Hydrology and Groundwater Movement of Laguna Bacalar and the Cenote Negro, Yucatan Peninsula, Mexico

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ABSTRACT

Laguna Bacalar is the second largest freshwater lake in Mexico, located along the southeastern perimeter of the Yucatán Peninsula. This unique ecosystem is maintained via groundwater input and direct rainfall, and is dominated by karst topography, making it known for its water of seven colors and the various cenotes that lie within it. This study expands on the knowledge of the lagoon's groundwater input, hydrology, and role of the Cenote Negro. Obtaining a greater understanding of Laguna Bacalar's groundwater hydrology and water quality is crucial in preserving the unique ecosystems health and longevity as anthropogenic contamination and pollution magnifies through the expansion of ecotourism. Transects were performed at central and northern locations. The sampling duration consisted of 4-weeks, between June 1st -29th, experiencing heavy rainfall events and tropical storms for a majority of the duration. Transect results gave substantial insight on current groundwater flow throughout the lagoon, as well as displayed distinct stratification and water column mixing. Definite groundwater sources at Xul-Ha, the Cenote Negro, and Buena Vista were indicated by an increase in specific conductivity (SpCond) and pH after rainfall events in comparison to central Laguna Bacalar transects. The Cenote Negro vertical profiles displayed a unique pattern of increased conductivity around 20-30 meters depth, suggesting this to be the zone that receives groundwater input, contributing to the flow of freshwater into Laguna Bacalar.

Introduction

The Yucatán Peninsula (YP) is classified as one of the world's largest karst topography aquifers, composed of limestone, gypsum, and dolomite carbonate sediment, being highly susceptible to dissolution by acid rain (Bauer-Gottwein et al., 2011). Laguna Bacalar is a freshwater, oligotrophic lake located in the Mexican state of Quintana Roo along the YP, stretching 55 km in length and approximately 1 km in width in average (Matzuk, 2020). Freshwater lakes within karst regions are rare and less studied, especially when characterized by tropical climates, as tropical lakes make up only ten percent of lakes globally (Lewis, 1996). Laguna Bacalar is a solely freshwater ecosystem with no saltwater tributaries, where the only miniscule saltwater input is via carbonate sediment dissolution (Lesser & Weidie, 1988). Although there are no saltwater tributaries, Laguna Bacalar is connected to the coastal estuary, Chetumal Bay, as it drains into the bay via channel systems in the northern and southern regions of the lagoon, utilizing surrounding bodies of water such as Laguna Chile Verde, Laguna Guerrero, Laguna Mariscal, and the Rio Hondo (Hernández-Arana et al.). This flooded channel system provides biological interconnections for aquatic species movement between the freshwater and brackish ecosystems (Hernández-Arana et al.).

Primary freshwater inputs enter Laguna Bacalar through abundant groundwater flow via springs in the Southern region of the laguna, Xul-Ha respectively (Matzuk, 2020). Heavy precipitation events feed the underground water flow via percolation. Groundwater input is significantly cooler, more acidic and possessing high specific conductivity (SpCond) composition. Groundwater inflow from Xul-Ha is transported to central Laguna Bacalar via the Los Rapidos, a long, narrow channel North of Xul-Ha (Fig. 2). This groundwater additionally feeds surface water into Canal de los Piratas and Laguna Mariscal, located in central Laguna Bacalar (Fig. 2).Laguna Bacalar is commonly referred to as the 'Laguna de siete colores' (lagoon of seven colors). The laguna water displays several hues of blue as a result of calcium-rich, flocculent white sand that is distinguishable due to the high water clarity (Perry et al., 2002, Liseth Perez et al., 2010) and low nutrient enrichment of nitrogen and phosphorus. Additionally, the YP's karst topography characterizes Laguna Bacalar by its abundance of submerged dolines (known as cenotes), formed by the collapse of caves due to karstification caused by the reaction between the carbon dioxide (CO_2) rich rainwater and the limestone bedrock (Schmitter-Soto et al., 2002). Cenotes are commonly circular with a conical shaped basin, reaching ~15m maximum depth (Lesser & Weidie, 1988), yet Laguna Bacalar contains four major unique cenotes along its west bank: Cenote Cocalitos, Cenote Esmeralda, Cenote Azul, and Cenote Negro. Cenote Negro (or Black Cenote) is the deepest submerged cenote in the region, characterized by its absence of a littoral zone and dark color that other cenotes in the region lack. Bathymetry of the Black Cenote was previously recorded by Carrillo et al. (2024), results indicating the greatest depth of 63.3 meters with a nontraditional basin shape, not possessing a conical basin.

