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The Impact Of Human Activities On A Lagoon Ecosystem On The Chiapas–Oaxaca Coast, Mexico: A Physicochemical Approach

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Abstract: *Water bodies in Mexico face growing environmental stress due to insufficiently treated wastewater and the runoff of agrochemicals—particularly fertilizers—from intensive agricultural activities. This issue is especially pronounced in coastal and estuarine systems, where contaminants accumulate before entering the marine environment, triggering significant ecological and socioeconomic consequences. The Mar Muerto Lagoon, situated along the Pacific coast shared by Chiapas and Oaxaca, Mexico, illustrates this challenge. This coastal lagoon supports artisanal fisheries that serve as a key source of livelihood for local communities. However, in recent years, a noticeable decline in fishery productivity has raised concerns about its ecological integrity. To assess water quality and spatial dynamics, 35 samples were collected and analyzed for five physicochemical parameters. The results revealed three distinct environmental zones—estuarine, transitional, and marine—associated with hydrological variation and phytoplankton succession. These findings highlight the pressing need for integrated management strategies to safeguard this vulnerable ecosystem.*

Keywords: *Anthropogenic Pollution, Coastal estuarine systems, Hydrological fluctuations, Physicochemical Zonation.*

1. INTRODUCTION

Estuaries are semi-enclosed bodies of water with a free connection to the open sea, but they also receive freshwater inputs from rivers (Pérez-Ruzafa et al., 2014). Coastal lagoons have low or no freshwater inputs and do not necessarily form part of an estuary (Kennish & Paerl, 2010). Coastal lagoons serve as nursery and feeding grounds for estuarine marine fish, making them important areas for aquaculture exploitation, which highlights their relevance in global marine ecosystems, as they are among the most productive aquatic ecosystems (Pérez-Ruzafa et al., 2014).

Anthropogenic pollution in aquatic ecosystems stems from efforts to meet basic societal needs (Lara-Lara et al., 2008; Herrera-Silveira et al., 2010). The expansion of economic activities and settlements near water bodies, combined with inadequate wastewater treatment, has led to the presence of pollutants—such as heavy metals, fertilizers, and emerging contaminants—posing risks to aquatic life and trophic networks (Erostate et al., 2022).

Additionally, some of these lagoons are undergoing critical transformation: over 50% have been modified through threshold dredging to improve navigation, disrupting their internal dynamics (Saarinen & Berglund, 2023), affecting species reproduction, and favoring predators.

These alterations compromise key ecosystem functions, from nutrient fixation by sediment-dwelling communities (Rodrigues‑Filho) to carbon cycle regulation, which is influenced by the dominant trophic structure (Saarinen & Berglund, 2023).

The growing concern over biodiversity loss has driven international commitments to conserve at least 10% of marine ecosystems, as reflected in targets such as Goal 14.5 of the United Nations Sustainable Development Goals and Target 11 of the Strategic Plan of the Convention on Biological Diversity (Saarinen & Berglund, 2023). Nevertheless, marine restoration has proven less effective than in continental environments, underscoring the importance of implementing preventive strategies.

Mexico has 164 coastal lagoons and nearly 12,000 km of coastal shoreline, where aquaculture production is the main economic activity, which has shown significant growth in its contribution to the national Gross Domestic Product (Herrera-Silveira et al., 2010). For this reason, water quality in coastal ecosystems is of economic and social interest at both national and international levels (Lara-Lara et al., 2008). These ecosystems are critical habitats for many species of commercial and ecological interest, making their conservation a priority to sustain fishery resources (Rodiles-Hernández et al., 2013).

In this study, we present the results of a comprehensive characterization of 35 water samples collected from the Mar Muerto coastal lagoon—an estuarine system located in the northern Gulf of Tehuantepec. As one of the largest coastal lagoons on Mexico's Pacific coast, Mar Muerto spans 60 km in length, up to 12 km in width, and covers an approximate surface area of 720 km², with depths ranging from 1 to 3.6 meters (Romero-Berny et al., 2018). This system supports intensive small-scale fisheries, particularly shrimp harvesting, which represents the region's main economic activity (Espejel & Espinoza-Tenorio, 2008). Therefore, a physicochemical assessment was carried out during the dry season, including measurements of salinity (%), temperature, dissolved oxygen (DO), turbidity (Turb), and hydrogen potential (pH), with the objective of identifying spatial variation in water quality and delineating potential biotopic zones within the lagoon.

