frontiers | Frontiers in Marine Science

TYPE Editorial
PUBLISHED 14 September 2022
DOI 10.3389/fmars.2022.1029027

Check for updates

OPEN ACCESS

EDITED AND REVIEWED BY
Angel Borja,
Technology Center Expert in Marine and Food Innovation (AZTI), Spain

*CORRESPONDENCE
Luis M. Mejía-Ortíz
luismejia@uqroo.edu.mx

SPECIALTY SECTION
This article was submitted to Marine Ecosystem Ecology, a section of the journal Frontiers in Marine Science

RECEIVED 26 August 2022
ACCEPTED 02 September 2022
PUBLISHED 14 September 2022

CITATION
Mejía-Ortíz LM, Chávez-Solís EM and Brankovits D (2022) Editorial: The effects of environmental change on anchialine ecosystems.
Front. Mar. Sci. 9:1029027.
doi: 10.3389/fmars.2022.1029027

Editorial: The effects of environmental change on anchialine ecosystems

Luis M. Mejía-Ortíz[1]*, Efraín M. Chávez-Solís[2] and David Brankovits[3]

[1]Biospeleology & Carcinology Lab, Sustainable Development Division, University Authonomus of Quintana Roo State, Cozumel, Mexico, [2]Fac de Ciencias, UMDI Sisal, National Autonomous University of Mexico, México City, Mexico, [3]Molecular Ecology Group, Water Research Institute, National Research Council, Verbania, Italy

KEYWORDS

marine connections, anchialine ecosystems, stygofauna, ecology, ecophysiology, organic matter, carbon cycle

Editorial on the Research Topic
The effects of environmental change on anchialine ecosystems

Anchialine ecosystems comprise interconnected groundwater habitats at the land-sea aquatic continuum within karstic and volcanic geological settings. Here, crevicular and cavernous environments are flooded by the subterranean estuary, the region of coastal aquifers where seawater and terrestrial-borne freshwaters mix (Moore, 1999), creating globally dispersed habitats for characteristic aquatic fauna with subterranean adaptations (Bishop et al., 2015; van Hengstum et al., 2019). These cave-adapted organisms are primarily invertebrates, often endemic, with metabolic, physiologic, and morphologic adaptations that allow them to thrive in dark and energy-limited environments. Historically, these habitats have been considered particularly stable environments (e.g., Sket, 1996). However, there is growing evidence that the functioning of anchialine ecosystems is greatly influenced by external meteorological, hydrological, and oceanic conditions that closely link them with adjacent terrestrial and marine habitats (e.g., Brankovits et al., 2018; Tamalavage et al., 2018). For all these reasons, anchialine ecosystems may be more susceptible to short- and long-term effects of environmental change than previously thought.

Organic matter availability is pivotal to the functioning of freshwater, estuarine, or marine habitats, because it regulates microbial community structure and dissolved oxygen concentrations in the water column and the sediments (e.g., Howarth et al., 2011). Anchialine ecosystems are typically oligotrophic environments with low dissolved oxygen content and, therefore, they can easily transition into anoxic eutrophic habitats when organic matter inputs increase from either terrestrial or marine sources (e.g., at sinkholes, cenotes, or other cave openings) (Pohlman, 2011). The inputs, composition, and bioavailability of organic matter are sensitive to changes in nearby surface habitats, human activities and pressures, tidal fluctuations, seasonal changes in precipitation, and extreme weather events, such as hurricanes and tropical storms (e.g., Brankovits et al., 2021).

This Research Topic was established with the aim to bring together the most recent outcomes and advances from a variety of scientific disciplines that link spatial and temporal changes in the environment to biogeochemical, ecological, and physiological changes at different biological scales in anchialine ecosystems, from microbes and macrofauna to habitat level. We have received contributions from disciplines spanning paleoecology, microbiology, biogeochemistry, and ecophysiology from four geographical regions around the world (Australia, Bermuda, The Bahamas, and the Yucatan Peninsula). Specifically, these studies aimed at characterizing the limits of physiological adaptations of cave-adapted crustaceans, the drivers of organic matter inputs over time, and how organic matter availability regulates microbial community structure and meiofauna assemblages (Figure 1). These contributions expand our understanding of anchialine ecosystem functioning and enable better predictions of future ecological changes within these coastal aquifer habitats.

Cresswell and van Hengstum (2022) evaluated links between changes in environmental factors and benthic foraminiferal assemblages in Bermuda using sediment cores that are the best-preserved stratigraphic succession currently known from an underwater cave. In addition to marked changes in salinity due to the vertical and horizontal migration of the mixing zone with sea-level fluctuations, the source of organic carbon was an important factor shaping the assemblages of benthic meiofauna over the last 10,000 years. In another study from The Bahamas, Risley et al. (2022) showed that microbial community structure is influenced by the origin of organic carbon at the time of deposition, linking changes in terrestrial vegetation on the surface and microbial sedimentary processes in the subsurface over the past 2,000 years. Beyond the sediments, the stratified water column is also inhabited by a consortium of microbes that regulate organic matter transformation. Using cell population

