



# Surface and groundwater flow exchanges and lateral hydrological connectivity in environments of the Matusagaratí Wetland, Panama

Eleonora Carol<sup>a,\*</sup>, María del Pilar Alvarez<sup>b</sup>, Manuel Arcia<sup>c</sup>, Indra Candanedo<sup>c</sup>

<sup>a</sup> Centro de Investigaciones Geológicas (CIG), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad Nacional de La Plata (UNLP), Argentina

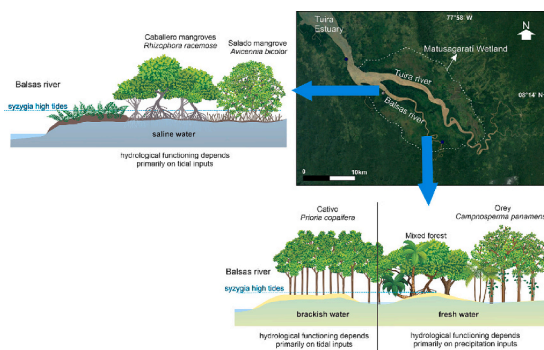
<sup>b</sup> Instituto Patagónico para el Estudio de los Ecosistemas Continentales (IPEEC), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad Nacional de la Patagonia San Juan Bosco (UNPSJB), Argentina

<sup>c</sup> Technological University of Panama (UTP), Republic of Panama

## HIGHLIGHTS

- Matusagaratí wetland is one of the largest wetlands in Central America.
- Hydrological connections were recognized in the different wetland forest.
- Mangroves dominate where saline groundwater connects with the tides.
- Cativo forests dominate in levee where brackish groundwater connects with the river.
- Alluvial plains have mixed and orey forests where rain sustains fresh groundwater.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The Matusagaratí wetland in the Panamanian Darien is one of the largest wetlands in Central America. These types of riverine wetlands, associated with large drainage basins, are complex hydrological environments where variations in water flows and exchanges condition the existence of different wetland habitats. The work aimed to establish the hydrological functioning of the Matusagaratí wetland in different sectors of the Balsas River, emphasizing the exchanges of surface and groundwater flows and the hydrological connectivity that exists between the different laterally linked wetland environments. For this purpose, a monitoring network for surface water and groundwater was established along transects intersecting various wetland environments in the middle and lower basin of the Balsas River. This network is complemented by measurement points for surface water located in streams and in the upper basin of the river. Data collected in sensors installed in boreholes were compared to river level and precipitation data. Continuous water level recording sensors were installed at the monitoring points, and samples were collected for the determination of major ions and stable isotopes. The results indicate that in the mangroves of the lower basin and in the cativo forests of the middle basin levee there is a strong exchange of water between the river and the shallow groundwater. This water exchange is strongly influenced by the tide which spreads from the estuary to the continent through the river. Meanwhile, in the

\* Corresponding author.

E-mail address: [eleocarol@fcnym.unlp.edu.ar](mailto:eleocarol@fcnym.unlp.edu.ar) (E. Carol).

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middle basin, mixed forests and orey forests developed on the alluvial plain exhibit a hydrological functioning that depends primarily on precipitation inputs. This study provides data that could serve as a basis for the management of this large tropical wetland that, despite having protection initiatives, could be hydrologically impacted by unsustainable socio-economic practices.

## 1. Introduction

Wetlands are critical environments that provide ecosystem services valued at trillions of dollars annually (De Groot et al., 2006; Barbier, 2011; Ivory et al., 2019). They help to mitigate flood risk, provide key freshwater resources, play an essential role in nutrient and carbon cycling, and support many local and regional economies (Costanza et al., 1998; Erwin, 2009; Ahmed, 2015; Adame et al., 2019; Cuthbert et al., 2022). Therefore, the degradation and destruction of wetlands not only lead to a deterioration and loss of biodiversity but also to a loss of the associated ecosystem services, with economic implications (Wasserman and Dalu, 2022).

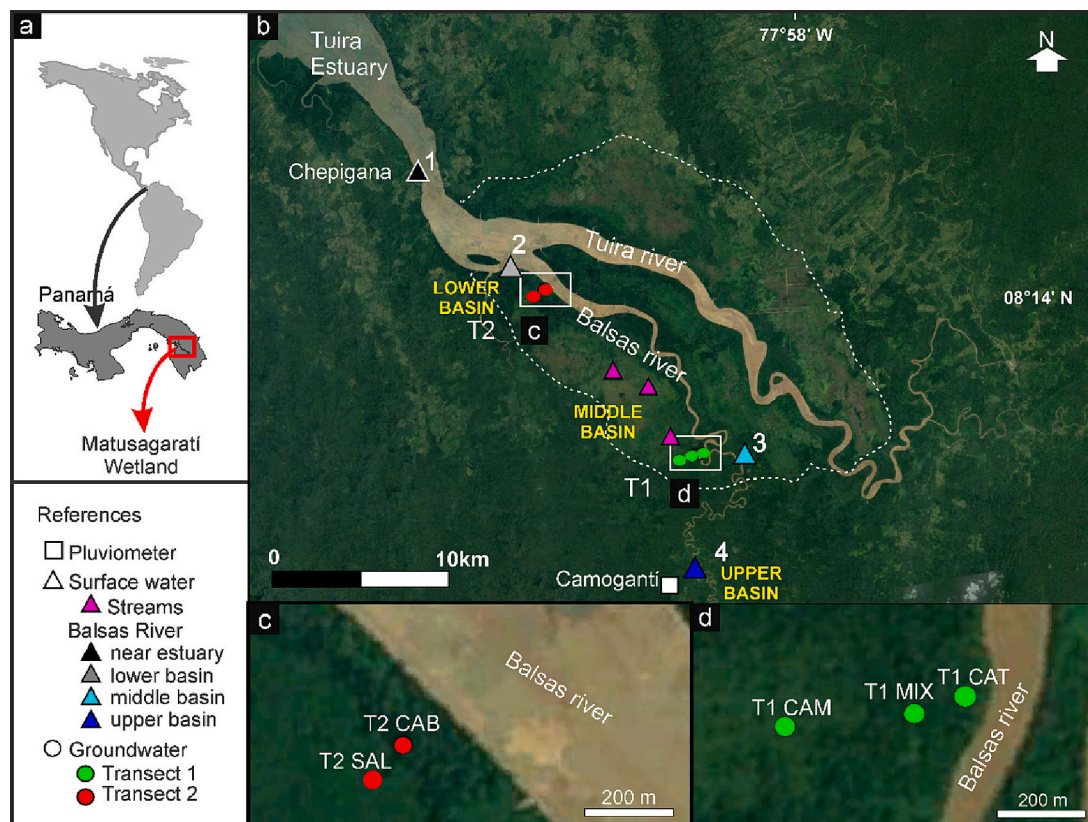
In riverine wetlands, water exchanges between the river and the shallow groundwater that sustain ecosystems are key processes that determine not only the environmental characteristics of wetland systems but also the connectivity among different habitats (Dube et al., 2019). In this sense, the study of surface and groundwater flows is valuable not only to define their functioning, but also to predict the impact that natural or human-induced hydrological changes may have on habitats that support wetlands. The sustainable use of wetlands and their management requires planning and a good scientific understanding of how these ecosystems function (Ahmed, 2015).