In recent years, Bacalar has become more popular as an ecotourism destination due to the unique beauty and appeal of these natural landmarks, but the accelerated rise in anthropogenic activity has created concerns regarding long-term nutrient enrichment to the ecosystem. Increase in tourism has created a higher demand for resort infrastructure construction that lack developmental plans and can escalate the degradation of the surrounding environment through increased surface runoff of nutrients and pollutants, unregulated wastewater discharge, and an increase in susceptibility of surface erosion into surrounding waters (Pare and Fraga, 1994, Yanez-Montalvo et al., 2020). Laguna Bacalar has formerly shown decline in ecosystem stability and water quality through fluctuation in water pigmentation after severe weather events, such as tropical storm Cristobal, resulting in 66% of the laguna transitioned from crystal blue to murky brown coloration (Nast, 2021). These events indicate the laguna to be sensitive to changes prompted by the environmental or surrounding civilization. Ongoing construction of the Tren Maya, starting in 2020, connects major tourism locations throughout the YP (Quintana Roo, Yucatán, Campeche, Chiapas, Tabasco), posing a great threat to surrounding ecosystems. Lack of environmental consulting and placement of regulation during the megaproject has caused civilian concern as the karstic topography of surrounding cenotes is fragile and susceptible to contamination of groundwater (Hernandez Yac, 2022, Hunter, 2024).

Thorough understanding of Laguna Bacalar's water quality and groundwater hydrology is crucial in this time of change to preserve and protect the unique ecosystems beauty and longevity, This study aims to contribute to the understanding of the hydrology of Laguna Bacalar while analyzing the environmental conditions of the surrounding water quality, addressing the hypothesis that groundwater flow via the Black Cenote at a specific depth range is a primary contributor to Laguna Bacalar groundwater inflow.

Materials and Methods

Study Site

The YP is located in southeastern Mexico, dividing the Gulf of Mexico and the Caribbean Sea. With a surface area of approximately 197,600 km^2 the YP fully encompasses the Mexico states of Campeche, Quintana Roo, Yucatán, northern regions of Tabasco, and northern Guatemala and Belize (Fig. 1) (Bauer-Gottwein et al., 2011). The region is characterized by tropical climate, with an average temperature of ~25°C and experiences heavy rainfall events between May and October, yet a majority of the rainfall is lost via evapotranspiration due to the high annual temperatures (Lesser & Weidie, 1988). Four different geomorphological regions make up the YP being the northern pitted karst plain, Sierrita de Ticul, southern hilly karst plain, and the eastern block-fault district (Weidie, 1985). Laguna Bacalar and surrounding waters, Chetumal Bay and the Rio Hondo River, lie within the eastern block-fault region; Laguna Bacalar formed via an 8-10m down-dropped fault block (Lesser & Weidie, 1988).

