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Hydrological dynamics, trophic status, and social perception of the Arroyo Moreno peri-urban estuary in the southwestern Gulf of Mexico

Dinámica hidrológica, estado trófico y percepción social del estuario periurbano Arroyo Moreno en el suroeste del Golfo de México

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RESUMEN

Antecedentes. El estuario Arroyo Moreno se encuentra inmerso en la zona conurbada Veracruz-Boca del Río-Medellín, las actividades antropogénicas afectan su dinámica hidrológica y provocan su deterioro. **Objetivo**. El presente estudio analiza la hidrología y el estado trófico del estuario periurbano Arroyo Moreno a través del análisis de factores fisicoquímicos, grado eutrófico y percepción social del estado ambiental. **Métodos**. Se realizaron muestreos en seis sitios durante un año. Se aplicaron 106 entrevistas a personas que conocen el estuario. Se registraron *in situ* la temperatura, pH, sólidos disueltos totales, salinidad (superficie y fondo) y oxígeno disuelto. Se aplicó un análisis de componentes principales, escalado multidimensional no métrico e índice trófico TIDO-pH. **Resultados**. La salinidad fue de 0.27 ±0.07 a 23.64 ±4.24, temperatura del agua de 25.71 ±0.75 °C a 33.13 ±2.38 °C, oxígeno disuelto de 0.32 ±0.11 a 6.33 ±1.60 mg/ml, sólidos disueltos totales de 284 ±69.64 a 28824 ±9816.60 ppt y pH de 7.05 ±0.03 a 7.9 ±0.30. El TIDO-pH mostró un estado eutrófico. La descarga de agua del canal de la central termoeléctrica aumentó la temperatura del agua y modificó su circulación. La descarga de aguas residuales y la suspensión de sedimentos dieron como resultado bajas concentraciones de oxígeno disuelto. **Conclusiones**. Los análisis mostraron que el Arroyo Moreno es un sistema hidrológicamente dinámico, debido a las tempordas climáticas, influencia de la marea y las descargas de aguas residuales de la zona urbana. Las personas entrevistadas perciben un mal estado ambiental del estuario, pero consideran que aún puede ser reversible. Los resultados del presente estudio son la base para un programa de monitoreo permanente del estuario y determinar a mediano plazo la influencia de la zona urbana sobre su estado ambiental.

Palabras clave: Agua residual, estratificación salina, eutroficación, hipoxia, ecosistema.

ABSTRACT

Background. The Arroyo Moreno estuary is located within the Veracruz-Boca del Río-Medellín metropolitan area. Anthropogenic activities affect its hydrological dynamics and cause its deterioration. **Goal**. This study analyzes the hydrology and trophic status of the peri-urban Arroyo Moreno estuary through the analysis of physicochemical factors, eutrophication level, and social perception of its environmental condition. **Methods**. Sampling was conducted at six sites over one year. 106 interviews were conducted with people familiar with the estuary. Temperature, pH, total dissolved solids, salinity (surface and bottom), and dissolved oxygen were recorded *in situ*. Principal component analysis, non-metric multidimensional scaling, and the TIDO-pH trophic index were applied. **Results**. Salinity ranged from 0.27 ± 0.07 to 23.64 ± 4.24, water temperature from 25.71 ± 0.75 °C to 33.13 ± 2.38 °C, dissolved oxygen from 0.32 ± 0.11 to 6.33 ± 1.60 mg/ml, total dissolved solids from 284 ± 69.64 to 28824 ± 9816.60 ppt, and pH from 7.05 ± 0.03 to 7.9 ± 0.30. The TIDO-pH indicator showed a eutrophic state. Water discharge from the thermoelectric power plant canal increased water temperature and altered circulation. Wastewater discharge and sediment suspension resulted in low dissolved oxygen concentrations. **Conclusions**. The analysis showed that the Arroyo Moreno estuary is a hydrologically dynamic system, influenced by climatic seasons, tidal forces, and wastewater discharges from the urban area. Those interviewed perceive the estuary's environmental condition as poor but believe it can still be reversed. The results of this study form the basis for a permanent monitoring program for the estuary and will determine, in the medium term, the impact of the urban area on its environmental status.

Keywords: Eutrophication, hypoxia, saline stratification, wastewater, ecosystem.

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INTRODUCTION

It has been estimated that about 1.2 billion people, corresponding to 23% of the world's population, live within 100 km of the coastline inland and up to 100 m above sea level (Small & Nicholls, 2003; Bittencourt *et al.*, 2022). The coastal zone has been over time a space where various human activities have flourished, such as urban development, tourism, fishing and port development. Estuaries have been affected by these activities directly or indirectly, which has resulted in their deterioration (Fernández-Iglesias & Marquínez-García, 2002; Sanay-González & Perales-Valdivia, 2022).

The State of Veracruz in the Gulf of Mexico has abundant freshwater resources, such that 35% of the country's surface waters cross Veracruz territory. It is important to highlight that the State has more than 40 rivers integrated into 10 hydrological basins, among which the most notable are the rivers Pánuco, Tuxpan, Cazones, Nautla, Papaloapan, Coatzacoalcos and Jamapa (Pérez-Maqueo *et al.*, 2011). These aquatic ecosystems provide habitat to a great diversity of species, such as fish and crustaceans with ecological and economic importance (Miranda-Vidal *et al.*, 2016). However, problems such as contamination from wastewater discharge (CSVA, 2004), eutrophication, and change of land use impact human and ecosystem health (Allan, 2004; Camargo & Alonso, 2007; Scholes *et al.*, 2007; Guevara *et al.*, 2008). Urbanization and industrialization in coastal areas and transitional waters (estuaries and coastal lagoons), have increased anthropogenic impacts (McLusky & Elliott, 2004; Lowe & Peterson, 2014; Lowe & Peterson 2015).

Because estuaries are a transition zone between the terrestrial and marine environments (Sierra *et al.*, 2002), freshwater and seawater mix following tide regime (Cameron & Pritchard, 1963; Contreras, 1993; Perigó *et al.*, 2006). Estuaries form a border between the dual fresh water and marine systems and are considered an ecotone, where processes of biological importance such as spawning and breeding of species of ecological and commercial importance occur (Berasategui *et al.*, 2004; Rodrigues, 2005; Berasategui *et al.*, 2006; Acha *et al.*, 2008; Derisio *et al.*, 2014). Likewise, estuaries are ecosystems with a high primary production, which makes them ecologically relevant systems given the various ecosystem goods and services they provide to the human communities that settle in them (Schelske & Odum, 1962; Potter *et al.*, 2015; Teuchies *et al.*, 2013). According to Soares *et al.* (2021), estuaries "are essential to sustain terrestrial and aquatic life and human communities".

The degree of mixing in the water column is influenced by factors such as tidal exchange, river discharge, and climatic seasons (Sierra *et al.*, 2002). These factors determine the degree of mixing of the water column, resulting in estuaries ranging from fully mixed to stratified with the presence of a salt wedge (Valle-Levinson, 2010). Salt wedge estuaries are characteristic of the coastal area where rivers flow into the sea, where tides are < 2 m (Ibañez *et al.*, 1997), and the greater the discharge, the smaller the salt wedge (Sanay-González & Perales-Valdivia, 2022; Gutiérrez-Mendieta *et al.*, 2006; De la Lanza-Espino & Gutiérrez-Mendieta, 2017).

Additionally, seasonal variation in tropical estuaries is defined by precipitation in combination with morphological characteristics such as substrate type, depth and distance from the sea (Álvarez-Arellano & Gaitán-Morán, 1994; Pérez-Ruzafa *et al.*, 2007). Therefore, estuaries are highly dynamic systems where the conditions of salinity, temperature, oxygen concentration and transparency are constantly changing (Elliott & McLusky, 2002; Potter *et al.*, 2010). It can be concluded that estuaries are complex and highly productive ecosystems, and according to Chapman & Wang (2001), they are areas with intense processes of sea-continent interaction.

