Science of the Total Environment

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

--Manuscript Draft--

Manuscript Number:	
Article Type:	Research Paper
Keywords:	Tropical wetland; Hydrodynamics; Hydrochemistry; Stable Isotopes; Ecohydrology
Corresponding Author:	Eleonora Carol, Ph Geological Research Center La Plata, ARGENTINA
First Author:	Eleonora Carol, Ph
Order of Authors:	Eleonora Carol, Ph
	María del Pilar Alvarez
	Manuel Arcia
	Indra Candanedo
Abstract:	The Matusagarati 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 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 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. Meanwhile, in the 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, which, despite having protection initiatives, could be hydrologically impacted by the unsustainable socio-economic practices.
Suggested Reviewers:	Luigi Tosi Institute of Geosciences and Earth Resources National Research Council Padua Branch luigi.tosi@igg.cnr.it
	Sandra Donnici Institute of Geosciences and Earth Resources National Research Council Padua Branch sandra.donnici@igg.cnr.it
	Lucia Santucci National Scientific and Technical Research Council luciasantucci@fcnym.unlp.edu.ar
	Carolina Tanjal National Scientific and Technical Research Council ctanjal@cig.museo.unlp.edu.ar
	Cristina Dapeña

	University of Buenos Aires dapenna@gmail.com
	Eduardo Mariño National University of La Pampa emarinio@exactas.unlpam.edu.ar
Opposed Reviewers:	

CONICET

Consejo Nacional de Investigaciones Científicas y Técnicas

December 13, 2023

Dear Editor,

We submit the manuscript entitled "Surface and groundwater flow exchanges and lateral hydrological connectivity in environments of the Matusagaratí Wetland, Panama" by Carol E., Alvarez M.P., Arcia M. and Candanedo I., to be considered for publication in Science of The Total Environment.

The work establishes 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. The Matusagarati wetland in the Panamanian Darien is one of the largest wetlands in Central America. The wetland area is developed in the Darien jungle, which is very difficult to access, a situation that limits the carrying out of research work.

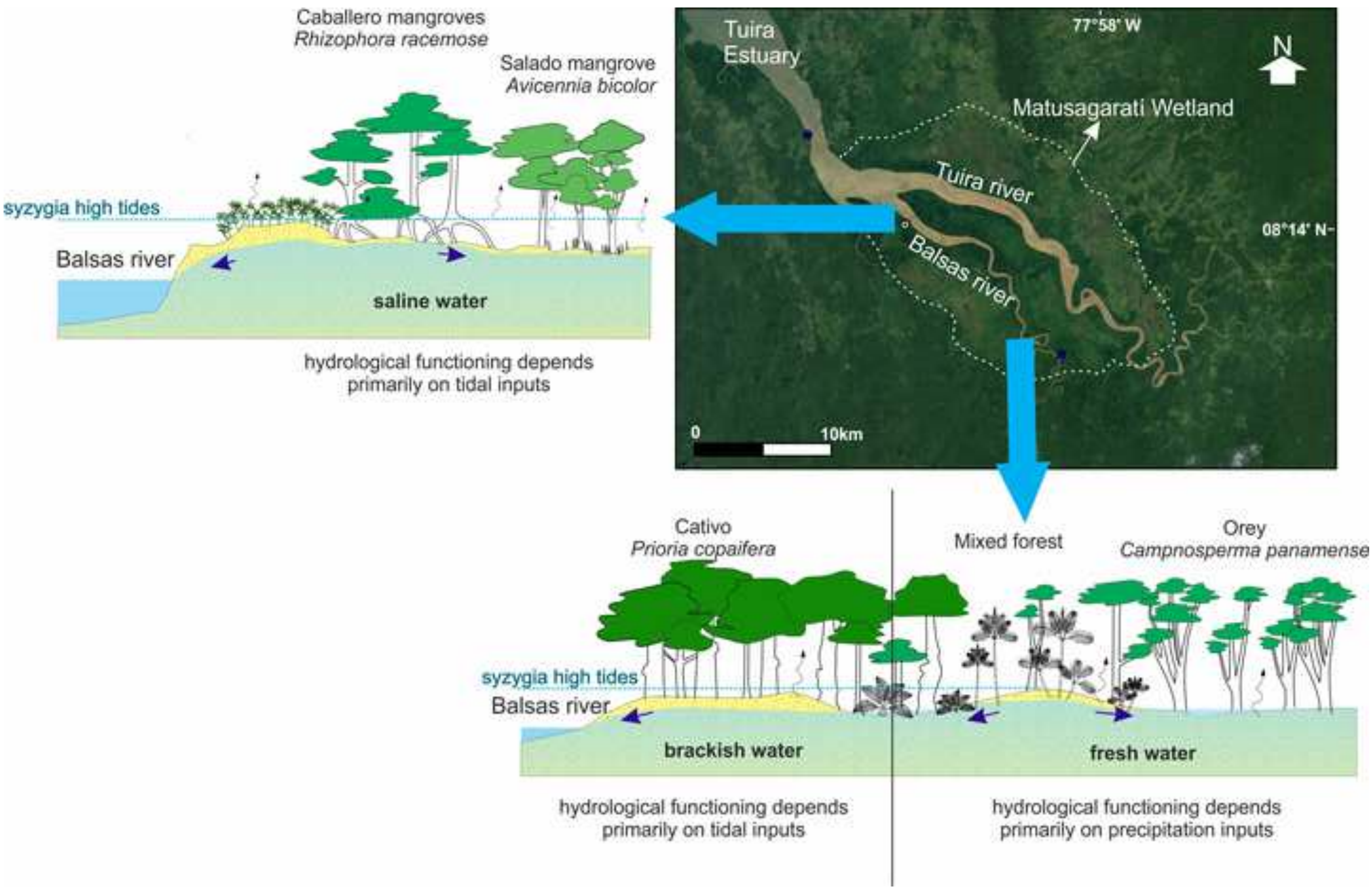
In our study, surface and groundwater monitoring networks were generated, where water level sensors were installed and the majority and isotopic chemistry of the water were analyzed. The joint analysis of the hydrological behavior with the wetland vegetation allowed us to recognize environments with different water inputs. The results obtained not only provide data in unstudied areas but also contribute to generating water management guidelines in an area where, although there are natural reserve areas, there are also anthropogenic pressures on land use.

This new article whose content has not been published, may be of particular interest to the readers of the journal.

Sincerely,

Carol Eleonora
Corresponding author

Graphical Abstract



Highlight

- Matusagaratí wetland is one of the largest wetlands in Central America.
- Different wetland environments are recognized in the Balsas River.
- The vegetation of the wetland is conditioned by the different water inputs.
- The water that contributes to the wetland in the lower basin is mainly of tidal origin.
- In the middle basin the wetland is mainly dependent on river and rainfall input.

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

Eleonora Carol[1*], María del Pilar Alvarez[2], Manuel Arcia[3], Indra Candanedo[3]

1- Centro de Investigaciones Geológicas (CIG). Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad Nacional de La Plata (UNLP), Argentina.

2- 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.

