Chapter 5

PHYSICO-CHEMICAL CHARACTERISTICS OF NEGATIVE ESTUARIES IN THE NORTHERN GULF OF CALIFORNIA, MEXICO

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ABSTRACT

We describe water quality in two hypersaline negative estuaries in the Northern Gulf of California, along the coast of Sonora, Mexico, over a two-year period. In the Northern Gulf, non-mangrove salt marshes known as esteros (negative estuaries) cover 134,623 ha. Esteros are characterized by an extreme tidal range, higher salinity at their head than at their mouth due to high evaporation, limited freshwater input and a mixed semi-diurnal tidal regime. Between 2005 and 2007, we sampled surface temperature, dissolved oxygen, salinity, pH, depth, chlorophyll, nutrients (NH₄, NO₃, NO₂, and PO₄), and total suspended solids across one wetland, Estero Morúa. We also led a participatory monitoring effort, where oyster farmers took daily measurements of surface temperature, salinity, pH, and dissolved oxygen in both Estero Morúa (31°17`09" N; 113° 26`19" W) and Estero Almejas (31°10`15" N; 113°03`53" W). These sites allow comparisons between distinct habitats and levels of oceanic influence. Estero Morúa is a high energy lagoon with a narrow mouth and a prominent permanent channel restricted by spits, while Almejas is an open bay with a large intertidal mudflat. Among the main findings are 1) Surface temperatures follow a seasonal pattern, with highest temperatures in June to September and lowest from December to February. 2) Low rainfall and runoff together with high seawater input and evaporative loss results in high salinities. 3) High dissolved oxygen concentrations and low nutrient levels are indicative of the recharge rate between the wetlands and the sea, and are characteristic of oligotrophic systems. It is likely that
residence time and tidal dynamics are the main factors dictating the physicochemical dynamics of these systems.

**INTRODUCTION**

Negative or inverse estuaries are those where seawater is concentrated by the removal of fresh water, either by evaporation that exceeds precipitation, or by freezing and the occurrence of sea ice [1,2]. The former type is usually associated with arid climates and occurs in both hemispheres including in the Red Sea, the Gulf of Suez, the Mediterranean Sea, the Adriatic Sea, the Arabian Gulf, South Australia, and the Gulf of California [2]. Negative estuaries can be permanent or can be negative only during part of the year where rainfall is strongly seasonal [3].

According to Miller et al. [4], salinity in negative estuaries can increase as one moves horizontally from the mouth of the estuary to the head, especially in the bottom layers. Gravitational circulation can lead to the export of high density lagoonal water, at the same time that ocean water fills into the lagoon as a low-density surface layer. The water exchange between the lagoon and the ocean is enhanced in the flood and ebb cycles. The physical and chemical characteristics of water within estuaries are heavily influenced by meteorological conditions [5], the amount of freshwater runoff [6] and tidal hydrology [7]. The interaction among tidal hydraulics, open water, benthic and marsh surface processes yields unique water chemistry profiles [7].

In Mexico, negative estuaries are hypersaline salt marshes where salinities may exceed > 40, pH ~ 9, oxygen is close to saturation and total nitrogen is low [8]. These wetlands are found in both the Gulf of Mexico and Pacific coasts of the country, and are common in the states of Baja California, Sonora and Oaxaca [9]. Negative estuaries in the Northern Gulf of California, above 29 °N, are non-mangrove salt marshes locally known as esteros [10] that connect to the open gulf by channels or inlets. The Northern Gulf is very arid, with mean annual rainfall < 125 mm and mean maximum annual temperature of 22 - 26 °C [11]. There are no perennial rivers [12], and the lack of freshwater input and excess evaporation result in an increasing salinity gradient towards the head of wetlands [13]. Tidal range in the Northern Gulf may exceed 8 m [14], so the wetlands empty out during low tides and at high tides the water floods the marsh surface, resulting in varied areas of open water habitat, exposed mudflat, and shallow water available daily [15]. Thus, tidal hydrology plays an important role in connecting different areas of the marsh that remain isolated during most of the tidal period.