2. MATERIALS AND METHODS

2.1. Study Area

The Mar Muerto coastal lagoon spans between 15°58′ and 16°17' N latitude and 93°50' to 94°25' W longitude (Tapia-García et al., 2011). Approximately 69% of its total area (47,000 ha) lies within the state of Oaxaca, while the remaining 31% (21,310 ha) is situated in Chiapas (Rodiles-Hernández et al., 2013). During the onset of the dry season, the lagoon's inlet becomes restricted by sandy spits locally known as Punta Chiapas and Punta Oaxaca (Contreras E. et al., 1997; Romero-Berny et al., 2018).

In this area, the tides are mixed and predominantly semidiurnal, with an average range of 1 meter. Annual precipitation increases from west to east, ranging from less than 1,000 mm to more than 1,600 mm. The average temperature is approximately 28 °C. The system is surrounded by mangroves, marshes, as well as agricultural and semi-urban areas. The climate is humid tropical with two distinct seasons: rainy (June–October) and dry (November–May) (Romero-Berny et al., 2018).

The Mar Muerto lagoon system has a permanent inlet (tidal inlet known as the Tonalá inlet) approximately 2 km² in width. The lagoon is very shallow: 49% of it has a depth of less than 1 meter, and only 2.3% reaches depths greater than 5 meters (Mera-Ortiz et al., 2015).

Several small rivers discharge into the lagoon, although many remain dry during the dry season. The most significant is the Tapanatepec River, which enters the lagoon in a region known as "El Escopetazo". The lagoon's internal water flow is primarily driven by tidal forces, which cause the inlet and outlet of water. However, this influence is relatively limited due to the narrow opening at the "Tonalá inlet" (Tapia-García et al., 2011).During the last quarter of the year, the "Nortes" or Tehuantepec winds intensify. Although they blow west to east, they generate a surface current toward the Tonalá inlet. This dynamic causes a significant drop in the lagoon's water level, a phenomenon that reverses once the winds subside starting in January. In contrast, during the rainy season, increased precipitation also drives currents toward the same mouth, thus modulating the lagoon system's hydrodynamic behavior (Tapia-García et al., 2011).

Geologically, the area is mainly composed of alluvial, volcano sedimentary, and lagoonal sediments. In the northwest, metamorphic rocks are present, formed from granitic and granodioritic rocks, while to the north of the lagoon, granitic and granodioritic rocks are also observed (Delgado-Argote & Carbadillo-Sánchez, 1990).

2.2. Collection of Water Samples

Prior to sampling, the sampling points were determined based on geomorphological, geological, hydrological, geohydrological, demographic, and primary economic activity data, among others, in order to consider those with the greatest representativeness. A total of 35 samples points were selected (Figure 1). The first campaign was conducted in April-May 2024 (dry season).

Figure 1. Map of sampling sites along the Mar Muerto Lagoon

2.3. Physicochemical Parameters

At each sampling site, a water sample was collected and allocated for the determination of various physicochemical parameters, including salinity (%), temperature, dissolved oxygen (DO), turbidity, and hydrogen potential (pH). Temperature, DO, and pH were measured using a multiparametric device

(Apera Instruments, model SX751). Turbidity was assessed by using a TN420 Turbidimeter from the same brand, while salinity was determined with a refractometer (RHA-503ATC, model ATC). All physicochemical parameters were determined in situ.

