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# Spatial and seasonal variations in surface water temperature and salinity in the Mexico-Belize riverine estuary: Possible comfort conditions for manatees?

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## Abstract

The Mexican Caribbean and Belize are home to one of the largest populations of Caribbean manatees (*Trichechus manatus manatus*). However, the transboundary Hondo River estuary is less examined compared to the surrounding protected areas. This paper provides a quantitative description of the spatial and temporal variability in abiotic factors and manatee distribution throughout the Hondo River estuary, with monthly field measurements during 2018–2019. Simultaneously, visual observations and side-scan sonar detection were implemented, with 84 manatee sightings reported (calves 11.9%, noncalves 88.1%). Heatmap and frequency analyses showed that most manatee sightings occurred at the riverine estuary limit, the confluences between the river and the bay into which it flows. The surface water temperature and salinity ranged 28°C ≤ T ≤ 32°C and 0.5 PSU ≤ S ≤ 4.5 PSU for ~72% of the manatees identified, potentially describing locally preferred conditions for manatees. During the regional mid-summer drought, higher temperature (31.5°C), salinity (18 PSU), and estuary extent (17.6 km) were recorded, including the maximum peak of manatee sightings (~31%). The roles of these abiotic factors are discussed as tentative environmental comfort conditions for manatees that could reduce their energy and maintenance costs. The identification of preferred conditions could broaden perspectives on how manatees interact with their habitats.

**KEYWORDS**
abiotic factors, Caribbean manatee, Hondo River, spatial and temporal variability, transboundary estuary

## 1 | INTRODUCTION

The overlapping of political and administrative domains is commonly present in transboundary estuaries (Pallero Flores et al., 2017), and represents a challenge for conservation management (Louzao et al., 2012). Management of the Hondo River, the natural border between Mexico and Belize, is based on current urban-use policies, tourism, and commercial growth together with the handling of protected areas for enhancing economic wellness (Salas, 2015; SEDATU, 2018). The management of the river has developed over binational historical processes and conflicts defined by the international territorial delimitation, the legal and economic framework, and the exploitation of natural resources (Hidalgo Castellanos, 2007; Kauffer, 2005; Morales-Vela et al., 2000; Olvera Alarcón et al., 2011; Tun-Canto et al., 2017). The Caribbean manatee subspecies (*Trichechus manatus manatus*), which is protected by Mexico, Belize, and internationally (Self-Sullivan & Mignucci-Giannoni, 2008), has become increasingly important as a tourist attraction in these two countries (Morales-Vela et al., 2000). However, it is classified as Endangered by the International Union for Conservation of Nature (IUCN), due to increased human activities and continued declines in the extent of occupied areas, the quality of manatee habitats, and population size (Self-Sullivan & Mignucci-Giannoni, 2008). Past studies on the distribution and status of manatees on the Mexican border with Belize are limited. Although manatee sightings have been reported in the Hondo River mouth, and along over 20 km of its length since the 1990s (Colmenero & Zárate, 1990), the complex economic and social binational framework between Mexico and Belize precluded consideration of the river as part of the natural protected areas at the time of their establishment (Morales-Vela, 2004). Moreover, human population settlements, border-based retail-oriented free zones, and transboundary checkpoints have been developed along the Hondo River estuarine environment and up to the limits of the coastal natural protected areas in both countries.

The Hondo River estuary and the surrounding lagoons with recurrent manatee presence (Morales-Vela et al., 2000; Castelblanco-Martínez et al., 2013), provide very attractive habitats for manatees due to the favorable conditions of sheltered, shallow aquatic environments (Alves et al., 2013; Jiménez-Domínguez & Olivera-Gómez, 2014). However, transboundary management in the Hondo River lacks international cooperative mechanisms (Morales-Vela, 2004; Olvera Alarcón et al., 2011). Most studies have focused on water management or on the international border relationship (e.g., Hidalgo Castellanos, 2007; Kauffer, 2005; Olvera Alarcón et al., 2011), so critical gaps in the knowledge of the environment and its manatee population still exist (Castelblanco-Martínez et al., 2012). Research related to manatee presence in the area has focused on the Manatee Sanctuary of Chetumal Bay, through aerial surveys (Morales-Vela, 2004) and studies on meteorological and physical water variables (Axis-Arroyo et al., 1998; Olivera-Gómez & Mellink, 2005), water quality (Álvarez-Legorreta, 2009; Herrera-Silveira et al., 2002), manatee movements (Morales-Vela et al., 2007; Castelblanco-Martínez et al., 2013) and trophic chains (Castelblanco-Martínez et al., 2012). Only one recent study focused on exploring the distribution of manatees in the Hondo River (Corona-Figueroa et al., 2020), but that study was limited to two seasons (i.e., the *nortes* and dry seasons).

The present paper aims to provide a quantitative description of the seasonal and spatial variations in abiotic components (i.e., surface water temperature, salinity, and pH) linked to manatee distribution (calves and noncalves), over the Hondo River estuary. Moreover, the potential preferred conditions for manatees, in terms of temperature, salinity, and proximity to freshwater sources were identified.

## 2 | MATERIALS AND METHODS

### 2.1 | Study area

The study area is located along the Hondo River in the southeastern portion of the Yucatan Peninsula. It forms part of a complex system of lagoons, streams, and groundwater discharges (Figure 1). This region is located in the wet-dry tropics, with variable rainfall and run-off episodes due to tropical seasonality (Alcérreca-Huerta et al., 2019; Carrillo et al., 2009b; Gong & Shen, 2011; Shivaprasad et al., 2013). In the study area, a dry season (DrS) typically occurs between February and April with low precipitation (~100 mm) and decreases in the frequency and intensity of rainfall (Carrillo et al., 2009a; Orellana et al., 2009). The rainy season (RaS) occurs between May and October (~1,000–1,500 mm) and is mostly influenced by trade winds, storms, and hurricanes (Márdero et al., 2012). A mid-summer drought (regionally named *canícula*) occurs during July–August as a phenomenon in the Yucatan Plains and

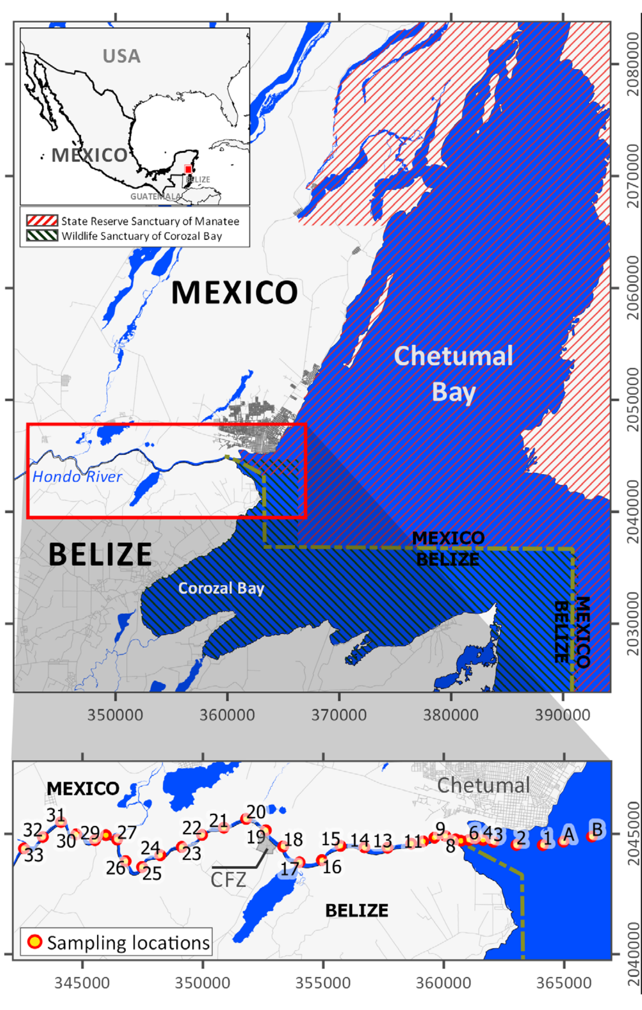


**FIGURE 1** The study area shows the location of the Hondo River, Chetumal Bay, surrounding water bodies, international limits, natural protected areas, and population settlements. The numbers and letters represent the sampling stations where monthly measurements were conducted.

the Caribbean in which high-pressure systems inhibit the formation of clouds, leading to decreased precipitation and increased solar radiation and temperature (Corrales-Suastegui et al. 2019; Magaña et al., 1999). From October to February, the region and the study area are under the influence of cold fronts with northerly wind directions (Mooers & Maul, 1998), leading to the locally known *nortes* season (NoS) (Carrillo et al., 2009b), which develops as a transition between the dry and rainy seasons (Walters et al., 1989).