The Matusagaratí wetland in the Panamanian Darien is one of the largest wetlands in Central America. In fact, Matusagaratí is a complex of wetlands that includes several types of flooded forests, flooded

grasslands and mangroves covering approximately 56,250 ha (Candañedo, 2021). Matusagaratí wetland lies along the margins and in the adjacent lowlands of the Tuira and Balsas rivers before emptying into the Pacific Ocean, forming an extensive estuary where fresh and marine waters meet (Figs. 1a and b). More inland, this wetland receives freshwater from small streams draining from nearby ridges.

Three protected areas provide legal protection to 70 % of the wetland: the Filo del Tallo-Canglon hydrological reserve, the Chepigana Forest Reserve, and the Matusagaratí Wildlife Refuge. Despite this legal protection, there is no on-the-ground management resulting in inappropriate practices such as the burning of herbaceous wetlands during the dry months by local cattle ranchers seeking to expand their pastures. Furthermore, during the last decade, nearly a third of the wetland has been tilled and part of it drained and converted to rice cultivation (CREHO, 2015; Ministerio de Ambiente, 2016), which has dramatically altered its hydrological behavior.

Until recently, there has been a lack of baseline studies to support better management and involvement of local communities in sustainable management, as access to the study areas is extremely difficult and costly due to the lack of roads. It is also an area where field survey is extremely dangerous due to the various threats that working in this type of wild and uninhabited environment represents. However, five years ago, a group of national and international researchers joined efforts to understand Matusagaratí's biodiversity and ecological functioning. Studies have been carried out on plants (Grauel, 2004; Ortiz et al., 2020;



**Fig. 1.** (a) Location of the study area. (b) Location of the sampling points: 1: Balsas River near estuary, 2: Balsas River lower basin, 3: Balsas River middle basin, 4: Balsas River upper basin, T1: Transect 1 and T2: Transect 2. The white dotted line indicates the location of the Matusagaratí wetland. (c) Details of transect 2. (d) Details of transect 1.

Ibáñez and Flores, 2020; Ortiz et al., 2022), bird communities (Aparicio, 2021), and the wetland's potential for carbon sink and fisheries (López and Cunampio, 2023). A map of the wetland's vegetation types was also produced (Candanedo, 2021).

The only previous studies on hydrological functioning in Matusagaratí were conducted along the Tuira River (Carol et al., 2020, 2022). These studies show that some wetland environments depend upon the exchanges of surface water - groundwater flows while other wetland types are dependent mainly on precipitation. Though the hydrological dynamics of the Tuira River wetlands are beginning to be understood, the Balsas River wetland system has yet to be studied. The aim of the work was to establish the hydrological functioning of the Matusagaratí wetland in different sectors of the Balsas River, emphasizing the exchanges of surface and groundwater flows and the hydrological connectivity between the different laterally interconnected wetland environments.

## 2. Study area

The Matusagaratí wetland, located in eastern Panama, is associated to the river basins of the Tuira and Balsas rivers (Fig. 1). The climate of the region is tropical, with annual precipitation close to 2900 mm, which tends to concentrate between the months of May and November (Fabrega et al., 2013). During the rainy season, river overflows are frequent, while during the dry season, high temperatures create favorable conditions for the incidence of fires in the grassland sectors of the wetland.

The basins of the Tuira and Balsas rivers cut through siliclastic rocks (mudstones, shales, and sandstones) of tertiary age, which are strongly folded and faulted, forming mountainous systems that border the river basins (Marshall, 2007; Gurocak-Orhun and Collins, 2017). Quaternary alluvial deposits are laid over these rocks on both sides of the Tuira and Balsas rivers. These deposits consist of sands, silts, and clays with a thickness of more than 4.5 m. The sands are associated with levee and paleochannel environments, while the clays are associated with alluvial plains (Carol et al., 2021). The Quaternary alluvial sediments host shallow groundwater within the wetland area, while the Tertiary formations contribute water to the wetland from springs and streams in the surrounding mountainous areas.

Six types of wooded vegetation and three non-wooded types have been described and mapped in the wetland (Candanedo, 2021). Among the wooded formations are caballero mangrove (*Rhizophora racemosa*), salado mangrove (*Avicennia bicolor*), alcornoque (*Mora oleifera*), cativo (*Prioria copaifera*), orey (*Campnosperma panamense*), and semi-deciduous forests. The non-wooded vegetation includes shrublands and groves, grasslands (*Typha dominguensis*), and mangrove fern (*Acrostichum danaeifolium*).

### 2.1. Methodology

The hydrodynamics and hydrochemistry of Matusagaratí were studied along two transects that run perpendicular to the bed of the Balsas River and cover different wetland environments (Fig. 1b). It is important to indicate that in order to carry out a representative study of the hydrological environments and the vegetation of the Matusagaratí wetland, it was considered that the arrangement of the transects intercepts the main forest formations of the wetland (Candanedo, 2021). Transect 1 intercepts three wetland environments. The river levee, the raised strip that develops adjacent to the river margin, is covered by an almost monotypic cativo forest (*Prioria copaifera*) with some alcornoque trees (*Mora oleifera*), and palms such as *Astrocaryum standleyanum*, *Euterpe oleracea* and *Elaeis oleifera*. Behind the cativo forest is a flooded evergreen mixed forest with a wider variety of species. These include sangrillo (*Pterocarpus officinalis*), alcornoque (*Mora oleifera*), cuchillito (*Pentaclethra maculosa*) and tangaré (*Carapa guianensis*). Finally, in a depression behind the flooded evergreen mixed forest is the orey forest

(*Campnosperma panamense*). The orey trees grow together with palm species such as *Euterpe oleracea* and occasionally *Elaeis oleifera*.

Transect 2 downstream, closer to the estuary, starts with a stand of mangrove fern (*Acrostichum danaeifolium*), followed by 20–25 m high caballero mangroves (*Rhizophora racemosa*) with their characteristic aerial roots that grow from the main stem, and resembling flying buttresses. More inland there is a nearly monotypic salado mangrove (*Avicennia bicolor*) that is between 15 and 20 m high with pneumatophores, specialized aerial root-like structures that allow the absorption of gases directly from the atmosphere, an adaptation to flooded environments.