Environmental conditions can be challenging for the organisms that inhabit esteros. Many species use negative estuaries opportunistically, entering only during high tides to rest, feed and reproduce [3]. Other species are residents with special adaptations to withstand the harsh environmental conditions. Esteros represent one of the hottest zones occupied by fish [16]; eurythermal species such as the gobies Gillichthys mirabilis, the longjaw mudsucker and the endemic Gillichthys seta, the shortjaw mudsucker are some of the most abundant residents [17,18]. These fish can withstand the daily temperature fluctuations in the wetlands that can range from 5° to 7° C seasonally [19]. Other species, such as the halophyte marsh plants Sarcocornia pacifica, Mönantochloe littoralis, and the endemic Distichlis palmeri, use the controlled uptake of Na⁺ into cell vacuoles to drive water into the plant tissues against a low external water potential.
The description of water quality in negative estuaries can be useful to understand the ecology of species that inhabit them and represents important background information on the dynamics of physical and chemical parameters. We evaluated seasonal variability of water quality in Estero Morúa and Estero Almejas in the state of Sonora, Mexico as part of a project to determine the causes of oyster mortality [21]. We recorded monthly measurements in Estero Morúa, as well as daily measurements in Estero Morúa and Estero Almejas as part of participatory monitoring, where members of local oyster cooperatives measured key parameters in their farms.

**METHODS**

**Survey Location**

We surveyed water quality in Estero Morúa (31°17’09” N; 113° 26’19” W; Figure 1) and Estero Almejas (31°10’15” N; 113°03’53” W; Figure 1). Estero Almejas and Morúa are negative estuaries with a higher salinity at the head than at the mouth [1]. These sites are located in the Northern Gulf of California, in the state of Sonora in Northwestern Mexico. Estero Morúa and Estero Almejas are within the municipality of Puerto Peñasco; the main city in the area is Puerto Peñasco (Pop. 44,875, [22].

The Northern Gulf of California is characterized by climatic conditions of a low-altitude coastal desert (Foster 1975), with scarce rain during the summer averaging 70 – 90 mm [24,10]. The annual temperature average is 20.1°C, fluctuating between 11.3°C in January and 30°C in August [10]. High evaporation rates, coupled with the lack of freshwater input, results in the increasing salinity gradient inside the estuaries [12]. The Sonoran coast experiences prevailing northerly and northwesterly winds in the winter, and southern and southeasterly winds in the summer. During the winter, offshore winds predominate and in the summer onshore winds are dominant [24]. Maximum wind speeds vary from 43 km h⁻¹ (maximum one-day mean) in winter to maximum 21.6 km h⁻¹ in summer, with occasional gusts reaching 118 km h⁻¹ [25].

Estero Morúa (Figure 2) extends over 1,097 ha [13], and is of deltaic origin; it formed as part of an estuarine system fed by the Sonoyta river, although the flow is now diverted for agriculture and no longer reaches the sea [26]. In the northeastern side of the wetland, remnant riparian vegetation remains in the dry river bed maintained by subsurface flow [13]. Estero Morúa is a high energy embayment with a narrow mouth and a central channel restricted by spits [27] that measures 11.58 km in length with a mouth 0.5 km wide. Rock outcroppings protrude through the sand at the mouth of the estero. Sediment grain at the mouth is coarse sand (0.5 mm) and particle size decreases inwards to fine sand in the side channels and silt in the upper reaches at the head [27]. The main lagoon is separated from the Gulf by barrier dunes that used to reached heights of ~100 feet [28], but have been partially been flattened during the construction of the surrounding residential developments. Estero Morúa houses four aquaculture cooperatives that farm Japanese oysters (*Cassostrea virginica*) along the main tidal channel.
Figure 1. Location of Estero Morúa and Estero Almejas, hypersaline negative estuaries in the state of Sonora, northwestern Mexico and (●) oyster cooperatives, where the participatory water quality monitoring program was implemented.

Figure 2. Estero Morúa, Sonora, México at neap tide, July 2009. Photo: Alejandro Castillo. CEDO Intercultural.
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Estero Almejas (Figure 3; also known as Bahía Salina) is located in Bahía San Jorge, and extends over 2,286.02 ha [10]. The wetland is a semi-open embayment with a sand bar to the north composed of consolidated dunes. When the tide recedes, it exposes extensive mudflats. The landward area is covered in salt flats, where salt was harvested in evaporative lagoons (Salinera del Desierto Rojo). The coastal beaches and mudflats of Estero Almejas formed during the Holocene, ~ 5,000 BP, when sea level reached its maximum. The beaches and mudflats were formed by wind-blown sediments and silt deposited by the tides and currents [13]. Estero Almejas has one oyster farm and a fishing camp in the vicinity (Pop. 41) [22] which sustains important artisanal fisheries for blue crab (*Callinectes arcuatus* and *Callinectes bellicosus*), rays, and pelagic fish [23].

In both Estero Morúa and Almejas, the wetland channels are surrounded by salt marsh vegetated with halophytes that rarely grow beyond 50-60 cm [29]. The immediate wetland margin is covered by low shrubs including Palmer's frankenia (*Frankenia palmeri*), white bur sage (*Ambrosia dumosa*), creosote bush (*Larrea tridentata*), salt bush (*Atriplex polycarpa, Atriplex canescens*), and desert thorn (*Lycium* spp.) [30]. Beyond, we find vegetation of the Sonoran Desert - Lower Colorado River Valley subdivision [29].