Over the last 40 years, the city of Veracruz port has expanded its urban development to areas that were previously dedicated to agricultural and fishing activities, such as the municipalities of Boca del Río, Medellín and Alvarado, resulting in the transformation of these into urban areas (Figure 1) (Castañeda-Chávez *et al.*, 2017; Castañeda-Chávez *et al.*, 2020; Sanay-González & Perales-Valdivia, 2022). Furthermore, the coastal zone in these areas, as well as the estuarine Mandinga Lagoon System, the Jamapa River estuary and the Arroyo Moreno estuary, have also become urbanized. As pointed out by Tagliani (2018) and Barletta *et al.* (2019), the lack of urban development planning is a consequence of the lack of environmental and urban management, resulting in environmental degradation. This degradation can include hypoxia, which can cause the loss of aquatic diversity, alterations in the physicochemical conditions of the water column and the impact on the ecosystem goods and services provided by the estuary (Kennish, 1991; Kitsiou & Karydis, 2011).

The importance of estuaries, such as Arroyo Moreno estuary, lies in the fact that they provide various ecosystem services, such as refuge areas, breeding and reproduction for species of commercial and ecological importance (Salas *et al.*, 2011; Teuchies, 2013; Arceo-Carranza & Chávez-López, 2019). This estuary has been classified as a state protected natural area (Secretaría de Desarrollo Social y Medio Ambiente, 2006).

In Arroyo Moreno estuary some problems have been mentioned that impact the environmental quality and ecosystem services. For instance, this is an area with increasing urbanization, growing tourism, considerable port activity and various agricultural activities (Ortiz-Lozano *et al.*, 2005). The lack of information on the impact of increasing human use directly on the estuary proper, the assessment of environmental services, the impact on hydrological dynamics and its repercussions on the quality of life of human communities is the result of poor planning within the basin, and therefore the lack of assessment of ecosystem services. That even the dramatic environmental situation, the region has been declared as Natural Protected Area (NPA). Therefore, the current study could be used to delineate and develop a resource management program for the NPA. The analysis of the estuary's environmental quality is based on variations in salinity, dissolved oxygen, temperature, pH, and total dissolved solids over an annual cycle, with a focus on differences associated with climatic seasons within the protected natural area.

MATERIALS AND METHODS

Study area. The Arroyo Moreno State Natural Area has a surface area of 287 hectares (2.87 km^2), and is in the Jamapa River basin, which originates in the Sierra Madre Oriental, on the slopes of Pico de Orizaba, within the central coastal plain of the state of Veracruz (Instituto de Ingenieria UNAM, 2014). The study area crosses the municipalities of Medellín de Bravo and Boca del Río, between 19º 05' and 19º 08' N and 96º 06' and 96º 09' W (Figure 1) (Secretaría de Desarrollo Social y Medio Ambiente, 2006). The climate of this region is warm subhumid Aw2 with summer rains, yearly means temperature range from 18 to 22°C. Annual precipitation is 1,500 to 2,000 mm, the most abundant ra-

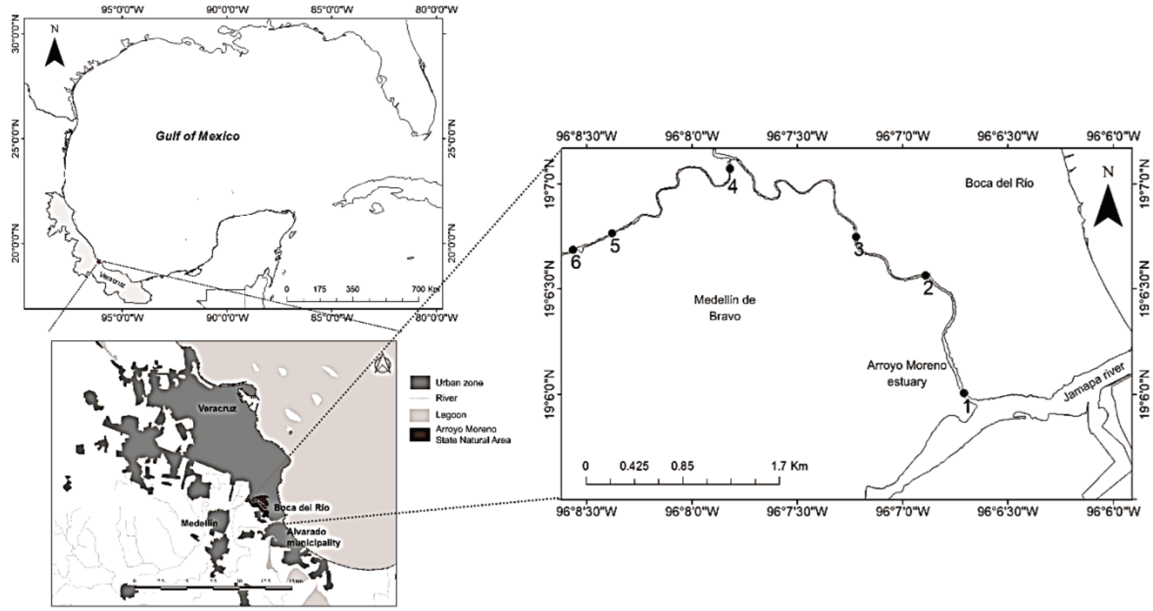


Figure 1. Location of the study area, where indicated the sampling stations (1, 2, 3, 4, 5 and 6) within the Arroyo Moreno estuary.

ins occur in June (García-Villar *et al.*, 2019; López-Portillo *et al.*, 2009). According to Morán-Silva *et al.* (2005), the study area has three climatic seasons: cold fronts (October to February), dry seasons (March to May) and rainy seasons (June to September). The types of vegetation recorded are poplar (*Heliconia* sp. and *Calathea* sp.), low deciduous forest, coastal dune vegetation and halophilous vegetation, and 4 mangrove species (*Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa* and *Conocarpus erectus*) (López-Portillo *et al.*, 2009).

Sampling. Monthly samples were taken along the Arroyo Moreno estuary within the Protected Natural Area between 2021 and 2022 during each the three climatic seasons (Dry, Rainy and Cold front) as defined above (Morán-Silva *et al.*, 2005; Salas-Monreal *et al.*, 2020). Six sampling stations, from the mouth of the Arroyo Moreno with the Jamapa River to its intersection with the CFE Dos Bocas thermoelectric station canal, were established: (1) Estuary mouth, (2) Urban area, (3) Mangrove area, (4) Zamorana Canal, (5) CFE Canal, and (6) Bridge (Figure 1), resulting in 72 samples taken during the study. The sampling stations were georeferenced with a Garmin GPSMAP model 60CSx. At each sampling station, the depth was obtained by Garmin GPSMAP model 530, and salinity (psu), temperature (^{o}C), dissolved oxygen (DO, mg/l), total dissolved solids (TSS, ppt) and pH were measured at the surface (Cházaro-Olvera et al., 2023). Salinity was measured both at the surface and bottom, because the objective of this study was to assess the salt wedge in the estuary. Salinity was used as the primary parameter to describe the hydrodynamic behavior of the estuarine system, as it is mainly influenced by tidal dynamics, fluvial discharge and local and remote wind stress (Sierra et al., 2002). All hydrologic variables were measured with a Hanna brand multiparameter model HI9298194.

DO-pH Trophic State Index. The DO-pH Trophic State Index considers the ratio of the percentage of dissolved oxygen saturation (DO) and the hydrogen potential (pH) values transformed to a logarithmic scale (O'Boyle *et al.*, 2013).

pH Interval = ((pHi_value)/(maximum_pHn_value /100))

DO Interval = ((DOi_value)/maximum_DOn_value/100))

TIDO–pH = (IntervalopH+Interval_DO)/2

Where "i" corresponds to the sampling date, "n" corresponds to the location.

The TIDO-pH index scale is: Clean (0 < 40), Intermediate (> 40 < 60), Potentially Eutrophic (> 60 < 75), and Eutrophic (> 75 - 100).

Social perception. To know the social sector perception of the environmental state of the Arroyo Moreno estuary 106 surveys were applied, to three groups of people, 38 were fishermen, 48 were students, and 20 were teachers. The questionnaire on environmental perception of the estuary was developed from the items proposed by Raffensperger and Tickner (1999). To validate the questions (Kerlinger 1975), they were initially applied to 20 researchers familiarized with estuary issues. Finally, the questions were then worded as follows:

1. Are there alterations due to activities carried out in the Arroyo Moreno estuary?
2. Do the environmental alterations in Arroyo Moreno affect human health?
3. Do you perceive unpleasant odors in Arroyo Moreno?
4. Do you notice that the color of the water in the stream has changed in recent years?
5. Is the threat of environmental disturbances to the stream water reversible?
6. Do potential environmental changes in Arroyo Moreno affect surrounding ecosystems?
7. Have you noticed that the number of species caught for human consumption has decreased in the Arroyo Moreno?
8. What is the extent of the damage to the water?