Cenote Negro Depth Profiling

To create a designated sample location, a weight was attached to 50 meters of rope and then lowered down to maximum depth on the floor of the cenote. A buoy was attached to the end of the rope marker, sitting approximately 2 meters below the water surface to act as a visual marker for the diver. The buoy remained submerged as the Black Cenote is a popular tourist attraction and exposing the buoy to the water surface will lead to tampering and movement of the exact sample location. This marked location has a depth of ~54m. It was not possible to reach maximum cenote depth of 63m due to irregular basin shape. This method was used to ensure accurate and precise repetition during each depth profiling sampling period. A YSI 6920 V2-2 multiparameter water quality sonde was used to carry out depth profiles. Sonde measurements were set for unattended sampling with a reading interval of 00:00:01, for 365 days, and labeled in respect to the sample location, number, and date of sampling. The multiparameter sonde was deployed at the marked sample location via a diver, who dove to the submerged buoy and attached the instrument to the marker rope using a carabiner. Once attached, the diver would return to the water surface and slowly lower the instrument down to maximum location depth. The multiparameter sonde was lowered with a rope which was marked in five meters intervals for a total of 60 meters, indicating approximate sonde depth. Once the sonde reached max depth, as indicated on marked rope and lack of tension on the line, the sonde was slowly brought back to the surface. The YSI sonde was deployed to record pH, dissolved oxygen (mg/L), specific conductivity (μS/cm), temperature (°C), and turbidity (NTU) in relation to relative depth (m). Once the sonde was retrieved, it was returned to Cren Javier Rojo Gomez college lab to stop logging data and to transfer data file for further analysis. This method was repeated to obtain a full vertical profile of the black cenote from 0-54m. Two different sondes were deployed for the initial depth profile to verify correct instrument performance in respect to the sensor(s). Depth profiling of the Black Cenote was carried out twice a week for a period of four weeks.

Lake Bacalar Cross Section Depth Profiling

Three cross-section locations were selected within northern and central Laguna Bacalar. Central and Northern cross section locations can be seen in Figure 4. Variable sample site depth shown in Figure 5. A 200m transect was taken at each cross-section location. Each 200m transect location was split into five vertical depth profiles (profile of 5m, 10m, 20m, 10m, 5m depth) every 50 meters, moving inland in an east to west direction (Fig. 4). Transects started ~300m offshore and ended ~50m offshore. A YSI sonde was deployed to record pH, dissolved oxygen (mg/L), specific conductivity (μS/cm), temperature (°C), and turbidity (NTU) in relation to depth (m) at each sample location. The deployed sonde was set for unattended sampling with a measurement reading of 00:00:05, for 180 days, and labeled in respect to sample number, site name, and sample date. The sonde was lowered into the water alongside the boat by a rope, which was marked in five meters intervals for a total of 60 meters, indicating approximate sonde depth (Fig. 6). Once the sonde reached the target maximum depth for each given profile, as indicated on marked rope and lack of tension on the line, the sonde was slowly brought back up to the surface. A YSI sonde hand-held instrument was used to stop sonde data logging after each of the three 200m transect sites within the central and northern locations, as well as to create individual files for each sample site (El Bajo, Balneario Ejidal, Amigos Hotelito and Buena Vista South, Town, North). The hand-held instrument was only used to stop and create files for the central and northern transects, while the Black Cenote recording was stopped via a computer at the Cren Javier Rojo Gomez lab. This is because the central and northern locations contain three sampling sites each, while the Black Cenote only has one. Taking into consideration that each location has numerous sites, drive time between each, the high density of data recorded at each site, and organization/analysis of the data, creating individual files for central and northern transects is more efficient. The coordinates and time stamps (launch and retrieval time) were recorded for each of the five profiles at each given sample site. Daily weather conditions were recorded during each sample period in respect to variable precipitation events. Once transects were completed, all data were transferred for further analysis. Depth profiling transects occurred twice a week at each given sample location in the central and northern sites for a four-week period.