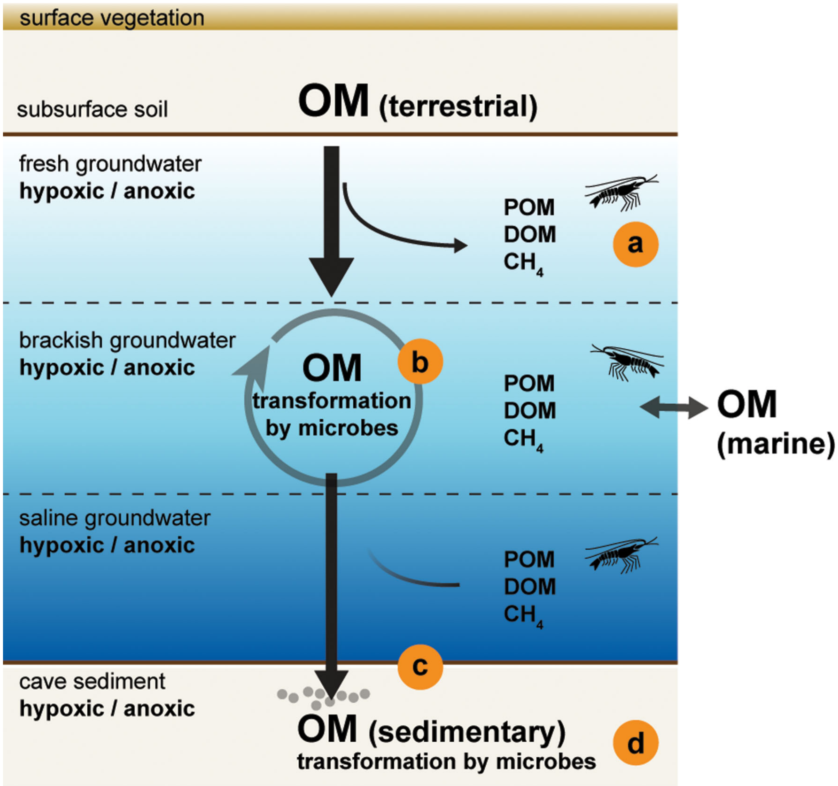

FIGURE 1
Conceptual model of organic matter (OM) inputs and transformation in a coastal cave environment flooded by fresh and saline groundwaters, a typical anchialine ecosystem. The inputs and consumption of OM affects the concentrations of dissolved oxygen, particulate organic matter (POM), dissolved organic matter (DOM), and methane (CH_4) in the water column. The salinity and chemical gradients create a set of habitats in this environment. Studies submitted to this Research Topic include investigations of **(A)** the physiological adaptations of cave-adapted crustaceans (Chávez-Solís et al., 2022), **(B)** microbial assemblages in the stratified water column (Elbourne et al., 2022), and the effects of sedimentary OM deposition over time on **(C)** meiofaunal assemblages (Cresswell and van Hengstum, 2022) and **(D)** microbial communities (Risley et al., 2022).

counts and 16S rRNA amplicon analyses, Elbourne et al. (2022) characterized the microbial communities along physicochemical gradients and depth profiles in the stratified water column of the Bundera Sinkhole, Australia. Although the high level of taxonomic novelty made it difficult to attribute metabolic functions to many of the key microbial players, potential chemolithotrophic processes, including sulfur-, ammonia-, and nitrite-oxidation, were supported by the study. This work highlights the effects of increased organic matter loading on microbially-mediated elemental cycling and their influence on shaping habitat variability in anchialine ecosystems. The observed salinity and dissolved oxygen gradients create heterogeneous habitats that affect physiological adaptations within macrofauna species and populations. Through a set of physiological and metabolic parameters, Chávez-Solís et al (2022) showed that closely related cave-shrimp species from the genus *Typhlatya* in the Yucatan Peninsula have different metabolic capacities that are in correspondence with the salinity they inhabit. This work has implications for understanding the evolutionary history of this cave-restricted genus and for the conservation efforts of anchialine ecosystems.

Collectively, the above contributions highlight how the interplay of environmental factors such as salinity, organic matter loading, and dissolved oxygen content control habitat variability and ecosystem functioning in anchialine ecosystems. Future studies should investigate direct linkages between microbes, biogeochemical processes, and trophic webs, considering the role of macrofauna in these processes. Focus is also needed on a more comprehensive identification of microbial assemblages; investigate regional and sub-regional drivers on the observed biogeochemical processes and differences between ecosystem models from different geographical regions. The use of modern molecular technologies would aid identifying such mechanisms and help shed light on evolutionary and adaptive processes. A conservation approach integrating physiology, niche width, and global environmental change projections for cave-restricted species and their habitats is paramount for the protection of anchialine ecosystems.

Author contributions

LM-O designed the Research Topic. LM-O, EC-S, and DB wrote the manuscript. DB made the figure. All authors contributed to the article and approved the submitted version.

Acknowledgments

The authors are grateful to all contributors to this Research Topic and to all reviewers whose comments improved the submitted manuscripts.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Bishop, R. E., Humphreys, W. F., Cukrov, N., Zic, V., Boxshall, G. A., Cukrov, M., et al. (2015). 'Anchialine' redefined as a subterranean estuary in crevicular or cavernous geological setting. *J. Crust. Biol.* 35, 511–514. doi: 10.1163/1937240X-00002335

Brankovits, D., Little, S. N., Winkler, T. S., Tamalavage, A. E., Mejía-Ortíz, L. M., Maupin, C. R., et al. (2021). Changes in organic matter sedimentation impact benthic meiofaunal communities in the marine sector of karst subterranean estuaries. *Front. Environ. Sci.* 9. doi: 10.3389/fenvs.2021.670914

Brankovits, D., Pohlman, J., Ganju, N. K., Iliffe, T., Lowell, N., Roth, E., et al. (2018). Hydrologic controls of methane dynamics in karst subterranean estuaries. *Global Biogeochem. Cycles* 32, 1759–1775. doi: 10.1029/2018GB006026

Howarth, R., Chan, F., Conley, D. J., Garnier, J., Doney, S. C., Marino, R., et al. (2011). Coupled biogeochemical cycles: Eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. *Front. Ecol. Environ.* 9, 18–26. doi: 10.1890/100008

Moore, W. S. (1999). The subterranean estuary: A reaction zone of ground water and sea water. *Mar. Chem.* 65, 111–125. doi: 10.1016/S0304-4203(99)00014-6

Pohlman, J. W. (2011). The biogeochemistry of anchialine caves: Progress and possibilities. *Hydrobiologia* 677 (1), 33–51. doi: 10.1007/s10750-011-0624-5

Sket, B. (1996). The ecology of anchihaline caves. *Trends Ecol. Evol.* 11, 221–225. doi: 10.1016/0169-5347(96)20031-X