The Hondo River is among the scarce surface streams within the Yucatan Peninsula. It is ~150 km in length and constitutes most of the international border between Mexico and Belize, sharing its basin with Guatemala. The Hondo River flows into the binational estuarine system of Chetumal-Corozal Bay (Mexico-Belize; Carrillo et al., 2009b), forming a delta featuring a funnel-shaped indentation on the western coastline of Chetumal Bay (Figure 1). The estuarine environment and the river serve as habitats for one of the largest populations of Caribbean manatees (Morales-Vela et al., 2000). However, only Chetumal and Corozal Bays are included in national programs for the conservation of manatees leading to natural protected areas (Figure 1): (1) the State Reserve Sanctuary of Manatee (SRSM) for ecological conservation in Mexico, which was declared in 1996 with an area of 2,813 $km^2$ and updated its limits in 2008 (Períodico Oficial Del Estado de Quintana Roo, 2008), and (2) the Wildlife Sanctuary of Corozal Bay (WSCB), which was declared in 1998 with an area of 720 $km^2$ (UNEP-WCMC & UICN, 2020).

The largest urbanized settlement in the study area is the city of Chetumal, with ~169,000 inhabitants in 2020 (INEGI, 2021). This city has developed over ~40 $km^2$ within the limits of the STSM and the river mouth (Figure 1). The establishment of the Corozal Free Zone (CFZ) in Belize, adjacent to the Hondo River and Mexico's border (Figure 1), forms part of the trading partnership between the two countries, owing to the retail sale of goods in the CFZ (Central Bank of Belize, 2018) that represent ~10% of the total exports out of Belize (Vivid Economics, 2019). Strategies to strengthen the economic activities of the CFZ are currently related to river management with an emphasis on tourism, cross-border commerce, riverine ports, and the agro-processing industry (Salas, 2015; Vivid Economics, 2019).

## 2.2 | Field measurements, sampling techniques, and data analysis

Monthly measurements of abiotic factors were conducted from February 2018 to December 2019 to consider the mean spatial and temporal variations that occur throughout the years. Water temperature, salinity, and pH were measured at a depth of 1 m from the surface employing a multiparameter Hanna HI9829 probe (Hanna Instruments, Mexico). The sampling locations comprised two stations; and are Station A (St. A) and Station B (St. B) within Chetumal Bay, nine stations over the river delta (St. 1–9), and 24 stations along the Hondo River course (St. 10–33), resulting in a 28-km-long transect (Figure 1). All stations refer to the distance from the river delta's downstream limit at St. 1. A distance of ~250 m was defined from St. 2 to St. 8 and of ~500 m from St. 8 to St. 12 to provide a higher resolution of the spatial variation of abiotic factors in the river delta, and a distance of 1 km was defined from St. 12 to St. 33 (Table 1). The increased resolution in and near the river delta was conducted to account for the measurement of possible relevant changes in temperature and salinity caused by the interaction between the Hondo River and Chetumal Bay.

Manatee distribution in the Hondo River was assessed from April 2018 to December 2019 (21 surveys). Direct sightings were performed visually by two observers using the boat as a floating observation platform and through a multibeam side-scan sonar. The visual and sonar sightings represent raw counts of manatees, but these measurements were not considered for population density estimations. The sightings were performed each month through 1-day surveys during daylight hours, along the ~28-km-long transect (St. 33–St. B; Figure 1). All surveys considered the same one-way direction from St. 33 to St. B. This avoided potential double-count of manatees due to their displacement along the study area.

The sightings covered a band/river width of nearly 30–40 m, leading to a total surveyed area of 1.12 $km^2$/month (112 ha/month), whereas the surveyed water volume totaled 9.3 million $m^3$/month when considering the use of

**TABLE 1** UTM-coordinates (16 N) of stations for field measurements along the Hondo River and the measured distance from the river delta's downstream limit.

| Station | X_UTM (m) | Y_UTM (m) | Distance[a] (km) |
|---|---|---|---|
| 33 | 342561 | 2044389 | 25.67 |
| 32 | 343346 | 2044865 | 24.64 |
| 31 | 344102 | 2045485 | 23.63 |
| 30 | 344734 | 2044973 | 22.63 |
| 29 | 345515 | 2044737 | 21.62 |
| 28 | 345966 | 2044939 | 21.12 |
| 27 | 346430 | 2044758 | 20.62 |
| 26 | 346785 | 2043860 | 19.61 |
| 25 | 347467 | 2043620 | 18.61 |
| 24 | 348227 | 2044109 | 17.62 |
| 23 | 349117 | 2044450 | 16.62 |
| 22 | 349956 | 2044948 | 15.61 |
| 21 | 350865 | 2045252 | 14.62 |
| 20 | 351789 | 2045613 | 13.62 |
| 19 | 352609 | 2045143 | 12.62 |
| 18 | 353329 | 2044470 | 11.62 |
| 17 | 354007 | 2043817 | 10.61 |
| 16 | 354936 | 2043901 | 9.62 |
| 15 | 355711 | 2044494 | 8.62 |
| 14 | 356704 | 2044434 | 7.62 |
| 13 | 357664 | 2044416 | 6.61 |
| 12 | 358647 | 2044586 | 5.61 |
| 11 | 359140 | 2044684 | 5.11 |
| 10 | 359612 | 2044839 | 4.61 |
| 9 | 360071 | 2044904 | 4.12 |
| 8 | 360494 | 2044766 | 3.66 |
| 7 | 360712 | 2044707 | 3.44 |
| 6 | 361044 | 2044741 | 3.10 |
| 5 | 361336 | 2044801 | 2.80 |
| 4 | 361633 | 2044741 | 2.50 |
| 3 | 362061 | 2044667 | 2.06 |
| 2 | 363014 | 2044531 | 1.10 |
| 1 | 364110 | 2044527 | 0.00 |
| A | 364969 | 2044675 | −0.86 |
| B | 366149 | 2044879 | −2.06 |

[a]Distance measured from the downstream limit of the river delta (St. 1) before reaching Chetumal Bay (Figure 1).

scanning sonar and the mean water depth in the riverine estuary (i.e., 8.3 m). All surveys were conducted in a boat moving at an average speed of ~8 km/hr to maintain good sonar imagery quality. Additionally, 5 min stops at each station (Table 1) were conducted for water sampling of surface temperature, salinity, pH, and water depth. Due to the higher concentration of stations around the river delta, the time spent was reduced at each stop in this region to keep a survey effort similar to that along the river estuary while ensuring the measurement of the relevant temperature and salinity variations. The total effort expended during the survey period from 2018 to 2019 was approximately 128.4 hr, including the travel time of the boat and station stops. Each survey was on average 6.4 hr long, considering the same stations, with the same observers on board along the 2-year period and of similar experience.