The tidal regime in the Northern Gulf is mixed semidiurnal (two high and two low tides of different elevations in 24 hours), with tidal amplitudes of 5-10 m [31]. In the Puerto Peñasco region tidal amplitude is 7.04 m, with lowest tides in April and highest in October [21]. During the highest spring tide the marshes flood completely, and at the lowest neap tide the wetlands empty, uncovering extensive mudflats where some water remains forming pools [15].

We describe sample collection and analysis for the monitoring program in Estero Morúa, where data were collected monthly during neap tide. We then describe the participatory monitoring program in Esteros Morúa and Almejas, for which data were collected daily.

Figure 3. Estero Almejas, Sonora, México at neap tide, July 2009. Photo: Alejandro Castillo. CEDO Intercultural.
Monitoring Program in Estero Morúa

Sample collection – In Estero Morúa, samples were collected between 2005 and 2007. We used a stratified random sampling design, to account for the difference in channel and creek area across the marsh. Starting in August 2005, for each month we selected ten random points across six sections. Each such set of ten points is referred to hereafter as a “survey”. In total, we sampled 220 points throughout 22 months (Figure 4). Samples were collected at the lowest tide of the neap tide, to minimize oceanic influence. Thus, collection times varied monthly. Sampling points were visited in 1-2 days. The time for sampling was selected using tidal prediction software (WXTide 32 Versión 4.7; http://wxtide32.com).

At each point we took three replicate measurements of each parameter: water temperature, dissolved oxygen (D.O.), salinity, and pH (Figure 3). We also recorded water depth, time and location. Dissolved oxygen, water temperature, and pH were measured with an Oakton multimeter 300 (Oakton Instruments, Vernon Hills, Il, EUA). Sensors were immersed in the water column until a constant value was obtained (Figure 5). Dissolved oxygen is expressed in mg/L and temperature in °C. Oxygen measurements were compensated by temperature but not for salinity, as salinity values were routinely higher than the instrument's compensation limits. A pipette was used to collect 2-3 drops of water, which were placed on a Vista refractometer to measure salinity on a 0-100 scale. Location was recorded with an eTrex Garmin GPS (Garmin Ltd., Olathe, KS, EUA), in the WSG1984 coordinate system.

Figure 4. Sampling locations in Estero Morúa, Sonora, México where seawater samples were collected in 2005 (●), 2006 (■), and 2007 (▲). Dashed lines indicate the six sections where random points were selected monthly using a stratified random sampling design. Figure also shows habitat types.
Starting in September 2005, we also collected 4 liters of water at six alternate points (usually points 1, 3, 5, 6, 8 and 10) for determination of dissolved nutrients (NO$_2^-$, NO$_3^-$, NH$_4^+$ and PO$_4^{3-}$) and particulate compounds (total suspended solids, TSS, chlorophyll $a$, $b$ and $c$). Samples for TSS collected in September and October were lost, so data are only available for this parameter from November 2005 to May 2007.

We also measured sea surface temperature on the open coast and ambient air temperature. Sea surface temperature was measured daily at approximately 9 am outside of Estero Morúa, at 31°17′21″ N; 113°29′47″ W. Between August 2005 and April 2006 temperature was measured using a partial immersion mercury thermometer. After this date temperature was measured using an electronic VWR waterproof remote probe thermometer with ± 0.1 °C precision (VWR International LLC, Batavia IL, USA). Ambient air temperature was recorded at CEDO's field station, ~ 0.6 km from Estero Morúa, using a Weather Monitor II station (Davis Instruments, Haywood, CA, USA). We report monthly averages based on hourly data.

Sample analysis - We analyzed TSS using the gravimetric method [32]. We filtered 700ml of seawater or less, as necessary to saturate an ash-free Whatman GF/C filter of known
weight (previously burned at 400 °C for four hours). The filters were then dried at 60 °C until of constant weight. The filters were re-weighed and the total solids were reported as the weight difference between the two weights adjusted for volume filtered in mg/L.

Chlorophylls were analyzed following Arar [33]. We analyzed 700 ml of seawater or less, as necessary to saturate a Whatman GF/C filter. We saved 20 ml of the filtered water for nutrient analysis; these samples were frozen until analysis. While filtering the last 10 ml of water we added 1 ml of saturated MgCO₃ suspension. The filters were wrapped in aluminum foil and frozen until analysis. For chlorophyll extraction, the filters were ground with 12 ml of acetone with a glass rod and incubated for 4 h in the dark (shaking every hour), and centrifuged at 1000 g for 5 min. The supernatant was read in a spectrophotometer at 750, 664, 647 and 630 nm. Concentrations of chlorophylls a, b and c were determined based on the trichromatic equations of Jeffrey & Humphrey [34] and expressed as mg/m³.