Tamalavage, A. E., van Hengstum, P. J., Louchouarn, P., Molodtsov, S., Kaiser, K., Donnelly, J. P., et al. (2018). Organic matter sources and lateral sedimentation in a Bahamian karst basin (sinkhole) over the late Holocene: Influence of local vegetation and climate. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 506, 70–83. doi: 10.1016/j.palaeo.2018.06.014

van Hengstum, P. J., Cresswell, J. N., Milne, G. A., and Iliffe, T. M. (2019). Development of anchialine cave habitats and karst subterranean estuaries since the last ice age. *Sci. Rep.* 9, 1–10. doi: 10.1038/s41598-019-48058-8

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 (±001 pH), salinity (±0.01%), and water temperature (±0.01°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

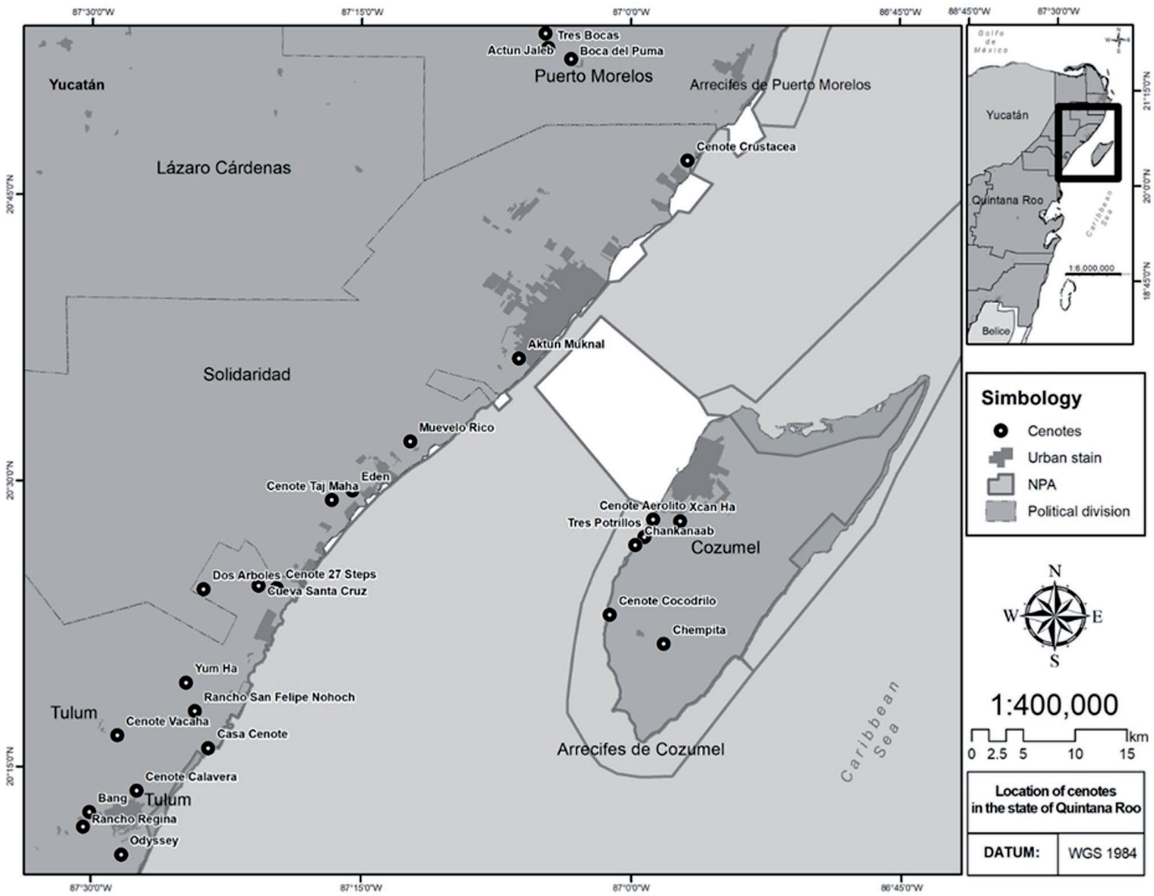

Figure 1.
Location of the different cenotes in the Riviera Maya and Cozumel.

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	*Typhlatya mitchelli;* Creaseriella anops*; Creaseria morleyi* Antromysis cenotensis
Tres Bocas	Freshwater		*Typhlatya mitchelli; C. anops; Creaseria morleyi A. cenotensis*
Actun Jaleb	Freshwater		*Typhlatya mitchelli; C. anops; Creaseria morleyi A. cenotensis*
Muevelo Rico	Freshwater		*Typhlatya mitchelli; C. anops; Creaseria morleyi A. cenotensis*
Aktun Muknal	Freshwater		*Typhlatya mitchelli; C. anops; Creaseria morleyi A. cenotensis*
Vacaha	Freshwater		*Typhlatya mitchelli; C. anops; Creaseria morleyi A. cenotensis Stygomysis holthuisi*
Cueva Santa Cruz	Freshwater		*Typhlatya mitchelli; C. anops; Creaseria morleyi A. cenotensis*
Dos Arboles	Freshwater		*Typhlatya mitchelli; C. anops; Creaseria morleyi A. cenotensis*
San Felipe Nohoch	Freshwater		*Typhlatya mitchelli; C. anops; Creaseria morleyi*
Yum Ha	Freshwater		*Typhlatya mitchelli; C. anops; Creaseria morleyi A. cenotensis*

Table 1.
Record of freshwater subterranean ecosystems with environmental conditions and fauna registered.