3- Technological University of Panama (UTP), Republic of Panama.

*Corresponding author: eleocarol@fcnym.unlp.edu.ar

Abstract

The Matusagarati 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 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 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. Meanwhile, in the 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, which, despite having protection initiatives, could be hydrologically impacted by the unsustainable socio-economic practices.

Keywords: Tropical wetland; Hydrodynamics; Hydrochemistry; Stable Isotopes; Ecohydrology.

1. Introduction

Wetlands are critical environments that provide ecosystem services valued at trillions of dollars annually (De Groot et al., 2009; Barbier, 2011; Ivory et al., 2019). They help 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., 1997; Erwin 2009; Ahmed, 2015; Adame et al., 2019; Cuthbert et al., 2022). Therefore, the degradation and loss of wetlands not only causes the deterioration and loss of biodiversity, but also results in the loss of associated ecosystem services, with economic implications (Wasserman and Dalu, 2022).

In river 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, studying the hydrological functioning of wetlands considering surface and groundwater flows is valuable not only to define their functioning, but also to predict the impact that natural or human-induced hydrological modifications can cause in habitats that support wetlands. The sustainable use of wetlands and their management requires planning and a good scientific understanding about how these ecosystems function (Ahmed, 2015).

The Matusagarati wetland in the Panamanian Darien is one of the largest wetlands in Central America. In fact, Matusagarati is a complex of wetlands that includes several types of flooded forests, flooded grasslands and mangroves covering approximately 56,250 hectares (Candanedo 2021). Matusagarati lies along the margins and adjacent lowlands of the Tuira and Balsas rivers before emptying into the Pacific Ocean, forming an extensive estuary where fresh and marine waters meet. More inland, this wetland also receives freshwater from small streams draining from nearby ridges.

There are three protected areas that provide legal protection to 70% of the wetland: the Filo del Tallo-Canglon hydrological reserve, the Chepigana Forest Reserve, and the Matusagarati Wildlife Refuge. Despite this legal protection, there is no on-the-ground management resulting in inappropriate practices such burning of herbaceous wetlands during the dry months by local cattle ranchers who seek to expand their cattle pastures. Furthermore, during the last decade, nearly a third of the wetland has been illegally titled and part of it drained and transformed into rice cultivation (Ministerio de Ambiente 2016; CREHO 2015), dramatically changing it hydrological behavior.

Until recently, there has been a lack of baseline studies to support better management and involvement of local communities in sustainable management due to the lack of roads which make access to study sites extremely difficult and costly. However, five years ago, a group of national as well as international researchers have joined efforts to understand Matusagarati's biodiversity and ecological functioning. Studies have been carried out on plants (Grauel and Putz 2004; Ortiz et al. 2020; Ortiz et al. 2022; Ibáñez and Flores 2020), bird communities (Aparicio 2020), and the wetland´s potential as carbon storage and fisheries (López and Cunampio 2023). A map on the wetland's vegetation types has also been developed.

The only previous study on hydrological functioning in Matusagaratí was 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 were dependant mainly on precipitation. Though the hydrological dynamics of the Tuira River's wetlands has started to be understood, the Balsas River wetlands system remain 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 that exists between the different laterally linked wetland environments.

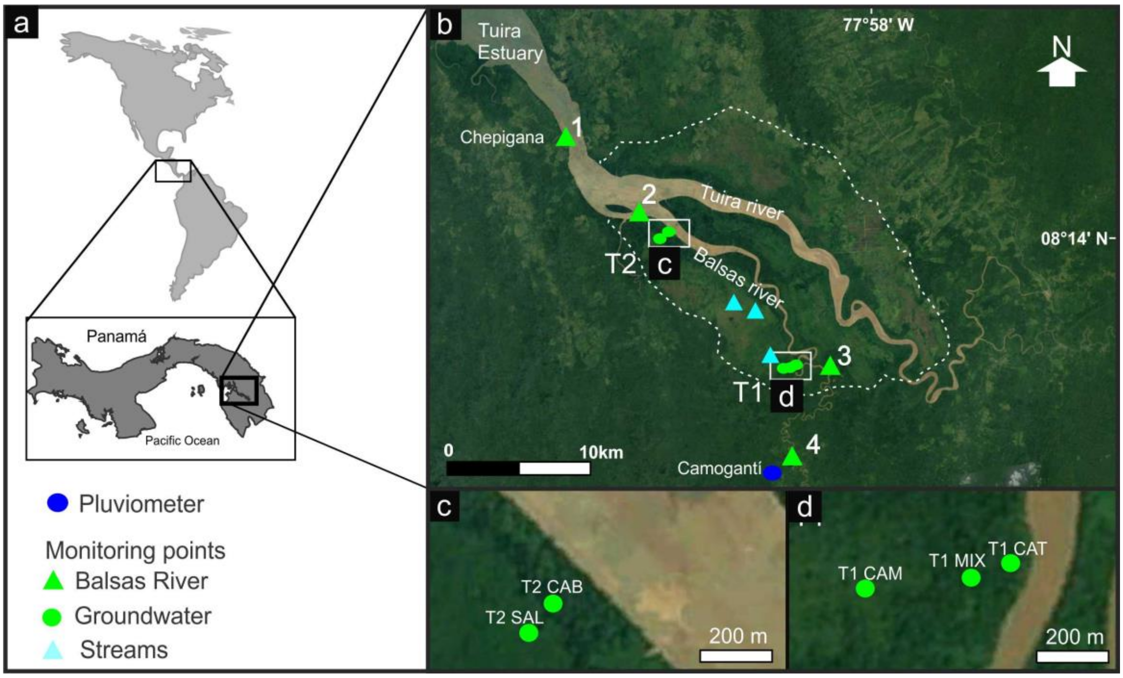


Figure 1: (a) Location of the study area. (b) Location of the sampling points 1: Balsas River near estuary, 2: Balsas River lower basin, 3: Balsas River middle basin, 4. Balsas River upper basin, T1: Transect 1 and T2: Transect 2. The white dotted line indicates the location of the Matusagaratí wetland.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

2. Methodology

To analyze the hydrodynamics and hydrochemistry of the wetland, two transects were defined in different sectors of the wetland. These transects were arranged perpendicular to the bed of the Balsas River and intercepting different environments within the wetland. 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* y *Elaeis oleifera*. Behind the cativo forest there is a flooded evergreen mixed forest that shows a wider variety of species. These include sangrillo (*Pterocarpus officinalis*), alcornoque (*Mora oleifera*), cuchillito (*Pentaclethra macroloba*) and tangaré (*Carapa guianensis*). Finally, located in a depression behind the flooded evergreen mixed forest, the orey forest (*Campnosperma panamense*) is found. This type of forest has just been recently mapped. The orey trees grow together with palm species such as *Euterpe oleracea* an occasionally *Elaeis oleifera*.

Transect 2 down the river, closer to the estuary, starts with a stand of mangrove fern (*Acrostichum danaeifolium*), followed by 20-25 m high caballero mangroves (*Rhizophora racemose*) with their characteristic aerial roots that grow from the main stem, resembling flying buttresses. More inland there is a nearly monotypic salado mangrove (*Avicennia bicolor*) 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.