2.4. Statistical Analysis

To assess variance homogeneity and data normality, Levene's test and the Shapiro-Wilk test were applied, respectively. If the data met normality assumptions, differences in the concentrations of measured parameters were analyzed using one-way ANOVA, followed by Tukey's post hoc test (significance level: $p < 0.05$). For non-normal data, the Kruskal-Wallis test was used, with Dunn's method to identify significant differences between groups ($p < 0.05$). All statistical analyses were performed using SigmaPlot 12.0.

3. Results and Discussion

Figure 1 clearly shows that the Mar Muerto Lagoon Basin (RH23D) is composed of five sub-basins, namely:

- Zanatenco River Sub-basin
- Mar Muerto Sub-basin
- La Punta River Sub-basin
- Las Arenas River Sub-basin,
- Tapanatepec River Sub-basin.

It is worth noting that the Mar Muerto Sub-basin is further subdivided into three micro-basins, identified by the authors of this study and named: Mar Muerto I, Mar Muerto II, and Mar Muerto III. This geohydrological division served as the basis for delineating the lagoon's zonation, since each sub-basin exerts its own influence over the water body. Additionally, the discharge points of the main rivers were considered when defining the lagoon's zonation.

Based on the above and taking into consideration what was outlined in previous publications (Tapia-García et al., 2011; Mera-Ortiz et al., 2015; Cervantes-Hernández F., 2016.) it was proposed that the representative sampling points for Zone I be: 1, 2, 3, 4, 5, 15, 16, 17, 14 and 18; those for Zone II are: 3, 5, 19, 6, 34, 13, 7, 8, 12, 9 and 10; and finally, those for Zone III: 11, 33, 31, 30, 32, 29, 28, 25, 24, 26, 23, 22, 21 and 27.

Figure 2 illustrates the distribution of data for each physicochemical parameter across the defined zones. The lowest turbidity levels were recorded in Zone I, near the Tidal inlet (Tonalá inlet) (southeastern part of the lagoon), ranging from 1.7 to 17 NTUs. In contrast, the highest value was observed in Zone III, reaching 45.6 NTUs. The one-way ANOVA revealed significant differences in turbidity among the studied zones ($p < 0.05$). Mean values and their corresponding standard deviations are reported in Table 1.

Table 1. Physicochemical Parameters (Mean Values ± SD) in Water from Different Zones of the Reservoir

Zone	Turbidity (NTU)	T (°C)	Salinity (%)	pH	DO (mg/L)
I	$8.1±4.6^{a}$	$33.7±1.4^{a}$	$36.3±4.1^{a}$	$7.1±0.7^{a}$	$5.1±2.7^{a}$
II	$19.6±9.0^{b}$	$34.1±1.1^{a}$	$38.0±7.6^{b\text{-}c}$	$7.8±0.7^{b\text{-}c}$	$6.0±2.6^{a}$
III	$29.4±9.5^{c}$	$34.7±0.4^{a}$	$49.2±7.2^{a\text{-}c}$	$8.7±0.6^{a\text{-}c}$	$6.8±1.1^{a}$

Note: The superscript different letters (a, b and c) indicate a significant difference in levels among different zones of the study area (Tukey's test or Dunn's method when appropriate, $p < 0.05$).

Similarly, the highest pH values were recorded in Zone III, which is the farthest from the mouth of the lagoon and the most influenced by freshwater runoff from the Tapanatepec River. Once again, a significant difference was observed between Zones I and III, as well as between Zones III and II ($p < 0.05$). However, no significant differences were found between Zones II and I ($p > 0.05$). These elevated pH and turbidity values suggest a higher biomass of phytoplankton, as photosynthetic organisms absorb dissolved CO_2 from the water as part of their metabolic activity. This process shifts the carbonate equilibrium toward the right, favoring the production of hydroxide ions (OH^-), which in turn raises the pH. To corroborate this interpretation, it is necessary to conduct a study that includes the identification and quantification of photosynthetic organisms, along with measurements of phosphorus and nitrogen concentrations.