The nutrient analysis was carried out in the Centro de Investigaciones Biológicas del Noroeste, in Hermosillo, Sonora. Water samples were thawed and analyzed using the microplate technique described by Hernández-López & Vargas-Albores [35]. This method is based on the formation of colored complexes in 96-well plates that are then measured by spectrophotometry, reducing costs while maintaining precision. Nutrient concentrations are presented in μM.

Figure 6. Water temperature (means ± SE) between August 2005 and May 2007. a. Monthly measurements in Estero Morúa (n = 30); b. Participatory monitoring in Estero Morúa, daily readings. c. Participatory monitoring in Estero Almejas, daily readings.
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**Participatory monitoring**

*Sample collection* - The participatory monitoring program collected daily data but had no spatial replication, as all samples were taken in a single point across time. Measurements were recorded between August 14, 2005 and May 15, 2007. In Estero Almejas, the Sociedad Cooperativa de Producción Pesquera y Acuícola (SCPPA) La Cinita collected data throughout the study period. In Estero Morúa, the SCPPA Unica de Mujeres collected data between August and November 2005, after this time it was replaced by the SCPPA Aquamar. Members of the cooperatives received a pH meter, a D.O. meter, and a refractometer from the Aquaculture Institute of the State of Sonora. We prepared a manual and training course on water quality monitoring, that were offered to members of each cooperative prior to the start of the project. We also assisted the cooperatives with equipment maintenance and calibration and maintained the database for the duration of the program.

Each day, a member of the cooperative registered near their oyster trays sea surface temperature, D.O., salinity and pH. Oxygen measurements were compensated for temperature but not for salinity, as salinity readings were routinely higher than the instrument’s compensation limits. We requested that measurements be carried out at or near the same time every day. In Estero Almejas, the measurements generally occurred between 6-8 am, and were recorded by 13 people who alternated. Readings were recorded on 95% of the days of the study period. In Estero Morúa, one person was routinely responsible for data collection, parameters were measured at variable times and compliance was only 77%. Several problems occurred during the participatory monitoring program, including equipment breakdown and errors while measuring and recording data. Thus, the quantity of data available by parameter and site is variable.

**Data Analysis**

We used linear regression to study the relationship between temperature, salinity, D.O., pH, total suspended solids, chlorophylls (a, b and c), and nutrients (NO$_2$, NO$_3$, NH$_4$ and PO$_4$) across the months surveyed. When negative values were present for parameters that conceptually can only be ≥0, such as nutrients and chlorophylls, we corrected the data by substituting negative values for 0. The Akaike Information Criterion (AIC) was used on the linear model to select the variables that best explained the structure of the data [36]. Data summarized in tables and graphs is untransformed. Data analysis was carried out in the R Open Source system (R Development Core Team).

**RESULTS AND DISCUSSION**

**Temperature, Salinity, pH and Dissolved Oxygen**

Mean water temperature in Estero Morúa throughout the study period was 19.8 ± 0.2 °C (Table 1). Temperature followed a seasonal pattern with highest temperatures in summer (30.3 ± 0.3 °C in August 2005) and lowest in winter (9.4 ± 0.3 °C in January 2006; F = 362.27, P < 0.001; Figure 6). Previous studies in Estero Morúa found similar temperature
intervals. Place & Hofmann [37] found that on average water temperature in the estuary ranged from 5° to 30°C during tidal cycles in winter and from 18° to 36°C during tidal cycles in summer. Buckley & Hofmann [19] recorded temperature in the water column of Estero Morúa between January and June 2001, and found a range from < 5°C in early January to higher than 33 °C in June. We also found significant variability in water temperature between sampling locations (F = 12.7, P < 0.001). Spatial variations in temperature in the wetland result from differences in water depth, tidal exchange and bottom sediments, which may play a role in the absorption or transfer of heat to overlaying waters [38].

Water temperatures from the participatory monitoring program were in agreement with monthly data, although the latter average measurements throughout the tidal cycle. Mean temperature was 22.2 ± 0.3 °C in Estero Morúa, and there was variation between surveys (F = 95.39, P < 0.001), with the highest mean in September 2005, 33 ± 0.4 °C, and lowest in November 2006, 13.3 ± 1 °C. In Estero Almejas, temperature varied between 33 ± 1.2 °C in August 2005, to 12.5 ± 1 °C in December 2005 (Figure 6), and there was significant variation amongst surveys (F = 61.36, P < 0.001). Water temperature in both wetlands follows the general patterns of sea surface and ambient temperature measured outside Estero Morúa (Figure 7). The main exception is in winter, when water temperatures in the estuary are lower because tidal areas are shallow and lack sufficient heat storage capacity. The pattern of variation in water temperature is the result of variations of solar heating, which is extreme in the desert climate of Northwest Mexico [1] and can also be related to seasonal changes in water masses [39].