In each transect, wells were installed within each of the wetland environments described above. The boreholes were made between 3 and 4 m deep with a manual auger. The boreholes were cased with a continuous grooved filter PVC pipe wrapped in a fine plastic mesh, filling the annular space with a pre-filter of siliceous gravel, and sealing the upper part of the annular space of the well. Hobbo level data logger and Odyssey® Capacitance Water Level sensors that continuously register studied variables were installed in all the boreholes, which were programmed to measure the water level every 15 minutes. To measure the Balsas River levels, similar sensors were installed up the river in transect 1 and down the river in transect 2 (Fig. 1).

Precipitation was measured using an Odyssey® tipping bucket rain gauge classic, located in Camogantí, in the upper basin sector of the Balsas River. Data collected in the sensors installed in the boreholes were later compared to the river level and precipitation data. The comparison between river and groundwater levels allowed the analysis of 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 taken at 3 points of the Balsas River located in the upper, middle, and lower basin, and in small streams that drain from the wetland to the main river, and in the wells (groundwater) installed in the transects. At all points electrical conductivity (EC) was measured *in situ* using a portable conductivity meter instrument (Lutron® WA-2017SD). Major ions and stable isotopes of the water molecule were determined in the water samples 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, 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 ± 0.05‰ and ± 0.5‰, for $\delta^{18}O$ and δ^2H, respectively. Isotopic results are presented as δ‰, defined as δ=1000(Rs–Rr)/Rr‰, where δ is the isotopic deviation in ‰ relative to Vienna Standard Mean Ocean Water (V-SMOW) (Gonfiantini, 1978); R is the isotopic ratio ($^2H/^1H$, $^{18}O/^{16}O$); r: international reference and s: sample. The isotopic values were compared with the local meteoric line $\delta^2H = 7.63\ \delta^{18}O + 6.51$ for the Pacific coast of central Panamá (Kern et al., 2016).

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 lower basin) and transect 2 (in the middle 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 water levels in the Balsas River (Fig. 1a) show oscillations related to tidal influence both in the lower basin sector and in the middle basin sector close to transect 1. The relative position of water levels in the river between both sectors shows that the upstream sensor generally registers a higher water level than the sensor in the downstream sector. This would indicate that the propagation of the tide along the river channel do not allow the river water to drain but accumulate upstream, causing rises in river levels in the middle section of the basin. In the lower basin, the rise in level is due to the entry of tidal water, while towards the middle - upper basin the rise is due to the obstruction of the drainage by the entry of the tide. In both sectors of the basin, the high tide and low tide peaks occur at the same time (Fig 2b). This supports the idea of the above-mentioned behavior and not that of a rise caused only by tidal propagation within the channel, which would be observed with a phase shift in the peaks caused by the delay time in which the tide takes to propagate within the channel.

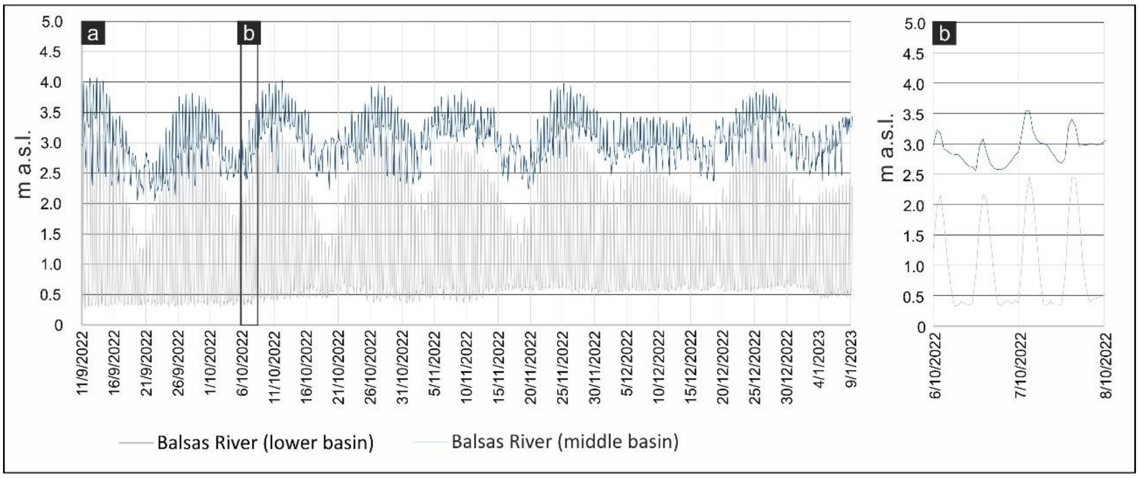


Figure 2: Variations of the water level in the Balsas River (in m a.s.l.) in sectors of the lower basin and middle basin.

The comparison of the water levels in the Balsas River with the phreatic 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 tide-related rises at all high tides that exceed 2.75 m a.s.l. At low tide or high tides below said level, the water table is mostly at values close to 2.90 m a.s.l., with the depth of the groundwater close to 0.08 m. Particularly starting in January 2023, when high tides are low and rainfall is very scarce, a decrease in the groundwater level in the cativo forest is observed. Minewhile, the groundwater in the mixed forest (T1 MIX) and orey forest (T1 CAM) has a very shallow water table (outcropping sometimes). In these environments, the water table does not present oscillations in relation to the tidal flow, but the rises can be associated in most cases with precipitation. An exception to this behavior was observed on the first half of September 2022, when the high tides reached the highest point on record and generated small rises in the water table in the mixed forest sensor.