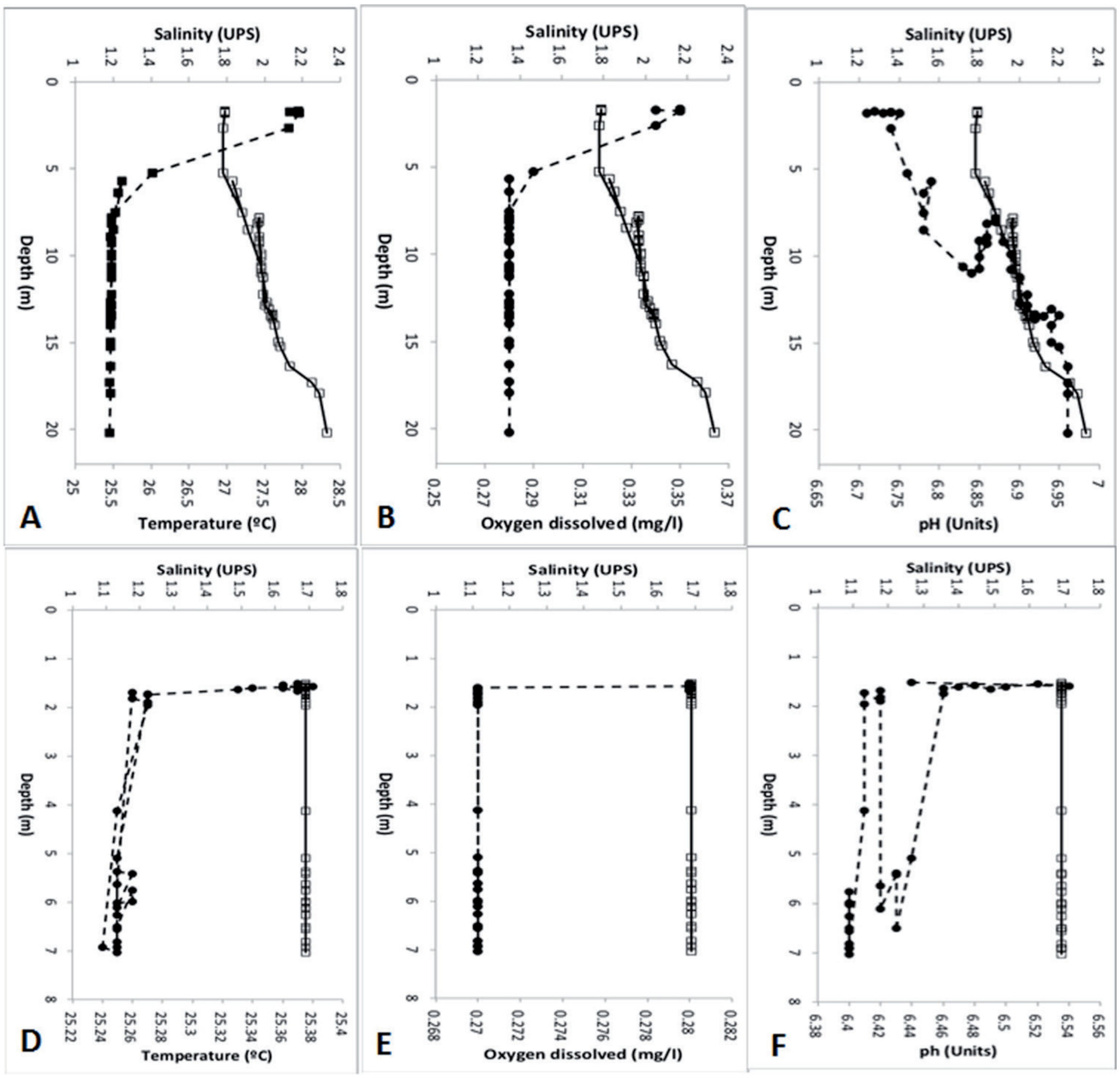

Figure 2.
Examples of profiles according to the depth of freshwater ecosystems. A, B, and C graphs are for the Santa Cruz system, and D, E, and F graphs are for the Vaca ha system. Salinity is represented by continuum lines with □, and temperature, oxygen dissolved, and pH are represented by dashed lines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