A Humminbird 899cxi HD SI sonar unit with an integrated GPS (Humminbird USA) was used with a 200/83 kHz DualBeam PLUS sonar system and a side imaging sonar frequency of 455 kHz, thus allowing the recording of images, the georeferenced locations of manatees, and water depth measurements. The full recordings of each survey, covering the ~28 km transect over the riverine estuary, were analyzed with SonarTRX-PRO v18.1 to visualize and identify the manatees' profiles, shapes, and exact locations. The high-resolution images used for the manatee identification obtained during the surveys corresponded to the characteristics of manatees as described by Gonzalez-Socoloske et al. (2009) in terms of the shape of the caudal fin, the curvature of the manatee body, and the projection of manatees (shadow) on the river bottom (Figure 2). Sonar was used as a complementary and effective low-cost alternative for acoustically detecting manatees. This method has been successfully applied in both turbid waterways and relatively clear waters (Gonzalez-Socoloske & Olivera-Gómez, 2012; Gonzalez-Socoloske et al., 2009; Niezrecki, 2010; Puc-Carrasco et al., 2017) with high detection rates (>80%) (Gonzalez-Socoloske & Olivera-Gómez, 2012; Gonzalez-Socoloske et al., 2009). Due to storm and rain events, no manatee detection was possible during each of August 2018 and 2019.

Validation process was conducted for sonar records without a visual corroboration in the field. The sonar images were evaluated independently by B.M.-V. and three external experts with many hours of experience in sonar manatee detection. Images without any or with a single positive confirmation from the reviewers were not included in the analyses.

An ID code was set for each manatee detection (i.e., GxxxMxxx_YYYYMMDD), where Gxxx indicates the number of the group of manatees (herein defined as two or more manatees observed within a separation of <50 m), Mxxx is the number of manatees within the group, and YYYYMMDD is the date of observation set by the year (YYYY), month (MM) and day (DD). All manatee observations were georeferenced using the sonar unit or through a

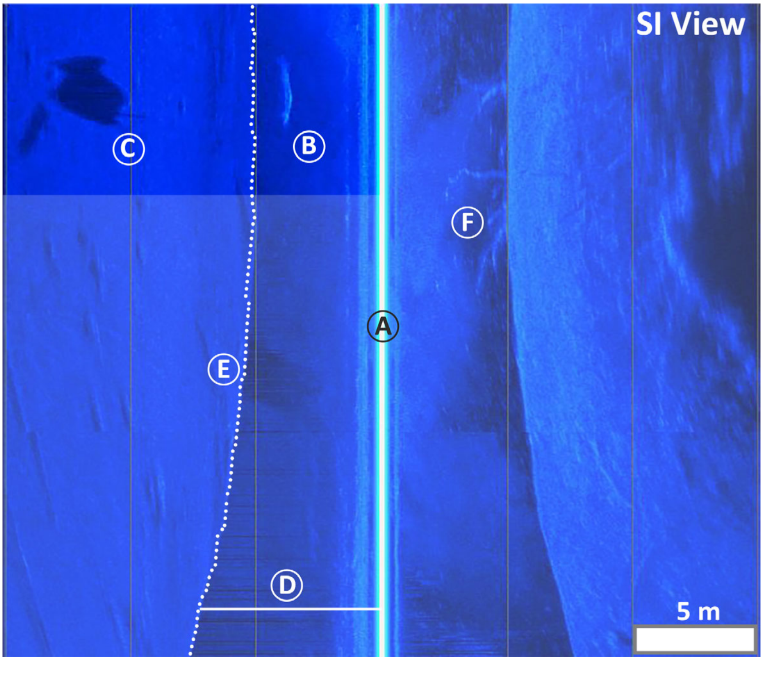


**FIGURE 2** Elements of a high-resolution side imaging (SI) view from a typical manatee identification record in the Hondo River: (A) central line of navigation, (B) manatee body, (C) manatee projection (shadow) on the river bottom, (D) water column, (E) river bottom, and (F) tree branches.

handheld marine GPS Garmin GPSMAP-78. The surface water temperature and salinity data were related to manatee observations by considering the nearest station measurements to each sighting.

A cluster analysis was performed assuming a complete linkage method and correlation coefficient distances. Thus, similarities among the surface temperature, salinity, depth (obtained with the echosounder at each station), and monthly variation measurements were estimated. The joint relative frequency of surface water temperature and salinity was also calculated through a contingency matrix, for which the classes were defined through the Sturges' formula. The temporal and spatial surface water temperature ($T_{AV}$), salinity ($S_{AV}$), and water depth ($h_{AV}$) were calculated at each station and for each month, through the average value of the two measured years (2018–2019). Salinity gradients ($\Delta S_{AV}/\Delta d$) were estimated to identify the separation of the estuarine river environment from that characterized by freshwater conditions.

Descriptions of the spatial and temporal distributions of manatees were obtained based on the observed seasonality in the study area, the distance from the downstream limit of the river delta, and the number of individuals within a given group. Histograms were obtained in consideration of a calf/noncalf classification. Furthermore, a kernel density estimation (KDE) was applied through the QGIS software plugin to obtain a heatmap in a geographical information system (GIS) (Athan et al., 2013) representing, independently of time, the concentrations of manatees and their locations within the Hondo River estuary and its delta. The kernel bandwidth used for the heat map was specified at 250 m with the spatial resolution provided by the existing minimum distance between the stations and to maintain the individual variations among the stations. Heatmaps are commonly used to detect relevant areas of natural and anthropic interactions (Semeyn et al., 2011).

The relations of the surface temperature and salinity with manatee presence were estimated by means of the graphical representation of the convergence matrix. The convergence matrix allows the description of the possible thermal and saline conditions (temperature/salinity intervals) at which manatees were observed. These temperature and salinity values could be used to identify possible comfort conditions that are adequate for manatees at which their physiological response involves the minimal energy consumption necessary for the development of their activities. This concept differs from that of the thermal threshold of survivability (i.e., 17°C–19°C), which is related to cold stress syndrome (CSS) (Bossart et al., 2002; Reynolds et al., 2018). The comfort conditions should be understood as they are normally described for humans (e.g., Olesen et al., 2001; Santamouris, 2019) and have been observed/developed in certain manatee studies and field observations (Gallivan et al., 1983; Laist & Reynolds, 2005; Rosas, 1994). The maximum, minimum, and standard deviation values of the water surface temperature and salinity are also provided.

## 3 | RESULTS

### 3.1 | Water abiotic factors

The average pH of the surface waters was 8.15, 8.02, and 8.60 in the Hondo River estuary, its delta, and Chetumal Bay, respectively. In general, pH was almost constant in the study area, with an average value of 8.14 ± 0.03 considering all the stations. Therefore, the pH was decided not to be considered in subsequent analyses. The cluster analysis showed that surface temperature and time (months) were associated with more than 70% similarity. A lesser relationship was noticed between time and salinity, which presented 60% similarity. Water depth resulted in an external group, which represents a completely independent variable with values of less than 22% similarity.