The wells were installed along the two transects, in each of the wetland environments described above (Fig. 1c and d). The boreholes were made between 3 and 4 m deep using a manual auger. The boreholes were cased with a continuous grooved filter PVC pipe wrapped in a fine plastic mesh. The annular space was filled with a pre-filter of siliceous gravel, and the upper part of the well's annular space was sealed. Hobo level data logger and Odyssey® Capacitance Water Level sensors were installed in all boreholes to measure the water level every 15 min. To measure the Balsas River levels, similar sensors were installed upstream in transect 1 and downstream in transect 2 (Fig. 1).

Precipitation was measured using a classic Odyssey® tipping bucket rain gauge, located in Camogantí, in the upper basin sector of the Balsas River (Fig. 1b). The dataset of levels collected with the sensors installed in the boreholes were compared with the river level and precipitation data to analyze the flow exchanges between surface water and groundwater. Comparison of groundwater levels with rainfall data was carried out to visualize the influence of rain infiltration.

Water samples were collected from 3 sites of the Balsas River in the upper, middle, and lower basin (Fig. 1b, c, and d), from small streams draining from the wetland into the main river, and from the monitoring wells (i.e., groundwater). At all points electrical conductivity (EC) was measured in situ using a portable conductivity meter instrument (Lutron® WA-2017SD). In each sample major ions and stable isotopes of the water molecule were determined in the laboratory. This work uses data from water samples collected in June 2022, June 2023, and August 2023. The determination of major ions was carried out using standardized methods (APHA, 1998) in the Geochemistry Laboratory of the Geological Research Center in La Plata, Buenos Aires, Argentina. Stable isotopes of the water molecule were determined by mass spectroscopy in the Stable Isotope Laboratory of the University of San Luis (Argentina), using a Thermo Finnigan MAT Delta Plus XL continuous flow mass spectrometer. The analytical accuracy is  $\pm 0.05\text{‰}$  and  $\pm 0.5\text{‰}$ , for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ , respectively. Isotopic results are presented as  $\delta\text{‰}$ , defined as  $\delta = 1000(R_s - R_r)/R_r\text{‰}$ , where  $\delta$  is the isotopic deviation in ‰ relative to Vienna Standard Mean Ocean Water (V-SMOW) (Gonfiantini, 1978); R is the isotopic ratio ( $^2\text{H}/^1\text{H}$ ,  $^{18}\text{O}/^{16}\text{O}$ ); r: international reference and s: sample. The isotopic values were compared with the local meteoric line  $\delta^2\text{H} = 7.63 \delta^{18}\text{O} + 6.51$  for the Pacific coast of central Panamá (Kern et al., 2016). Likewise, a theoretical mixing line was defined for the samples from the tidal zone that deviate from the local meteoric line, which has as end members the theoretical average composition of seawater (Clark, 2015) and river - rain water in the area of intersection with the meteoric line.

## 3. Results

### 3.1. Wetlands hydrodynamic

The description of the hydrodynamic results will begin with the analysis of the variations in the values of water levels in the river, comparing data from the middle basin and the lower middle basin where continuous recording sensors were installed. Subsequently, the relationship between river water and groundwater in the different wetland environments intercepted by transect 1 (in the middle basin) and transect 2 (in the lower basin) will be analyzed. For these last cases, it will

also be analyzed whether there is any relationship between water levels and precipitation.

The records of the water levels in the Balsas River (Fig. 2a) show oscillations driven by tidal fluctuations both in the sector of lower basin and in the middle basin close to transect 1. The relative position of the water levels in the river between the two sectors shows that the upstream sensor generally registers a higher water level than the sensor in the downstream sector. This would indicate that the tidal propagation along the river channel does not allow the flow out, but accumulates upstream, leading to an increase in the river level in the middle section of the basin. In the lower basin, the rise in the water level of the river is due to the entry of tidal water, while the water level rise towards the middle - upper basin is due to the obstruction of the outflow by the entry of the tide. In both sectors of the basin, the peak values of ebb and flood tides occur at the same time (Fig. 2b). This suggest the behavior above described and not an increase caused only by the propagation of the tides within the channel, which would be observed if the peak were phased by the lag time required for the tides to propagate within the channel.

The comparison of the water levels in the Balsas River with the groundwater levels in the wells of transect 1 show that there are different behaviors (Fig. 3). The sensor located on the river levee in an environment dominated by cativo forest (T1 CAT) shows water table rises at all high tides that exceed 2.95 m a.s.l., but at low or high tides below this level, the water table do not oscillate with the tide and remains near the surface. Particularly from late December 2022, when flood tides are lowest and rainfall is very scarce, a decline in the groundwater level in the cativo forest is observed. Mine while, the groundwater in the mixed forest (T1 MIX) and ore forest (T1 CAM) has a very shallow water table (which sometimes rise above ground surface). In these environments, the water table shows no fluctuations with the tidal flow, but the rises can in most cases be associated with precipitation. An exception to this behavior was observed in the first half of September 2022, when the tides reached the highest level ever measured and caused a slight rise in the water table in the mixed forest sensor.

In transect 2, the comparison of the groundwater levels with the river levels shows a different behavior in relation to transect 1 (Fig. 4). In both environments of transect 2 (caballero mangrove and salado mangrove), the water table rises when the river level exceeds 2.75 m a.s.l. during high tide (mainly during syzygy tide). From May to November 2022, at low tide and high tides less than 2.75 m a.s.l., the water table oscillate between 2.30 m a.s.l and 2.75 m a.s.l. It is worth mentioning that the water table levels in salado mangrove are always lower than in the caballero mangrove. In this period of the record (Fig. 4) the syzygy high tides exceed 2.75 m a.s.l. and rainfall is abundant. From December 2022, when rainfall rarely exceeding 10 mm a change in the water table level is observed, which tends to decrease mainly in the salado mangrove. However, the water table rises rapidly when high tides above 2.75 m a.s.l. occur during this period.

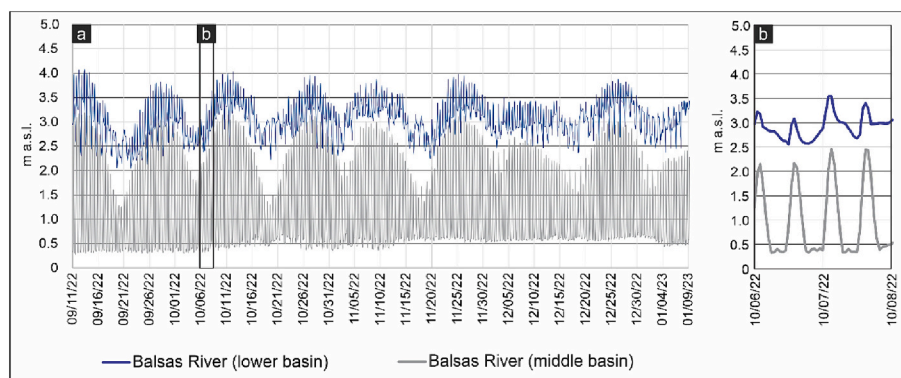


Fig. 2. Variations of the water level in the Balsas River (in m a.s.l.) in sectors of the lower basin and middle basin.

