Ecohydrogeochemical functioning of coastal freshwater herbaceous wetlands in the Protected Natural Area, Ciénaga del Fuerte (American tropics): Spatiotemporal behaviour

Lorena Elisa Sánchez-Higueredo1 | José Alfredo Ramos-Leal2 | Janete Morán-Ramírez3 | Patricia Moreno-Casasola Barceló1 | Ulises Rodríguez-Robles4 | María Elizabeth Hernández Alarcón1

1Red de Ecología Funcional, Instituto de Ecología (INECOL), Xalapa, México
2División de Geociencias Aplicadas, Instituto Potosino de Investigación Científica y Tecnológica (IPICYT), San Luis Potosí, México
3Catedras Conacyt-Instituto de Geofísica, Universidad Nacional Autónoma de México (UNAM), Coyoacán, México
4Departamento de Ecología y Recursos Naturales, Centro Universitario de la Costa Sur, Universidad de Guadalajara, Autlán de Navarro, Jalisco, México

Abstract
Coastal zones are characterized by the interactions between continents and oceans and, therefore, between fresh and salt surface and groundwater. The wetlands of coastal zones represent transitional ecosystems that are affected by these conditions, although little is known about the hydrogeochemistry of wetlands, especially coastal wetlands. In the present study, the hydrogeochemical characterization of coastal freshwater herbaceous wetlands in the Ciénaga del Fuerte Protected Natural Area in Veracruz, Mexico, in the American tropics was carried out per plant community. Four herbaceous wetlands (alligator flag, saw grass, cattail, and floodplain pasture) were monitored to understand the origin of the water feeding these ecosystems, the hydrogeochemical composition of groundwater, and the relationship between the groundwater and ecology of these ecosystems during dry and rainy seasons. The results indicate that Ciénaga del Fuerte is located in a regional discharge area and receives local recharge, so it is fed by both regional and local flows. The chemical composition varied temporally and spatially, creating unique conditions that determined the habitat occupied by the hydrophytic vegetation. The spatiotemporal behaviour of groundwater is one factor that, along with the hydroperiod, determines wetland dynamics and affects wetland biota (eco-hydrogeochemistry). Generalist plant communities established in zones of local recharge, whereas other more specialized and/or plastic communities inhabited zones receiving regional flows with greater ion concentrations. This information forms the basis for establishing an appropriate scale (municipal, state, or larger regions) for the sustainable management of goods and services provided by the wetlands.

KEYWORDS
Cladium jamaicense, coastal freshwater wetlands, hydrogeochemistry, natural resources management, Thalia geniculata, Typha domingensis, wetland function
INTRODUCTION

Coastal zones are highly dynamic and productive areas where the continents, oceans, and atmosphere interact. Diverse ecosystems are present in these zones, including beaches, dunes, and wetlands such as reefs, mangroves, floodplain forests, coastal lagoons, estuaries, and herbaceous wetlands (e.g., tules, carrizales, and popoles). Evidence of the dynamic nature of coastal zones includes erosion processes, which affect beaches and dunes, and meteorological phenomena, such as hurricanes and torrential rainfall, which affect extensive coastal areas. Additionally, coastal zones serve as discharge areas for groundwater and surface water originating from the continent. However, coastal regions are also vulnerable to climate change and rising sea levels and phreatic levels as well as the marine intrusion and/or soil salinization (Spalding et al., 2014). These factors can lead to the loss and/or migration of wetlands, habitat fragmentation, and the reduction or ecosystem services loss (Intergovernmental Panel on Climate Change, 2014; Nicholls & Cazenave, 2010).

Wetlands, particularly coastal wetlands, are important ecosystems because of the large quantity and variety of ecosystem services that they provide to society (Costanza et al., 1997). As transitional ecosystems between terrestrial and aquatic environments (Mitsch & Gosselink, 2015), wetlands are strongly influenced by hydrology (Gusyev & Haitjema, 2011). Additionally, wetlands are often located in discharge areas and therefore have an important contribution of groundwater (Winter, 1999), which is crucial for nutrient transport and for wetland salinity (Jolly et al., 2008). Both of them (nutrient and salinity) and water have ecological effects, influencing the presence or type of vegetation that establishes, for example (Morris, 1995). Finally, in coastal wetlands, all these factors should consider interactions with both groundwater and marine water too (Qu et al., 2017).