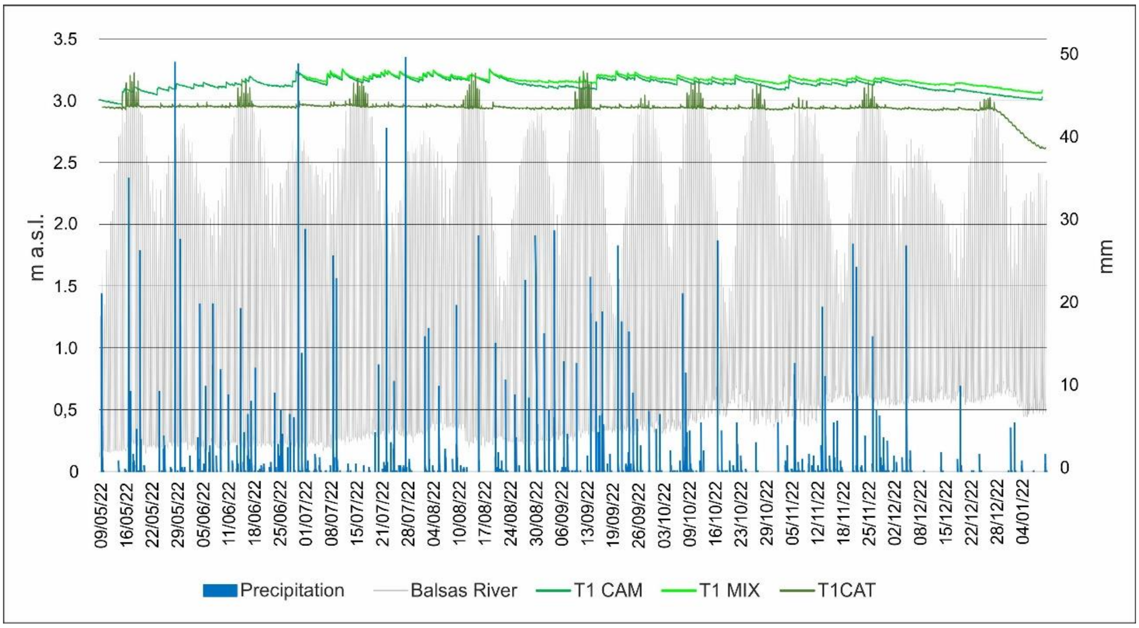


Figure 3: Variations of the groundwater level in different environments of transect 1, the Balsas River level (in m a.s.l.), and daily precipitation data (in mm).

In transect 2, the comparison of the phreatic levels with the river levels shows a different behavior (Fig. 4). The groundwater level in the caballero mangrove (T2 CAB) is less than 0.05 m deep and in the salado mangrove (T2 SAL) it is less than 0.22 m deep. In both environments, the water table rises when the river level exceeds 2.75 m a.s.l. during high tide (mainly syzygy tide). At low tide and high tides less than 2.75 m a.s.l., the groundwater had a level close to 2.70 m a.s.l., between May and November 2022. In this section of the record (Fig. 4) the syzygy high tides exceed 2.75 m a.s.l. and rainfall is abundant. Starting in December 2022, a change in the groundwater level is observed, which tends to decrease mainly in the salado mangrove. This second section of the record is characterized by lower syzygy high tides and for being a drier period with rainfall that rarely exceeds 10 mm. However, the water table rises rapidly when high tides above 2.75 m a.s.l. occur within this period (see date of January 20, 2023).

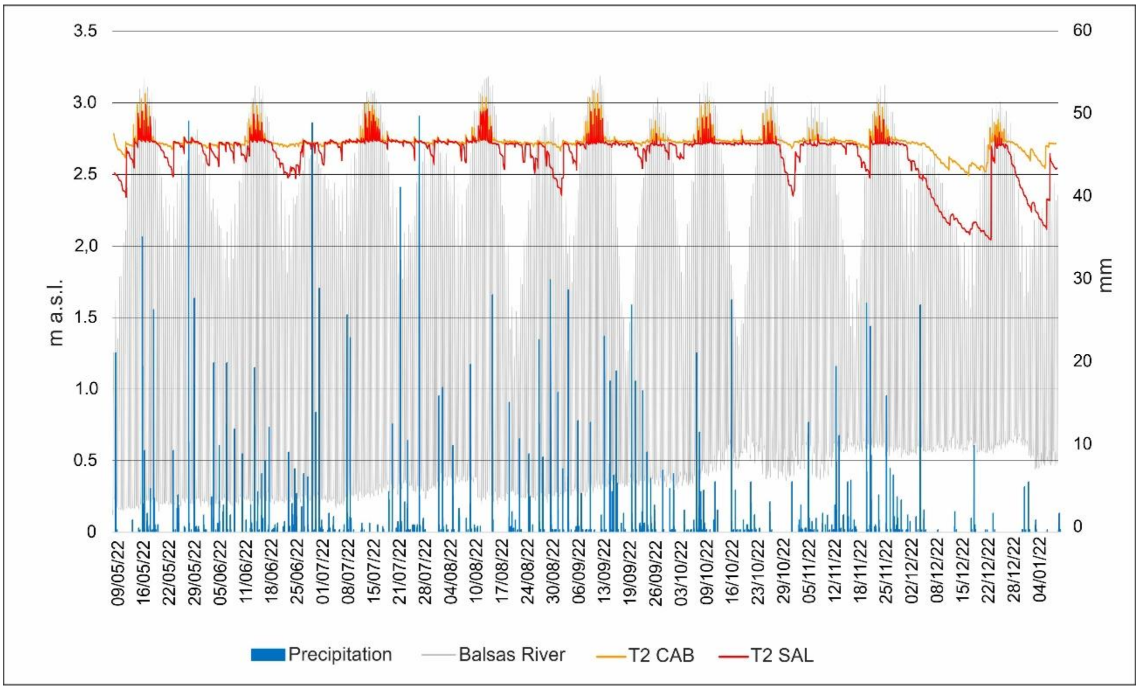


Figure 4: Variations of the groundwater level in transect 1 and the level of the Balsas River (in m a.s.l.) and daily precipitation data (in mm).

3.2.3.2. 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 µS/cm, in the middle basin between 118 and 484 µS/cm and in the lower basin between 13940 and 21200 µ/cm. The small streams that drain towards the river have low EC with values between 69 and 282 µS/cm. These differences in the EC are reflected in the contents of major ions and hydrochemical facies (Fig. 5).

In the Balsas River, the dominant ions in the upper basin vary, depending on the sampling, between Ca^{+2} (0.64 - 0.73 meq/L) and Mg^{+2} (0.64 - 0.70 meq/L) and HCO_3^- (1.43 - 1.51 meq/L), or between Na^+ and Cl^- (0.16 – 0.22 and 0.07 – 0.08 meq/L). While, in the middle and lower basin an increase in the concentrations of Na^+ (80.22 and 103.18 meq/L in the middle and lower basin respectively) and Cl^- (4.04 and 153.96 meq/L in the middle and lower basin respectively) is observed, being these markedly dominant over the other major ions, particularly in the lower basin. These spatial variations determine a change in hydrochemical facies in the river water with sodium-calcic bicarbonate and sodium chloride trends in the upper basin that transition to sodium chloride in the middle and lower basin. In the streams that flow to the main river, dominant ions are sodium chloride to sodium bicarbonate-chloride, with the average content of 22.32 meq/L for Na^+, 16.95 meq/L for HCO_3^- and 20.86 meq/L for Cl^-.

The groundwater in transect 1 presents different EC values in each wetland environment. In three samples of groundwater taken in the cativo forest (T1 CAT), higher EC was recorded than in the groundwater in the mixed forest (T1 MIX) and orey forest (T1 CAM). The EC in the cativo forest varied between 1423 and 3680 µS/cm, while in the mixed and orey forest the electrical conductivity was similar in May 2022 and June 2023 with values between 55 and 311 µS/cm. cm. However, in August 2023 a significant increase was recorded in the mixed forest reaching values of 2600 µS/cm. The hydrochemical facies in relation to the content of major ions are sodium chloride in the cativo forest and sodium bicarbonate-chloride in the mixed and 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 14142 and 34250 µS/cm, while in the salado mangrove (T2 SAL) between 29870 and 46200 µS/cm. In both cases, the high EC is associated with a high concentration of Na^+ ions (mean values of 1894.29 meq/L in T2 CAB and 5200.15 meq/L T2 SAL) and Cl^- (mean values of 3654.34 meq/L in T2 CAB and of 10352.76 meq/L T2 SAL). In this sector of the wetland there is a dominance of sodium chloride facies in both the river and the groundwater (Fig. 5).