The spatial and temporal variations in water surface temperature ($T_{AV}$) and salinity ($S_{AV}$) over the study area are shown in Figure 3. The minimum and maximum $T_{AV}$ values registered were $T_{AV,min} = 26.2°C$ and $T_{AV,max} = 31.5°C$. Based on the results of the cluster analysis and the average water surface temperature (Figure 3a), the following seasonal and spatial variations were described:

- *Nortes season (NoS)*. The lowest surface water temperatures were recorded within this season ($T_{AV} = 26.0$–$27.4°C$) and were linked to cold fronts occurring during November–March (Figure 3a). The spatial distribution was almost uniform along the riverine estuary, with a very slight increase in temperature ($\Delta T_{AV}/\Delta d = 0.04°C/km$) measured in the downstream region. A wider fluctuation in temperature was observed within the extent of the river delta and Chetumal Bay (i.e., from St. 1–9, St. A, and St. B). In the river delta, increasing water temperatures of $\Delta T_{AV}/\Delta d = 0.06°C/km$ resulted from the upstream to the downstream direction during January–February, but with a general decreasing value ($\Delta T_{AV}/\Delta d \approx 0.25°C/km$) during November–December (Figure 3a). The latter

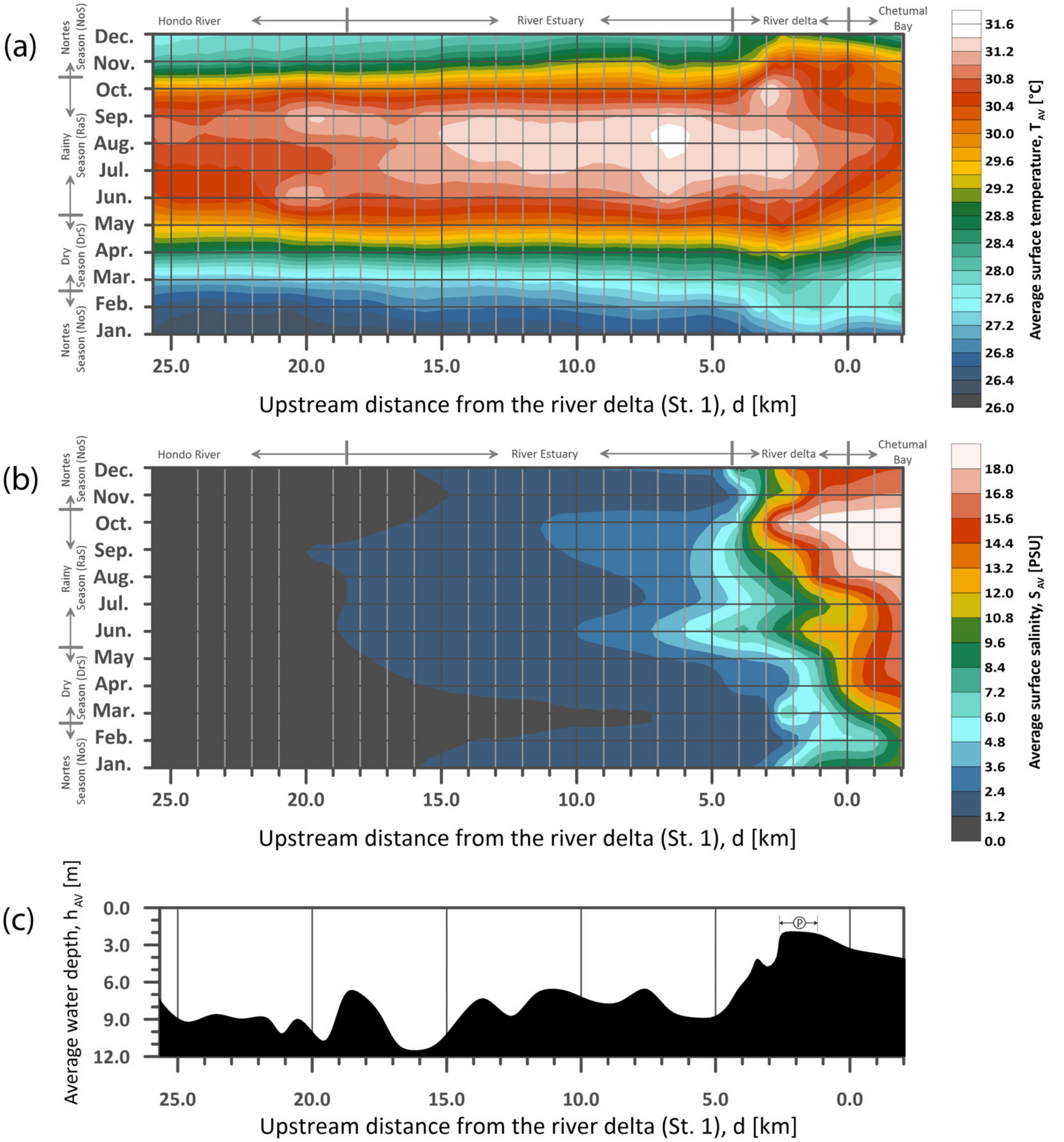


**FIGURE 3** Average spatial and temporal variations in surface temperature and salinity measured during 2018–2019 referred to the river delta's distance upstream. (P) denotes an observed platform within the limit of the riverine estuary and the delta from d = 1.1–2.5 km.

describes the state in which Chetumal Bay is colder than the riverine estuary and its delta for these two months (November and December), corresponding to the tendency of the rainy season.

- *Dry season (DrS)*. The surface water temperature was within the interval of $T_{AV} = 27.4–29.8°C$, with an increasing trend observed for temperatures (1.2°C/month) between March and May. This increase was almost uniform throughout the study area, similar to the trend observed during the NoS. Slight changes were noticed in the river delta but did not exceed $\Delta T_{AV}/\Delta d = 0.03°C/km$.
- *Rainy season (RaS)*. An increase in the surface water temperature occurred, with $T_{AV} > 30.0°C$, during the first months of the rainy season (May–July) up to a maximum peak resulting from the mid-summer drought. The maximum temperature was recorded in August 2018 ($T_{max} = 32.8°C$) (Figure 3a). High $T_{AV}$ values were found at $d = 2–15$ km in the riverine estuary during July–September, representing the warmest area and period. Outside the estuary, the temperatures ranged from $30.4°C < T_{AV} < 31.2°C$. After the mid-summer drought and before the NoS (i.e., August–November), the $T_{AV}$ values decreased nearly 1.2°C/month. The riverine estuary and the delta were warmer than Chetumal Bay, a tendency continued from the RaS and also observed during the first months of the NoS.

Notably, the temperature interval of $T_{AV} = 29.0–30.0°C$ measured along the study area mostly developed over short periods (i.e., one month) and as a seasonal transition into and out of the rainy season. Therefore, warmer-rainy (RaS, with $T_{AV} > 30°C$) and colder-dry conditions (NoS and DrS, with $T_{AV} < 29°C$) were identified in the estuarine environment depending on the season.

The salinity gradient varied with a continuously increasing tendency of $\Delta S_{AV}/\Delta d > 0.08$ PSU/km, starting from ~17.6 km upstream towards the river delta. This salinity gradient is caused by the influence of Chetumal Bay, where the maximum salinity values were reached ($S_{AV} > 18.0$ PSU) (Figure 3b). Thus, the Hondo River estuary characterizes the transition between the maximum upstream limit of freshwater conditions (St. 24) and the beginning of the river delta (St. 9) (Figure 1).

The riverine estuary exhibits a monthly surface salinity ranging from 1.2 to 7.2 PSU. The maximum extent of salinity in the estuary occurred amid the RaS and NoS. Lower $S_{AV}$ values were registered in February, but the estuary's minimum extent is given at $d = 7$ km during March, with $S_{AV} > 1.2$ PSU (Figure 3b). A bimodal behavior of the river estuary was observed, with peaks during June and September (RaS). The slight decrease in the estuary extent observed towards Chetumal Bay in August coincides with the mid-summer drought (Figure 3a). The transition between the DrS and RaS (i.e., June) in the riverine estuary resulted in higher $S_{AV}$ values measured along the estuary with mean salinity gradients of 0.5 PSU/km and up to 1.9 PSU/km close to the river delta. The salinity gradients in the river delta increase downstream throughout the year with a mean salinity gradient of 2.1 PSU/km and a maximum salinity gradient of 3.1 PSU/km recorded in October and December. The salinity values in the sampled locations within Chetumal Bay ranged from 9.8 to 19.4 PSU, i.e., nearly one order of magnitude higher than those measured in the riverine estuary.