Traditionally, ecological studies in wetlands have been carried out to characterize vegetation composition, biodiversity, water quality, and its effects on wetlands dynamics. Water studies in wetlands tend to be limited to surface water (Kors et al., 2012) and, occasionally, to interstitial water (water present at the root level, Weterbach et al., 2016), without understanding the role of groundwater in wetlands, its chemical composition, or the hydrogeochemical processes influencing these ecosystems (Hunt, Krabbenhoft, & Anderson, 1997; Liu & Mou, 2016). With respect to hydrogeochemical studies in coastal areas, this have been carried out to understand the water quality of aquifers for human use (Chidambaram et al., 2018; Lee & Song, 2007) and, more recently, to identify the causes of salinization (salt intrusion, geological processes, or anthropic contamination, Böhlke & Denver, 1995; Lee & Song, 2007; Bouzourra, Bouhlila, Elango, Slama, & Ouslati, 2017). Some hydrogeochemical studies have been focused to understand dynamics between groundwater and surface water to reduce anthropic effects but without an ecological approximation (Ladouche & Weng, 2005). Liu and Mou (2016) described some interactions between groundwater–surface water and wetlands and the necessity of a new approach to study this ecosystem. Few hydrogeochemical studies have been carried out in tropical coastal wetlands, so the hydrogeology of these ecosystems is largely unknown, including the origin and evolution of the water that feeds them (Hunt et al., 1997; Carol, Maspia, & Kruse, 2013). In a temperate climate (Scotland), Malcolm and Soulsby (2001) performed the hydrogeochemical characterization of a coastal aquifer associated with an interdunal wetland complex to understand its biodiversity and its capacity to maintain the quality of fresh water despite its location and land-use change. House and Sorensen (2015) characterized a riparian wetland in the United Kingdom using a model that incorporated temperature and botanical indicators (hydrophytes species present in sampling sites) in order to determine the dynamics between groundwater and surface water. In Latinamerica, Carol et al. (2013) characterized the wetlands in the Bay of Samborombón, Argentina, with the objective of establishing criteria for the conservation of their water resources, and Yetter (2004) characterized the hydrogeochemistry, the origin, and the quantity of water that is feeding mangroves and herbaceous wetlands in the Ramsar Site La Mancha in Mexico.

Generally, these authors conclude that information is lacking on groundwater (quality and quantity), one of the main flows to wetlands, and that such information is crucial for the adequate management and conservation of these ecosystems and their goods and services, especially due to the population growth in coastal areas. It is estimated that 50% of the world population is living within 100 km of the coast (Small & Nicholls, 2003) and that 10% of the population in coastal areas is located at an elevation of lower than 10 masl (Spalding et al., 2014). In the state of Veracruz, for example, 27% of the population lives less than 20 km from the coast (Mendoza-González, Martínez, Lithgow, Pérez-Maqueo, & Simonin, 2012), which is a concern, considering that this Mexican state is one of the most vulnerable to climate change (Monterroso et al., 2014) and to rising sea levels, with reported increases of 1.9 mm year$^{-1}$ (Zavala-Hidalgo, de Buen Kalman, Romero-Centeno, & Hernández Maguey, 2010).

2 | METHODOLOGY

2.1 | Study area

2.1.1 | Ciénaga del Fuerte PNA

The Ciénaga del Fuerte PNA is a state reserve of 4,269 ha located in the municipality of Tecolutla, Veracruz, in the touristic region of Costa Esmeralda, on the Gulf of Mexico (Figure 1). The climate is subhumid
warm, with rainfall in summer. The annual average temperature is 27.5°C, and the total annual rainfall is 1,490.8 mm (Coordinación Estatal de Medio Ambiente, 2002, Figure 2). It is located in the hydrographic watershed of the Tecolutla River, which belongs to the hydrological region of Tuxpan-Nautla (RH-27). It has an area of 7,446 km² and is fed by four rivers originating in the Northern Sierra of Puebla: the Necaxa, Lajajalpan, Tecuantepec, and Apulco Rivers (from north to south; Osuna-Osuna et al., 2015).