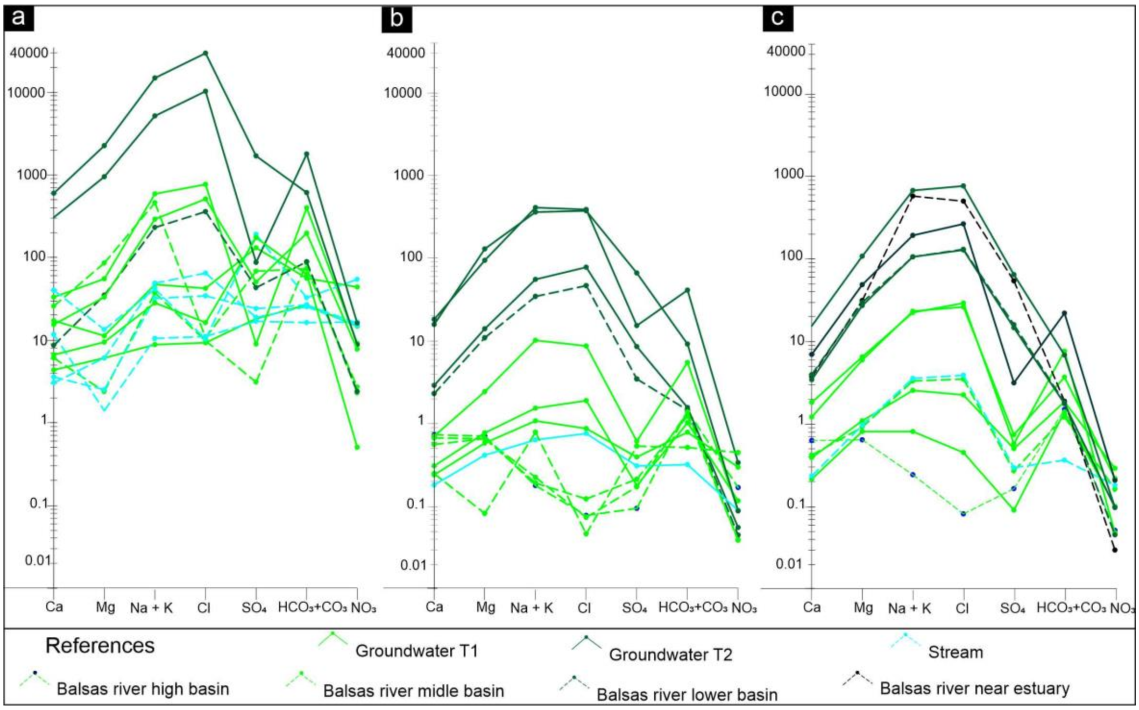


Figure 5: Schoeller plots representing the concentration of major ions in meq/L and the designs of the hydrochemical facies. (a) May 2022, (b) June 2023, (c) August 2023.

The δ ^{18}O vs. δ ^{2}H graph (Fig. 6a) shows the results of the isotopic signal for samples taken in the upper and middle basin of the Balsas River, in the streams and in the groundwater samples of transect 1. All of them are located around the local meteoric line. The rainwater sampled in May 2022 is also located on this line, however, it shows the least enriched values.

The isotopic signal of the samples from the lower basin of the Balsas River and the groundwater of 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 δ ^{18}O vs. EC (Fig. 6b) shows that the samples from the upper and middle basin of the Balsas River, as well as those from the streams and the groundwater in transect 1, present isotopic variations associated with a small increase in the EC.

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

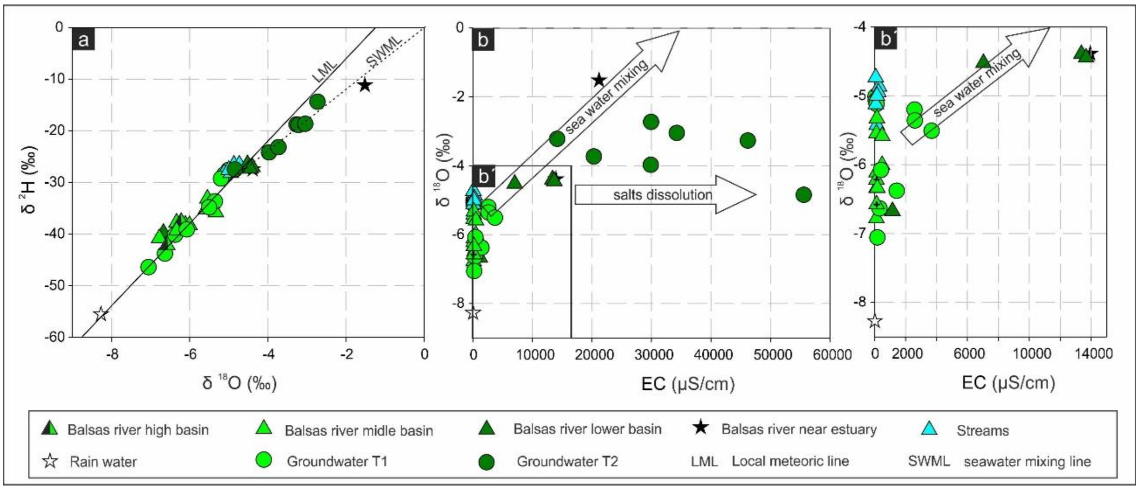


Figure 6: (a) $\delta^{2}H$ vs. $\delta^{18}O$, (b) $\delta^{18}O$ vs. EC, (b´) detail of figure (b).

4. Discussion

The hydrological dynamics of wetlands associated to estuaries and large river basins is very complex (Ivory et al., 2019, Xiao et al., 2019). Because in wetlands hydrology plays a key role in the development of vegetation, 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 and groundwater can be recognized with variations in lateral hydrological connectivity.

Although 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, tidal influence is also significant (Carol et al., 2022) as shown by the hydrodynamic and hydrochemical differences recorded in different sectors of the Balsas River. In terms of hydrodynamics, the river in lower and middle basin showed oscillations that respond to the entry of the tide 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 shows up to 2 orders of magnitude more EC compared to the middle and upper basin. On the other hand, in response to the influx of the tide in the middle and upper basin, the levels rise because of the accumulation of river water that cannot drain into the estuary. These sectors of the river, the middle and upper basin, accumulate fresh water. The tidal influence also causes spatial variations in the major ion composition of the water (Fig. 5). The river presents sodium-calcium bicarbonate and sodium chloride facies in the upper basin that transition to sodium chloride in the middle and lower basin. Furthermore, the isotopic signal confirms the idea that in the lower basin there is tidal influence, as samples from this area present greater isotopic enrichment with trends towards seawater. In contrast, in the middle and upper basin, the signal is like that of the local rainfall (Fig. 6).