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

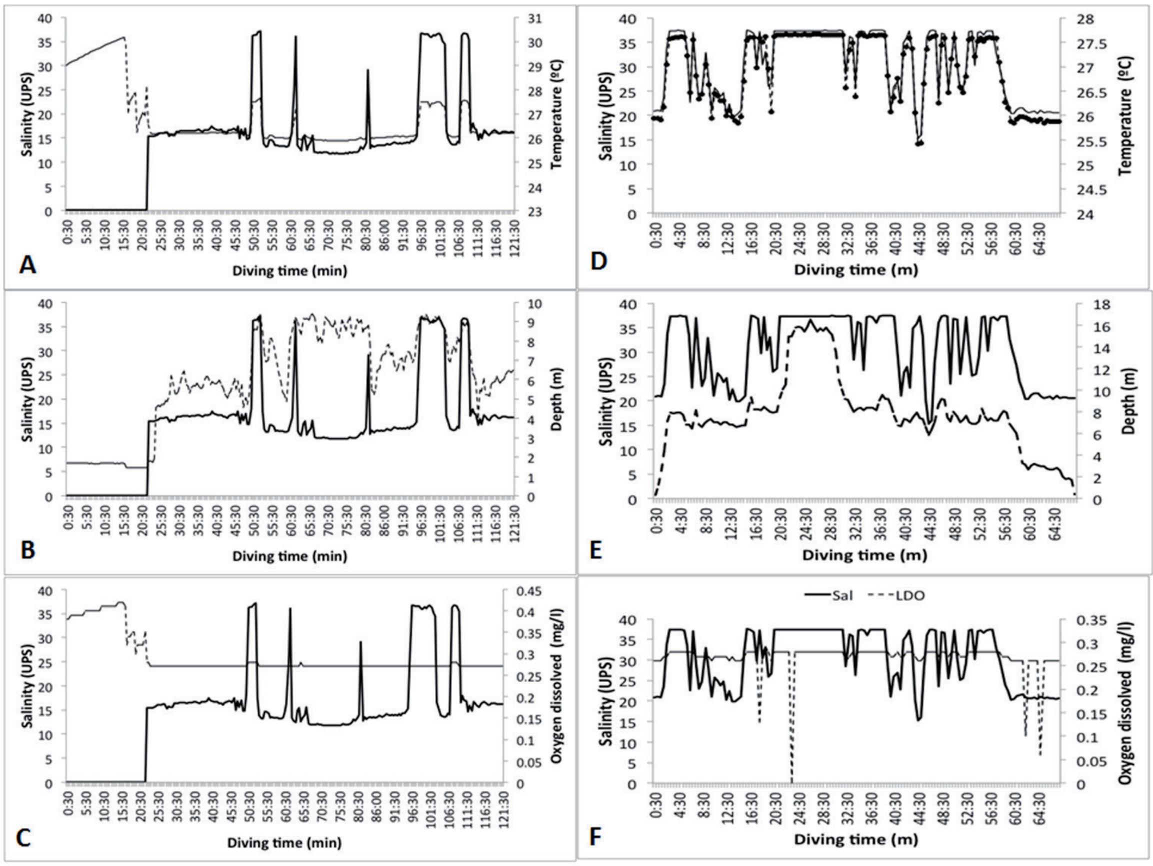

Figure 3.
Examples of profiles of brackish/marine ecosystems according to diving time. A, B, and C graphs are for casa cenote from the Actun ha system, and D, E, and F graphs are for cenote Aerolito in Cozumel. Salinity is represented by continuum lines, and temperature, oxygen dissolved, and pH are 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	*Typhlatya pearsei; Metacirolana mayana*
Aerolito	Brackish/Marine water		*Procaris mexicana; Metacirolana mayana; Xibalbanus cozumelensis;* Copidaster cavernicola*;* *Ophionereis conmutabilis*

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].

DOI: http://dx.doi.org/10.5772/intechopen.106437

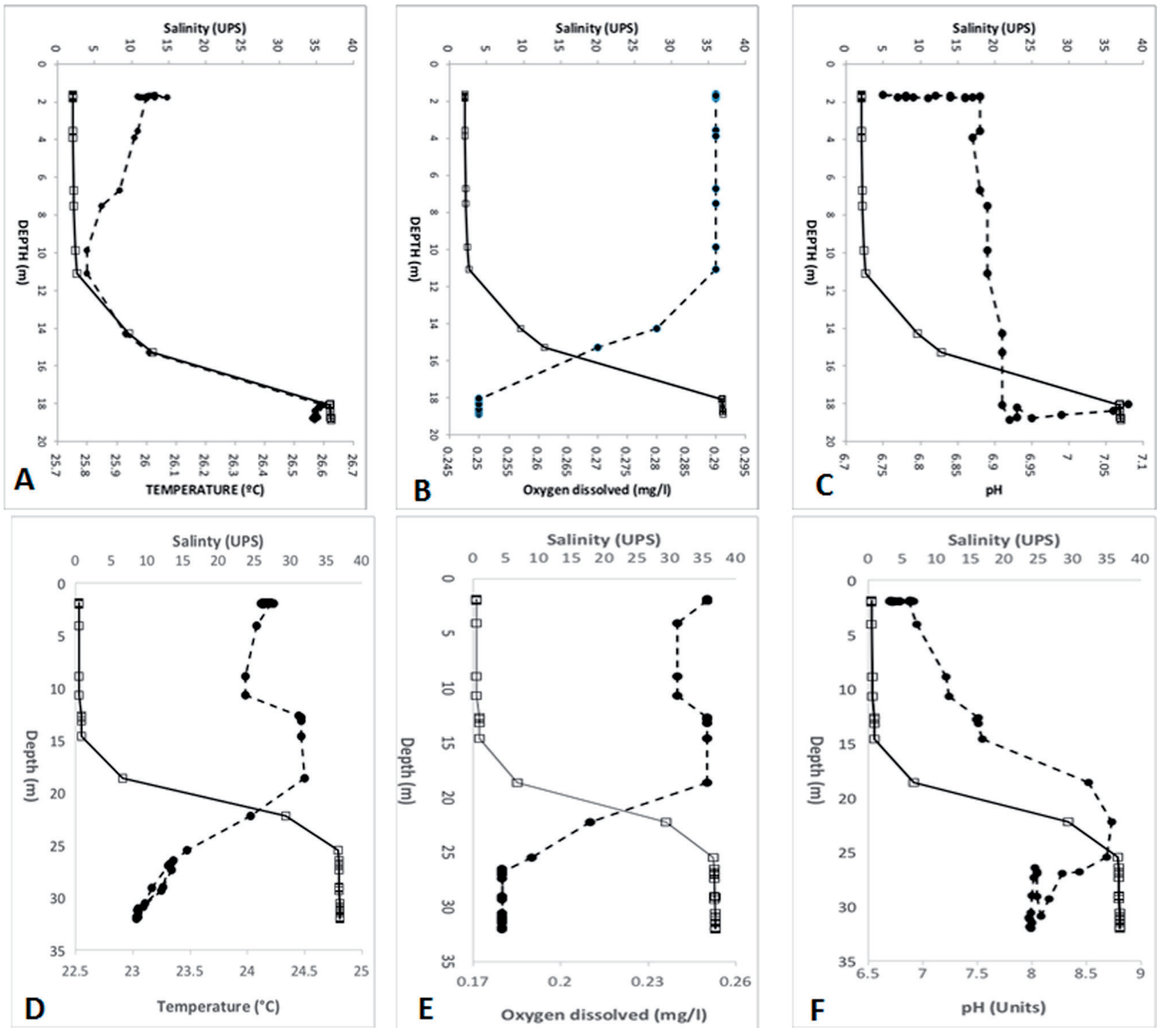

Figure 4.
Examples of profiles according to the depth of the water column of anchialine ecosystems. A, B, and C graphs are for cenote Calavera, and D, E, and F graphs are for cenote Chempita in Cozumel. Salinity is represented by continuum lines with □, and temperature, oxygen dissolved, and pH are represented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