### 2.2 Geology of the study area

The study area is located near the regional discharge area of the Western Sierra Madre (WSM). This latter mountain range is composed of numerous geological units of marine origin that are strongly folded.
due to orogenic processes, forming cavities with differing degrees of competence (Moran-Ramirez et al., 2018) as well as regional fractures and faults, which increase the hydraulic conductivity of these materials (Morán-Ramírez, Ramos-Leal, López-Alvarez, Carranco-Lozada, & Santacruz-De León, 2013).

The underlying Pimienta Formation of the Jurassic period it is composed of lime mudstone and wackestone and black or dark grey clay–limestone intercalated with thin layers of calcareous or carbonate shale, with a maximum width of approximately 600 m (Cantú-Chapa, 1971; Heim, 1926). Over this latter unit, the undifferentiated Tamaulipas Formation was deposited during the Middle Cretaceous. It is composed of lime mudstone and wackestone with some intercalations of shale and loam, with a thickness of 400 m (Stephenson, 1922). The Agua Nueva Formation of the Upper Cretaceous covers this latter unit. It is formed by lime mudstone and wackestone with intercalations of shale, with a thickness of 127 m (Stephenson, 1922). Over this latter formation, the Méndez Formation from the Upper Cretaceous is found. It is composed of shale and loam alternated with bentonitic shale, with a varying thickness of 100 to 1,000 m (Jeffreys, 1910). The Cretaceous formations are covered by the Chicontepec Formation of the Tertiary period. It is constituted by an alternation of clay sandstone with siltstone, sandy loam, and grey shale, with a varying thickness of 1,500 to 3,300 m (Dumble, 1918). Additional geological units composed of clay–sand materials cover the Chicontepec Formation (Figure 3). The sediments in the coastal plain in the Gulf of Mexico are composed of clays of which Cruz-Orozco, Machado Navarro, Alba Cornejo, and Téllez Ortiz (1987) identified: montmorillonite 32% to 50%, illite from 20% to 34%, kaolinite from 19% to 34%, and chlorite with the lowest values from 10% to 29%. According to vegetation, Campos et al. (2011) detailed major soil properties by depth in different vegetation communities from Ciénaga del Fuerte (Table 1). The volcanic rocks that have been reported in the region correspond to rhyolites with quartz, potassium feldspar, oligoclase, biotite, amphibole, and pyroxene, as well as dacites with plagioclase (oligoclase, albite) with a higher content of potassium and amphiboles (SGM, 2004).

With respect to the hydrogeological functioning (Figure 4), the recharge area of the WSM experiences high rainfall and humidity, favouring the infiltration of water. Once water infiltrates, it flows towards regions of lower hydraulic head according to Darcy’s law or, in this case, towards the Gulf of Mexico. Along this route, groundwater interacts with different geological materials and becomes enriched with ions, resulting in the modification of its hydrogeochemical signature until its capture and/or arrival at the discharge area. Because of the stratification of the region, multiple sedimentary units of low hydraulic conductivity are present. Water contained in the sedimentary units of the Cretaceous period is confined to aquifers and can only ascend to the surface or mix with more local flows through faults or fractures (Figure 4). Ciénaga del Fuerte is located near the coast, in the discharge zone, within a regional hydrogeological system. In this context, the recharge occurs mainly in the limestone of the mountainous area in the Sierra Madre Oriental. These sedimentary rocks are covered by other less permeable clay formations, giving it the character of a confined aquifers. On the other hand, on the Cretaceous sedimentary rocks, there are volcanic rocks with a certain permeability that collect the local recharge along the Gulf Slope.

### Table 1

Soil properties in a popal-carrizal (Thalia geniculata and Cyperus giganteus) reported by Campos et al. (2011)

| Depth (cm) | Layer type | Texture class |
|-----------|------------|---------------|
| 0–10      | Organic    | Clay          |
| 10–20     | Organic    | Clay          |
| 20–42     | Organic    | Clay          |
| 42–76     | Organic    | Clay          |
| 76–105    | Organic    | Clay          |

**Figure 3** Geology of the study area and location of the regional geological section of the Western Sierra Madre (shown in Figure 4) in Tecolutla, Veracruz.
2.3 | Vegetation