The rises of the river caused by the syzygy high tides flood the wetland environments on the river levee and the alluvial plain. In the middle river basin, the study of transect 1 allowed us to recognize three wetland environments with different plant communities in which different hydrological behaviors are recognized. 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), which indicates that the groundwater that supports this forest is recharged by river water. The high tide floods the levee, and the river water infiltrates the sediments, causing rapid rises in the water table. The groundwater in this environment of the transect 1 presents one of the highest EC because of the tidal influence. It also exhibits brackish characteristics and sodium chloride facies like those of the river in this basin sector. 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. Only a series of slight increases in water table levels are observed in the mixed forest during extraordinary spring tides (Fig. 3). In the water level records, slight variations are observed, sometimes associated with rainfall. However, the water table is very close to the surface or is outcroping, resulting in rejected recharge. Under these conditions, a shallow water layer accumulates on the surface or drains through small streams that cross the levee and discharge into the river. The electrical conductivity (EC) of the groundwater here is very low in both environments (fresh groundwater), and 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 like that of rainwater. All these hydrodynamic and hydrochemical characteristics indicate that these wetland forests are primarily sustained by rainwater and do not receive tidal influence.

Laterally, the forest environments are connected through underground flow. However, these lateral inputs are minimal compared to the flooding from 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 Figure 7.

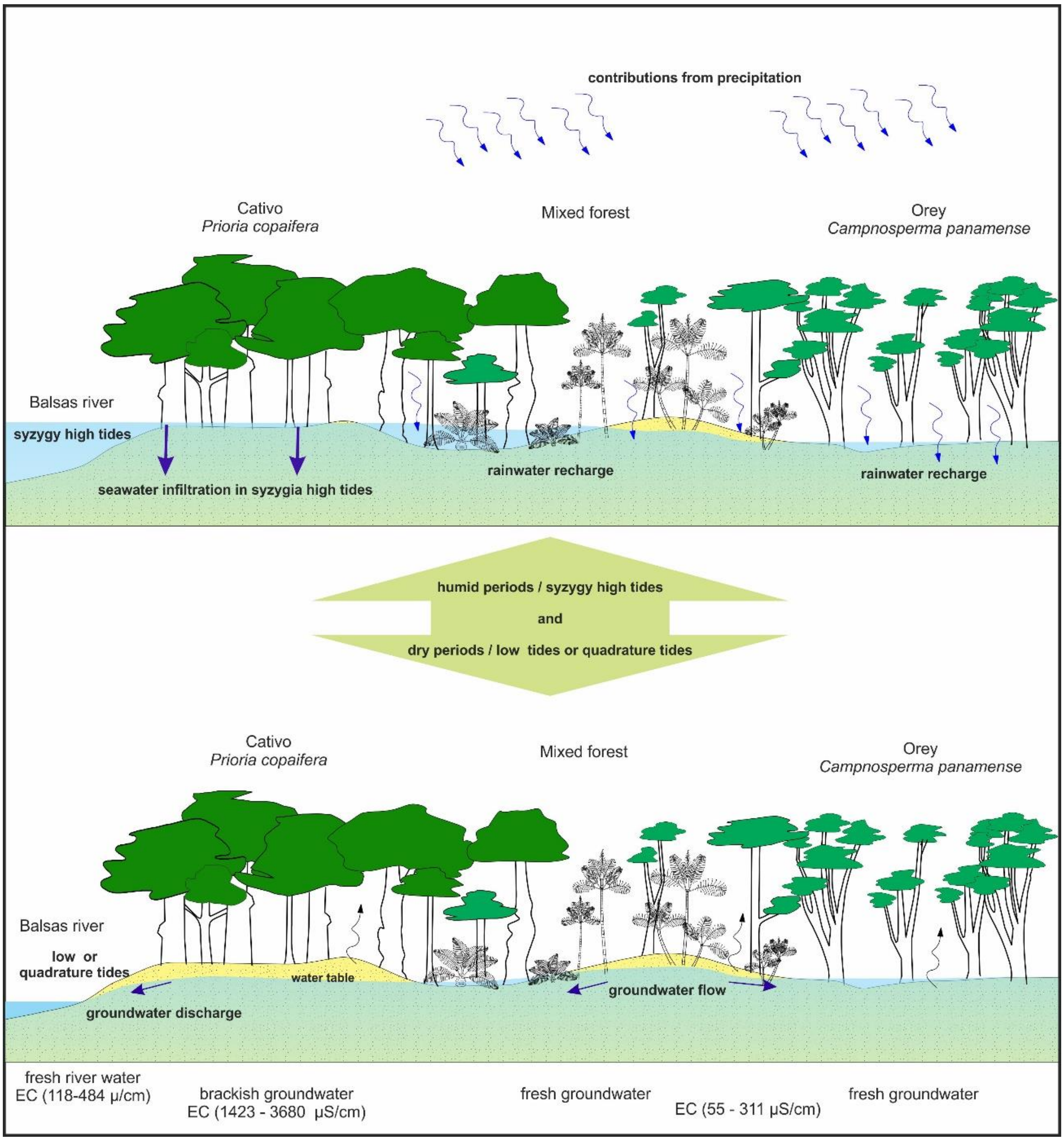


Figure 7: Diagram showing surface and groundwater flows and lateral hydrological connectivity in different wetlands environments in the middle basin of the Balsas River (Transect 1).

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 dominant vegetation is mangrove, with sectors identified as either dominated by caballero mangrove or salado mangrove. In both mangrove forests, the groundwater level increases during spring tide events (Fig. 4), indicating that the groundwater supporting the mangroves is primarily recharged by river water.

The high tide exceeds the river levee and floods the mangrove areas located behind it, with river water infiltrating the sediments, causing rapid rises in the water table. This tidal influence causes the groundwater to have high electrical conductivity, saline characteristics and sodium chloride facies like those of the river in this basin sector.

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 in the river water, resulting from salt dissolution processes (Fig. 6b) suggesting that the tidal water that inundates the mangrove accumulates on the surface, and in some areas, it may completely evaporate, 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 marked decreases in the water table during periods of low precipitation and low spring tides (Fig. 4). While the contribution of precipitation is not 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 Figure 8.