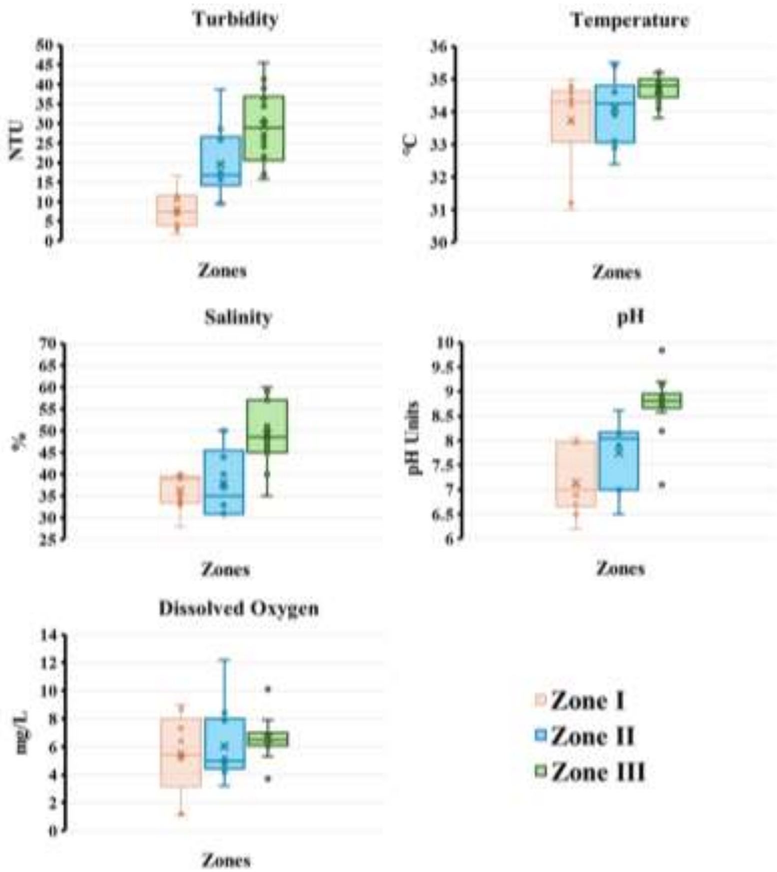

Figure 2. Physicochemical parameter distribution in each zone of the Mar Muerto lagoon during the dry season

These results may be associated with the levels of dissolved oxygen concentration in each zone, given that a greater amount of phytoplankton biomass generally leads to higher oxygen production during the light phase. However, no significant differences were found with respect to this parameter. This could be mainly attributed to the prevailing wind regime in the region, particularly the Tehuantepec winds, which move from north to south. Along the coastal strip of Chiapas, these winds typically enter from the north, channeled through the Isthmus of Tehuantepec. As a result, although there is greater oxygen production in Zone III, the constant exchange between the aerial and gaseous phases within the lagoon prevents the identification of zones with higher concentrations of dissolved oxygen from one area to another.

Finally, the highest salinity was observed in Zone III of the lagoon, while the lowest was found in Zone I ($p<0.05$). These values suggest that Zone III reaches hypersaline levels that progressively decrease toward the tidal inlet, where marine conditions prevail. This pattern is primarily attributed to high evaporation and limited exchange with seawater. Additionally, Zone III is shallower and exhibits limited circulation, which likely contributes to an increase in surface temperature—further enhancing evaporation and salinity concentration. Although temperature did not show significant differences among zones, the highest values were recorded in Zones III and II, while the lowest were found in Zone I (marine zone).

Based on these preliminary results, in terms of turbidity during the dry season, three well-defined zones can be established in the lagoon: Zone I (marine), Zone II (diffuse), and Zone III (estuarine) (Figure 3-a). However, regarding pH and salinity, since no significant differences were found between Zones I and II, it was concluded that only two zones exist: Zone I (Marine) and Zone II (Estuarine) (Figures 3-b and 3-c).