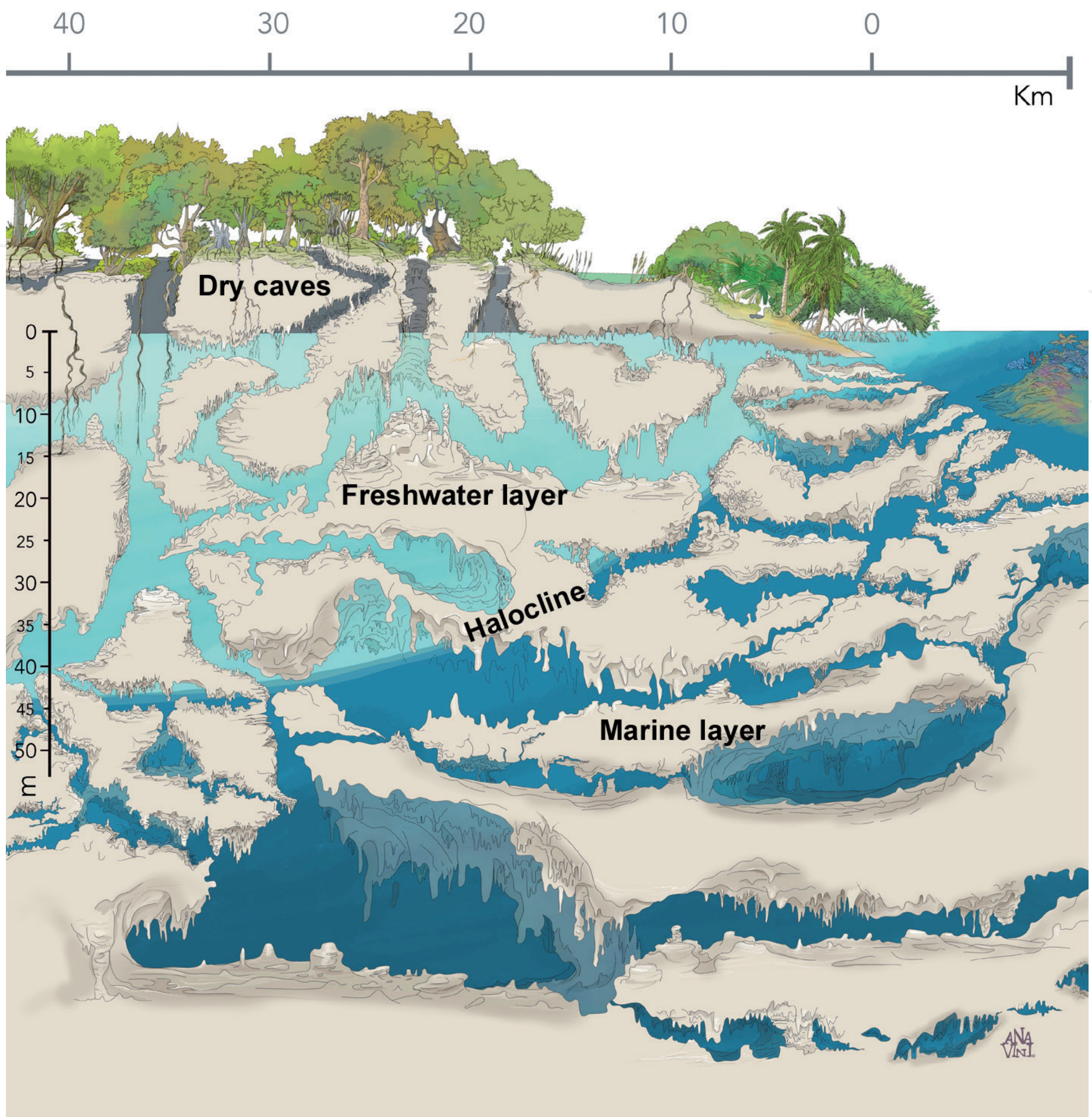

Figure 5.
Schematic underwater profile where it is possible to see the relationship (halocline) between freshwater (light blue) and marine (dark blue) layers, according to depth and distance from the sea. The tree roots that reaching the aquifer to maintained the semi-evergreen state of tropical forest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