Cenote Negro Outflow Transects

A total of four, 200m surface transects were carried out at the mouth of the Black Cenote to record inflow into Laguna Bacalar, measuring conductivity at and below the water surface. Transect one measured the entrance of the Black Cenote, T1. Three additional transects, T2, T3, and T4 were then measured by moving 20m east from the black cenote and kayaking in north to south and south to north directions (Fig. 7). Surface transects were carried out by towing a programmed YSI multiparameter sonde in a floating device behind a kayak, allowing measurements of only surface water conductivity. Water column conductivity measurements were carried out via lowering a handheld conductivity meter to the middle of the water column at the beginning, middle, and end of each transect location and recording the data directly. The programmed YSI sonde and handheld conductivity meter both measured the same transect point. The deployed sonde file was set for an unattended sampling period with a measurement reading of 00:00:05, for 180 days, and labeled by transect number and sample date. Once all data were recorded, the sonde instrument was returned to the lab to stop data logging and transfer all data for further data analysis.

Results and Discussion

Cenote Negro Depth Profiling Analysis

Throughout the four-week sampling period, only one depth profile recorded adequate data. A total of five depth profiles were performed at the Black Cenote via the multiparameter sonde. Methodology remained consistent among the five profiles throughout the project duration, including the same diver executing the procedure, yet only one profile (1BC07624) successfully recorded a full 50-meter depth profile. This full profile was one of two initial profiles recorded at the black cenote, when both multiparameter sondes were deployed. Profile '1BC07624' was recorded on the sonde 1, while profile '2BC07624' was recorded on the sonde 2. As depicted in (Fig. 8 and Fig. 9) the sonde 1 recorded a complete profile to maximum depth of ~50m, while the sonde 2 only recorded a profile to a maximum of ~20m. All following depth profiles and transects measurements were carried out with the sonde 1 as sonde 2 displayed depth sensor errors that interfere with accurate data readings. Despite performing the verification trial via deploying both sondes, all depth profile at the Black Cenote following the initial profile only recorded a maximum depth of ~23 meters, while sampling at the same marked location with sonde 1. Verification trails were repeated but results of both sonde 1 and sonde 2 showed maximum depth reached to be ~23m. Due to these unpredictable depth sensor error(s), a predominant amount of the Black Cenote depth profile data is insufficient and not capable of being used for data analysis as a full profile is required.

The complete profile, '1BC07624' (Fig. 8), exhibits a distinct pattern of fluctuation in specific conductivity between 20 to 50m. This pattern starts at 20 meters where conductivity increases from 2,700 to approximately 2,780 uS/cm, then dropping back down to 2,700 uS/cm at 50m. We can see this pattern at 20m repeat to a limited extent in other profiles (Fig. 9), but we cannot verify this without a full 50-meter depth profile. Due to the karst topography of the YP, before groundwater enters the Black Cenote it contains dissolved ions such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, $SO4^{2-}$, and $HCO3^{-}$. This causes the groundwater to be characterized by high conductivity and pH in comparison to other water sources, such as direct rainfall, that has to have a lower conductivity and pH. This is suggested (Fig. 8 and Fig. 9) as surface water of the Black Cenote is characterized by low conductivity, while deeper columns are characterized by high conductivity. Additionally, the data shows this banded pattern repeat in regard to temperature, where temperature fluctuates between 20-50m in the complete profile, '1BC07624' (Fig. 10). This indicates that the repeated pattern of increased conductivity and temperature between 20 to 50m where saline groundwater enters the Black Cenote.

Laguna Bacalar Central and Northern Transect Analysis

Over the four-week sampling duration there were drastic changes in weather patterns and precipitation events. During the first week of sampling, June 9th-15th , weather conditions remained constant with sunshine, little cloud coverage, and little precipitation. The remainder of the sampling duration, June 16th-29th, weather conditions were overcast with heavy precipitation events. A weather station located at the CREN Javier Rojo Gomez college recorded all data during the sampling duration.