For questions one through seven, the response options followed the Likert scale: SA, strongly agree, A, agree, NAND, neither agree nor disagree, D, disagree, SD, strongly disagree. Question eight followed the alternatives: C, considerable; CAT, catastrophic; MOD, moderate; INS, insignificant.

Statistical analysis. The stratification of the water column for each of the sampling stations was obtained through the stratification parameter (Ep) according to Haralambidou *et al.* (2010):

$$Ep = (S_{bot}-S_{sur})/[0.5(S_{bot}+S_{sur})]$$

Where: S_{bot} = Bottom salinity and S_{sur} = Surface salinity. When $Ep < 0.1$ the water column is considered completely mixed, while if $Ep > 1$ it is considered that a salt wedge exists.

Mean (± SD) values were obtained for each of the variables by month and sampling station. A Shapiro-Wilk (S-W) normality test was applied to the data for each variable (Sokal & Rohlf, 2003). A regression analysis was performed between salinity vs total solids and pH vs dissolved solids, to determine the possible origin of total dissolved solids in the estuary. A Two-way analysis of variance (ANOVA) (Sokal & Rohlf, 2003) was used to compare each hydrologic variable seasonally by station Further, a principal component analysis (PCA), including all hydrological variables, was used to integrate these variables and to determine the contribution of each to characterizing the Arroyo Moreno estuary seasonally. The Bray-Curtis similarity index was applied (Clark & Gorley, 2006), for which the surface salinity values obtained for each sampling station were used to obtain the groups of sampling stations based on non-parametric multidimensional scaling (nMDS) was applied to obtaining the dynamics of the estuary (Warwick & Clarke, 1991; Cobas *et al.*, 2011).

To distinguish the differences between the answers given by the three groups of people about the social perception of the estuary ($p < 0.05$), a Chi-square analysis (X^2) was applied (Sokal and Rolf, 2003) by social perception.

The S-W, X^2 and ANOVA analyses were performed using PAST (Hammer & Harper, 2001), and the PRIMER program was used for PCA, Cluster, and nMDS analysis (Clarke & Gorley, 2001, 2006).

RESULTS

Hydrological characterization. The mean salinity varied over the months, the minimum value was found during September (0.27 ± 0.07), and the maximum value in April (23.64 ± 4.24) (Figure 2A). Statistically significant differences were found between the salinity values per site of sampling ($F_{2,69}$ = 28.41, $p < 0.001$). On the other hand, the mean salinity values obtained by sampling site showed that the site 5 presented the minimum value with 6.10 ± 7.52, and site 3 the maximum value with 9.03 ± 9.233 (Figure 3A). There were no statistically significant differences between the mean salinity values per sampling site ($F_{5,66}$ = 0.19, p = 0.962). Statistically significant differences were observed in the mean salinity between climatic seasons ($F_{2,69}$ = 70.32, $p < 0.001$).

The mean water temperature varied seasonally with monthly mean values fluctuating between 25.71 ± 0.75 °C in November, and 33.13 ± 2.38 °C in May (Figure 2B). Between sampling sites statistically significant differences were found ($F_{2,69}$ = 21.66, $p < 0.001$). Spatially, the lowest mean temperature record was obtained at the sites 1 and 2 with 28.41 ± 2.11 °C and 29.19 ± 2.26 °C respectively (Figure 3B). The highest mean temperature was seen at the site 5 with 31.75 ± 3.09 °C (Figure 3B). Statistically significant differences in the mean temperature values among of the sampling sites were found ($F_{5,66}$ = 2.55, p = 0.035). Significant differences were found in the mean temperatures both between the climatic seasons ($F_{2,66}$ = 31.61, $p < 0.001$) and between the sampling stations ($F_{5,66}$ = 6.52, p = 0.006).

Dissolved oxygen was lowest in November (0.32 ± 0.11 mg/ml) and the maximum value in February (6.33 ± 1.60 mg/ml (Figure 2C), and there were no significant differences among seasons ($F_{5,66}$ = 2.55, p = 0.771). Mean sites DO values ranged from a low of 2.27 ± 2.03 mg/ml at site 2 to a high of 3.96 ± 1.70 mg/ml at site 5 (Figure 3C), with no significant differences among the sampling sites ($F_{5,66}$ = 1.25, p = 0.296).

There are significant differences among the months for TSS ($F_{2,69}$ = 26.55, $p < 0.001$), where September had the lowest mean (284 ± 69.65 ppt), while April had the highest mean (28824.00 ± 9816.61 ppt), (Figure 2D). On the other hand, there were no statistically significant differences in TSS among the sampling sites ($F_{5,66}$ = 1.73, p = 0.139). Site 6 had the minimum mean value (4754.75 ± 6974.87 ppt) while site 3 had the highest average (8915 ± 11089.84 ppt), (Figure 3D). Significant differences were observed in the mean TSS between climatic seasons ($F_{2,69}$ = 56.86, $p < 0.001$). The correlation coefficient for the salinity-TSS relationship was 0.88 (R^2 = 0.78), indicating a positive correlation between TSS and salinity (p = 0.000). Similarly, the correlation coefficient for the pH-TSS relationship was 0.44 (R^2 = 0.181), suggesting that, although the model does not demonstrate strong predictive power, TSS is positively correlated with pH (p = 0.000).

Mean monthly pH values ranged from 7.05 ± 0.03 (July) to 7.59 ± 0.30 (April) (Figure 2E), with significant differences among the sampling seasons ($F_{2,69}$ = 16.14, $p < 0.001$). In contrast, there were no significant differences in pH among the sampling sites ($F_{5,66}$ = 0.97, p = 0.438), with the lowest mean value at site 3 (7.25 ± 0.11) and the maximum value at site 5 (7.39 ± 0.16) (Figure 3E). Significant differences were observed in the mean pH between climatic seasons ($F_{2,69}$ = 18.15, $p < 0.001$).

The average depth varied throughout the sampling months, with its lowest average value in April -2.60 ± 0.32 m (dry season), while the month with the highest average depth was September -3.50 ± 0.20 (rainy season) (Figure 2F). Spatially, the site with the least average depth corresponded to site 5 (CFE Canal) with -2.73 ± 0.36 m, while the site corresponding to the urban area, site 2, registered the greatest average depth (-3.30 ± 0.29 m) (Figure 3F).

Stratification and temporal-spatial behavior of the estuary. The Ep values, obtained from the difference between bottom and surface salinity at each sampling site (Figure 4), were used to determine the stratification in the Arroyo Moreno estuary (Table 1). The vertical position of the halocline is related to both the climatic season as well as the tidal dynamics of the area. Note that the sites with a marked stratification correspond to June, rainy season; however, the rest of the seasons of the year are presented as partially mixed and mixed (Table 1).