The results of the water depth ($h_{AV}$) are described in Figure 3c. A mean water depth of 8.3 ± 1.4 m was determined within the estuary. The bathymetric changes show a highly irregular river bottom ($h_{AV} = 6.5–11.3$ m). A remarkably prominent mound was observed 16.6–19.6 km from the river delta with a minimum $h_{AV} = 6.6$ m that was coincident with the riverine estuary's defined upstream limit. Similarly, the downstream limit was given by the starting point at which a mound was developed. The mound spans the river delta, and a drastic bathymetric change was observed at approximately $d = 2$ km, where $h_{AV}$ passes from 8.1 m to 1.9 m before reaching Chetumal Bay (Figure 3c). A flat platform (P) was observed in the riverine estuary on top of the mound, extending nearly 1.4 km with $h_{AV} = 2.0$ m (Figure 3c). This platform provides a physical barrier with a significant influence on the water temperature and salinity, possibly describing the following relevant fluctuations in the study area:

- Warmer conditions occurred over the river delta mound's top platform throughout the year (0.5–1.0°C) and were mainly recorded at the beginning of the NoS (Figure 3a). These conditions are possibly caused by the effects of solar radiation on the shallow waters of the platform ($h_{AV} = 2.0$ m; Figure 3c) and over a wider area (Figure 1).
- The salinity gradients reached their maximum values at the river delta (1.9–3.1 PSU/km). The delta limits the extension of freshwater conditions ($S_{AV} < 1.2$ PSU) into Chetumal Bay during the NoS, as well as salinity intrusions into the riverine estuary ($S_{AV} > 16$ PSU) during the RaS (Figure 3).
- The platform modifies the river flow by reducing the river depth, which increases the flow velocity. However, this effect is compensated for by the widening of the cross-section of the river delta (Figure 1).

## 3.2 | Spatial and temporal manatee observations

From manatee sightings, 77% were visually confirmed in the field, whereas 23% resulted from sonar records without a visual corroboration in the field, but that were validated by experts to confirm the possible manatee presence. Only four individuals were not confirmed through the validation of the sonar images (i.e., approximately 4.5% of all expected sightings). Additionally, 57% of the sightings resulted from detections that occurred during boat motion. Evidence of visual sightings of manatees and sonar detections are given in Figure 4. The manatees and group sizes were identified during 2018–2019. Both calves and noncalves were detected during the surveys (e.g., G032M048-049_20190406, G047M082-084_20191203, G001M001-002_20180501; Figure 4). Calves were distinguished by their continued proximity to an adult individual and their relatively small size. Furthermore, individuals and groups not noticed during sightings were identified through sonar methods (e.g., G004M005-006_20180502, G041M068-073_20190706; Figure 4).

The temporal and spatial distributions of the manatees are shown in Figure 5, with distinction between calves and noncalves. A larger number of manatee observations occurred during April, May, July, and December than during other months, with 19.0%, 13.1%, 32.1%, and 15.5% of the total sightings reported during 2018–2019, respectively, together representing nearly 79.7% of all observations.

The RaS (June–October) presented most of the observations, with 40 individuals (47.6%) compared to those of the DrS (34.5%) and NoS (17.9%), even though no manatees were observed in August (Figure 5a). Further monthly peaks of manatee observations showed delays of 1–2 months from the corresponding seasonal changes.

From January to March 2018, a possible underestimation of manatee detections could be expected, as only visual surveys were conducted during this period. The last months of the NoS and beginning of the DrS (January–March) only represented 3.4% of the total number of observations, related to water surface temperatures of $T_{AV} < 28.8$°C and salinity values of $S_{AV} > 2.4$ in the river delta and Chetumal Bay (Figure 3). Manatee calves were observed by the end of the DrS, beginning of the RaS, and in the first months of the NoS. Calves represented approximately 11.9% of the total observations, of which 60% took place during the DrS-RaS.

Approximately 63.1% of the manatees were observed at the transition between the river delta and the riverine estuary during 2018–2019. At this location, warmer temperatures were typically observed throughout the year, and the area provided a varying depth profile ranging from shallow waters over the river delta (i.e., $h_{AV} \approx 2.0$ m) to deeper zones in the river ($h_{AV} \approx 6.0$–8.0 m). These water depth changes provide broader conditions that manatees could benefit from, such as light, solar exposure, sheltering, or thermal regulatory zones. The manatee sightings were maximal at the transition between the river estuary's maximum extent and the upstream freshwater conditions of the Hondo River ($d \approx 15$–21 km) (Figure 5b), with nearly 15.5% of the total manatee observations. A further peak was noticed at $d \approx 9$–12 km with ~5.9% of the observations. These three peaks were accompanied by observations of calves at a frequency of ~1–6 individuals per month (Figure 5b).

The manatee sighting locations recorded during 2018–2019 are represented through the heatmap in Figure 6. Most of the manatees were found in the river delta ($d \approx 0$–4.1 km), as well as in the upper ($d \approx 17.6$ km) and lower ($d \approx 4.1$ km) limits of the riverine estuary. The observation peaks described in Figure 5b at $d \approx 19$–21 km and $d \approx 9$–