When analyzing the transect data there is notable change in the data before and after heavy rainfall events. The first week of sampling when there was little to no rainfall, all central sample locations showed explicit stratification regarding specific conductivity (SpCond) and pH (Fig. 11 and Fig. 12), while northern locations did not. Prior to rainfall there is a significant increase in SpCond and decrease in pH at/below 10m (Fig. 10, A), indicating this is the depth groundwater enters the central region water column via southern groundwater from Xul-Ha that feeds the lagoon. After heavy rainfall, central locations no longer showed stratification. Due to the lagoon being relatively shallow and homogeneous in temperature, along with strong tropical winds, these heavy rainfall events prompt the water column to mix, disrupting stratification. Furthermore, the change in water chemistry, such as the decrease in SpCond can accentuate water column mixing. During heavy rainfall events the stratification in the water column starting at 10m is disrupted and the low pH, high SpCond groundwater layer disappears, (Fig. 11, B and Fig. 12, B). After a period of time, CO_2 will degas out of the fully mixed lagoon resulting in the SpCond and pH to approach pre-rain levels (Fig.11, C & Fig.12, C). There is no significant change in dissolved oxygen (DO) before and after heavy rainfall events. Water column mixing due to heavy rainfall events will inject DO throughout the water column however any influx of available DO can be readily used by benthic mats for various metabolic processes. This possibly is why there is no significant change in DO after heavy rainfall. When comparing central and northern cross-sections, the northern locations have considerably higher SpCond (Fig. 13) in comparison to the central locations. This is a result of the northern sample location, Buena Vista, possessing a much greater residence time than central Laguna Bacalar (Matzuk, 2020). The water in the northern region of the lagoon sits much longer, resulting in higher rates of evaporation and increased salinity. Residence time of central and northern locations were previously calculated, showing Buena Vista to have a residence time in 2017 to 2019 of 11.04 $\pm$ 0.040 yr, while central in 2017 to 2019 is 0.33 $\pm$ 0.03 yr (Matzuk, 2020).

Cenote Negro Outflow Analysis

When analyzing the sonde readings taken at the Black Cenote mouth and the transects moving outwards into Laguna Bacalar, the sonde only recorded data measurements for the Black Cenote mouth (T1) and the first outflow transects (T2). Outflow transects (T3 and T4) show no accurate data measurements as sonde readings were frozen at the measurements of 15.971 m, 0 mg/L, 0 μS/cm, 50°C, and a pH of 6.8. These fixed sonde readings, over an extended recording period, indicate sonde sensor error(s), resulting in faulty data. T1 and T2 transects were recorded prior to the sonde sensor error(s) and the data shows a slight increase in temperature, DO, and pH, and a slight decreased in SpCond in T2, in respect to outwards distance from the Black Cenote. Due to the inability to collect the remainder of the transect data accurately, along with the lack of data collected, no conclusion regarding water inflow from the Black Cenote into Laguna Bacalar can be made.

Conclusion

Data in this study, along with previous years (Matzuk, 2020), indicate that the hydrology of Laguna Bacalar is primarily sustained through groundwater input sources at Xul Ha, the Black Cenote, and Buena Vista. Vertical depth profiles carried out in the northern regions of Laguna Bacalar, being Buena Vista, support this conclusion as data shows the water composition to possess a significantly higher specific conductivity and lower pH in comparison to profiles in central Laguna Bacalar. Furthermore, the discovery of the increased specific conductivity pattern, characterized at specifically 20-50m depth of the Black Cenote, support the claim of groundwater flow entering Laguna Bacalar via the Black Cenote. The vertical profiles executed throughout Laguna Bacalar in addition conveys that during the raining season, heavy rainfall events disrupt water column stratification as a result of strong tropical storm winds and direct rainwater input in the lagoon, possessing a dissimilar water composition, inducing the water column to mix.

Maintaining a continual understanding of the hydrology and groundwater movement of Laguna Bacalar is a fundamental element in preserving and maintaining this ecosystems health and longevity while climate change continues to alter ecosystems globally. As anthropogenic activities and tourism continues to expand within the small town of Bacalar, affirming the lagoons conditions and recognizing change is crucial. For six years now, student led research has evaluated the same subjects and questions surrounding Laguna Bacalars water quality. The data presented in this paper aids to better understand the present-day hydrology and ecosystem health of Laguna Bacalar, as well as to assist future studies of Laguna Bacalar to preserve its history and beauty.

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