The first two components of the PCA analysis explained 68.64% of the data variation. Two groups were formed, on the right-side dry season and the left the transition between rainy season and cold fronts; both are related to environmental factors (Figure 5). The CP1is made up of salinity and total dissolved solids (0.583 and 0.568, respectively) and CP2 is represented by temperature (0.905). The contribution of the va-

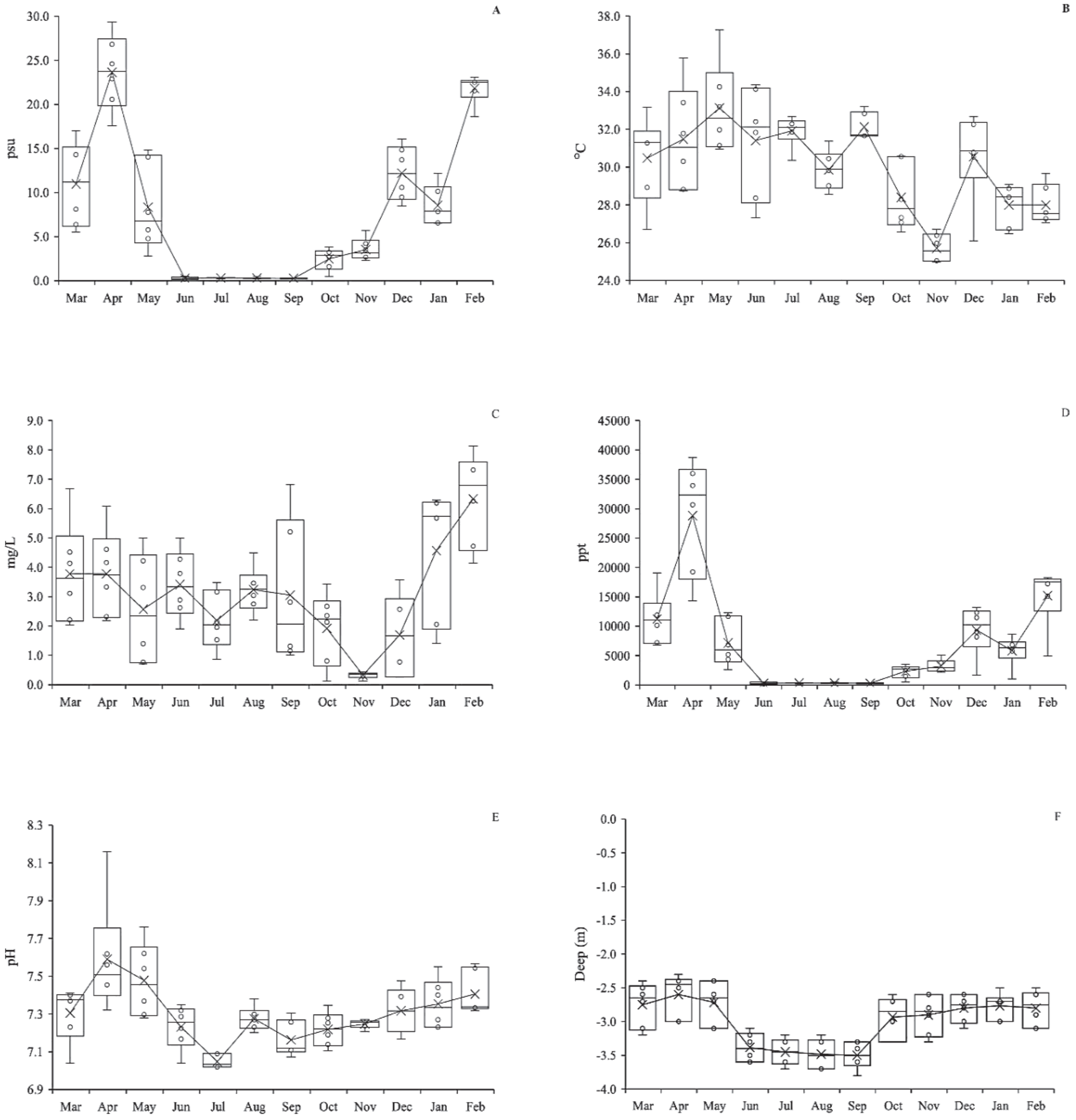


Figure 2. Plot of values per month for salinity (A), temperature (B), dissolved oxygen (C), total dissolved solids (D), pH (E) and deep (F) obtained for Arroyo Moreno in the annual sampling, boxes represent the data variability, and whiskers represent the minimum and the maximum values, (x = mean).

riables in the first component (CP1) was higher and are directly related to the dry season (Figure 5).

The diagram obtained by the nMDS is also made up of two groups and two subgroups each (Figure 6). Group I is made up of two subgroups (A and B in blue and green respectively) and represents the rainy season. Group A was formed by June, July and September considering the main sampling sites 5 and 6. Group B was made up of in the months of June, July, and August considering the main sampling sites 2, 3 and 4. Then, group I is characterized by behaving as an oligohaline system with salinities ranging from 0.28 to 2.48.

Group II is also made up of two subgroups, the first (C in red) represents the transition from cold fronts to dry fronts, which was grouped together in the months of December, January, February and March with mainly sites 1, 2 and 3. Subgroup D (in black) represents the cold front season, grouping the months of January, March, May, October, November and December. Group II represents increasing salinity values fluctuating between 8.34 to 23.64, presenting a gradual increase over time (Figure 6).

The TIDO-pH trophic index presented values of 87.2 to 96.85 between the months of January and November, only in December was the value of 72.68, which is slightly lower than the limit to be eutrophic all year round. On the other hand, the TIDO-pH index showed that all sites are eutrophic, since the value ranged from 82.74 at site 6 to 91.31 at site 5 (Figure 7).

Social perception. When comparing the proportions of answers of the three groups of people surveyed that are related to the estuary, the X^2 values ranged between 3.26 and 6.64 and showed no statistically significant differences (P > 0.05). Thus, the social sector considers that environmental alterations are caused by the activities carried out in the Arroyo Moreno (92%) such as wastewater discharges. The perception is that potential environmental alterations affect human health (89%). The sector noticed that the number of species that were fished for human consumption has decreased (85%). Regarding the perception of water quality, it was mentioned that unpleasant odors are released in the Arroyo Moreno (85%) and that a change in the color of the water has been noticed (85%). The social sector agreed and totally agreed (100 %) on the assertion that the potential environmental alterations in the stream affect the surrounding ecosystems. Although the social sector perceives that the extent of the damage to the water is considerable (92%), it also considers that the environmental alterations of the stream water can still be reversible (73%) (Figure 8).

DISCUSSION

Salinity is considered one of the main factors that determines the dynamics of the estuary and is related to the dynamics of the tide and the entry of fresh water resulting from the rainy season. Thus, the Arroyo Moreno estuary showed mean salinity values ranging from 0.27 ± 0.06