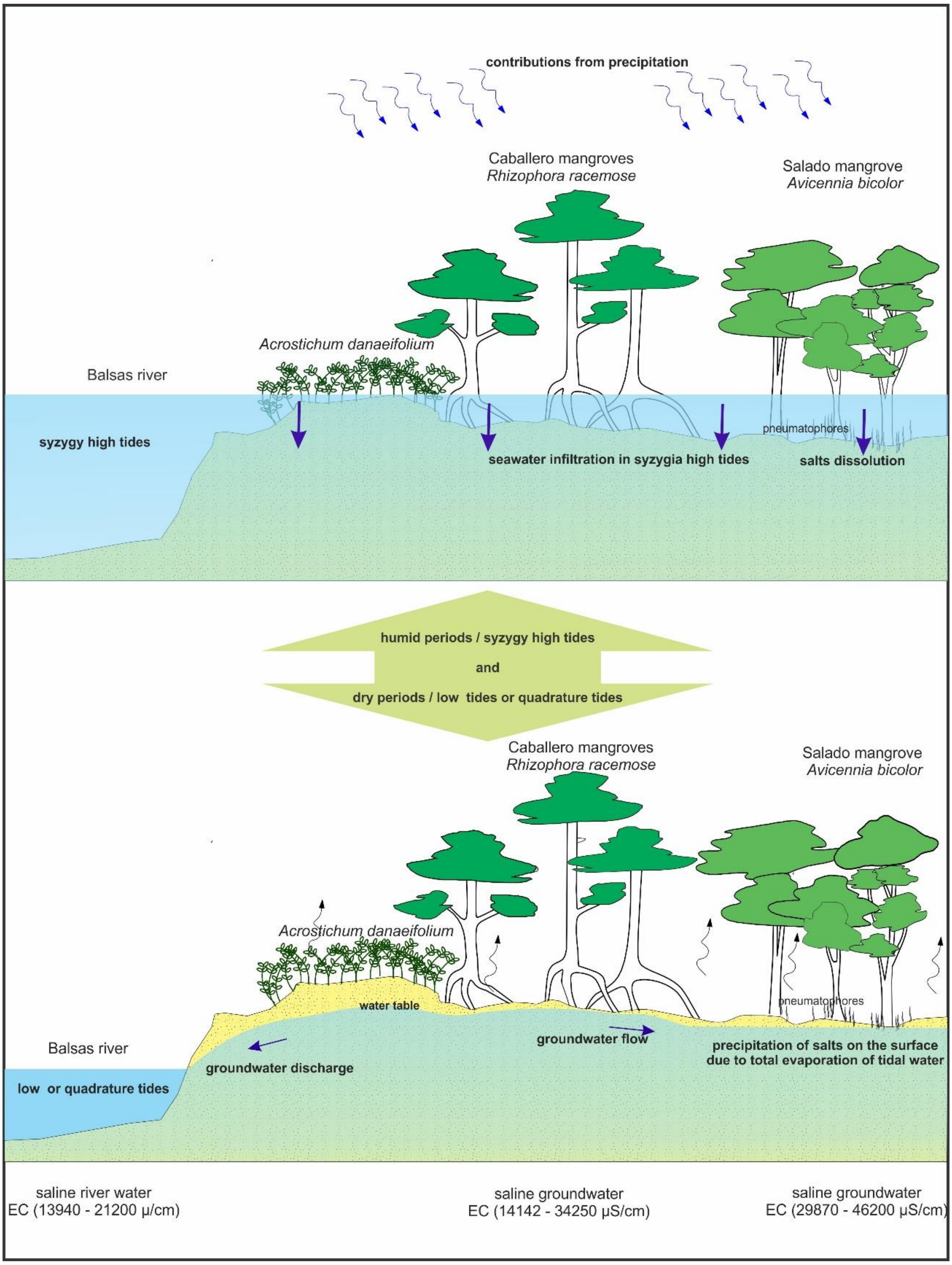


Figure 8: Diagram showing surface and groundwater flow exchanges and lateral hydrological connectivity in different wetlands environments in the lower basin of the Balsas River (Transect 2).

The study of transects 1 and 2 indicate that there are wetland environments that primarily depend on tidal flow (wetlands in the lower basin and embankment sectors in the middle basin) and others that rely mainly on rainfall (wetlands behind the embankment in depressed areas within the middle basin). Similar behavior had been observed in studies conducted in wetland environments associated with the Tuira River (Carol et al., 2020; 2021; 2022).

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 Gorelick, 2007; Muneepeerakul et al., 2008). However, despite observing similar hydrological behaviors between the Balsas and Tuira rivers' wetlands, the observed plant communities are different. This seems to indicate that in Matusagaratí, there are different plant communities adapted to similar hydrological conditions.

Ecohydrological models provide a useful tool for understanding 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 different environments within the Matusagaratí wetland but also enable the identification of vegetation adapted to each of the defined hydrological conditions. This constitutes a crucial tool for developing water management guidelines and promoting sustainable management of wetland areas, which, despite being legally protected, continue to face anthropogenic pressures from the 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 hydrology conditions the development of the different plant species in the wetland.

The hydrodynamics of the Balsas River are significantly influenced by 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 influx of tidal water causes variations in the salinity of the river water. In the upper and middle basins, the water is freshwater with hydrochemical facies characterized by bicarbonate-chloride composition and an isotopic signal like rainfall. On the other hand, 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 develop in the alluvial plain. In these areas, variations in water table levels and the major chemical and isotopic composition of groundwater reveal different hydrological processes.

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

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

In the lower basin, the hydrodynamics and hydrochemistry of the Balsas River and the mangrove wetlands, specifically mangle caballero and mangle salado, show a significant tidal influence. Syzygy tides inundate these mangroves with saline water, and the water infiltrates, causing rises in groundwater levels. The wetland's groundwater exhibits sodium chloride hydrochemical facies and an isotopic signal associated with tidal contributions. However, groundwater in the mangroves, especially in mangle salado, has higher electrical conductivity than 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 foundation 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.

Acknowledgments

This research would not have been possible without the generous funding from the National Secretariat for Science, Technology, and Innovation (SENACYT) through the project Hydrology, Carbon Reserves, Plants, and Fish Diversity of Matusagaratí (PFID-FID-2021-114). We also express our gratitude to the Ministry of Environment for granting the necessary permits for the collection and exportation of soil, water, and plant samples. Many thanks to our thesis student, Ian Deago, for his willingness and endurance during the challenging fieldwork conditions. Finally, our heartfelt gratitude to Hayro Cunampio, Jorge Tomi, Aurelio Flaco, Jhon Flaco, Eduardo Garabato, Ismael Flaco y Antonio Martínez, residents of Afrodescendant and Emberá communities, who always supported us with their expertise and knowledge of these valuable wetland ecosystems.

1. References

Adame M. F., Franklin H., Waltham N. J., Rodriguez S., Kavehei E., Turschwell M. P., Ronan M. 2019. Nitrogen removal by tropical floodplain wetlands through denitrification. Marine and Freshwater Research, 70 (11), 1513-1521.

Ahmed S., 2015. Local Level Perspectives of Wetland Management Policy and Practices in Bangladesh: A Case of Hakaloki Haor (master's thesis). The University of Manitoba, Winnipeg, Manitoba.

Aparicio K. 2021. Aves de Matusagaratí. Informe de resultados del Proyecto Hidrología, Vegetación y Avifauna del Complejo de Humedales de Matusagaratí, Darién. 38 pp.

Barbier E.B., 2011. Wetlands as natural assets. Hydrological Sciences Journal 56, 1360-1373.

Candanedo I. 2021. Matusagaratí: el Pantanal de Panamá. Resumen para tomadores de decisión. Universidad Tecnológica de Panamá. Universidad Tecnológica de Panamá. Secretaría Nacional de Ciencia, Tecnología e Innovación (SENACYT). Panamá. 24 pp.