**Table 1. Physical and chemical parameters of water in two coastal wetlands of the Northern Gulf of California, measured between August 2005 and May 2007**

<table>
<thead>
<tr>
<th>Model</th>
<th>Estero Morúa</th>
<th>Participatory monitoring</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Estero Morúa</td>
</tr>
<tr>
<td>Temp. (°C)</td>
<td>Mean ± Max</td>
<td>Min</td>
</tr>
<tr>
<td></td>
<td>19.77 ± 0.24</td>
<td>33.1</td>
</tr>
<tr>
<td>Sal.</td>
<td>46.13 ± 0.38</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>pH</td>
<td>8.06 ± 0.02</td>
<td>10.25</td>
</tr>
<tr>
<td>D.O. (mg/L)</td>
<td>8.68 ± 0.07</td>
<td>16.12</td>
</tr>
<tr>
<td>NO₃ (μM)</td>
<td>2.92 ± 0.16</td>
<td>6.52</td>
</tr>
<tr>
<td>NO₂ (μM)</td>
<td>0.001 ± 0.0002</td>
<td>0.01</td>
</tr>
<tr>
<td>NH₄⁺ (μM)</td>
<td>0.006 ± 0.0006</td>
<td>0.02</td>
</tr>
<tr>
<td>PO₄ (μM)</td>
<td>0.002 ± 0.0004</td>
<td>0.04</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>18 ± 0.45</td>
<td>40.95</td>
</tr>
<tr>
<td>Chl a (mg/m³)</td>
<td>0.13 ± 0.02</td>
<td>0</td>
</tr>
<tr>
<td>Chl b (mg/m³)</td>
<td>0.03 ± 0.01</td>
<td>2.54</td>
</tr>
<tr>
<td>Chl c (mg/m³)</td>
<td>0.07 ± 0.02</td>
<td>2.92</td>
</tr>
</tbody>
</table>
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Figure 7. Ambient and sea surface temperature (b.) measured in the CEDO field station and outside of Estero Morúa during the study period (means ± SE).

Salinity values were high in Estero Morúa, overall 46.2 ± 0.4 (Table 1), and varied between 53.2 ± 3.2 in April 2006 to 41.1 ± 0.45 in May 2007 (Figure 8). These hypersaline values are likely due to excess evaporation and lack of freshwater input. The Puerto Peñasco region receives < 100 mm of rain per year [24]. Although there was variation among surveys (F = 10.15, P < 0.001) there was no seasonal pattern. We also found significant variation between sampling locations (F = 83.8, P < 0.001), a product of the spatial variability in salinity, with higher values at the head of the estuary compared to the mouth, where there is more water exchange with the Gulf. Salinity increases in the inner arms of bays and lagoons are typical in regions where evaporation exceeds river flow and precipitation [8]; in the Northern Gulf evaporation exceeds precipitation by 250 cm/yr-1 [1].

In the participatory monitoring program, daily salinity readings in Estero Morúa (43.8 ± 0.2; 45.21 ± 0.56 April 2006 – 38.9 ± 0.5 August 2005) and Estero Almejas (47 ± 0.2; 49.7 ± 0.7 May 2006 – 42.4 ± 0.5 August 2005) were equivalent to monthly data. At both sites, salinity varied among surveys (Estero Morúa: F = 6.44, P < 0.001; Estero Almejas: F = 20.24, P < 0.001; Figure 8). Salinity values recorded in both Estero Morúa and Almejas are similar to those reported for other inverse estuaries. In Bahía San Quintin, on the Pacific Coast of the Baja California Península, México, average salinities range from 34.7 in summer to 33.8 in winter [40]; while in Estero La Cruz, in the central Gulf of California, salinity averages 36.8
We found water salinity values as low as 31 in October 2005 and as high as >100 in June 2006. These extreme values are common in negative estuaries. Valenzuela-Siu et al. [42] found salinity varied between 35 – 42 in summer and 37 – 39 in winter at Estero Lobos.