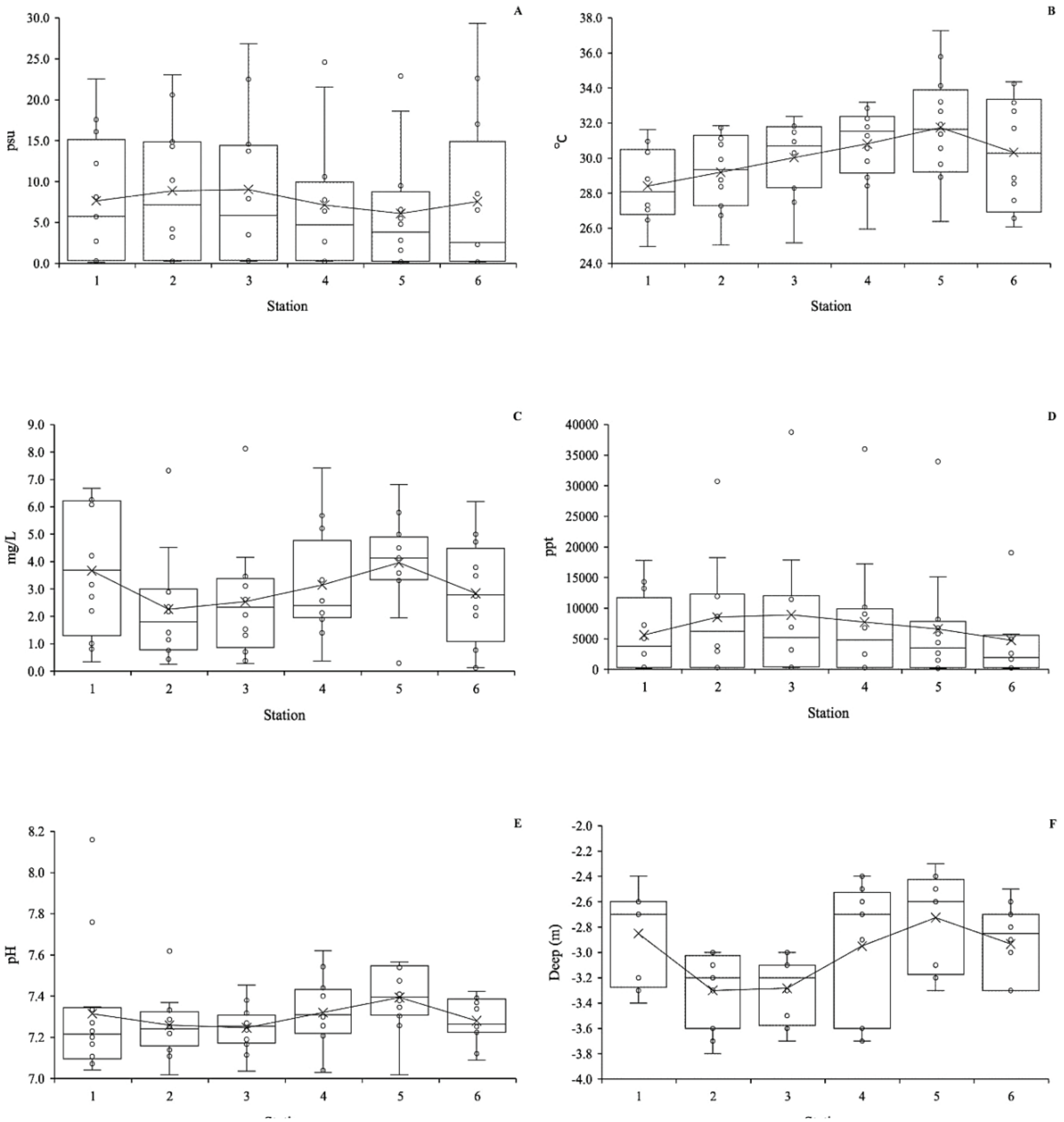


Figure 3. Plot of values per sampling station (1, 2, 3, 4, 5 and 6) for salinity (A), temperature (B), dissolved oxygen (C), total dissolved solids (D), pH (E) and deep (F) obtained for Arroyo Moreno in the annual sampling, boxes represent the data variability, and whiskers represent the minimum and the maximum values, (x = mean).

Table 1. Water column stratification values of stratification parameter (Ep) obtained for sampling stations in Arroyo Moreno estuary over the 12 months. If the value of Ep > 1.0, a salt wedge is present (shared area); if the value of Ep < 0.1, the estuary is considered well mixed.

Site	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Feb
1	0.0628	0.4324	0.8808	1.9627	0.1285	0.0469	0.0067	0.016	0.1556	0.0063	0.0451
2	0.0042	0.1939	0.1003	1.9327	0.0349	0.0134	0.0275	0.0502	0.0556	0.0155	0.0155
3	0.0161	0.018	0.0924	1.8719	0.0314	0.0271	0.0106	0	0.0387	0.0241	0.0227
4	0.8741	0.0093	0.5897	1.8882	0.0251	0.0009	0.0294	0.0686	0.4733	0.0235	0.0218
5	1.0009	0.0082	0.6376	1.9321	0.0059	0.0194	0.0134	0.0724	0.1039	0.0063	0.0471
6	0.0241	0.2599	0.2077	1.8016	0.4061	0.0409	0.6611	0.4643	0.0228	1.2356	0.0005

for the rainy season (September) to 23.64 ± 4.23 in the dry season (April). The above partially agrees with Cházaro-Olvera *et al*. (2023) who report the maximum salinity value in May (dry season) with 35.65 ± 0.01 for the area at the mouth of the Jamapa River, while the lowest record was in September (rainy season) with 0.97 ± 0.06 corresponding to the area in front of the mouth of the Moreno Stream with the Jamapa River. Likewise, the records obtained in the present investigation generally agree with the behavior of salinity for the Jamapa River estuary reported by Aké-Castillo *et al*. (2016) ranging from 10 to 20. It can be concluded that the climatic seasons determine the hydrological behavior of the Arroyo Moreno, decreasing salinity during the rainy season and increasing it during the dry season, as reported by De la Lanza-Espino & Gómez-Rojas (2004) and González-Vázquez *et al*. (2019) for coastal ecosystems of the Gulf of Mexico. According to the Venice System (Ito, 1959), the Arroyo Moreno estuary can be generally characterized as polyhaline, while the stations found within the estuary are mesohaline (salinity 5 to 18), a result of the discharge of water from the CFE canal and the Zamorana canal, in addition to the tidal influence that occurs during the dry season (González-Vázquez *et al*., 2019).

Salas-Monreal *et al*. (2019) mention that the hydrological dynamics of the rivers of Veracruz have changed due to the construction of dams and agricultural activities, decreasing the flow of fresh water to coastal areas, resulting in increasing salinity at the mouth of rivers as a result of tidal influence and stratification of the water column, as is the case with the Arroyo Moreno estuary. In general, there is a greater mixing of the water column during the cold front season due to the decrease in temperature in Gulf of Mexico estuaries (Salas-Monreal *et al*., 2020). However, in the case of the Arroyo Moreno estuary, this pattern is disrupted due to the continuous input of heated water from the cooling channel of the CFE thermoelectric plant. The estimated discharge volume of 1,400 to 1,600 liters per second (Gómez-Nogales, 2025) constitutes a significant source of thermal and hydrological alteration within the estuarine system. This influx of warm water influences local temperature regimes, potentially modifying stratification patterns, dissolved oxygen levels, and biogeochemical processes. Consequently, permanent stratification is prevented throughout the cold front and dry season; instead, the system favors the formation of a saline wedge. Meanwhile, during the rainy season, when the highest temperature values are recorded (29.86 to 33.13 °C), the estuary appears partially or fully mixed due to the influx of freshwater from rainfall, surface runoff, and discharges from the Zamorana channel, which concentrates rainwater from the Veracruz–Boca del Río metropolitan area into the

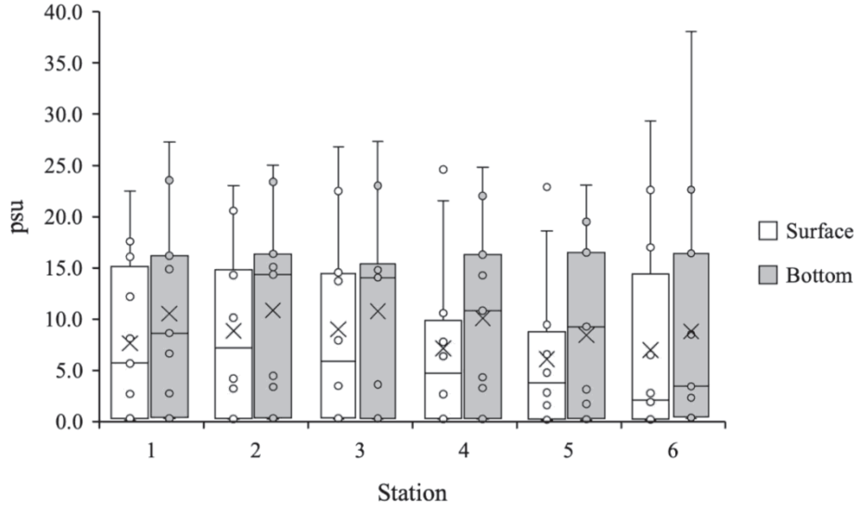
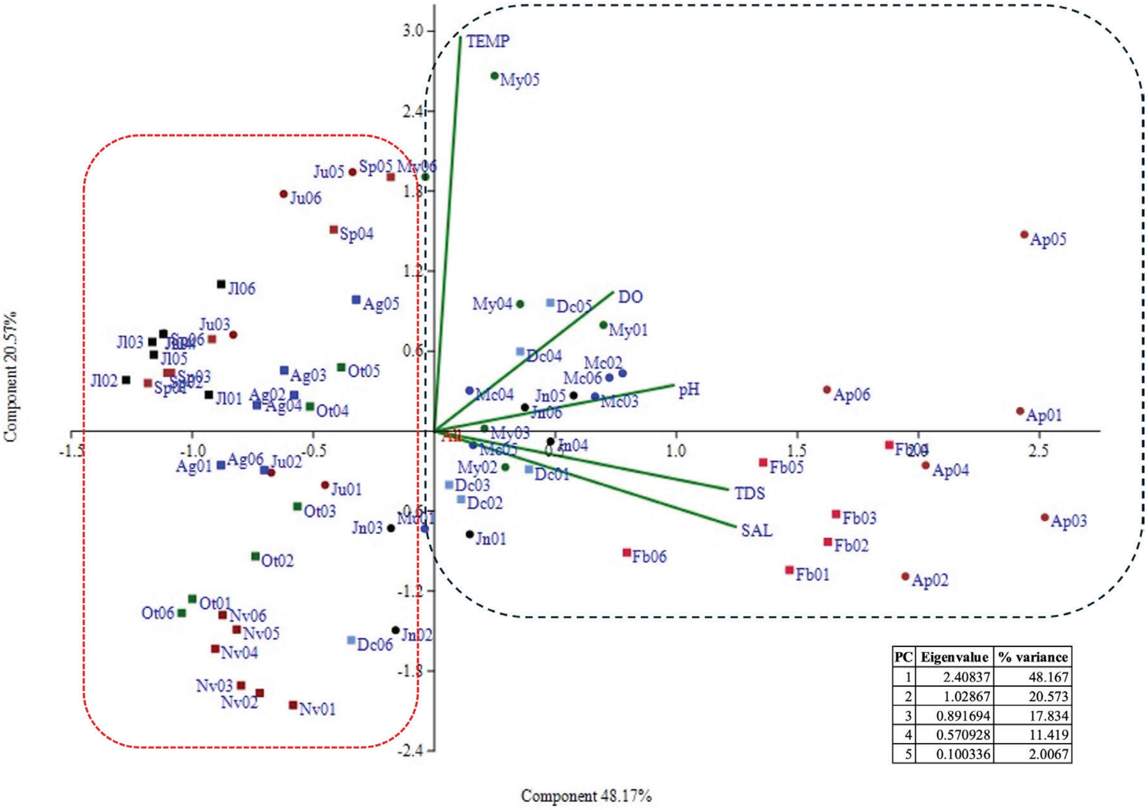