The PNA contains a wetland complex with different types of tropical wetlands. There are different herbaceous freshwater wetlands, and these are locally known according to the dominant species: \textit{popales} (broadleaf species, i.e., \textit{Thalia geniculata}), \textit{tulares} (vegetation with long and thin leaves, e.g., \textit{Typha domingensis} and \textit{Cladium jamaicense}), \textit{carrizales} (vegetation with cylindrical stems and thin and/or modified leaves, e.g., \textit{Cyperus giganteus} and \textit{Phragmites australis}) as well as native floodplain pastures (\textit{Leersia hexandra} and \textit{Leersia oryzoides} with creepers, e.g., \textit{Ipomea tilacea} and \textit{Ipomea Indica}) and floodplain pastures (introduced grass species mixed with native species, such as \textit{Lippia nodiflora}, Coordinación Estatal de Medio Ambiente, 2002). In addition, there are several patches of floodplain forest containing different aquatic and forest species, such as \textit{Pachira aquatica}, \textit{Zygia latifolia}, \textit{Diospyrus digyna}, \textit{Attalea butiracea}, \textit{Pithecellobium recordii}, and \textit{Inga vera}. The PNA is surrounded by Valencian orange orchards and cattle ranching (Infante, Moreno-Casasola, Madero-Vega, Castillo-Campos, & Warner, 2011; Sánchez-Luna, 2018).

2.4 | Monitoring sites

The sites with the greatest presence of hydrophytic species in Ciénaga del Fuerte were selected for monitoring. In total, four sites representative of each herbaceous wetland community were selected (Figure 1): one \textit{popal}, two \textit{tular-carrizal} communities with different species composition located in distinct sites, and one floodplain pasture (this last site was previously a wetland, Figure 5).

In each site, three linear 100-m transects were established parallel to one another and separated by a distance of 50 m, except in the floodplain pasture, where transects were separated by larger distances because of the water flow and vegetation (Figure 5d). The transects were placed in the direction of the water flow. A nest of standpipe piezometers was placed at the extreme ends of each transect and was constructed according to Peralta, Infante, and Moreno-Casasola (2009). Piezometers reached a depth of up to 6 m except in the site \textit{Typha-Cladium} with 4 m depth. To characterize dominant vegetation, in each \(1 \text{ m} \times 1 \text{ m} \) quadrant, the per cent cover and height of each species were monitored.

2.5 | Hydrogeochemical analysis

In the four monitoring sites, a total of 96 groundwater samples were taken directly from the piezometers in the rainy season (October 2016) and the dry season (April 2017), corresponding with four \textit{Samples} \times \textit{Transect} \times \textit{Site} \times \textit{Season} (4 \times 3 \times 4 \times 2 = 96 samples). The laboratory analyses were performed according to the methods established in Welch et al. (1996) and Apha (2005). In each site, physical parameters (temperature, electric conductivity, Total Dissolved Solids (TDS), pH, salinity, dissolved oxygen, and oxidation-reduction potential (ORP)) were measured in situ using a YSI 556\textsuperscript{©} multi-parametric probe. All groundwater samples were collected in high-
density polyethylene bottles for major ion analysis; prior to use, all bottles were triple washed with abundant deionized water.

The water samples for cation and metal analyses were immediately acidified after being taken with ultrapure nitric acid until reaching a pH < 2. All samples were conserved at 4°C. The principal ions were analysed in the Ecological Engineering and Wetland Biogeochemistry Laboratory (Laboratorio de Ingeniería Ecológica y Biogeoquímica de Humedales) of the Institute of Ecology using ion chromatography (Dionex Chromeleon ICS-1100). The anions were analysed using an eluent of 4.5-mM Na₃CO₃/0.8-mM NaHCO₃ in an Anion Self-Regenerating Suppressor (ASRS 300 2 mm) in Auto Suppression Recycle Mode at a flow rate of 0.25 ml min⁻¹, a temperature of 30°C, an applied current of 7 mA, and an injection volume of 5 μl. The cations were analysed using an eluent of 20-mM methanesulfonic acid via suppressed conductivity detection in a Cation Self-Regenerating Suppressor (CSRS Ultra II, 2 mm) in Auto Suppression Recycle Mode at a flow rate of 0.25 ml min⁻¹, an ambient temperature, an applied current of 15 mA, and an injection volume of 2.5 ml. The alkalinity was quantified in situ by the titration method (Association of Official Analytical Chemists, 1980). All chemical analyses had an ionic balance lower than 10%, which was considered acceptable.

