.) Lindl. and *Selenicereus testudo* (Karw. Ex Zucc.) Buxb.

The height of trees in the semi-evergreen seasonal tropical forest ranges from 18 to 25 m [24]. Trees of up to 35 m can also be found [4]; these are associated with better environmental conditions [18] such as areas with greater soil depth and karst water bodies (cenotes). The vegetation associated with these cenotes has the same floristic composition of the semi-evergreen seasonal tropical forest, but the tree stratum shows to be characteristically evergreen with a greater abundance of epiphytes (Figure 6) [4, 19].

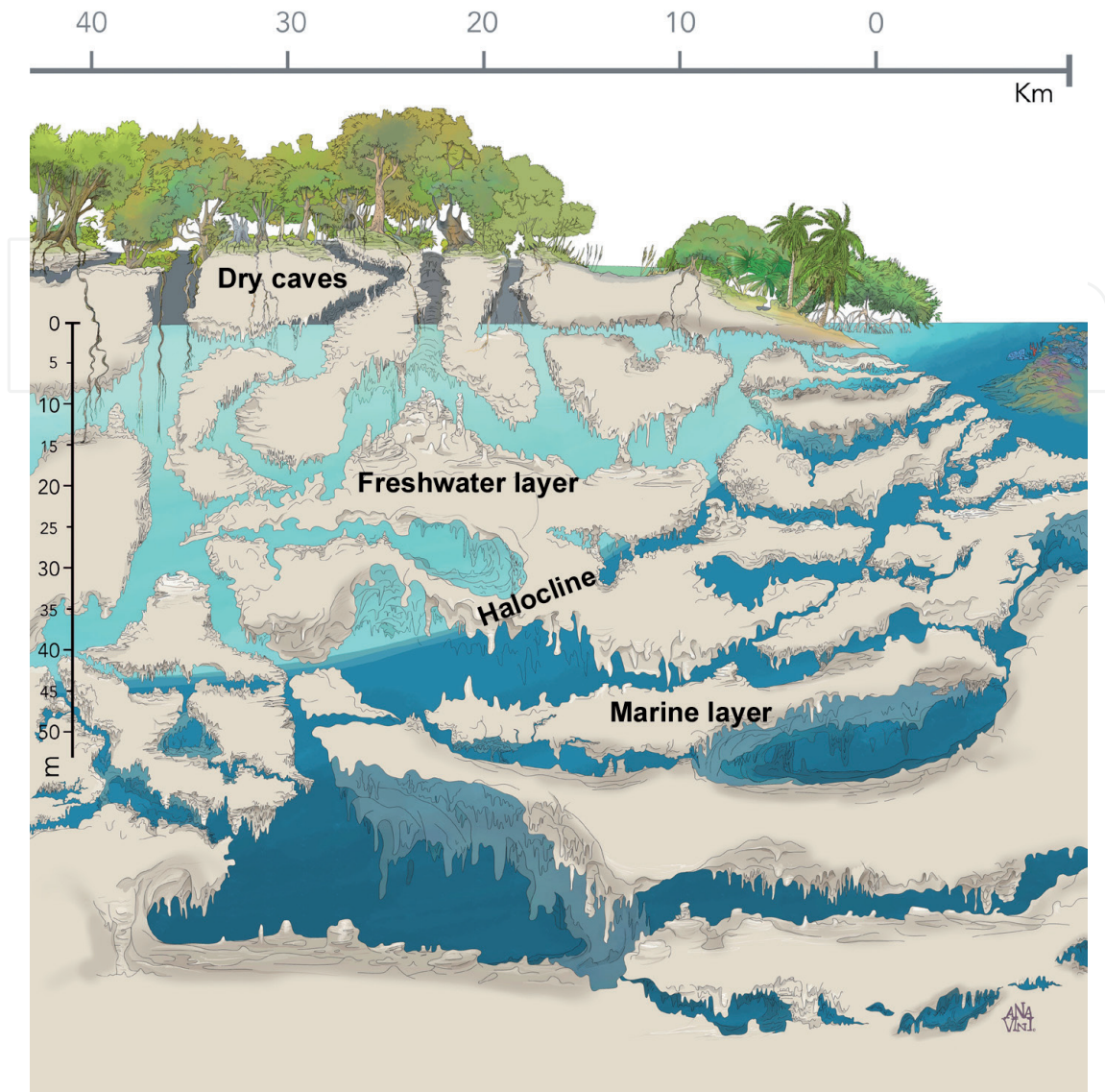


Figure 5. Schematic underwater profile where it is possible to see the relationship (halocline) between freshwater (light blue) and marine (dark blue) layers, according to depth and distance from the sea. The tree roots that reaching the aquifer to maintained the semi-evergreen state of tropical forest and mangrove vegetation.