pH values in Estero Morúa were on average 8.4 ± 0.2 (Table 1), with a high of 9.1 ± 0.1 in February 2006 and a low of 7.4 ± 0.2 in September 2006. The overall mean is slightly higher than pH values for seawater in equilibrium with atmospheric CO₂ (8.1-8.3) [38]. There was no significant variation in pH values among sample locations or surveys (Figure 9). We found that pH readings were very sensitive to small changes in how measurements are collected, which could explain some of the high values. It is unlikely that high pH values are related to plant growth which reduces CO₂ content, as we did not sample the marsh surface. pH data from the participatory monitoring program showed less variation than monthly data (Figure 9). pH values in Estero Morúa varied between 8.1 ± 0.02 in November 2005 to 7.6 ± 0.03 February 2007 (7.9 ± 0.02 overall). In Estero Almejas, mean pH during the study period was 7.9 ± 0.02, and varied from 8.2 ± 0.1 November 2005 to 7.4 ± 0.1 in October 2006 (Figure 9). Lower pH values, especially in the summer, could reflect the production of CO₂ by the decay of organic matter in bottom muds [8].

Figure 8. Water salinity (means ± SE) between August 2005 and May 2007. a. Monthly measurements in Estero Morúa (n = 30); b. Participatory monitoring in Estero Morúa, daily readings. c. Participatory monitoring in Estero Almejas, daily readings.
Figure 9. pH (means ± SE) between August 2005 and May 2007. a. Monthly measurements in Estero Morúa (n = 30); b. Participatory monitoring in Estero Morúa, daily readings. c. Participatory monitoring in Estero Almejas, daily readings.

Dissolved oxygen concentrations in Estero Morúa were high (8.68 ± 0.07 mg/L), and varied between 11.34 ± 0.18 mg/L in July 2006 to 6.21 ± 0.22 mg/L in August 2005 (Figure 10). We found that D.O. values varied with location (F = 2.46, P < 0.001) and survey (F = 64.5, P < 0.001), with a general pattern of increasing concentrations in warmer months, but no definite seasonal pattern (Figure 10). In other coastal lagoons, such as Estero La Cruz, Sonora, D.O. shows a clear seasonal pattern with higher values in winter (8.58 ml/L) to (2.58 ml/l) in spring and summer [41].

The D.O. values we found are within the intervals previously reported in other coastal lagoons in the Gulf of California [40]. Dissolved oxygen in Estero Almejas and Estero Morúa measured during the participatory monitoring showed a similar pattern, with low values of 6.1 ± 0.08 and 6.09 ± 0.08 mg/L respectively in August 2005, to highs of 10.91 ± 0.22 mg/L on April 2007 in Morúa and 10.61 ± 0.11 mg/L on December 2006 in Almejas (Figure 10). The high D.O. concentrations can be attributed to the high exchange rate between the wetland and
the sea, and the low depth of the water column during sampling, while high values in winter are related to increased solubility at low temperatures [41].

![Dissolved oxygen](image)

**Figure 10.** Dissolved oxygen (means ± SE) between August 2005 and May 2007. a. Monthly measurements in Estero Morúa (n = 30); b. Participatory monitoring in Estero Morúa, daily readings. c. Participatory monitoring in Estero Almejas, daily readings.

### Dissolved Nutrients

We found that nutrient concentrations in Estero Morúa were low, likely a result of low precipitation and runoff. Figure 11 shows the fluctuations of the various forms of nitrogen and of phosphate in water throughout the study period. Nitrate was the main inorganic N form in Estero Morúa, with concentrations of 3.17 ± 0.15 μM (Table 1). The other nutrients were present in lower concentrations, NO$_2^-$, 0.001 ± 0.0003 μM, PO$_4$, 0.002 ± 0.0004 μM, and NH$_4^+$, 0.006 ± 0.0006 μM. Nitrogen concentrations are lower than values reported for other hypersaline wetlands in the Northern Gulf. In Estero Lobos, NO$_2^- +$ NO$_3^-$ ranged from 1.2 – 1.1 μM seasonally and NH$_4^+$ increased from 0.6 μM in summer to 1.2 μM in winter [42]. The dynamics of biophilic elements, such as nitrogen and phosphorus, in tidal estuaries are strongly related to the variation in tidal cycle [43]. These changes are strongly dependent on the spring-neap stage or amplitude [7], current velocity [44] winds [45] and precipitation rate,
which affect runoff [6]. The nutrients found in Estero Morua probably stem from internal recycling and wind; desert dust may provide nutrient inputs to wetlands in arid areas [46]. Runoff during rain is most certainly an insignificant factor, as in 2006, Puerto Peñasco received only 2.27 cm of rain and between January and June 2007 only 0.13 cm (Data: CEDO Intercultural). In Northwest Sonora, there are no other nutrient sources, such as rivers or the shrimp aquaculture farms that are present in coastal lagoons in the southern part of the state [47]. The observed increase in NH$_4^+$ and NO$_2^-$ during 2007 (Figure 11) could be related to upwelling frequently present on the eastern coast of the Gulf of California during winter-spring [48].