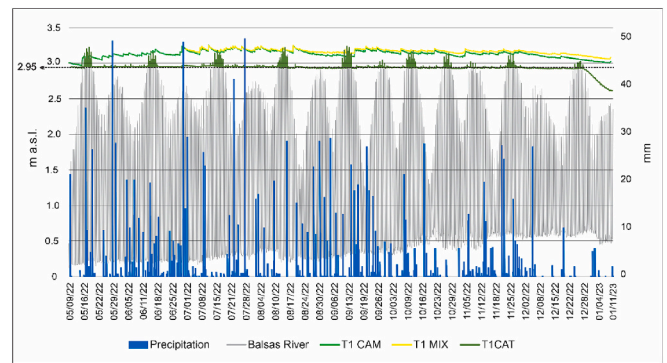


Fig. 3. Variations of the groundwater level in different environments of transect 1, the Balsas River level (in m a.s.l.), and daily precipitation data (in mm). The water level of 2.95 m a.s.l. is indicated, which represents the tide level above which the river water floods the cativo forest.

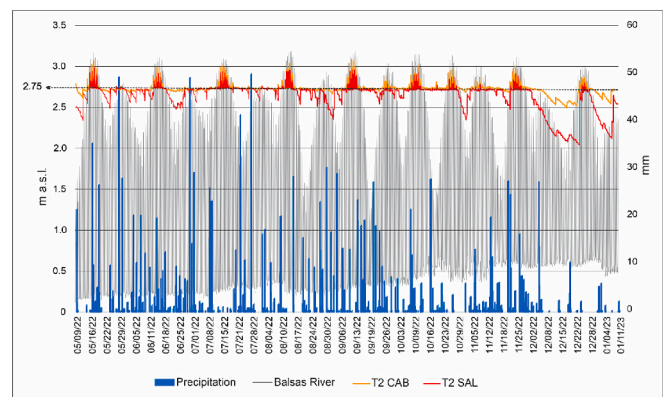


Fig. 4. Variations of the groundwater level in transect 2 and the level of the Balsas River (in m a.s.l.) and daily precipitation data (in mm). The water level of 2.75 m a.s.l. is indicated, which represents the tidal level above which the river water floods the mangrove environments.

### 3.2. Hydrochemistry and stable isotopes of the water molecule

In the water of the Balsas River, an increase in the EC of the water is recorded from the upper basin to the lower basin. In the upper basin the EC varies between 115 and 125  $\mu\text{S}/\text{cm}$ , in the middle basin between 118 and 484  $\mu\text{S}/\text{cm}$ , and in the lower basin between 13,940 and 21,200  $\mu\text{S}/\text{cm}$ . The small streams that drain towards the river have low EC with values between 69 and 282  $\mu\text{S}/\text{cm}$ . These differences in the EC are reflected in the contents of major ions and hydrochemical facies (Table A of Supplementary material and Fig. 5).

In the Balsas River, the dominant ions in the upper basin vary between  $\text{Ca}^{+2}$  (0.64–0.73 meq/L) and  $\text{Mg}^{+2}$  (0.64–0.70 meq/L) and  $\text{HCO}_3^-$  (1.43–1.51 meq/L) or between  $\text{Na}^+$  and  $\text{Cl}^-$  (0.16–0.22 and 0.07–0.08 meq/L), depending on the date of sampling. In the middle and lower basin, an increase in the concentrations of  $\text{Na}^+$  and  $\text{Cl}^-$  can be observed. In the middle basin,  $\text{Na}^+$  and  $\text{Cl}^-$  reach 19.13 and 3.17 meq/L respectively, however,  $\text{HCO}_3^-$  remains a dominant ion. In the lower basin, the values for  $\text{Na}^+$  and  $\text{Cl}^-$  reach 101.7 and 132.05 meq/L respectively, clearly dominating over the other major ions. These spatial variations determine a change in hydrochemical facies in the river water, which registers magnesium-calcium bicarbonate in the upper basin, and sodium chloride in lower basin. In the streams that flow into the river, the hydrochemical facies are sodium chloride and sodium bicarbonate-chloride dominate, with an average content of 1.62 meq/L for  $\text{Na}^+$ , 1.34 meq/L for  $\text{Cl}^-$  and 0.39 meq/L for  $\text{HCO}_3^-$ .

The groundwater in transect 1 has different EC values in each wetland environment. In three groundwater samples taken in the cativo forest (T1 CAT), the EC value was higher than in the groundwater of the mixed forest (T1 MIX) and in the orey forest (T1 CAM). The EC in the cativo forest varied between 1423 and 3680  $\mu\text{S}/\text{cm}$ , while the EC in the mixed and orey forest was similar in May 2022 and June 2023 with values between 55 and 311  $\mu\text{S}/\text{cm}$ . In August 2023, however, a significant increase to values of 2600  $\mu\text{S}/\text{cm}$  was recorded in the mixed forest. The hydrochemical facies in term of major ions content are sodium chloride in the cativo forest (with mean  $\text{Na}^+$  and  $\text{Cl}^-$  values of 17.3 meq/L and 18.5 meq/L respectively). In the mixed and orey forest the hydrochemical facies are sodium bicarbonate-chloride with mean  $\text{Na}^+$ ,  $\text{Cl}^-$  and  $\text{HCO}_3^-$  values of 7.4 meq/L, 8.5 meq/L and 1.6 meq/L respectively for the mixed forest and 1.3 meq/L, 1.0 meq/L and 1.0 meq/L, respectively for the orey forest (Fig. 5).

In transect 2, the groundwater EC values are up to two orders of magnitude higher than in transect 1. In the caballero mangrove

environment (T2 CAB) the EC varied between 14,142 and 34,250  $\mu\text{S}/\text{cm}$ , while in the salado mangrove (T2 SAL) it was between 29,870 and 46,200  $\mu\text{S}/\text{cm}$ . In both cases, the high EC is associated with a high concentration of  $\text{Na}^+$  ions (mean values of 268.2 meq/L in T2 CAB and 391.4 meq/L T2 SAL) and  $\text{Cl}^-$  (mean values of 312.8 meq/L in T2 CAB and 493.5 meq/L T2 SAL). In this sector of the wetland the sodium chloride facies dominate both in the river and in the groundwater (Fig. 5).