To characterize the dominant vegetation, in each quadrant, percent cover and height of each species were monitored. Percent cover was calculated using the Westhoff, and van de Maarel (1978) cover-abundance scale.

The resulting hydrogeochemical data were used to generate Piper diagrams to determine the water families and descriptive statistics and are presented in Table 2; Mifflin diagrams were used to define the flow systems; Gibbs diagrams helped to identify the influence of evaporation processes, water-rock interactions, and rainfall; and biplots were used to identify the occurrence of other processes such as ionic exchange, mixing, and the overall evolution of groundwater.

3 | RESULTS AND DISCUSSION

3.1 | Vegetation

The first site is located near the centre of the PNA. It is a popal wetland dominated by T. geniculata (commonly known as alligator flag) and L. hexandra (southern cut grass) containing one to five species; it was labelled as Thalia (Figure 5a). The second site is located near the outer limit of the PNA and is surrounded by agricultural fields. It is a
tular community dominated by *C. jamaicense* (saw grass) followed by *T. domingensis* (cattail) and *C. giganteus* (giant flatsedge or Mexican papyrus) containing one to six species; it was labelled as *Cladium-Typha-Cyperus* (Figure 5b). Notably, this site presented the highest flood levels. The third site is located near the centre of the PNA in an area surrounded by hills dedicated to livestock ranching. It is also a tular community dominated by *T. domingensis* followed by *C. jamaicense* containing two to four species; it was labelled as *Typha-Cladium* (Figure 5c). The fourth and final site is located in an area of extensive livestock ranching adjacent to the PNA. It is dominated by

![FIGURE 6](image.png) Piper diagram of the hydrochemical facies in the Ciénaga del Fuerte Protected Natural Area
Lippia nodiflora (tangle fogfruit) but contains one to 10 species of diverse introduced and native grasses; it was labelled as floodplain pasture (Figure 5d).

3.2 | Hydrogeochemistry

3.2.1 | Hydrochemical facies

In the Piper diagram (Figure 6), five main water types were identified: 40% of the samples corresponded with CaHCO₃ type (Type II), 20% with NaCl type (Type I), 27% with NaCaHCO₃ type (Type III), 12% with NaHCO₃ type (Type VI), and only one sample with CaMgCl type (Type IV).

The samples in the rainy season (October) were mainly distributed in Types II, III, and VI (CaHCO₃, NaCaHCO₃, and NaHCO₃, respectively). The samples in the dry season (April) were mainly concentrated in Types I and II (NaCl and CaHCO₃, respectively) and some in Type III (NaCaHCO₃).

Spatially, two groups can be observed. Group 1 includes the sites of the floodplain pasture and Cladium-Typha-Cyperus, and Group 2 includes the sites of Thalia and Typha-Cladium. Overall, these groups present present temporal behaviour. During the rainy season, all Group 1 samples were Type II (CaHCO₃), corresponding with recently infiltrated rainwater. The Group 2 samples were mainly Type III (NaCaHCO₃) and Type VI (NaHCO₃). During the dry season, the Group 1 samples did not vary considerably with respect to the rainy season, but some samples did correspond with Type III (NaCaHCO₃), coinciding with the increased temperatures in this season. Meanwhile, Group 2 differed the most between seasons. During the dry season, the large majority of its samples were Type I (NaCl). A few samples were Type II (CaHCO₃), and a couple of samples were Type III (NaCaHCO₃) and Type VI (NaHCO₃). Therefore, Group 2 is characterized by the presence of more evolved water samples.

3.2.2 | Origin of groundwater and water–rock interactions

The evolution of groundwater is related to its physicochemical content, due to the interaction of the medium through which it circulates. It is also a function of residence time and distance travelled; in such a way, that recent infiltration waters have low concentrations of their physicochemical parameters, whereas more evolved waters have a higher concentration of these components (Tóth, 1999). Therefore, groundwater will have less dissolved solids in the recharge zone. These solids will increase as water circulates. This type of relationship was addressed by Mifflin (1968), which related the content of Na + K vs Cl + SO₄ with flow systems (small local, local, and regional) and was corroborated with tritium.

The SO₄ + Cl versus Na + K relationship in the Mifflin diagram (Figure 7a) enabled the water samples to be characterized into three flow types: local, intermediate, and regional. Local and regional flows were dominant. Only a few samples were indicative of intermediate flow and, possibly, mixing between local and regional flows.