The low nutrient levels observed in Estero Morúa be an artifact from collecting samples at low tide in wetlands nutrients can be rapidly sequestered by microbial activity in benthic surfaces, in which case water column monitoring such as ours can result in an underestimation of nutrient availability [50].

NO$_2^-$ and NH$_4^+$ concentrations were higher in winter and spring 2007 (Figure 11) relative to other surveys (F = 11.28, P < 0.001; F = 34.72, P < 0.001), while PO$_4$ showed few differences between surveys (Figure 11). Nitrate concentrations were higher, 3.17 ± 0.15 μM, than for other nutrients and showed high variability as a function of sampling location (F = 2.76, P = 0.02) and survey (F = 11.03, P < 0.0001), but there is no clear monthly or yearly pattern. Patterns in the variability of total dissolved N (NO$_3^-$ + NO$_2^-$ + NH$_4^+$) in Estero Morúa will reflect the concentrations of NO$_3^-$, since levels of the other forms of nitrogen were so low.

![Figure 11. Nutrient concentrations (means ± SE) between August 2005 and May 2007 in Estero Morúa (n = 6).](image-url)
Particulate Compounds

The average TSS concentration was 18.06 ± 0.45 mg/L (Table 1). We sampled in low tide where water depth during the study period was 15.26 ± 0.43 cm. In shallow areas, light can penetrate to the entire water column and hydrodynamics are affected by bottom morphology and wind, which promote the resuspension of materials, nutrients and small biota from the bottom surface into the water column [50]. TSS is also influenced by the type of vegetation, land cover and land use surrounding the site. Estero Morúa is surrounded by Sonoran Desert, with low lying, scarce vegetation [29], and nearby residential developments (Figure 2) have contributed to erosion by destroying vegetation and flattening the dunes that surrounded the site on the seaward edge [28].

We found that TSS concentration varied between survey (F = 6.77, P < 0.001; Figure 12) and sampling location (F = 4.36, P < 0.001). A high TSS concentration was present in May 2006 (27.75 ± 1.33 mg/L) and some summer months (Figure 12), but there was no clear seasonal pattern. In estuaries, the cycling of suspended particles depends on processes such as re-suspension and settling, mudflat processes and particle-particle interactions (i.e. Brownian motion, differential settling and coagulation), which are driven by river flow, tidal energy and storms and tend to be accentuated in shallow environments [51]. In Estero Morúa, the variation in TSS is likely driven by wind and the tidal regime, as river flow and runoff are not important factors in the region [10].

Chlorophylls

The chlorophyll a (Chl a) concentrations observed in Estero Morúa indicate a system with low primary productivity. Although the Gulf of California is very productive [13]. The Northern Gulf exhibits patches of high Chl (up to > 2 mg/m3) even during summer due to
Physico-Chemical Characteristics of Negative Estuaries…

tidal mixing which carries cold and nutrient rich waters to the surface, throughout the year [52].

In esteros of the Northern Gulf, the oceanic influence is strong, resulting from the exchange of water during high tides [41]. A stable isotope analysis of trophic food webs in Estero Morúa found that marine derived phytoplankton contributes the most carbon to the system [53]. Mean Chl a concentrations were on average 0.13 ± 0.02 mg/m³ for the study period (Table 1). Chl a concentrations showed a significant variability between sampling locations (F= 2.96; P = 0.009) and surveys (F= 2.26; P = 0.004; Figure 13). The highest concentration was found in June 2006 (0.50 ± 0.32 mg/m³; Figure 13) but there was no seasonal pattern. The average Chl a concentrations in Estero Morúa are on the low range of previously reported values for other arid wetlands. Gilmartin and Relevante [49] found values between 0.2 – 19.9 mg/m³ in 12 coastal lagoons of the Gulf of California. Negative estuaries in the Northern Gulf are usually less productive than positive estuaries because of the scarcity of organic matter, especially at their head waters [1].

The concentrations of chlorophyll b (Chl b) and chlorophyll c (Chl c), were low (0.03 ± 0.01 and 0.07 ± 0.02 mg/m³ respectively). These parameters were only detected in a few surveys. Both were found in January, February, and June 2006. Chlorophyll b was also found in April 2007 and Chl c was detected in August 2006, and January and March 2007.