Figure 4. Plot of values per sampling station (1, 2, 3, 4, 5 and 6) for salinity by surface and bottom in Arroyo Moreno over the 12 months by sampling station.



PC	Eigenvalue	% variance
1	2.40837	48.167
2	1.02867	20.573
3	0.891694	17.834
4	0.570928	11.419
5	0.100336	2.0067

Figure 5. Correlation of variables (salinity (SAL), temperature (TEMP), dissolved oxygen (DO), total dissolved solids (TDS), pH and sampling stations) resulting from principal component analysis. On the right-side dry season (in blue) and left-side the transition between rainy season and cold fronts (in red).

estuary. This freshwater input reduces salinity in the water column and promotes vertical mixing.

Therefore, mixing or stratification in the estuary is defined by various factors, including the degree of mixing in the water column, morphology and depth of the system (Valle-Levinson, 2010), which results in stratified, mixed or salt wedge estuaries. Salt wedges occur at the mouth of rivers with the sea, where the tide is one of the main factors of this dynamic (Ibañez *et al*., 1997) together with river discharge. Thus, river discharge results in a marked stratification of the water column (Geyer & Ralston, 2011; Ibañez *et al*., 1997).

The results obtained in the present investigation suggest that both the presence of the salt wedge as well as the mixing of the water column in the estuary occurs temporarily, which partially coincides with what was reported by Avendaño *et al*. (2019) and González-Vázquez *et al*. (2019) for the Jamapa River. Therefore, it can be inferred that the presence of the salt wedge in the estuary may be determined by tidal effects, particularly in June, when greater stratification of the water column is observed (Table 1, Figure 4), due to climatic seasonality (Salas-Pérez & Granados-Barba, 2008; Salas-Monreal *et al*., 2019).

The Arroyo Moreno estuary is a system diurnal mixed microtidal estuary (Sanay-González & Perales-Valdivia, 2022). These types of estuaries are systems susceptible to impacts caused by various anthropogenic activities carried out in them or in their area of influence, affecting the formation and permanence of the salt wedge, depending on the climatic season. According to Warwick *et al*. (2018), the salt wedge facilitates the accumulation of dissolved and suspended solids in the water column, consequently, it can favor greater primary production and the subsequent eutrophication process, which negatively impacts the concentration of dissolved oxygen in the water column.

Perales-Valdivia *et al*. (2018) point out that microtidal estuaries show stratification when the river flow increases, so most of the time it remains as a partially mixed estuary, as is the case of the Arroyo Moreno estuary. The values obtained in the present study provide new and extensive information to that obtained by Sanay-González & Perales-Valdivia (2022) since they only focused on the Jamapa River, and not the entire Arroyo Moreno estuary.

Water temperatures in the study area vary seasonally, with the highest mean values occurring during the rainy and dry seasons (29.86 ± 1.01 to 33.13 ± 2.38, Zavala-Hidalgo *et al*. 2006; Morán-Silva *et al*., 2005; Morán-Silva *et al*., 2017), like values recorded in this study. In contrast, the lowest mean water temperature values were recorded from Arroyo Moreno in the cold front season during the months of November, January and February, and these values are generally higher than previously reported minimum temperatures near of 26°C recorded in the cold front season by Contreras-Espinoza (2016) for the Jamapa

River and by Castañeda-Chávez *et al.* (2017) who recorded 23 °C for the same season in the Jamapa River. However, these previous studies did not include Arroyo Moreno. We found that the differences detected in our study in the mean minimum values observed in the Moreno stream (25.71°C) are due to the discharge from the CFE thermoelectric plant, whose higher outlet temperature impacts the entire estuary and its mean value.

The discharge from the CFE thermoelectric plant is a factor that increases the water temperature of the Arroyo Moreno at all sampling stations and during the three climatic seasons. The permissible limit of discharge water temperature is 35°C, in accordance with NOM-001-SEMARNAT-2021 (DOF, 2021). Our study allowed us to establish that the Arroyo Moreno has not been significantly impacted by high water temperatures since high temperatures observed were within the established norm.

The concentration of dissolved oxygen in the water column depends on the temperature (Bain 1999) and DO is one of the most important parameters since it determines the quality of the habitat due to its influence on a series of biogeochemical processes that affect the well-being of organisms (Moore *et al.*, 2009; Brown & Power, 2011). In recent decades, the number of hypoxic sites (<2 mg/l) in coastal systems has been increasing (Iriarte *et al.*, 2015), making dissolved oxygen depletion one of the priority environmental problems at an international level. The Arroyo Moreno estuary presents temporary episodes of hypoxia, particularly during the cold front season with values ranging from 0.32 to 1.92 mg/l. Values of DO < 2.0 mg/l, which causes episodes of hypoxia, have been reported from the northern portion of the Jamapa River, where the discharge from the Arroyo Moreno is located (Avendaño-Álvarez *et al.*, 2019). This drop in dissolved oxygen concentrations is likely a consequence of the entry of organic matter of fluvial origin and the discharge of wastewater into the estuary in rainy season (Revilla *et al.*, 2000). However, the low oxygen concentrations observed during the cold front season (Figure 2) may be determined by sediment resuspension in the estuary during cold fronts events. As this is a shallow system, these events can stir the water column and resuspend sediments rich in organic matter, which may consume the available dissolved oxygen in the water column. According to de Madariaga (1995), the Arroyo Moreno estuary can be considered a heterotrophic system.

Another factor to consider in this drop in DO is the relationship between temperature, season and sampling sites. This study observed that in the different sampling sites and by season there were significant differences, which occurred because of climatic temporality and tidal exchange of the water column as reported by Iriarte *et al.* (2015) and Castañeda-Chávez *et al.* (2017) in the Jamapa River.