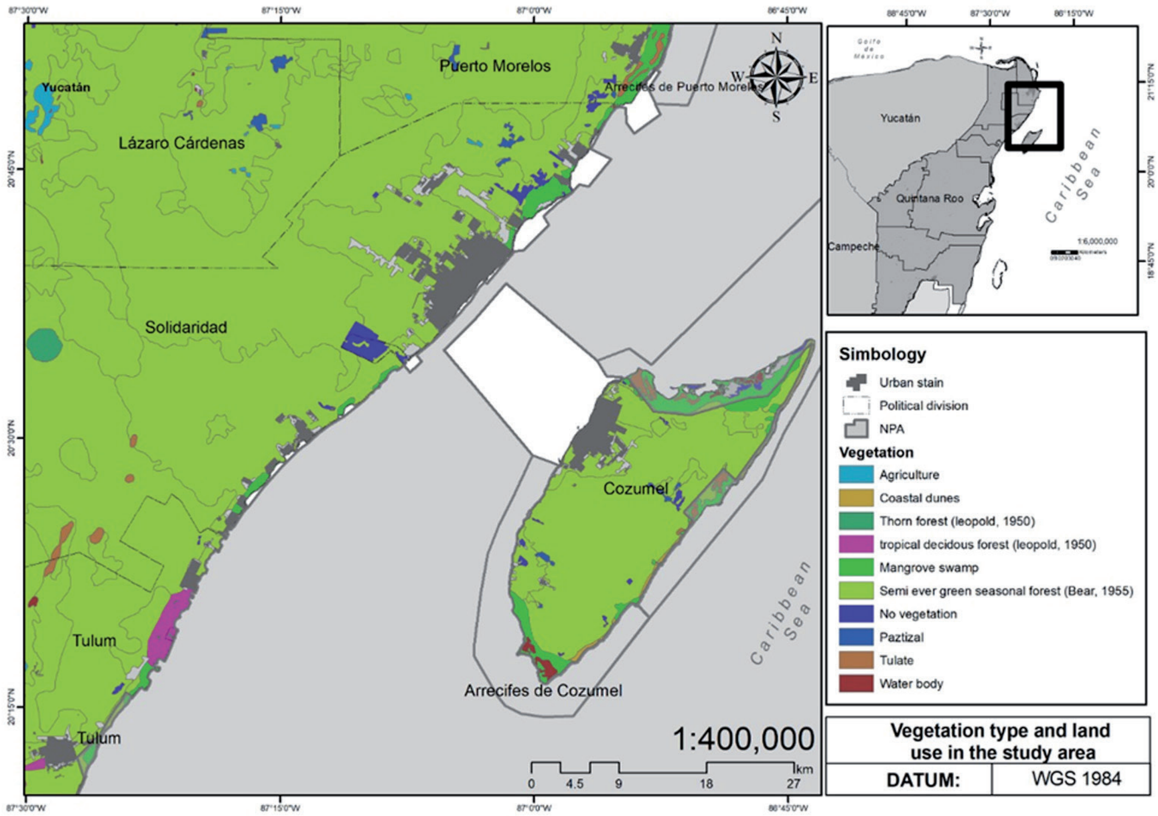

Figure 6.
Vegetation type and land use for the study area.

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	*Tulumella sp.*
Chankanaab	Anchialine; Halocline at 7 m		*Xibalbanus cozumelensis; Barbouria cubensis* Macrobrachium carcinus; Macrobrachium faustinum;
Tres Potrillos	Anchilaline; Halocline at 12 m		*Agostocaris zabaletai, Procaris mexicana, Typhlatya sp., Barbouria cubensis; Calliasmata nohochi; Metacirolana mayana*
Taj Maha	Anchialine; Halocline at 14 m		*Typhlatya pearsei; Xibalbanus tulumensis;* Antromysis cenotensis
27 Steps	Anchialine; Halocline at 15 m		*Xibalbanus tulumensis; Barbouria cubensis; Typhlatya pearsei; Typhlatya mitchelli; A. cenotensis*
Crustacea	Anchialine; Halocline at 15 m		*Typhlatya pearsei; Xibabalbanus tulumensis; Xibalbanus fuchscockburni; Metacirolana mayana; A. cenotensis*
Odyssey	Anchialine; Halocline at 18 m		*Typhlatya pearsei; Typhlatya mitchelli; A. cenotensis*
Bang	Anchialine; Halocline at 16 m		*Typhlatya pearsei; Typhlatya mitchelli; A. cenotensis*
Calavera	Anchialine; Halocline at 18 m		*Typhlatya pearsei; Xibalbanus tulumensis; Typhlatya mitchelli; Mayaweckelia sp.*
Eden	Anchialine; Halocline at 18 m		*Typhlatya pearsei; Typhlatya mitchelli*
Regina	Anchialine; Halocline at 20 m		*Xibalbanus tulumensis; Typhlatya mitchelli; Typhlatya pearsei*
Chempita	Anchialine: Halocline at 24 m		*Anchialocaris paulini, Agostocaris zabaletai, Xibalbanus sp; Metacirolana mayana; Mayaweckelia sp. Tulumella sp.*
Xcan Ha	Anchialine; Halocline at 24 m		*Agostocaris bozanici;*

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 Riveria 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.

Acknowledgements

The authors give thanks to Ana Vini for drawing the schematic view of the interaction between freshwater and marine layers. We are also grateful to the cave workers that helped us with our fieldwork: Germán Yañez, Guillermo Ruiz, Joey Pakes, Michel Vazquez, Fernando Paulin, and Amelia Weiss. This work is an outcome from projects supported by Quintana Roo Autonomous State University, the National Council of Science and Technology (CONACYT), and SEP-PRODEP..

Conflict of interest

The authors declare no conflict of interest.

Author details

Luis M. Mejía-Ortíz[1]*, Alejandro L. Collantes-Chávez Costa[2], Cruz López-Contreras[3] and Oscar Frausto-Martínez[4]

1 Sustainable Development Division, Biospeleology and Carcinology Lab, Quintana Roo Autonomous State University, Mexico

2 Sustainable Development Division, Plant Ecology Lab, Quintana Roo Autonomous State University, Mexico

3 Tourism Department, Sustainable Development Division, Quintana Roo Autonomous State University, Mexico

4 Sustainable Development Division, Spatial Observatory Lab, Quintana Roo Autonomous State University, Mexico

*Address all correspondence to: luismejia@uqroo.edu.mx

References

[1] Cejudo E, Ortega-Almazan PJ, Ortega-Camacho D, Acosta-González G. Hydrochemistry and water isotopes of a deep sinkhole in North Quintana Roo Mexico. Journal of South American Earth Sciences. 2022;**116**(103846):1-7

[2] Perry E, Velázquez OG, Marín L. The hydrogeochemistry of the karst aquifer system of the northern Yucatan Peninsula, Mexico. International Geology Review. 2002;**44**:191-221

[3] Bauer-Gottwein P, Gondwe B, Charvet G, Marín LE, Rebolledo-Vieyra M, Merediz-Alonso G. The Yucatán Peninsula karst aquifer, Mexico. Hydrogeology Journal. 2011;**19**(3):507-524

[4] Flores JS, Espejel I. Tipos de vegetación de la Península de Yucatán. In: Flores JS, editor. Etnoflora Yucatanense. Mérida Yucatán: Universidad Autónoma de Yucatán; 1994. p. 135

[5] Murphy PG, Lugo AE. Dry forest of Central America and the Caribbean Islands. In: Bullock SH, Mooney HA, Medina E, editors. Seasonally Dry Tropical Forest. New York: Cambridge University Press; 1995

[6] Mejía-Ortíz LM, Sprouse P, Tejeda-Mazariegos JC, Valladarez J, Frausto-Martínez O, Collantes-Chavez-Costa AL, et al. Tropical subterranean ecosystems in Mexico, Guatemala and Belize: A review of aquatic biodiversity and their ecological aspects. In: Natural History and Ecology of Mexico and Central America. Croacia: InTech Published; 2021

[7] Rodríguez-Castillo F, Frausto-Martínez O, Uhu-Yam WD, Colín-Olivares O. Morphometric characterisation of karst depressions: Coastal zone of the North-Eastern Yucatan Peninsula, Mexico. Ecosistemas y Recursos Agropecuarios. 2022;**9**(2) e3216:1-14