Carol E., Alvarez M.P. 2016. Processes regulating groundwater chloride content in marshes under different environmental conditions: A comparative case study in Península Valdés and Samborombón Bay, Argentina. Continental Shelf Research, 115, 33-43.

Carol E., Alvarez M.P., Candanedo I., Saavedra S., Arcia M., Franco A. 2020. Surface water-groundwater interactions in the Matusagaratí wetland, Panama. Wetlands, Ecology and Management. DOI.org/10.1007/s11273-020-09762-9.

Carol E., Alvarez M.P, Candanedo I., Arcia M. 2021. Estudiando el funcionamiento hidrológico del Humedal de Matusagaratí. Universidad Tecnológica de Panamá. Secretaría Nacional de Ciencia, Tecnología e Innovación (SENACYT). Panamá. 32 pp.

Carol E., Alvarez M.P., Santucci L., Candanedo I., Arcia M. 2022. Origin and dynamics of surface water – groundwater flows that sustain the Matusagaratí Wetland, Panamá. Aquatic Sciences 84: 16.

CREHO (Centro Regional Ramsar para la Capacitación e Investigación en Humedales en el hemisferio occidental). 2015. Diagnóstico socioambiental, Laguna de Matusagaratí, CREHO, CEASPA, ACD.

Chui T. F., Low S. Y., Liong S. Y. 2011. An ecohydrological model for studying groundwater–vegetation interactions in wetlands. Journal of Hydrology, 409(1-2), 291-304.

Costanza R., de Groot R., Farber S., Grasso M., Hannon B., Limburg K., Van Den Belt, M. 1998. The value of the world# s ecosystem services and natural capital. Ecological economics, 25 (1), 3-15.

Cuthbert R.N., Wasserman R.J., Keates C., Dalu T., 2022. Food webs. In: Dalu, T., Wasserman, R.J. (Eds.), Fundamentals of Tropical Freshwater Wetlands: From Ecology to Conservation Management. Elsevier, Cambridge.

De Groot R. S., Stuip M., Finlayson C., Davidson N. 2006 Valuing wet- lands: guidance for valuing the benefits derived from wetland ecosystem services Ramsar Technical Report No. 3/CBD Technical Series No. 27 Technical Series No. 27(Montreal: Ramsar Convention Secretariat, Gland, Switzerland & Secretariat of the Convention on Biological Diversity)

Dube T., Pinceel, T., De Necker L., Wepener V., Lemmens P., Brendonck L. 2019. Lateral hydrological connectivity differentially affects the community characteristics of multiple groups of aquatic invertebrates in tropical wetland pans in South Africa. Freshwater biology, 64(12), 2189-2203.

Dwire K. A., Kauffman J. B., Baham J. E. 2006. Plant species distribution in relation to water-table depth and soil redox potential in montane riparian meadows. Wetlands, 26(1), 131-146.

Erwin K. L. 2009. Wetlands and global climate change: the role of wetland restoration in a changing world Wetlands Ecol.Manage. 17 71

Fabrega J., Nakaegawa T., Pinzón R., Nakayama K., Arakawa O., Sousei T. 2013. Hydroclimate projections for Panama in the late 21st Century. Hydrological Research Letters, 7(2), 23-29.

Galliari J., Santucci L., Misseri L., Carol E., Alvarez M.P. 2021. Processes controlling groundwater salinity in coastal wetlands of the southern edge of South America. Science of the Total Environment, 754, 141951.

Gonfiantini, 1978. Standards for stable isotope measurements in natural compounds. Nature 271 (5645), 534.

Grauel W.T. 2004. Ecology and management of wetland forests dominated by Prioria copaifera in Darien, Panama. PhD. Thesis. University of Florida. Florida, USA. 163 pp.

Ibáñez A., R Flores. 2020. Phyllanthus fluitans (Phyllanthaceae): a new record of an aquatic plant for the flora of Panama. Acta Botanica Mexicana 128: e1767. DOI: 10.21289/abm128.2021.1767.

Ivory S. J., McGlue M. M., Spera S., Silva A., Bergier I. 2019. Vegetation, rainfall, and pulsing hydrology in the Pantanal, the world's largest tropical wetland. Environmental Research Letters, 14(12), 124017.

Kern Z., Harmon R.S., Fórizs I. 2016. Stable isotope signatures of seasonal precipitation on the Pacific coast of central Panama. Isotopes in Environmental and Health Studies 52: 128-140. doi: 10.1080/10256016.2015.1016021.

Loheide S. P., Gorelic, S. M. 2007. Riparian hydroecology: a coupled model of the observed interactions between groundwater flow and meadow vegetation patterning. Water Resources Research, 43(7).

López H., Cunampio H.2023. Pesca Artesanal y Estrategia de Sobrevivencia en Comunidades de Matusagarati, Darién. Proyecto Hidrología, Carbono, Plantas y Peces de Matusagaratí. Informe de campo. 29 pp.

Ministerio de Ambiente. 2016. Estudio Técnico Justificativo para la creación del área protegida Humedal Laguna de Matusagaratí. Dirección Nacional de Áreas Protegidas y Vida Silvestre. 99 páginas.

Muneepeerakul C. P., Miralles□Wilhelm F., Tamea S., Rinaldo A., Rodriguez□Iturbe I. (2008). Coupled hydrologic and vegetation dynamics in wetland ecosystems. Water Resources Research, 44(7).

Ortiz O.O., Ibáñez A., Trujillo-Trujillo E., Croat T.B. 2020. The emergent macrophyte Montrichardia linifera (Arruda) Schott (Alismatales: Araceae), a rekindled old friend from the Pacific Slope of lower Central America and western Colombia. Nordic Journal of Botany 38(9): 1-10. https://doi.org/10.1111/njb.02832

Ortiz O.O., Croat T.B., Rodríguez-Reyes O., Ceballos J., Cedeño-Fonseca M., Mora M. 2022. Taxonomic Novelties in Philodendron subg. Philodendron (Araceae) from Panama. Novon 30: 18-42.

Ridolfi L., D'Odorico P., Laio F. 2006. Effect of vegetation-water table feedbacks on the stability and resilience of plant ecosystems, Water Resour. Res., 42, W01201, doi:10.1029/2005WR004444.

Wasserman R. J., Dalu T. 2022. Tropical freshwater wetlands: an introduction. In Fundamentals of Tropical Freshwater Wetlands (pp. 1-22). Elsevier.

Xiao K., Li H., Shananan M., Zhang X., Wang X., Zhang Y., Zhang X., Liu H. 2019. Coastal water quality assessment and groundwater transport in a subtropical mangrove swamp in Daya Bay, China. Science of the Total Environment, 646, 1419-1432.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author Contributions

Carol E.: Investigation, field surveys, conceptualization, data curation, formal analysis, writing—original draft preparation, writing—review, and editing.

Alvarez M.P.: Investigation, field surveys, conceptualization, data curation, formal analysis, writing—original draft preparation, writing—review, and editing.

Arcia M.: Field surveys, data acquisition, data curation, writing—review, and editing.

Candanedo I.: Field surveys, project administration, funding acquisition.