The U.S. Environmental Protection Agency (EPA) established that a DO concertation of 5 mg/l or more is suitable for healthy aquatic life

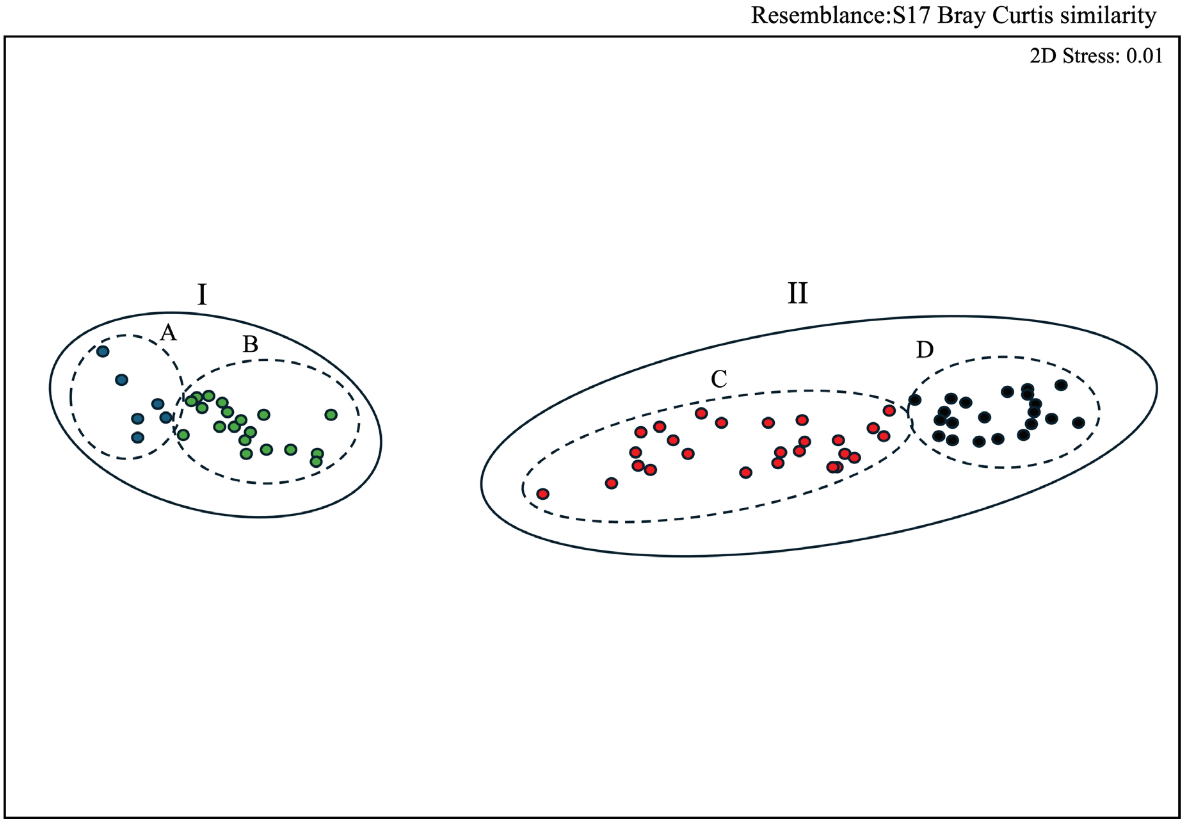
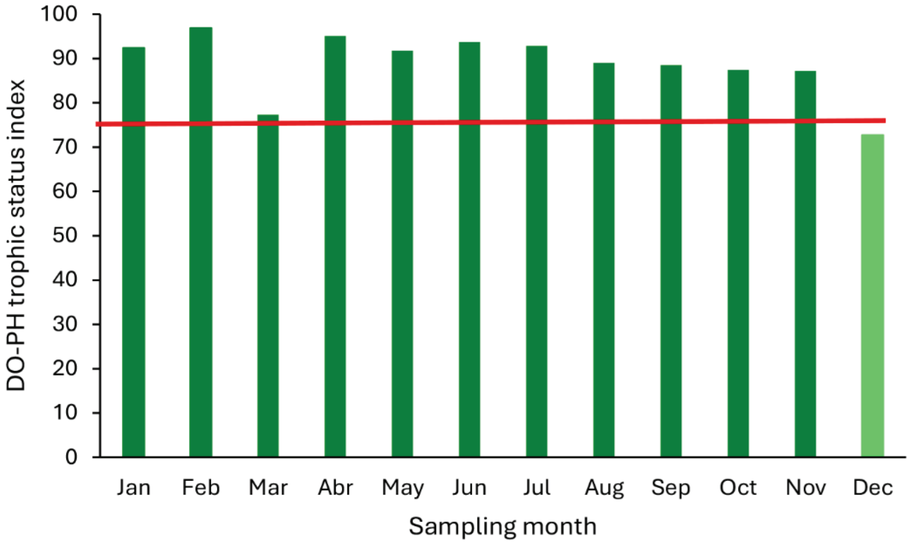


Figure 6. Analysis of the non-parametric multiple dimensional scaling test (MDS) obtained through the salinity values by station-month, Arroyo Moreno estuary. Two groups are observed, I consist of subgroups A and B (in blue and green, rainy season); and II with subgroups C and D (red and black, transition from cold fronts to dry season).



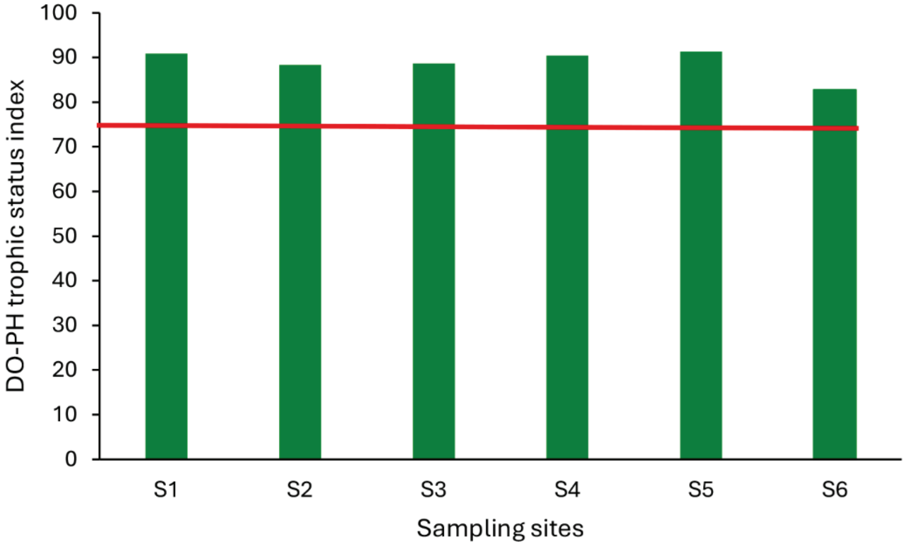


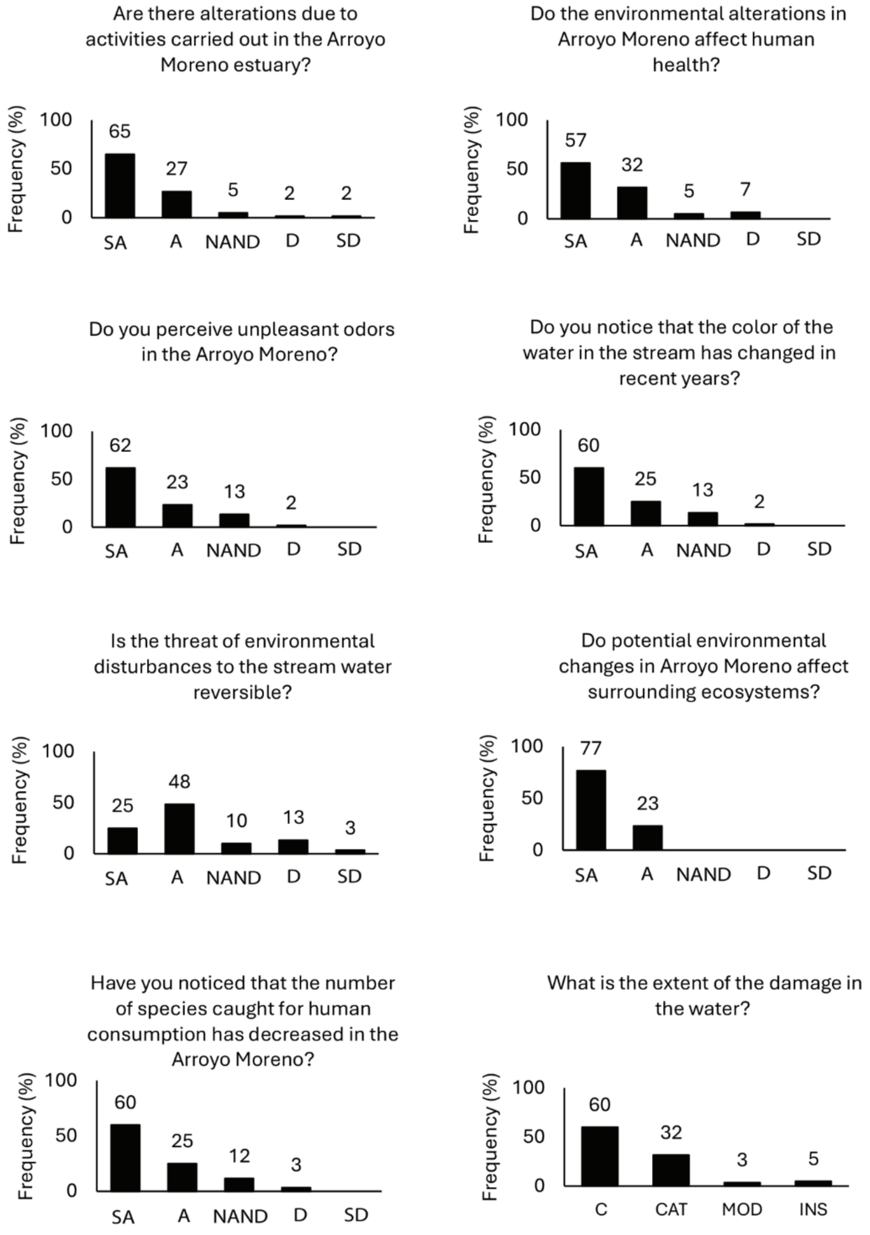
Figure 7. DO-pH Trophic State Index in the peri-urban estuary Arroyo Moreno. Sampling months and sites (S).