4. Discussion

4.1 Tourist activity in the cenotes and its impacts

The great diversity and scenic beauty of the Riviera Maya, both on the surface and underwater, is related to the different types of ecosystems and large amounts of natural resources. This has facilitated the diversification of tourist activity, which now also includes exploring underground rivers, cenotes, and caves [27].

Visits to cenotes have increased significantly. The arrival of sargassum on the coast of Quintana Roo has motivated visitors to move to these spaces [28], since tourism service providers have recognized them as a substitute for beaches.

The cenotes have great landscape and cultural importance. Their underwater landscapes are geologically sculptural, which, together with their link to the general Mayan culture, creates a synergy in the visit. The cultural importance of cenotes dates

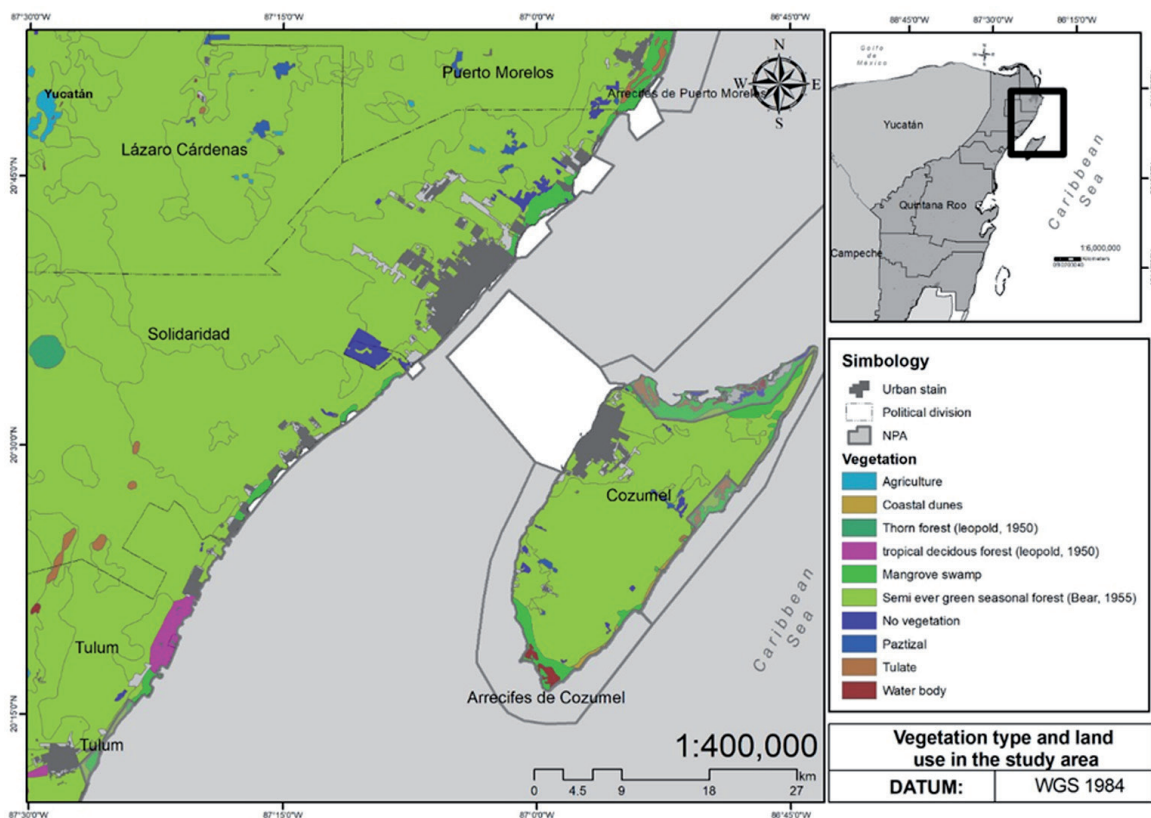


Figure 6.
Vegetation type and land use for the study area.