Regarding the isotopic signal in the  $\delta^{18}\text{O}$  vs.  $\delta^2\text{H}$  graph (Fig. 6a), it is observed that both the samples from the Balsas River in the upper and middle basin, as well as the samples from the streams and the groundwater from transect 1 are located around the local meteoric straight line. The rainwater sampled in May 2022 is also located on this line, which has the least enriched values. The isotopic signal of the samples from the lower basin of the Balsas River and the groundwater from transect 2, on the other hand, deviates from the trend described above as they are located around a mixing line between river water and sea water (Fig. 6a). In contrast, the graph of  $\delta^{18}\text{O}$  vs. EC (Fig. 6b) shows that the samples from the upper and middle basin of the Balsas River and the sample from the streams and groundwater in transect 1 have isotopic variations associated with a small increase in the EC.

The groundwater samples from transect 1, which is located in the cativo forest (Fig. 6c), slightly deviate from this general trend, and tend towards mixing with seawater. Likewise, all groundwater samples from transect 2 show a strong increase in EC associated with small variations in  $\delta^{18}\text{O}$  according to a trend of salt dissolution (Fig. 6b).

#### 4. Discussion

The hydrological dynamics of wetlands associated to estuaries and large river basins are very complex (Ivory et al., 2019; Xiao et al., 2019). Because in wetlands hydrology the development of vegetation plays a

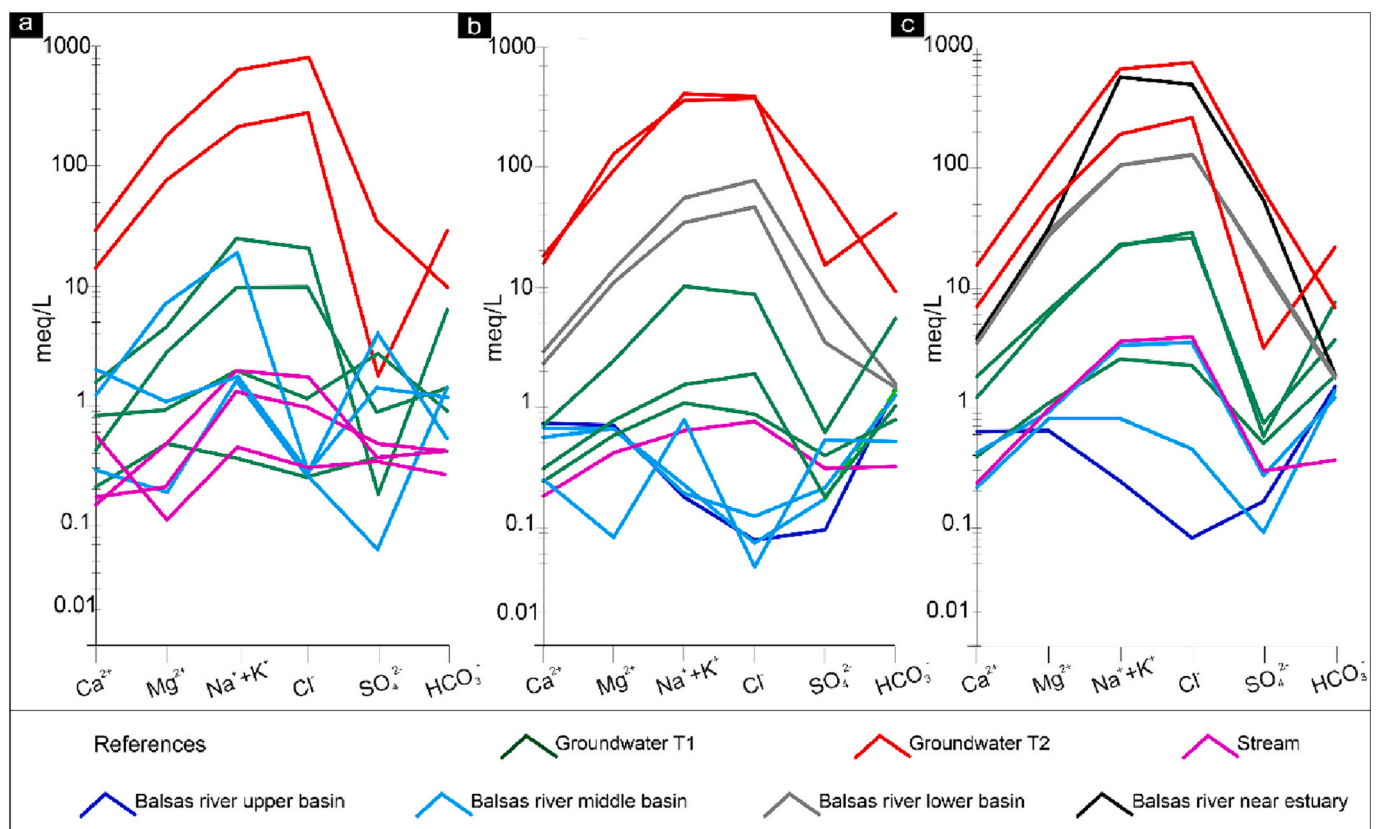
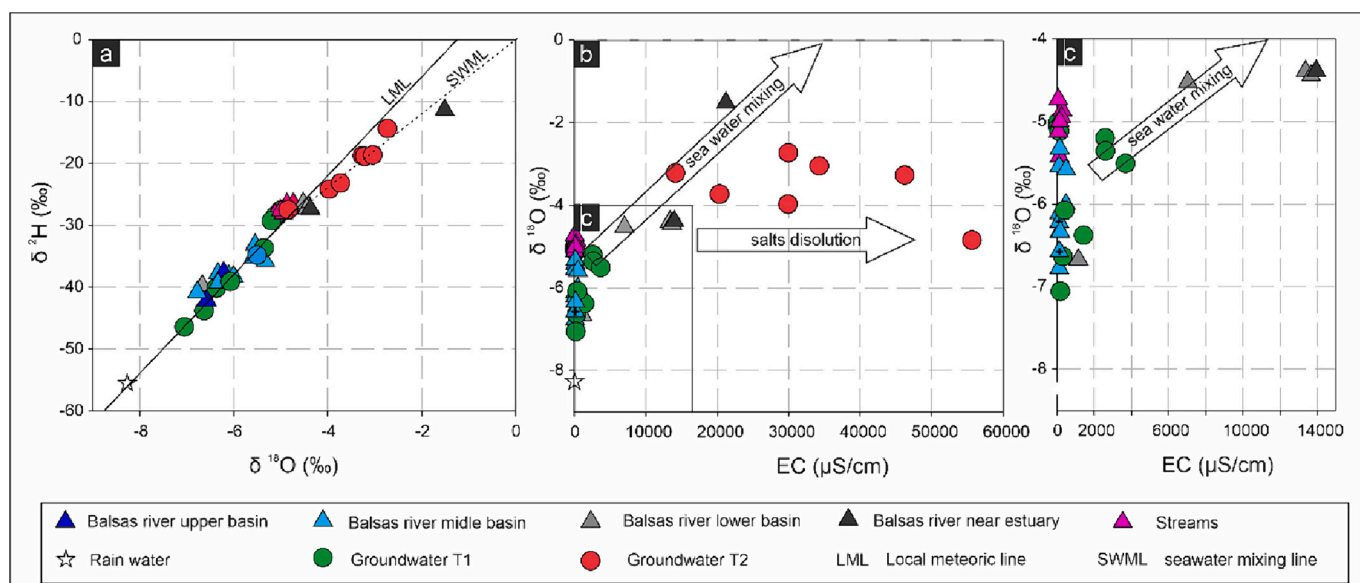


Fig. 5. Schoeller plots representing the concentration of major ions in meq/L and the designs of the hydrochemical facies. (a) May 2022, (b) June 2023, (c) August 2023.