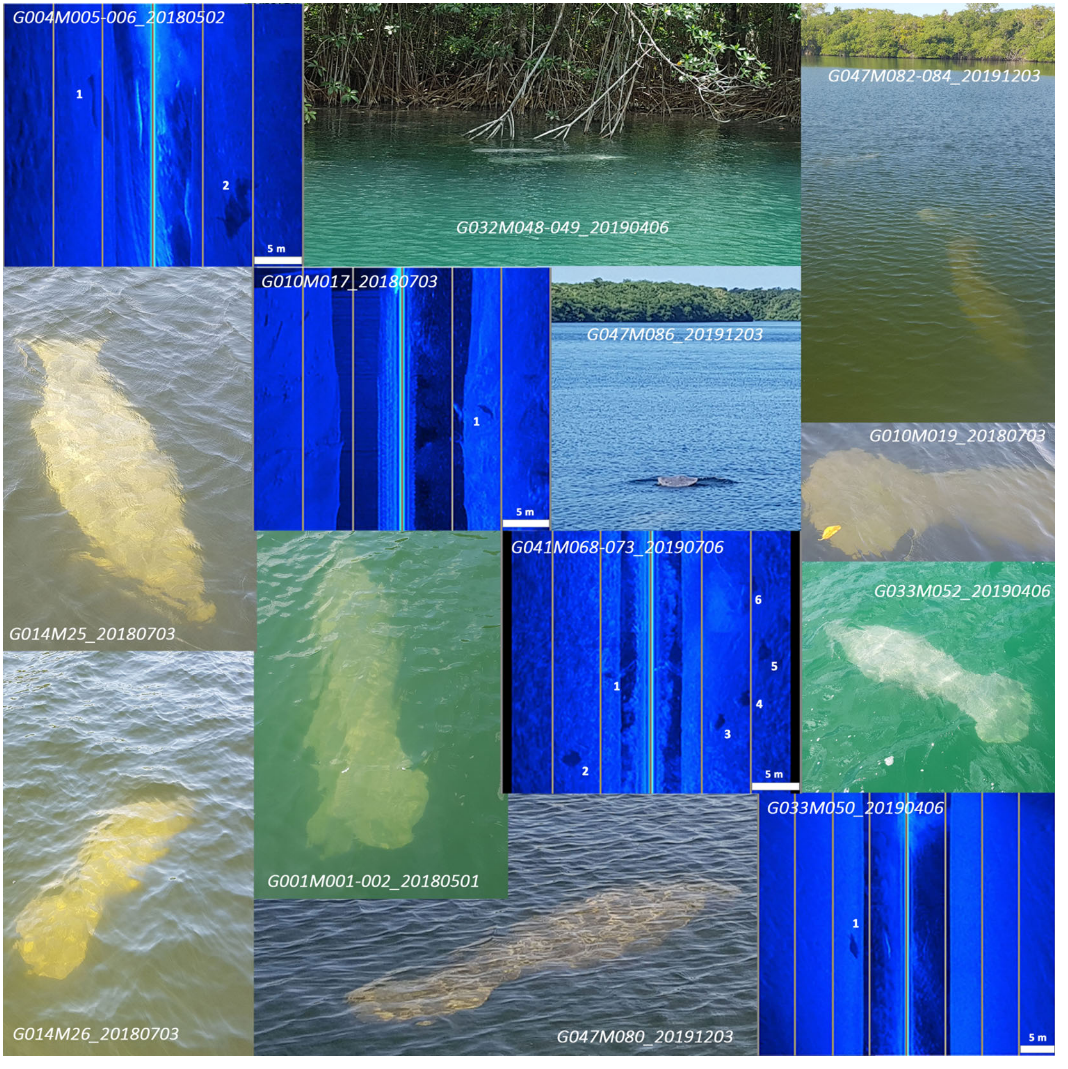


**FIGURE 4** Evidence of manatee observations along the study area from sightings and echo-sounding methods conducted during field surveys during 2018–2019.

12 km correspond to the Hondo River's connection with the Chaac River (a tributary of the Hondo River) and the Four Miles Lagoon. The field surveys conducted during 2018–2019 accounted for the Chaac River, but no manatees were observed over its course or up to the confluence with Milagros Lagoon. Sightings of manatees at the mouth of the Four Miles Lagoon and the river delta were accompanied in some cases by the presence of a small group of dolphins (~2–4 individuals).

During the field surveys, river segments were noticed with scarce or no observed manatees (Figure 5b and Figure 6). The manatees were distributed in small groups, mainly at the confluences between water bodies or streams. Groups of 2–3 manatees were observed but ranged as high as nine individuals (Table 2). Approximately 56.8% of the visual sightings of manatees and sonar detections consisted of solitary manatees, mostly observed during the RaS. Manatee groups of two individuals represented 20.5% of the sightings, of which adult-calf pairs represented 66.6%. Manatee groups with more than three individuals represented 9.1% of the observations.

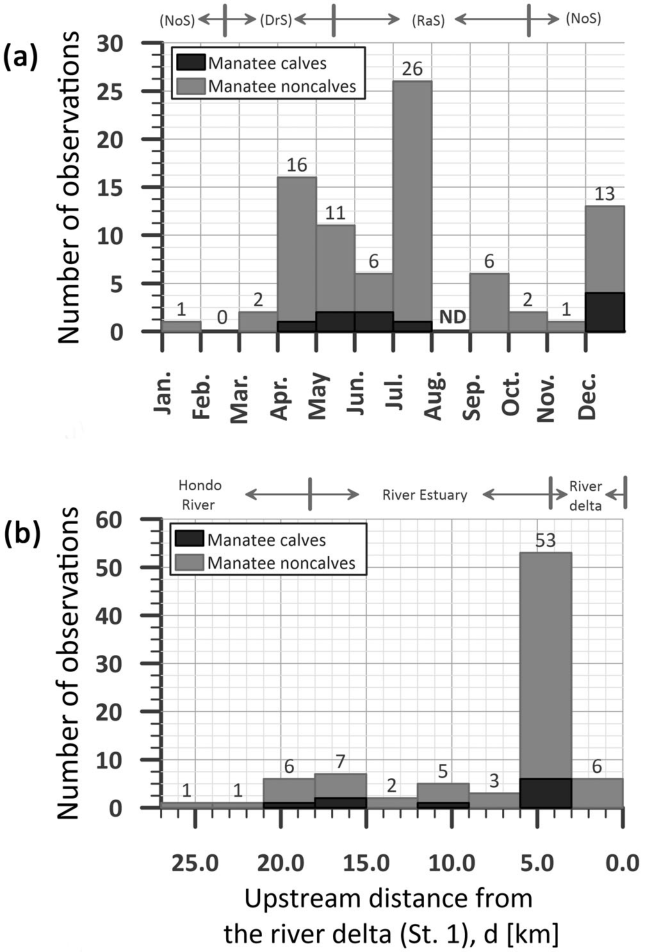


**FIGURE 5** Number of observations of total manatee calves and noncalves during 2018–2019 considering the (a) month and (b) distance upstream from the Hondo River delta.

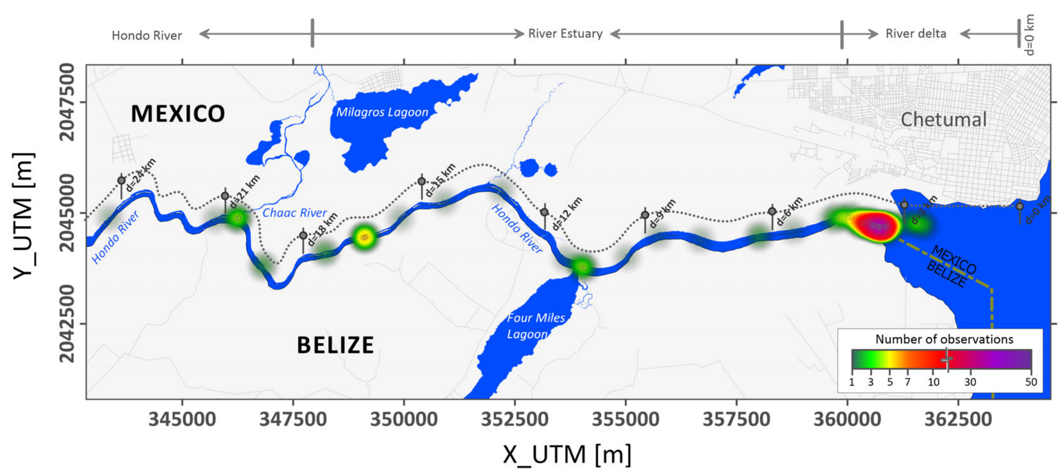


**FIGURE 6** Heat map of manatee observations recorded along the Hondo River, the river estuary, and the river delta during 2018–2019. The upstream distance from the river delta is marked with a dotted line.

**TABLE 2** Relationship of the number of manatees in the groups observed during 2018–2019 by season.

| Manatees in a group | # of groups NoS | DrS | RaS | Total | Percentage |
|---|---|---|---|---|---|
| 1 | 6 | 8 | 11 | 25 | 56.8% |
| 2 | – | 3 | 6 | 9 | 20.5% |
| 3 | – | 4 | 2 | 6 | 13.6% |
| 4 | – | 1 | – | 1 | 2.3% |
| 5 | – | – | 2 | 2 | 4.5% |
| 9 | 1 | – | – | 1 | 2.3% |
| Total of groups | | | | 44 | 100.0% |