Relationship between Parameters

Explanatory linear models for the variables measured are found in Table 2. We found a significant negative relationship between temperature and dissolved oxygen, likely due to the relationship between water temperature and gas saturation that results in less oxygen being available at higher temperatures [41]. We also found a negative relation of temperature with pH, and a positive response in relation to depth. There was a positive relationship between variability of NO₂⁻ and NO₃⁻, and a negative relation between NO₃⁻ and NH₄⁺, as expected since NH₄⁺ is sequentially oxidated to NO₂⁻ and then to NO₃⁻ during bacterial denitrification [54]. In some cases these nitrogen forms were also related to D.O., pH, temperature, depth, salinity. Strong positive relationships were found between PO₄, salinity, D.O. and NO₃-. Phosphate concentrations and dissolved oxygen are linked and controlled by the rate of water exchange and biological processes [55]. Lower TSS values were associated with lower depths, salinity, temperature, and Chl a. Finally, Chl a concentrations showed a negative relation with TSS and were a positive function of PO₄, water temperature, depth, and salinity, underscoring the fact that microalgal biomass is sensitive to changes in environmental conditions [43], and is regulated by light [41].

CONCLUSIONS

Estero Morúa and Almejas are hypersaline systems, where temperature, dissolved oxygen concentrations, pH, and salinity are highly dependent on depth, tidal circulation, and solar heating. The hypersaline conditions are prevalent year-round because of the low precipitation and high evaporation present in the region [1]. We found that environmental conditions
resulting from physical and chemical factors can be extreme: temperatures ranged between 6° and ~40 °C and salinity reached > 100. Overall levels of dissolved oxygen were high > 8 mg/L and nutrient concentrations were low, except for nitrate, particularly in summer and autumn, resulting in oligotrophic conditions. The complex interactions between biological, physical and chemical parameters of water in these estuaries can exert stress in the organisms found in different environments in the marsh, many of which are important commercial species in the region.

Table 2. Linear models for the selected physical and chemical variables in Estero Morúa, Sonora. Asterisks indicate explanatory variables (ANOVA, ns: not significant, . P < 0.1, * P < 0.05, ** P < 0.01, ***: P < 0.001). Models with lowest AIC values were selected. Negative relationships are underlined.

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<th>Model</th>
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<th>Depth</th>
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We found that seasonal cycles clearly determine physicochemical variables such as temperature and salinity, but the seasonal effect was not as clear for other variables such as TSS (Figure 12) and Chlorophylls (Figure 13). These variables might experience higher spatial variability or be influenced by the spring-neap variations in tidal cycle [41]. On a time scale of hours, the entry of sea water could be responsible for changes in salinity, nutrient concentrations, and suspended solid content [43]. Mixing and strong currents due to the macrotidal regime likely preclude the formation of vertical gradients during high tide [42]. Current velocities in the mouth of Estero Morúa can reach 50 cm/s and decrease to 10 cm/s in the arms of the wetland and residence time is only 6 hours [21]. As a result, during high tides, physicochemical parameters likely approximate seawater. For example, water salinity during spring tides in Estero Morúa is closer to sea water, 38.2 ± 0.4 (A. Iris Maldonado, unpublished data).

Our study is a first step in describing the environmental conditions of negative estuaries in northwest Sonora. Further studies are needed that consider the spring-neap tide, depth profile variations and fluxes of nutrients and net metabolism [i.e. 42] to evaluate changes in the system and the effect of human activities. Coastal wetlands in the Gulf of California, like Esteros Morúa and Almejas, are under increasing stress from coastal zone development [56] and other human activities that cause changes in tidal hydrology, increased pollution, and changes in flora and fauna [57]. Particular attention should be placed on waterborne health risks, since estuaries in the region contribute to the local economy through fisheries production and oyster culture [23]. Our sampling did not reveal the high levels of nutrients common in other wetlands in Sonora, that have been impacted by the shrimp farms or other
human activities [47], but erosion of coastal dunes surrounding Estero Morúa and other local wetlands could increase sediment deposition. In Estero Morúa and Almejas, a state water quality monitoring program continues to ensure that farmed oysters are safe for human consumption (more information available at http://www.cosaes.com).

Figure 13. Chlorophyll \( a, b, \) and \( c \) concentrations (means ± SE, \( n=12 \)) measured monthly in Estero Morúa between October 2005 and May 2007.

**ACKNOWLEDGMENTS**

This study was funded by The David and Lucile Packard Foundation grants 2004-26759 and 2006-30328 to CEDO Intercultural and by the Secretaría de Agricultura, Ganadería, Desarrollo Rural y Pesca - Comisión Nacional de Acuacultura y Pesca - Instituto de Acuacultura del Estado de Sonora, O.P.D. through the Grupo Interinstitucional de Investigación en Moluscos Bivalvos and the project “Determinación de agentes causales de alta mortalidad en los cultivos del Ostión Japonés, *Crassostrea gigas*, de las costas de Sonora”. A. Castillo López, R. Fraser, A. García Sanchez, S. López Alvirde, S. Mason, S. Reyes Fiol, and A. Rosemartin participated in sample collection. J. Hernández-López at

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