**Fig. 6.** (a)  $\delta^2\text{H}$  vs.  $\delta^{18}\text{O}$  showing the distribution of the samples around the local meteoric line (LML) or the mixing line between river - rainwater and the average composition of seawater (SWML), (b)  $\delta^{18}\text{O}$  vs. EC where the arrows indicate the trends associated with the mixing of river - rainwater with seawater, or the trends of salt dissolution and (c) detail of figure (b).

key role, it is possible to recognize different wetland environments with their own hydrological behaviors and plant communities (Chui et al., 2011). In this sense, the results show that the Matusagaratí wetland presents different environments where different degrees of interaction between surface water and groundwater can be recognized with variations in lateral hydrological connectivity.

Although the high rainfall, typical of the humid tropical climate with values close to 2900 mm per year (Fabrega et al., 2013), determines much of Matusagaratí's hydrology, influence of tides is also significant (Carol et al., 2022), as shown by the hydrodynamic and hydrochemical differences observed in different sectors of the Balsas River. In terms of hydrodynamics, the river showed oscillations in the lower and middle basin responding to tidal entry from the Pacific Ocean (Fig. 2). The entry of tidal water through the river channel produces an increase in salinity in the lower basin area, which has up to 2 orders of magnitude more EC compared to the middle and upper basin. In the middle and upper basin, the river level rises due to the accumulation of water that cannot drain into the estuary, resulting in the presence of fresh water in these sectors of the river. The tidal influence also causes spatial variations in the major ion composition of the water (Fig. 5). The river exhibits sodium-calcium bicarbonate and sodium chloride facies in the upper basin, which change to sodium chloride in the middle and lower basin. Furthermore, the isotopic signal confirms the idea that there is a tidal influence in the lower basin, as samples from this area show greater isotopic enrichment with trends towards seawater. In contrast, the signal in the middle and upper basin correspond to that of the local rainfall (Fig. 6).

The rises of the river caused by the syzygy high tides inundates wetland environments at the river levee and in the alluvial plain. In the middle river basin, the study of transect 1 revealed three wetland environments with different plant communities that exhibit different hydrological behaviors. Next to the river, on the levee, the cativo forest develops. In this environment, the groundwater level sensors showed rises in accordance with the syzygy high tides (Fig. 3), indicating that the groundwater supporting this forest is recharged by river water. This tidal influence causes the groundwater in the levee to have the highest EC within transect 1, adopting brackish characteristics and sodic chloride facies similar to those of the river in this sector of the basin. Isotopically, although a signal like that of local rainfall is observed, there is a slight deviation towards the trend of waters affected by mixing with

tidal water (Fig. 6b).

In the mixed forest and in the orey forest located behind the river levee, the hydrodynamics and water chemistry show a different behavior. The water table levels in these two wetland environments do not vary with the tide and is always very close to de surface. Only a series of slight increases in the water table levels are observed in the mixed forest during exceptional spring tides (Fig. 3). Slight variations are observed in the water level records, sometimes associated with rainfall. Under these conditions, water table could emerge and a shallow water layer accumulates on the surface or drains through small streams that cross the levee and discharge into the river. The EC of the groundwater here is very low in both environments (fresh groundwater), and the hydrochemical facies may vary, although sodium-calcium bicarbonate facies dominate (Fig. 5). The isotopic signal of groundwater and the water that accumulates on the surface or drains through small streams is similar to that of rainwater. All these hydrodynamic and hydrochemical characteristics indicate that the mixed and the orey wetland forests are primarily sustained by rainwater and do not receive tidal influence. Likewise, it is observed that the mixed forest is located in a slightly higher topographic area with respect to the adjacent orey forest and cativo forest. This determines that the water table in the mixed forest is also higher and there is a groundwater flow towards the adjacent environments. However, these lateral inflows are minimal compared to the flooding by tidal water in the cativo forest or the contribution of rainfall in the mixed and orey forests. A summary of lateral hydrological flows and connectivity is shown in Fig. 7.

Transect 2 is in the lower basin, where tidal influence on the hydrodynamics and water chemistry of the river is more pronounced. In this wetland environment, the vegetation is dominated by caballero mangrove and salado mangrove. In both forests, the groundwater level rises during the spring tide events (Fig. 4), indicating that the groundwater supplying the mangroves is primarily recharged by river water. The high tide overtops the river levee and floods the mangrove areas behind it, with the river water infiltrating the sediments and causing the water table to rise rapidly. Because the river water is saline, this tidal influence causes the groundwater to have high EC, saline characteristics, and sodium chloride facies like those of the river in this basin sector. At low tide the water table in caballero mangrove is located at a higher position with respect to the river water level and to the water table in salado mangrove (Fig. 4). This shows that at low tide there is a