Spatially, the samples are separated into two groups. Group 1 is composed of samples from the floodplain pasture and Cladium-Typha-Cyperus sites. These samples are concentrated near the origin,
corresponding with the lowest $\text{SO}_4 + \text{Cl}^−$ and Na + K values. Accordingly, these samples are characteristic of local recharge or rainwater. Group 2 is associated with samples from the Thalia and Typha-Cladium sites. These samples tend to correspond with more evolved waters and regional flow.

Meanwhile, the Cl/(HCO$_3$ + Cl) versus TDS relationship is presented in the Gibbs diagram (Figure 7b). The graph is indicative of the major processes controlling groundwater chemistry: evaporation and crystallization, rock dominance, and atmospheric precipitation. As observed in most of the samples, evaporation processes are most influential followed by water–rock interactions.

Overall, during the rainy season, both groups present a greater concentration of TDS compared with the dry season. This may be due to the transportation of sediments and dissolved contaminants in water originating from anthropogenic activities, such as land-use change. Both groups presented a lower concentration of chlorides in the rainy season versus the dry season. The increase in chlorides during the dry season is more notable in Group 2 and is associated with evaporation as a result of high temperatures.

The diagram of the HCO$_3$ + SO$_4$ versus Ca + Mg relationship is presented in Figure 8a to discern whether groundwater circulates in carbonate rocks or rocks rich in silicates. Most samples (both dates) fall in the field of silicate alteration, whereas only a few correspond with carbonate dissolution, which is likely related with the previously described geological context. The Group 1 samples present low dispersion independently of season. Meanwhile, the Group 2 samples present higher dispersion: In the month of October, alteration by silicates appears to be more influential, whereas during the dry season, interaction with carbonates is evidenced.

The Ca/Na versus HCO$_3$/Na relationship is presented in Figure 8b. This graph has been used to understand the interactions between water and the geological medium through which it circulates (water–rock interactions). In the figure, evolution curves initially representing local recharge or rainwater were identified (I and II). The first curve (I) corresponds with water that has had a greater interaction with volcanic rock, leading to a higher alteration by silicates. The second curve (II) also corresponds with rainwater that has interacted with volcanic rock and has undergone silicate alteration, although it additionally shows evidence of evaporative processes. The evaporative processes observed in curves I and II are consistent with the characteristics of Ciénaga del Fuerte: Evapotranspiration occurs in shallow water bodies, and the aquifer has a depth of only 4 m.

In the month of April, the samples are once again divided into two groups: One group contains the samples from the floodplain pasture and Cladium-Typha sites, and a second group contains the samples from the Thalia and Typha-Cladium sites. During the rainy season, the Group 1 samples are located in the field of meteoric water, whereas the Group 2 samples show greater evolution and interaction with rocks rich in silicates. However, during the month of April, the Group 1 samples show little interaction with silicate rocks (as rhyolite and dacite), whereas the Group 2 samples present greater evolution and interaction with silicates and indicate evaporation, which is consistent with the high temperatures during this month.

The Na/Ca versus Mg/Ca relationship is presented in Figure 8c. This graph lets us to identify the interaction between groundwater and rocks rich in silicates (as rhyolite and dacite), limestone, and dolostone as well as mixtures with sea water/saltwater intrusion and irrigation return. Most samples are located in Quadrants 1, 3, and 4 (indicating the influence marine and weathering silicates). The groups are similarly separated. Overall, in both October and April, the Group 1 samples are mainly distributed in the limestone and silicate zone and indicate little evaporation. The Group 2 samples show interaction with silicates and the influence of evaporative processes, irrigation return, and/or evaporation. This finding is congruent given the location of the study area in a discharge area near citrus orchards and the temperatures of the region.