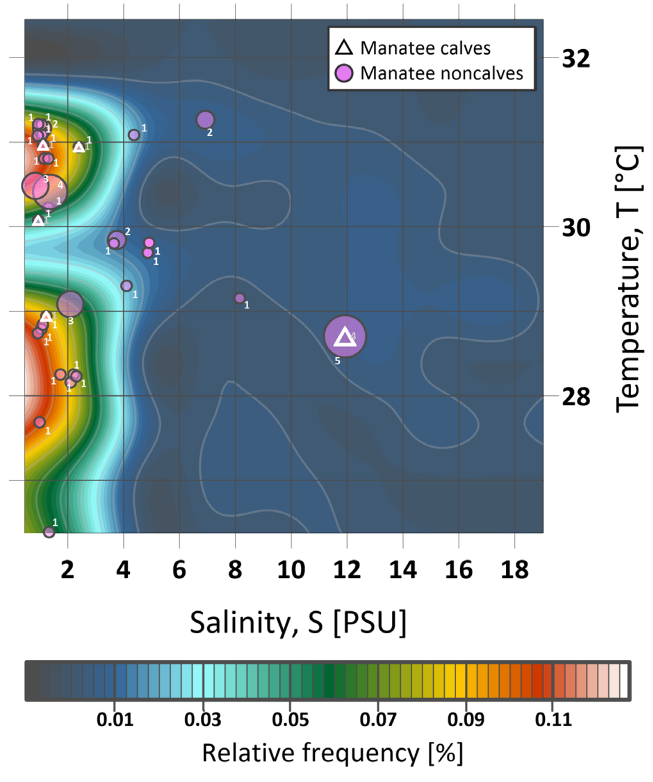


**FIGURE 7** Joint relative frequency of surface temperature and salinity in the whole study area and of manatees (triangles = calves, circles = noncalves) during 2018–2019. The bubbles represent the number of observations of manatees; the sizes from small to large range from 1 to 5.

The joint relative frequency of water surface temperature and salinity is given in Figure 7. This frequency depicts the number of manatees related to the salinity and temperature conditions during their sighting. The conditions for manatees in the Hondo River during 2018–2019 are given by T = 26.0–32.8°C, S = 0.5–22.6 PSU and, $T_{mean}$ = 29.1 ± 1.6°C and $S_{mean}$ = 3.4 ± 4.8 PSU. The temperature interval was limited during 2018–2019, while salinity showed a broader range of variation.

Two primary riverine temperature conditions were identified despite the typical seasonality in the region (NoS, DrS, and RaS). These conditions are described as warmer-rainy (the RaS and part of the NoS, with $T_{AV}$ > 30°C) and colder-dry (the NoS and DrS, with $T_{AV}$ < 29°C) with two 1-month transitional periods, relating to 48.5%, 27.3%, and 24.2% of manatee sightings, respectively (Figure 7). Surface salinity was found to be mostly within the interval of 0–4.5 PSU with ~78% of the sightings. Manatee groups (1–5 individuals) were also identified at salinities up to 12 PSU, including both calves and noncalves.

**TABLE 3** Contingency table of water surface temperature and salinity matching manatee observations.

| | Surface temperature (°C) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Surface salinity (PSU)** | **26.8** | **27.6** | **28.4** | **29.2** | **30.0** | **30.9** | **Sum** |
| **1.8** | 0.03 | 0.03 | 0.17 | 0.08 | 0.08 | 0.28 | 0.67 |
| **3.7** | 0.00 | 0.00 | 0.00 | 0.03 | 0.06 | 0.03 | 0.11 |
| **5.5** | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | 0.03 |
| **7.3** | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | 0.03 | 0.06 |
| **9.2** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **11.0** | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.03 |
| **Sum** | 0.03 | 0.03 | 0.19 | 0.14 | 0.17 | 0.33 | |

*Note*: Both salinity and temperature values refer to the class marks (midpoint of the interval considered). Manatee sightings without temperature and salinity measurements consisted of nearly 10%.

About 83% of manatees were linked to T > 28°C (Table 3). Of all recorded manatees, 50% were observed at T > 30°C, and 33% were observed at 28°C < T < 30°C (Figure 7). All calves were found at T > 28°C, with the peak number of sightings recorded during December. Regarding the salinity values, 78% of manatees were found at 0.5–4.5 PSU. Summaries of the seasonal variability in abiotic factors, the manatee distribution along the study area, and the spatial features are given in Figure 8.

## 4 | DISCUSSION

The spatial and temporal distributions of 84 individual manatee sightings (noncalves: 88.1%, calves: 11.9%) were reported along the estuary and delta of the Hondo River during 2018–2019 (Figure 5 and Figure 6). The maximum number of sightings per survey (of 18 individuals) was reached during July 2018, whereas no detection occurred in October 2018 or February 2019. Other peaks of manatee sightings occurred during April and May (DrS), in agreement with the findings described by Corona-Figueroa et al. (2020) for the study area. However, another smaller peak occurred in December (NoS). A higher number of female-calf pairs observed in December than at other times throughout the study period could be associated with the ability of females to select warm water areas for their calves during the occurrence of cold fronts (Marsh et al., 2011; Reynolds & Odell, 1991). This record of females and calves in December coincided with an aerial survey of the manatee distribution over Chetumal Bay during a cold front (December 4–5, 2019), in which a significant and unusual proportion of manatees aggregated in a small area of the southwest coast of Chetumal Bay was observed (Morales-Vela & Prado-Cuellar, 2020), including the delta of the Hondo River (B.M.-V., personal observation). Also, evidence of how a released 16-year-old orphan Caribbean manatee radio-tracked responds to the severe cold fronts in Chetumal Bay is described (Morales-Vela & Prado-Cuellar, 2020). Additionally, the effects of the regional mid-summer drought that occurs during July were detected in the temperature ($T_{AV}$ > 30.4°C) and salinity ($S_{AV}$ > 18.0 PSU) measurements as well as in the extent of the estuary (reaching higher values); but also describing the maximum peak number of manatee sightings (~30.9%). In contrast to the results of the study by Corona-Figueroa et al. (2020), which was limited to the DrS and NoS, the largest count of manatees in the riverine estuary was recorded in this study during the RaS with ~47.6% sightings. This could occur due to seasonal changes in temperature and salinity, which decrease during colder-dry conditions in the DrS and NoS (Morales-Vela et al., 2000).

The manatee heatmap (Figure 6) and the spatial distribution of abiotic variables (Figure 3) identified key locations for manatees directly linked to the riverine estuary. These locations mainly corresponded to the confluence of the Hondo River with other watercourses (i.e., the Chaac River in Mexico) or water bodies (i.e., Four Miles Lagoon in