to pre-Hispanic times, and rituals and offerings learned from their Mayan ancestors are still performed these days to request rain, care for crops, and to ask for permission to enter the cenote [29]. Cenotes contain unique fauna and flora, formations such as stalagmites and stalactites, and ritual elements of the Mayan civilization. In addition, the areas around the cenotes are usually surrounded by jungle, mangrove, or palm and with different species of fauna that give each site an evocative power. This is why it is in these areas that observation and interpretation walks of the Mayan culture are offered.

The cenotes not only have unique esthetic natural characteristics that entice people to visit them, but they are also repositories of unique species of flora and fauna, which is where the biological and ecological importance of these systems lies [30]. Although cenotes are highly fragile ecosystems, there are currently no regulations for their use and management. In addition, since they are not isolated systems but rather they connect with groundwater that sometimes connects with the sea [31], their inappropriate use can cause unquantifiable impacts on the rest of the ecosystems with which they interact [28].

The excess of tourists in the cenotes is putting the aquifer and its aquatic biota at risk. Visitors introduce physical, chemical, and biological agents into the cenotes, such as garbage, sunscreens, repellents, creams, and fecal matter. These contaminants can alter the system, causing changes in temperature, erosion, increase in fecal coliforms, and excess nutrients that can generate irreversible impacts [27, 28]. Several of the cenotes studied experience high tourist activity (**Table 1**) because they are being offered as recreational spaces for swimming, snorkeling, diving, and hiking.

Systems	Salinity	Environmental conditions	Organisms recorded
Cocodrilo	Anchialine; Halocline at 8 m	The water profile is stratified with lower values in deeper area (marine layer) for temperature; oxygen dissolved and pH increase to alkaline values according with the deeper area	<i>Tulumella sp.</i>
Chankanaab	Anchialine; Halocline at 7 m		<i>Xibalbanus cozumelensis; Barbouria cubensis Macrobrachium carcinus; Macrobrachium faustinum;</i>
Tres Potrillos	Anchialine; Halocline at 12 m		<i>Agostocaris zabaletai, Procaris mexicana, Typhlatya sp., Barbouria cubensis; Calliasmata nohochi; Metacirolana mayana</i>
Taj Maha	Anchialine; Halocline at 14 m		<i>Typhlatya pearsei; Xibalbanus tulumensis; Antromysis cenotensis</i>
27 Steps	Anchialine; Halocline at 15 m		<i>Xibalbanus tulumensis; Barbouria cubensis; Typhlatya pearsei; Typhlatya mitchelli; A. cenotensis</i>
Crustacea	Anchialine; Halocline at 15 m		<i>Typhlatya pearsei; Xibalbanus tulumensis; Xibalbanus fuchscockburni; Metacirolana mayana; A. cenotensis</i>
Odyssey	Anchialine; Halocline at 18 m		<i>Typhlatya pearsei; Typhlatya mitchelli; A. cenotensis</i>
Bang	Anchialine; Halocline at 16 m		<i>Typhlatya pearsei; Typhlatya mitchelli; A. cenotensis</i>
Calavera	Anchialine; Halocline at 18 m		<i>Typhlatya pearsei; Xibalbanus tulumensis; Typhlatya mitchelli; Mayaweckelia sp.</i>
Eden	Anchialine; Halocline at 18 m		<i>Typhlatya pearsei; Typhlatya mitchelli</i>
Regina	Anchialine; Halocline at 20 m		<i>Xibalbanus tulumensis; Typhlatya mitchelli; Typhlatya pearsei</i>
Chempita	Anchialine; Halocline at 24 m		<i>Anchialocaris paulini, Agostocaris zabaletai, Xibalbanus sp; Metacirolana mayana; Mayaweckelia sp. Tulumella sp.</i>
Xcan Ha	Anchialine; Halocline at 24 m	<i>Agostocaris bozanici;</i>	

Table 3.
Record of brackish/marine water subterranean ecosystems with environmental conditions and fauna registered.