[8] Kambesis PN, Coke JG IV. The sac Actun system, Quintana Roo, Mexico. Boletín Geológico y Minero. 2016;**127**(1):177-192

[9] Back W, Hanshaw BB, Pyle TE, Plummer LN, Weidie AE. Geochemical significance of groundwater discharge and carbonate solution to the formation of Caleta Xel ha, Quintana Roo, Mexico. Water Resources Research. 1979;**15**:1521-1535

[10] Aguirre Barajas YM, Quezada Ramírez MF, Jáuregui DJ, A. Perfil sociodemográfico y laboral de los inmigrantes interestatales indígenas en Quintana Roo (México), 1990-2020. Notas de Población. 2022;**113**:193-216

[11] Castillo-Pavón O, Méndez-Ramírez JJ. Los desarrollos turísticos y sus efectos medioambientales en la Riviera Maya, 1980-2015. Quivera Revista de Estudios Territoriales. 2017;**19**(2):101-118

[12] El E-CH. origen del proyecto turístico Cancún, México: Una valoración de sus objetivos iniciales a 42 años de su nacimiento. Limina R. 2013;**11**(1):154-167

[13] Secretaría de Turismo. Rueda de prensa. [Gaceta]. 2022. Available from: https://sedeturqroo.gob.mx/ARCHIVOS/Gacetas/Gaceta-01-2022.pdf. [Accessed: May 15, 22]

[14] Consejo Civil Mexicano para la Silvicultura Sostenible 2022. Península

de Yucatán: las amenazas al territorio. CCMSSAC. 2022. Available from: http://ccmss.centrogeo.org.mx/cms/PYamenazasterritorio? [Accessed: June 13, 2022].

[15] Alvarez F, Iliffe TM, Benitez S, Brankovits D, Villalobos JL. New records of anchialine fauna from the Yucatan Peninsula Mexico. Checklist. 2015;**11**(1) 1505:1-10

[16] Mejía-Ortíz LM. Cave crustacean decapods from Mexico. In: Lachance N, editor. The Zoological Guide to Crustacea. New York, Nova Science Publisher; 2019. pp. 1-71

[17] Liévano-Beltrán LA, Simoes N. Update distribution of the mysid Antromysis cenotensis (Crustacea: Peracarida), a protected key species in Yucatan Peninsula cenotes. Diversity. 2021;**13**(154):1-17

[18] Pennington TD, Sarukhán J. Árboles tropicales de México: manual para la identificación de las principales especies. CdMx: UNAM; 2005

[19] Flores JS. Vegetación de cenotes, rejolladas, haltunes y cavernas. In: Durán- García R, Méndez-González M, editors. Biodiversidad y Desarrollo Humano en Yucatán. México DF. CICY, PPD-FMAM, CONABIO, SEDUMA, 2010. p. 43

[20] Yun Y, Wang H, Man B, Xiang X, Zhou J, Qiu X, et al. The relationship between pH and bacterial communities in a single karst ecosystems ad its implication for soil acidification. Frontiers in Microbiology. 1955;**2016**(7):1-14

[21] Cabrera Cano E, Sousa Sánchez M, Téllez Valdés O. Imágenes de la Flora Quintanarroense. Chetumal, Centro de investigaciones de Quintana Roo A.C. (CIQRO). 1982. p. 224

[22] Leopold AS. Vegetation zones of Mexico. Ecology. 1950;**31**(4):507-518

[23] Rzedowski J. Vegetación de México. 1ra. Edición digital, Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. México: Cd; 2006

[24] Miranda F, Hernández EX. Los tipos de vegetación de México y su clasificación. Boletín de la Sociedad Botánica de México. 1963;**28**:29-178

[25] Köppen W. Climatología: Con un estudio de los climas de la tierra. México DF: Fondo de Cultura Económica; 1948. p. 479

[26] Durán García R, Contreras GG. Distribución espacial de la vegetación. In: Durán-García R, Méndez-González M, editors. Biodiversidad y Desarrollo 61 Humano en Yucatán. México D. F. CICY, PPD-FMAM, CONABIO, SEDUMA. 2011. pp. 131-135

[27] Enseñat F. Impactos y manejo del visitante en cenotes del caribe mexicano. In: Bautista F (Compilador), Los territorios karsticos de la península de Yucatán: caracterización, manejo y riesgos. Cd de México. Asociación Mexicana de Estudios sobre el Karst (AMEK). 2021. pp. 124-132

[28] Casas-Beltrán DA, Gallaher CM, Hernandez Yac E, Febles Moreno K, Voglesonger K, LealBautista RM, et al. Seaweed invasion! Temporal changes in beach conditions Lead to increasing cenote usage and contamination in the Riviera Maya. Sustainability. 2020;**12**(6):2474

[29] Aguilar Y. La importancia cultural, natural, ecológica y económica del anillo de cenotes: el caso de Homún. In: Bautista F (Compilador), Los territorios karsticos de la península de Yucatán: caracterización, manejo y riesgos. Cd. De

México. Asociación Mexicana de Estudios sobre el Karst (AMEK). 2021. pp. 161-171

[30] Cervantes-Martínez A, Gutiérrez-Aguirre MA. Copépodos en cenotes de Quintana Roo. ECOfronteras. 2017;**21**(59):7-7

[31] Ruíz-Ramírez JD, López Montejo GD, Cabrera GRJ. Manglares, desarrollo turístico y cambio climático en Playa del Carmen, corazón del caribe mexicano. Cuadernos de biodiversidad. 2018;**55**:28-40

[32] Mejía-Ortíz LM, Culver DC PT, Sprouse P. The blurred line between photic and aphotic environments: A large Mexican cave with almost no dark zone. International Journal of Speleology. 2018;**47**(1):1-12

[33] Casas-Beltrán DA, Hernández-Pedraza M, Alvarado-Flores J. Estimation of the discharge of sunscreens in aquatic environments of the Mexican Caribbean. Environments. 2020;**7**(2):1-11