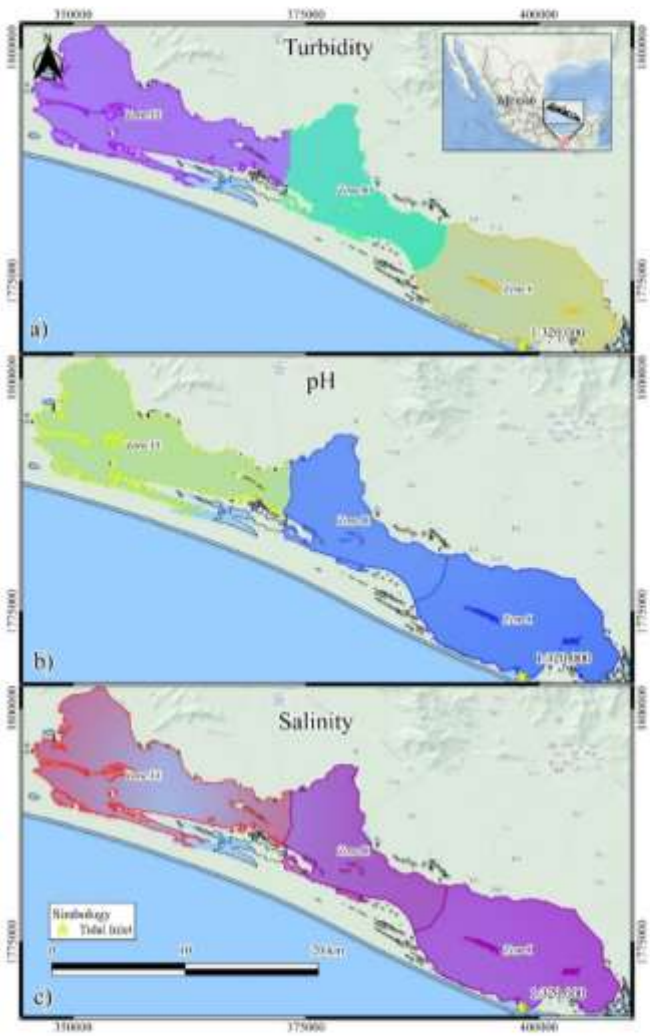

Figure 3. Zonification of Mar muerto Lagoon according to the different physicochemical parameters.

4. CONCLUSIONS

This study highlights the critical influence of hydrodynamic variability and anthropogenic pressures on water quality in the Mar Muerto Lagoon, a vital coastal system on Mexico's Pacific coast. Through the spatial analysis of five physicochemical parameters—salinity, temperature, dissolved oxygen, turbidity, and pH—three distinct zones were identified, each characterized by varying environmental conditions. Zone III, marked by higher turbidity and pH, appears to be heavily influenced by freshwater inflows and phytoplankton activity, while salinity gradients suggest hypersaline conditions with limited exchange in shallow regions.

Although differences in dissolved oxygen were not statistically significant, regional wind dynamics may mask spatial variability typically linked to phytoplankton biomass. The results point to a system under hydrological stress, where anthropogenic inputs—particularly agricultural runoff—could exacerbate eutrophic tendencies and threaten aquatic biodiversity. The data underscore the need for targeted monitoring of primary producers (e.g., phytoplankton) and nutrient loading, as well as the formulation of integrated conservation policies. Ultimately, safeguarding the lagoon's ecological function and socio-economic importance hinges on bridging scientific assessment and inclusive coastal management.

5. RECOMMENDATIONS

To advance our understanding of the Mar Muerto Lagoon's ecological dynamics and its vulnerability to anthropogenic impacts, future research should prioritize integrated, longitudinal studies that include seasonal variations and expanded biological monitoring, especially of phytoplankton communities, nutrient profiles (nitrogen and phosphorus), and trophic linkages. Investigating sediment composition, contaminant retention, and benthic community structures could offer insights into long-term ecosystem resilience and degradation pathways. Moreover, applying remote sensing and hydrodynamic modeling would help visualize and predict shifts in water quality and circulation patterns under changing climate and land-use conditions. Collaborations with local stakeholders and the inclusion of traditional ecological knowledge may also enhance the relevance and applicability of scientific findings for sustainable lagoon management.

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