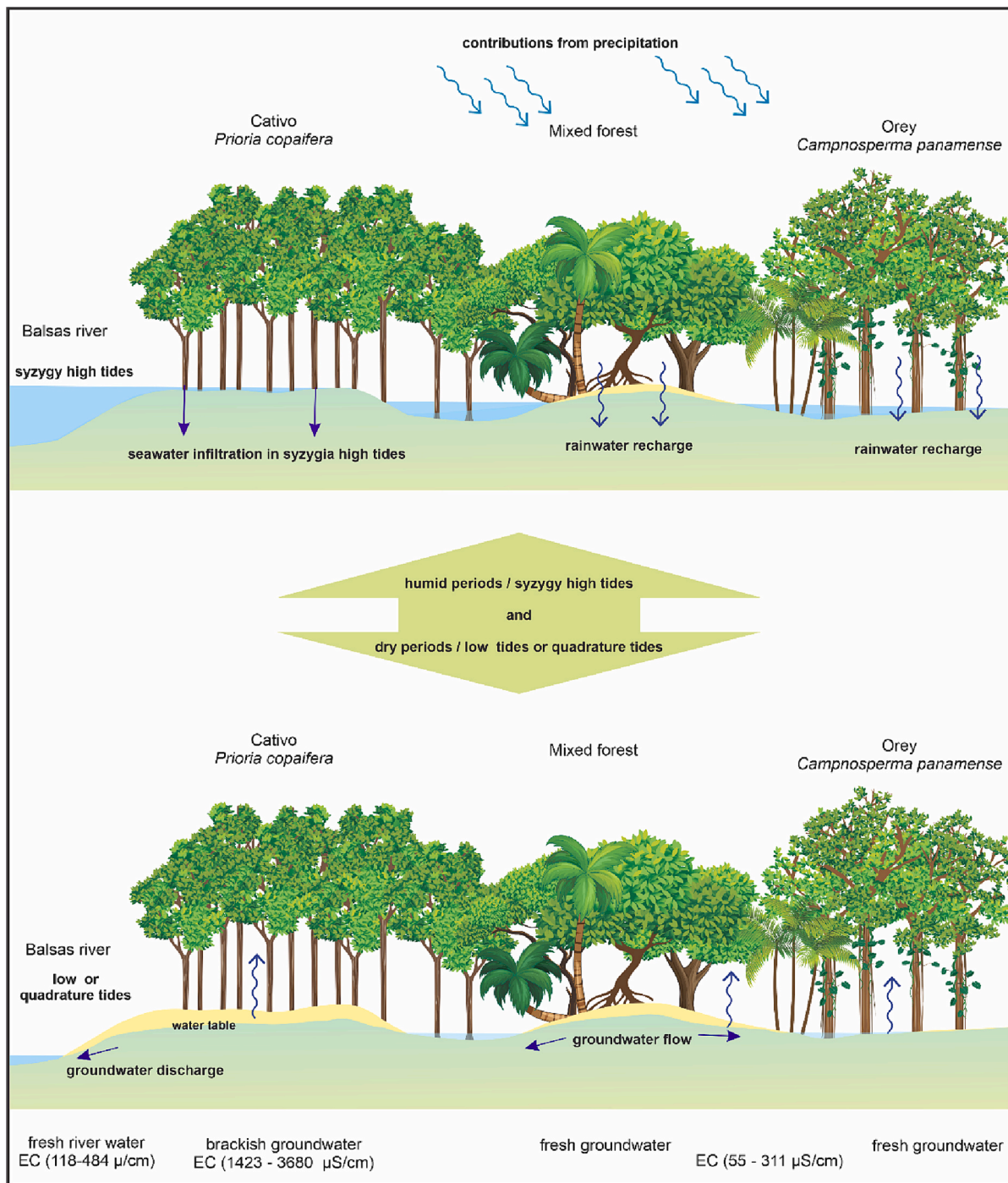
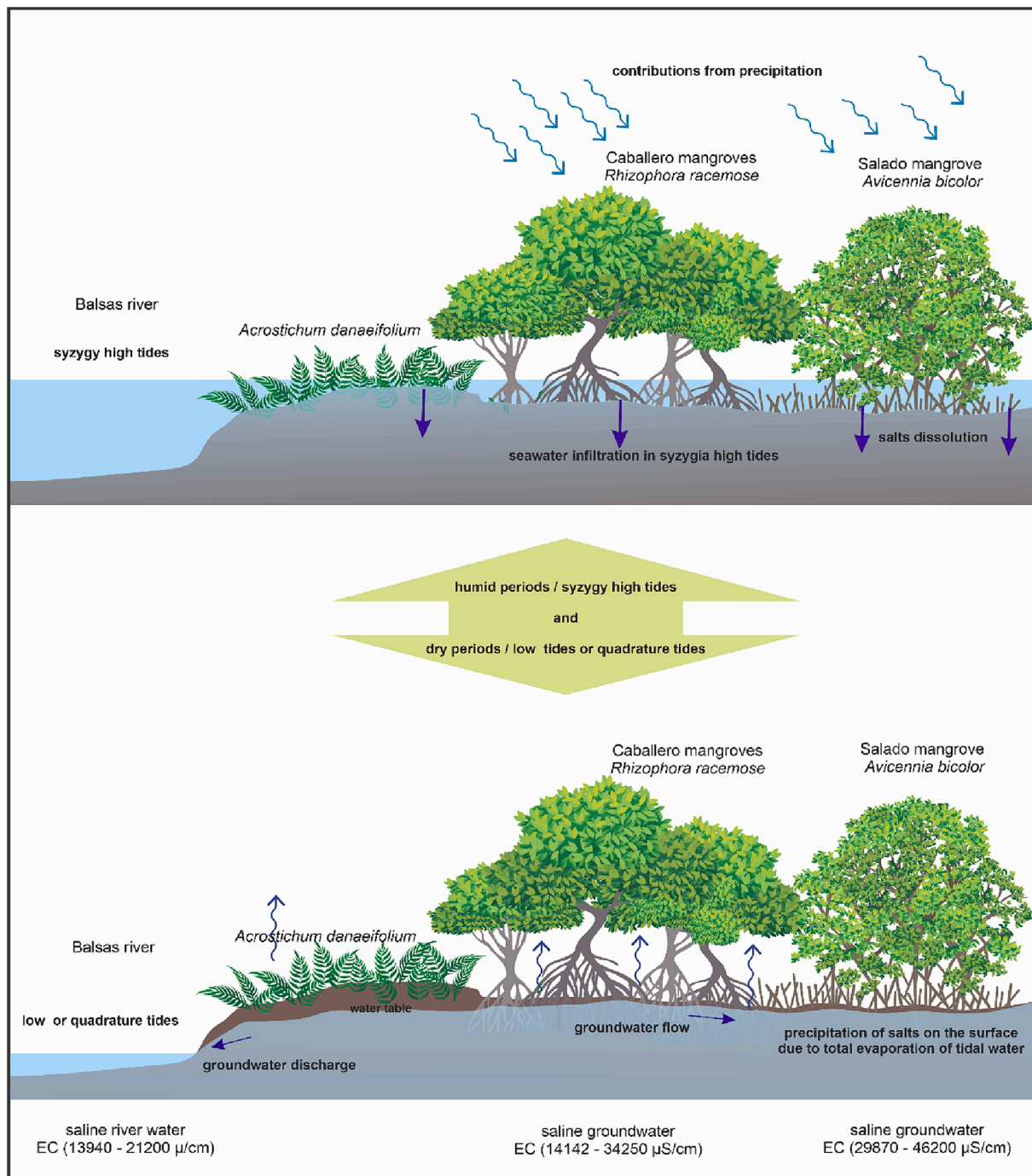


Fig. 7. Diagram showing surface and groundwater flows and lateral hydrological connectivity under different hydrological conditions for the wetland environments recognized in the middle basin of the Balsas River (Transect 1).

groundwater flow from the caballero mangrove environments to the river and to the salado mangrove environments, which are topographically slightly more depressed.