The three ecosystem types discussed have a strong relationship with the dynamics of tropical dry forest function, especially in those that are far away from the coast. However, these relationships also exist in coastal areas where the vegetation type is characterized by mangrove and dune. How as been reported to terrestrial cave environments they are not isolated and in these cases the cave systems fully of water have interesting relationship with the out ecosystems surrounding [32]. The freshwater from the aquifer in Quintana Roo is one of the best-conserved reservoirs in the country, but at same time it faces several threats. Exponential population growth has occurred in Playa del Carmen, Tulum, Puerto Morelos, Akumal, Cozumel, and Puerto Aventuras, thus increasing demand for water. Tourism activity is changing from sun and beach activities to activities in the cenotes and adjacent ecosystems, especially the dry tropical forest [14]. This transition in tourism increases the threat to all underground systems because these new activities cause pollution by dissolved agents and solid wastes, as has been reported by several local organizations [33].

System	Use
Crustacea	Little tourist activity
27 Steps	Little tourist activity
Taj Maha	Frequent tourist activity
Casa Cenote	Frequent tourist activity
Vacaha	Frequent tourist activity
Calavera	Frequent tourist activity
Santa Cruz	Frequent tourist activity
Yum Ha	Little tourist activity
Rancho Regina	No tourist activity
Rancho San Felipe Nohoch	Frequent tourist activity
Aerolito	Little tourist activity
Xcan Ha	Frequent tourist activity
Tres Potrillos	No tourist activity
Cocodrilo	No tourist activity
Chankanaab	Tourist use only for observation
Chempita (Jade Caver)	Frequent tourist activity
Boca del Puma	Frequent tourist activity
Tres Bocas	Frequent tourist activity
Actun Jaleb	No tourist activity
Eden (jardin del EDEN)	Frequent tourist activity
Muevelo Rico	No tourist activity
Aktun Muknal	No tourist activity
Dos Arboles	No tourist activity
Odyssey	No tourist activity
Bang	No tourist activity

Table 4.
Tourist activity in cenotes.

This region is experiencing a continual increase in tourism and mobility infrastructure [10] that together with the water demands evidently change the underground water conditions because exist the risk that if the pumping water increase the marine layer occupied these subterranean spaces and this work show the first photograph of these ecosystems under study which, possibly in one or two decades will be change. All these threats are present due to the economic benefits of tourist activity in the area. The different options to diminish the damage include environmental instruments and laws established by institutions such as the Federal Attorney for Environmental Protection (PROFEPA), Secretariat of Environment and Natural Resources (SEMARNAT), and National Commission of Natural Protected Areas Mexico (CONANP). Some proposed actions to reduce the harmful impacts of increased tourism include wastewater treatments, avoiding developing artificial greens like golf courses, stadiums, and parks, forbidding the injection of wastewater to deeper aquifers, and environmental education.

The discussed ecosystems are facing natural and anthropogenic impacts, highlighting their vulnerability. As such, monitoring their water conditions is highly important (Tables 3 and 4).

5. Conclusions

This chapter presented results of our study of groundwater conditions (temp, pH, oxygen dissolved, and salinity) in nineteen cenotes and underground rivers of the Mexican Caribbean corridor from Tulum to Puerto Morelos (Riviera Maya, Yucatan Peninsula) and six cenotes of Cozumel. We also profiled the predominant vegetation on the surface of this region, which is a seasonally dry tropical forest, to understand the components and functioning of these subterranean ecosystems to assess their vulnerability and identify their threats from human development (population growth, tourism development, mobility capacity). We identified three types of underground aquatic ecosystems: freshwater, brackish/marine water, and anchialine.

Rapid growth in tourism in the Riviera Maya and Cozumel, among other locations, is polluting and contaminating these regions' ecosystems and thus it is of great importance to monitor these ecosystems and the fauna that inhabit them to identify their capacity for resilience.

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Conflict of interest

The authors declare no conflict of interest.

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