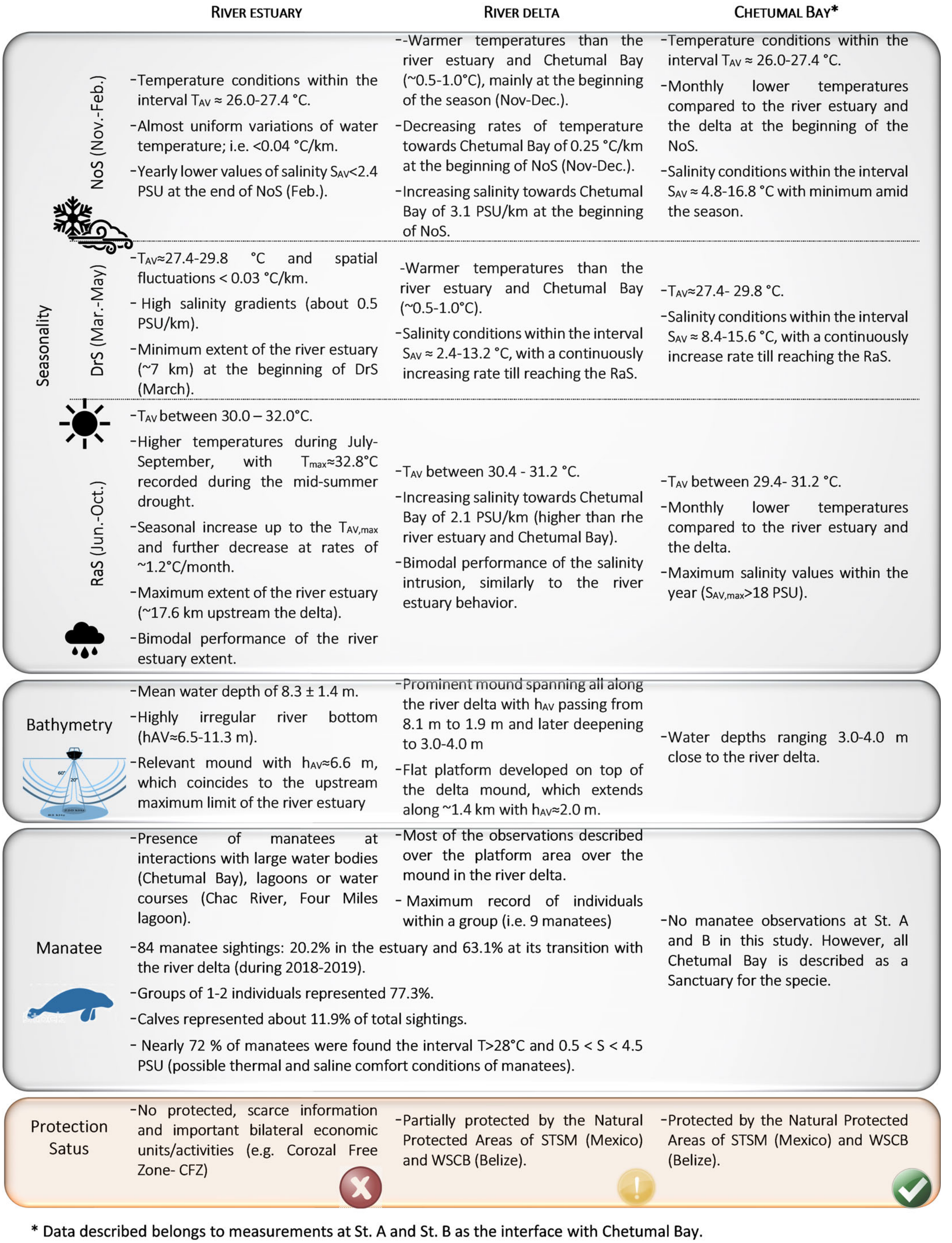


**FIGURE 8** Summary of the seasonal variability in abiotic factors, their distributions along the study area, and the spatial features of manatees obtained from the results.

Belize; Chetumal Bay in Mexico; Corozal Bay in Belize) as well as at the upstream and downstream limits of the estuarine environment (frontal areas). These results are consistent with those of Corona-Figueroa et al. (2020), in which approximately 88.1% of the manatees were in these areas within the river estuary segment. Similar findings were reported for the hydrological basin comprising the Usumacinta and Grijalva rivers in the southern Gulf of Mexico (Jiménez-Domínguez & Olivera-Gómez, 2014) and for other systems, such as the San San River in Panama (Gonzalez-Socoloske et al., 2015). The response of manatees in the Hondo River estuary outlined a seasonal behavior similar to that described for the Amazonian (Marmontel et al., 1992) and African manatees (Powell, 1996), which move to the upstream regions of estuaries during the RaS and return to lower reaches (e.g., river deltas) during the DrS.

The field measurements conducted in this study contributed to the detailed description of the seasonal/spatial distributions of water surface temperature, salinity, and the maximum estuarine extent into the river (>17 km upstream). Side-scan sonar was confirmed as a valuable tool for manatee detection and was used to complement visual sightings and enhance specific information on the species' current distribution (Arévalo-González et al., 2014; Gonzalez-Socoloske & Olivera-Gómez, 2012; Puc-Carrasco et al., 2016, 2017; Serrano et al., 2017).

The results showed two seasons largely defined by temperature: (1) warmer-rainy (RaS, with $T_{AV} > 30^\circ$C) and (2) colder-dry conditions (NoS and DrS, with $T_{AV} < 29^\circ$C), with 1-month transitional periods between them with $T_{AV} \approx 29.0$–$30.0^\circ$C. According to the highest recorded salinity values, the estuary's maximum extent was noticed during the NoS. The effect of northerly winds in the NoS with a western component (i.e., winds coming from the west-northwest, northwest, or north-northwest direction) could drive a water level decrease on Chetumal Bay's west coast, that might enhance the river discharge and the retreat of the riverine estuary towards Chetumal Bay.

The joint relative frequency of thermal and saline water conditions ranged in the interval of $28^\circ\text{C} < T < 32^\circ\text{C}$ and $0.5\ \text{PSU} < S < 4.5\ \text{PSU}$ for ~72% of the manatee sightings. This high joint frequency of manatee sightings within relatively small surface water temperature and salinity intervals over the two studied years reveals the potential preferable conditions for manatees in the Hondo River estuary. The temperature intervals are more than 8°C above the threshold limit established for preventing CSS in the Florida manatee. Thus, these environmental conditions could reduce energy and maintenance costs for manatees (Buckingham et al., 1999; Irvine, 1983; Langtimm et al., 2011). The water conditions ($T > 28^\circ$C) determined in this study are similar to those described for the Amazonian (Gallivan et al., 1983; Rosas, 1994) and Caribbean manatees due to their low metabolic rate and limited ability to generate heat (Davis, 2019; Irvine, 1983). Manatee thermoregulation requires further research, as it is recognized as being important for recognizing the interaction of manatee species with their habitats (Erdsack et al., 2018). Salinity is also an important factor since low salinity relates to freshwater drinking sources, that could explain the manatee's distant travel upstream during the RaS, when the riverine estuary extent is at its maximum. About 78% of the observed individuals were found at 0–4.5 PSU, near the riverine estuary's frontal areas. Although they can tolerate a wide range of salinity conditions, studies have shown that dehydration can occur in manatees after an extended period of freshwater deprivation (Ortiz et al., 1998). A further reason for manatees being found upstream near the limits of the riverine estuary could be that changes in salinity provide an osmotic shock mechanism used by the manatee to maintain skin epibiont control, as is the case for barnacle (Hartman, 1979) and tanaid infestations (Morales-Vela et al., 2008).

These tentative environmental comfort conditions were related only to physical factors. Additional elements could be associated with manatee presence, such as access to shore vegetation and the avoidance of boats or the development of anthropogenic activities. The identification of apparently comfortable spaces requires further review and assessment in other areas or conditions before these spaces can be considered as a generality. Nevertheless, the Hondo River estuary could constitute a warm-water refuge ($T > 28^\circ$C), a sheltered environment, and an area with fresh drinking water (0.5–4.5 PSU) for manatees. It also represents a corridor for manatees traveling outside-inside the Mexico-Belizean sanctuary boundaries in areas that are not yet protected, as only half of the delta is under protection status.

The management and protection of endangered species such as manatees involve understanding their population patterns and obtaining fully comprehensive descriptions of their environments (Flamm et al., 2005; UNEP, 2010). Thus, the interpretation of these results is given with caution, as further research might be needed assuming that the surveyed area is relatively small compared to the home range of the subspecies and that surveys were only conducted during the daylight hours. The manatee sightings were relative to the survey effort and were used to relate manatee presence with environmental information. However, the identification of comfort conditions could broaden perspectives regarding the ways in which manatees interact with their surrounding environment. Long-term studies that include bias estimations for manatee detection methods might be required to better understand the role of abiotic factors in adaptative and integrated coastal zone management under the area's binational framework.

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## AUTHOR CONTRIBUTIONS

**Mariana Callejas-Jimenez:** Conceptualization; data curation; formal analysis; investigation; methodology; software; visualization; writing-original draft; writing-review & editing. **Benjamin Morales-Vela:** Methodology; resources; supervision; validation; writing-review & editing. **Laura Carrillo:** Resources; supervision; validation; writing-review & editing.

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