The relationship between the cation chloride ratio index and Cl/alkalinity is shown in Figure 9a. Two groundwater evolution curves can be identified: The first begins with Ca + Mg >> Na + K but shifts to Ca + Mg = Na + K as water evolves. Some samples begin at Ca + Mg << Na + K and tend to show similar values as water evolves, initiating with ionic exchange and subsequent alteration of silicates and evapotranspiration as water evolves. Temporally, in the month of October, the Group 1 samples tend to group on the left and show characteristics of rainwater that has undergone little evolution. These samples show greater vertical distribution and, correspondingly, little variation in HCO$_3$ and Cl. The Group 2 samples are distributed towards the right and are associated with more evolved waters, evapotranspiration processes, and ionic exchange with the clay material present in the soil. In April, the Group 1 samples are slightly dispersed towards the right, showing some influence from evaporation due to the high temperatures.
but maintaining their vertical distribution. Meanwhile, the Ca, Mg, and Na values of the Group 2 samples are similar and show a horizontal dispersion associated with evapotranspiration and silicate alteration.

The Cl versus residual alkalinity relationship is shown in Figure 9b. The samples are divided into two regions. The upper region indicates greater presence of bicarbonate ions and ionic exchange. The lower region indicates a lower concentration of HCO3 than Ca–Mg as well as greater evapotranspiration. Two evolution curves can be observed, with values of residual alkalinity starting near zero. A grouping can also be observed near the right side of the graph, indicating an increase in chlorides and, accordingly, greater evolution and evapotranspiration. Temporally, the residual alkalinity is positive in October and negative in April (dry season), which is congruent with the temperatures during this latter month (25°C to 27°C). On both dates, Groups 1 and 2 are separated. Group 1 tends to have a residual alkalinity near zero, whereas Group 2 has a positive or negative residual alkalinity depending on the season (rainy or dry, respectively).

The Cl versus Na relationship is shown in Figure 9c. This relationship can be used to identify processes of ionic exchange and alteration by albite or processes of reversible ionic exchange. The Group 1 samples tend to be concentrated near the origin and have low Na and Cl values, whereas the Group 2 samples show higher concentrations of both ions. Notably, all samples are located in the region of ion exchange and albite alteration, which is consistent with the presence of clay materials and rocks rich in silicates.

### 3.3 Ecological implications

#### 3.3.1 Wetlands distribution

The local recharge sites (Group 1) are mostly stable with respect to ion concentrations, which are low in both seasons. In contrast, regional recharge sites (Group 2) show slightly diluted ion concentrations in the rainy season, so some water mixing processes likely occur during this season. These differences can be visualized on species distribution (Table 3).

**Wetlands in local recharge areas**

The groundwater samples from the floodplain pasture and Cladium-Typha-Cyperus (Group 1) showed characteristics of rainwater and varied little between seasons (rainy and dry). So the sites of this group are likely present in the local recharge area despite being located near the coastline and the outer border of the PNA (Figure 5b,d).

![Image](image.png)

**TABLE 3** Wetland types and dominant vegetation by per groundwater flow system

| Groundwater flow system | Group | Monitoring sites                  | Dominant plant species per site                          |
|-------------------------|-------|----------------------------------|----------------------------------------------------------|
| Local flow              | 1     | Floodplain pasture               | Lippia nodiflora-native and introduced grass             |
|                         |       | Cladium-Typha-Cyperus            | Cladium jamaicense-Typha domingensis-Cyperus giganteus   |
| Regional flow           | 2     | Thalia                           | Thalia gigantea-Leersia hexandra                         |
|                         |       | Typha-Cladium                    | Typha domingensis-Cladium jamaicense                     |
mental flow to wetlands and coastal wetlands. freshwater to communities in lowlands and to maintain the environ-
mountain zones in recharge of watersheds to secure the provision of
with jurisdiction over regional recharge area in WSM. This information
at the regional level, including federal entities and their municipalities
Fuerte requires management at the local level (municipality) as well as

3.3.2 Implications for management

The Ciénaga del Fuerte PNA is a discharge area fed by groundwater
from local and regional flows, indicating that some of the wetlands of
the PNA are fed by water from regional flows whereas others are fed
by local recharge or rainwater. This indicate that PNA Ciénaga del
Fuerte requires management at the local level (municipality) as well as
at the regional level, including federal entities and their municipalities
with jurisdiction over regional recharge area in WSM. This information
is an indication of the necessity to conserve and recover forested
mountain zones in recharge of watersheds to secure the provision of
freshwater to communities in lowlands and to maintain the environ-
mental flow to wetlands and coastal wetlands.