In transect 2, the isotopic signal of groundwater shows a clear trend towards mixing with seawater (Fig. 6a). The EC values in the mangrove groundwater are considerably higher than those of the river water, which can be attributed to salt dissolution processes (Fig. 6b). This indicates that the tidal water that inundates the mangrove accumulates on the surface and in some areas even evaporates completely, forming saline precipitates on the substrate. These precipitates are later dissolved in the next tidal inundation (Carol and Alvarez, 2016; Galliari et al.,

2021). High temperatures and evapotranspiration rates contribute to the formation of evaporitic salts. This salinization process is much more pronounced in the salado mangrove, which also experiences a significant drop in the water table during periods of low precipitation and low spring tides (Fig. 4). Even if the contribution of precipitation cannot be ruled out, the observed hydrodynamics and hydrochemistry indicate that tidal influence is much more significant. Laterally, the mangrove environments are connected to each other through underground flow. However, these lateral contributions are minimal compared to the flooding caused by tidal water. A summary of lateral hydrological flows and connectivity in the transect 2 area is shown in Fig. 8.



**Fig. 8.** Diagram showing surface and groundwater flows and lateral hydrological connectivity under different hydrological conditions for the wetland environments recognized in the lower basin of the Balsas River (Transect 2).

The hydrological connectivity in the alluvial plains of the Matusagaratí wetland can occur through surface flows during flood pulses and through shallow groundwater hydraulically connected to the river. The latter also connects to different wetland environments that support different types of wooded vegetation. During spring tides, the river connects with the groundwater at the levee and the alluvial plain by overflow. The direction of this connection is reversed during lower flow states, where groundwater tends to discharge into the river. This bidirectional movement of water facilitates the exchange and transport of solutes between the river and the riverine wetlands (Ren and Packman, 2005; Bracken et al., 2013; Covino, 2017). As a result, surface and groundwater, hydrodynamics and hydrochemistry, vary spatially and

temporally in different sectors of the wetland. The study of transects 1 and 2 indicates that there are wetland environments that depend primarily on tidal flow (wetlands in the lower basin and levee sectors in the middle basin) and others that rely mainly on rainfall (wetlands behind the levee in the low-lying areas in the middle basin). Similar behavior has been observed in studies conducted in wetland environments associated with the Tuira River (Carol et al., 2020, 2021, 2022).

Even though hydrology plays a key role in the distribution and development of plant communities in wetlands (Ridolfi et al., 2006; Dwire et al., 2006; Loheide and Gorelic, 2007; Muneeppeerakul et al., 2008). The results obtained show that some wetland vegetation can develop under different hydrological conditions. Such is the case of the

semi-deciduous mixed forest that develops on the levee in the middle basin of the Tuira River, where the river overflow occurs during spring tides, and where the groundwater is brackish (Carol et al., 2022). This suggests that this type of forest can thrive in environments with different hydrological connectivity, encompassing both shallow freshwater and brackish groundwater. On the other hand, mangroves show a strong dependence on tidal connection, typically developing in saline environments along both the Balsas and Tuira rivers in the lower basin sectors (Carol et al., 2022). In contrast, the orey forests located in inland areas away from river channels (Candanedo, 2021) seem to be associated with environments where flooding by precipitation is the main hydrological determinant. It is worth noting that, although the number of transects studied is limited, they cover representative wooded wetlands and complement previous studies (Carol et al., 2020; Carol et al., 2021).

Ecohydrological models are a useful tool for understanding the interactions between surface water, groundwater, and vegetation (Chui et al., 2011). In this regard, the obtained results and conceptual models not only improve our understanding of the hydrological functioning of the different environments in the Matusagaratí wetland, but also allow the identification of vegetation adapted to each of the defined hydrological conditions. This constitutes a crucial tool for developing guidelines for water management and promoting sustainable management of wetland areas that, although protected by law, remain under anthropogenic pressure due to unsustainable development practices in the region.

## 5. Conclusions

This study identified the surface and groundwater flow exchanges and lateral hydrological connectivity in different environments associated with the Balsas River in the Matusagaratí Wetland. Each of these environments presents a characteristic type of vegetation, which shows that the hydrology is a conditioning of the development of the different plant species in the wetland.

The hydrodynamics of the Balsas River are significantly influenced by the tides. In the lower basin, tides enter through the estuary, causing rises in the river level during high tides. In the middle basin, high tides lead to increases in river levels due to the accumulation of water that cannot drain towards the estuary. The inflow of tidal water causes variations in the salinity of the river water. In the upper and middle basins, the water is fresh with sodium-calcic bicarbonate to sodium chloride hydrochemical facies and with isotopic signal like rainfall. In contrast, in the lower basin, the river water is saline, with sodium chloride facies and isotopic trends resembling seawater.

Spatial variations in hydrodynamic and hydrochemical behavior are also recognized in the wetlands associated with the river. In the middle basin, environments such as cativo forests develop on the levee, and mixed forests and orey forests in the alluvial plain. In these areas, variations in water table levels and the major chemical and isotopic composition of the groundwater reveal different hydrological processes.

In the cativo forest, which is closest to the river basin, there is an interaction between the groundwater of the wetland and the river water. This interaction takes place during the spring tides when the Balsas River locally floods the levee, and river water infiltrates, causing the water table to rise during these tides. The input of river water results in brackish groundwater in the cativo forest with a slight isotopic trend towards sea water.

On the other hand, mixed forest and orey environments, developed in low-lying alluvial plain, exhibit hydrodynamics and hydrochemistry that are primarily associated with precipitation inputs. In these environments, the water table levels do not fluctuate in relation to tides, and the water is freshwater with an isotopic composition similar to that of rainfall. These wetland areas are drained by small streams whose surface water has similar chemical and isotopic characteristics.

In the lower basin, the hydrodynamics and hydrochemistry of the

Balsas River and the mangrove wetlands, specifically caballero mangroves and salado mangroves, show a significant tidal influence. Syzygy tides inundate these mangroves with saline water, which infiltrates and rises the groundwater levels. The wetland's groundwater exhibits sodium chloride hydrochemical facies and an isotopic signal associated with tidal contributions. However, the groundwater in the mangroves, especially in salado mangroves, has a higher electrical conductivity than the river water due to the dissolution of salts precipitated during the complete evaporation of tidal water during periods when the wetland is not flooded.

The findings of this study on the Balsas River, along with previous work on the Tuira River, highlight the complex hydrological dynamics of the Matusagaratí wetland. The data provided forms a basis for the management of this extensive tropical wetland, which despite having protection initiatives could be hydrologically impacted by unsustainable practices, such as the construction of drains and embankments for rice cultivation, occurring in the region.

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## CRediT authorship contribution statement

**Eleonora Carol:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **María del Pilar Alvarez:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Manuel Arcia:** Writing – review & editing, Data curation. **Indra Candanedo:** Project administration, Funding acquisition, Data curation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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