in coastal systems. Thus, concentrations below this value, as we found in Arroyo Moreno, can negatively impact the growth, reproduction and activity of the organisms found there, such as fish and crustaceans (Castañeda-Chávez *et al.*, 2017).

The total dissolved solids values obtained in the present investigation were lower than those reported by Cházaro-Olvera *et al.* (2023) for the Jamapa River, who report a maximum value of 35.65 ± 0.01 ppt for the month of May and a minimum value of 0.97 ± 0.06 ppt for the month of September between the confluence with the Arroyo Moreno and the mouth of the Jamapa River. In contrast, the highest mean values we obtained were 28.82 ± 9.81 ppt in April, while the lowest occurred in September with 0.28 ± 0.06 ppt. Likewise, the temporal behavior partially agrees with what was reported by Cházaro-Olvera *et al.* (2023), since the highest values occur during the transition between cold fronts and dry fronts, while the lowest values occur during the rainy season. This may be related to a greater mixing of bottom sediments caused by the influence of winds on the water column during the cold front season and by the entry of runoff and increased flow during the rainy season. The TDS values obtained for the present study are within the permissible limits established by NOM-001-SEMARNAT-2021 (DOF, 2021) except for the month of April (28.82 ppt), which is higher than the standard value of 28 ppt.

The pH values obtained in the present study ranged from 7.05 to 7.59, which are within the permissible limits for drinking water (6.5-8.5; NOM-127-SSA1-1994) (DOF, 1996). The values are like those obtained by Cházaro-Olvera *et al*. (2023) in the Jamapa River. The variations in pH are related to the climatic temporality, particularly the rainy season. The entry of sediments and organic matter is a result of the contributions of wastewater and drainage from the basin, thus decreasing the pH and the concentration of dissolved oxygen through the degradation of organic matter (Castañeda-Chávez *et al*., 2017).

In conclusion, estuaries located in tropical areas, such as Arroyo Moreno estuary, are characterized by having wide environmental variations, the river discharges represent the main driver of the hydrological dynamics (De la Lanza-Espino & Gutiérrez-Mendieta, 2017), as seen in estuaries in Brazil (Honorato da Silva *et al*., 2004) and Mexico (Arceo-Carranza & Chávez-López, 2019; Sanay-González & Perales-Valdivia, 2022). Previous work has shown that temporal variations in the environmental dynamics of Arroyo Moreno estuary are determined mainly by the climate, tidal action, winds and depth (Morán-Silva *et al*., 2005; Colvin *et al*., 2006; Cobas *et al*., 2011).



Are there alterations due to activities carried out in the Arroyo Moreno estuary?

Do the environmental alterations in Arroyo Moreno affect human health?

Do you perceive unpleasant odors in the Arroyo Moreno?

Do you notice that the color of the water in the stream has changed in recent years?

Is the threat of environmental disturbances to the stream water reversible?

Do potential environmental changes in Arroyo Moreno affect surrounding ecosystems?

Have you noticed that the number of species caught for human consumption has decreased in the Arroyo Moreno?

What is the extent of the damage in the water?

Figure 8. Social perception of the environmental of the peri-urban estuary Arroyo Moreno. SA, strongly agree, A, agree, NAND, neither agree nor disagree, D, disagree, SD, strongly disagree. Question eight followed the alternatives: C, considerable; CAT, catastrophic; MOD, moderate; INS, insignificant.

The metropolitan coastal area of Veracruz – Boca del Río – Medellín – Alvarado is home to a population of 846,961 inhabitants (Secretaría de Economía, 2023). The Arroyo Moreno estuary is immersed in this urban area and receives a series of impacts that affect its environmental dynamics, presenting a constant deterioration because of urban expansion, port, industrial and agricultural development that take place in its area of influence (Fernández-Iglesias & Marquínez-García, 2002). These activities directly and indirectly impact this ecosystem through runoff and wastewater discharges, affecting the hydrological and productive dynamics (Honorato da Silva *et al*., 2004) beyond effects of natural climatic variation.

The social sector perceived that the hydrological alterations to the Arroyo Moreno estuary affect human health and the surrounding ecosystems, for example, that the number of species for consumption has decreased, in this regard Tlapa-Almonte *et al*. (2020) mention that pollution is a factor that threatens and affects peri-urban systems. Fishermen consider that unpleasant odors are produced with a change in the color of the water, in this regard, Agudelo-Valencia *et al*. (2019) mention that some chemical pollutants from domestic discharges are toxic and precursors of serious problems that lead to mortality of flora and fauna, as well as giving rise to unpleasant odors in the channel. Regarding damage in time, space and magnitude, the perception is that the intensity of alteration is high, with damage to vegetation and water, likewise. In the issue of restoration, the threat is reversible but costly and with a certain degree of difficulty. Given the above, Manning & Krymkowski (2010) and Tlapa-Almonte *et al*. (2020) consider that the application of current legislation is necessary to regulate the appropriate use and exploitation of the natural resources of peri-urban Natural Protected Areas, so a conservation strategy based on a command-and-control approach is required. This implies that the rules are codified in regulations, administrative rules, public policies and applicable laws as soon as possible.

In Mexico, the most widely used index to determine the trophic status of coastal and marine systems is the TRIX (Muciño-Márquez *et al*., 2017), however, Rivas-Márquez *et al*. (2024) used the ITOD-pH trophic index, with which adequate levels and potentially trophic assessments were obtained. It is for this reason that in this study the ITOD-pH also provides an evaluation of the trophic index according to both the data of the abiotic parameters analyzed in this work and the perception of the social sector that knows and has been in constant contact with the waters and resources of the estuary. As obtained, the Arroyo Moreno estuary is a eutrophic system both throughout the year and through the monitored sampling sites. It has been found in the northern part of the Gulf of Mexico that most U.S. estuaries (65 percent) are moderately to highly eutrophic due to high organic matter and nutrients loads (National Center for Coastal Ocean Science, 2025).

CONCLUSION

Finally, the results of this study allowed us to define the Arroyo Moreno estuary as a heterotrophic estuary, partially mixed, with direct influence from the climatic seasons and impacted by the anthropogenic activities, in its area of influence. Located within the Veracruz-Boca del Río-Medellín metropolitan area, the periurban Arroyo Moreno estuary is heavily impacted by urban sprawl and the discharge of wastewater generated in the vicinity of the protected natural area. Furthermore, the lower Jamapa-Cotaxtla basin is characterized by artisanal fishing and agricultural activities, which further increase the pressure on this ecologically important estuary. We suggest that management agencies develop a permanent monitoring program that allows identification of trends in hydrological behavior, as well as the impacts generated by the activities carried out in the area and the effect of urbanization. The baseline data provided here, along with additional monitoring, would allow the development of strategies for the management and conservation of the area.

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