The water chemistry of Ciénaga del Fuerte PNA is influenced by its
location near the coastline and extensive citrus orchards. In fact, the area
outlying the PNA is part of the most important region for the production
of Valencian orange in the country (Sistema de Información Agroalimentaria y
Pesquera, 2018). Accordingly, a large portion of the water samples were
taken near the zone of saltwater intrusion and/or irrigation return, espe-
cially those in Group 2, so if salinization is due to irrigation return, strategies
targeting the sustainable development and management of agriculture
should be implemented to maintain the quantity and quality of water inflow
(whether local or regional in origin) in Ciénaga del Fuerte. If salinization is
due to salt intrusion, then it is even more important to maintain the quality
and quantity of local and regional flows to minimize or stop it. Further stud-
ies are necessary to distinguish which of these latter two processes is most
influential for the water chemistry of the PNA.

Currently, there are important efforts to restore the forest high up in
the mountains. This work is giving accurate information about a necessity
to take care of these recharge areas to conserve wetlands coast.

The flow characteristics of Ciénaga del Fuerte demonstrated that
future studies and management should consider the surface charac-
teristics (vegetation and surface hydrology) and the underground
characteristics (especially water chemistry) of wetlands in order to
understand their functioning and plant communities as well as the ori-
gin of water.

4 CONCLUSIONS

1. The Ciénaga del Fuerte PNA is located in a regional discharge
area and, based on the Mifflin hydrogeochemical diagram, it is
mainly fed by local and regional flows.

2. Two groups of groundwater were identified in the Gibbs diagram.
Group 1 was associated with the floodplain pasture and Cladium-
Typha-Cyperus sites, and Group 2 was associated with the Thalia
and Typha-Cladium sites. The Group 1 samples had characteristics
similar to those of local recharge or rainwater, whereas the Group
2 samples appeared to be more evolved or originate from regional
flows.

3. The groundwater of Ciénaga del Fuerte was more influenced by
silicate alteration than by carbonate dissolution.

4. The chemical signatures of the groundwater of Ciénaga del
Fuerte were influenced by interaction with the rocks through
which groundwater circulated. Spatiotemporally, the character-
istics of the Group 1 samples are more similar to those of
local recharge, whereas those of the Group 2 samples evi-
dence the occurrence of water–rock interaction and evaporation.

5. The spatiotemporal behaviour of the water samples shows that
groundwater underwent evapotranspiration, possibly as a result
of saltwater intrusion and/or irrigation return from agricultural
activities.

6. Groundwater in Ciénaga del Fuerte first undergoes processes of
ion exchange and, as it evolves, evapotranspiration occurs. This is
congruent with the region’s climate and the clay content in wet-
land soil.

7. The residual alkalinity showed that, as groundwater begins to
evolve, spatiotemporal variation is near zero. However, in the
rainy season, the Group 2 samples had positive residual alkalinity,
which then turned negative in the dry season. This indicates that
the hydrophytic communities associated with Group 2 likely
exhibit plasticity to variation in the chemical components of
water. The hydrophytic communities associated with Group 1 are
more restricted in their habitat to sites with lower salt
concentration.

8. The chemical composition of groundwater in Ciénaga del Fuerte
creates unique conditions that determine the areas or habitats
occupied by hydrophytic species.

9. The spatiotemporal behaviour of groundwater chemistry is one
factor that, along with the hydroperiod, determines the dynamics
and functioning of wetlands (eco-hydrogeoperiod).

10. The characterization and spatiotemporal behaviour of the hydro-
geochemistry of wetlands are critical for understanding the origin
of water feeding wetlands and the interaction between different
water flows and wetland ecosystems and their dynamics. Ulti-
mately, this information will provide a better understanding of
the influence of water chemistry on the ecology of wetlands, over
their floristic composition and to propose management plans
including discharges areas (wetland zones) and recharges areas
(upstream).

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DATA AVAILABILITY STATEMENT
We declare the data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID
Lorena Elisa Sánchez-Higuero  https://orcid.org/0000-0002-6219-8994
José Alfredo Ramos-Leal  https://orcid.org/0000-0003-4715-7411
Janete Morán-Ramírez  https://orcid.org/0000-0002-3209-0069
Patricia Moreno-Casasola Barceló  https://orcid.org/0000-0003-0468-0851
Ulises Rodríguez-Robles  https://orcid.org/0000-0001-5667-8898
María Elizabeth Hernández Alarcón  https://orcid.org/0000-0002-1285-632X

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