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RESEARCH ARTICLE

# Origin and dynamics of surface water - groundwater flows that sustain the Matusagaratí Wetland, Panamá

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## Abstract

The Matusagaratí Wetland in the Panamanian Darien develops in fluvial environments associated with the Tuira River. The aim of this research is to determine the origin and dynamics of the water flows that sustain the Matusagaratí Wetland, studying the flows of surface water and groundwater, as well as the contributions derived from precipitation. Understanding the contributions and flows of water within the wetland acquires both hydrological and ecological significance, since flood events contribute to the accumulation of sediments and the transport and dispersal of seeds and fish larvae, playing an important role in the wetland ecosystems and vegetation variability. A monitoring network was designed as perpendicular transects to the Tuira River, encompassing wetland environments with different geomorphology and vegetation. Water flows were studied from the measurement of water levels and sampling in the Tuira River, in groundwater and in streams that drain from Filo del Tallo, also evaluating the influence of rainfall. In addition, the origin of the different sources of water that enter the wetland was assessed using stable water isotopes. The analysis show that different hydrodynamic behaviours exist along the river associated with the levee and floodplain sectors. The dynamics of the water in the Tuira River is determined by the runoff of excess rainfall, which is overlaid by a tidal regime resulting from the propagation of the tide from the estuary. This propagation causes variations in salinity along the river. The study of groundwater levels, water levels in the Tuira River and rainfall, supported by stable isotopes, allowed the identification of different environments, some of which depend mainly on the water contribution of the Tuira River, others on rainwater, and others where the contribution of water to the wetland is mixed. The results presented in this research contribute data to the generation of hydrological baseline for the understanding of the hydrological functioning of the wetland and the generation of management guidelines against the advance of anthropic activities that can modify it.

**Keywords** Tropical wetland · Surface water-groundwater exchange · Estuarine influence · Salinity · Stable isotopes

## Introduction

Wetlands generally develop within floodplains areas and prevent erosion, improve water quality by filtering nutrient-laden sediments, and provide a habitat for plants and animals (Yu et al. 2015). Water fluxes determine the environmental characteristics of fluvial wetlands with important surface water-groundwater exchange processes (Winter 1999; Neff and Rosenberry 2018; Li et al. 2019). Such exchange processes are largely controlled by the wetland physiography, which depends on the topography and the geomorphological and geological features of an area (Winter et al. 1998). In addition, rainfall and evaporation control inflows and outflows to and from the wetland (Koreny et al. 1999).

The biodiversity of wetlands is often related to the different water flows that sustain them (Phillips 2013). Wetlands

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that depend exclusively on groundwater inputs have relatively constant humidity, temperature and salinity conditions (Lowry et al. 2007). In contrast, fluvial wetlands are highly dynamic and heterogeneous, being the fluctuations in the water levels of the associated rivers one of the main factors that determine the different environments that develop within them (Royan et al. 2015; Bodmer et al. 2018). These water level fluctuations determine the interaction between surface and groundwater flows (Lisenby et al. 2019), that can vary both spatially and temporally. Therefore, the hydrological functioning of these wetlands is even more complex (Fritz et al. 2018). In particular, wetlands in estuarine areas that additionally receive tidal inputs associated with both river and sea water are characterized by a marked variability of salinity (Carol et al. 2012; Galliari et al. 2020). Likewise, in a same type of wetland, variations in rainfall and evaporation rates can also strongly establish the salinity and chemistry of the water and consequently the variability in the environmental conditions of the wetland substrate (Amoros and Bornette 2002; Galliari et al. 2021). In this way, the study of the interaction of surface and underground water flows that sustain wetlands, as well as water inflows and outflows associated with climatic variables, is of vital importance to understand their hydrological functioning and promote their rational use and conservation of ecosystem services. Despite river-aquifer connections through baseflows have been studied in the last decade, there is a lack of literature regarding the study of these connections in wetland environments (Džubáková et al. 2015) and specifically in fluvial wetlands in the tropics (Beven and Binley 1992; Birkel et al. 2020; Marthews et al. 2021).

The importance of different water sources for a particular wetland will depend on the climate, the properties of the underlying aquifer, and the geomorphic environment (Larocque et al. 2016). The joint study of surface water and groundwater levels and rainfall data constitutes a useful tool for understanding the dynamics of water flows that sustain river wetlands (Sanchez et al. 2017). Furthermore, the use of stable water isotopes to discern water sources showed promise for better understanding the hydrodynamic functioning of wetlands (Carol et al. 2013; Santucci et al. 2019).

Matusagaratí Wetland in the Panamanian Darien (Fig. 1) is a system that includes flooded forests of various types, grasslands dotted with islands of forests and lagoons of varying size with floating aquatic plants (Ibañez and Flores 2020). Despite the importance that water flows have in the sustenance of the wetland and in generating the environmental conditions that contribute to its biodiversity, hydrological studies in this wetland are scarce (Carol et al. 2020). The scarcity of studies is largely due to the extremely difficult access to the wetland due to the wild nature of the site for field data collection which makes it very complicated. The aim of the work is to determine the dynamics and origin of the water flows that sustain the Matusagaratí Wetland, from the joint study of the variations of surface water and groundwater levels, rainfall, and the analysis of salinity and stable isotopes of the water molecule. This allows the generation of hydrological data for a baseline that contributes to the understanding of the hydrological functioning of the wetland and the generation of management guidelines against the advance of anthropogenic activities that can modify it.

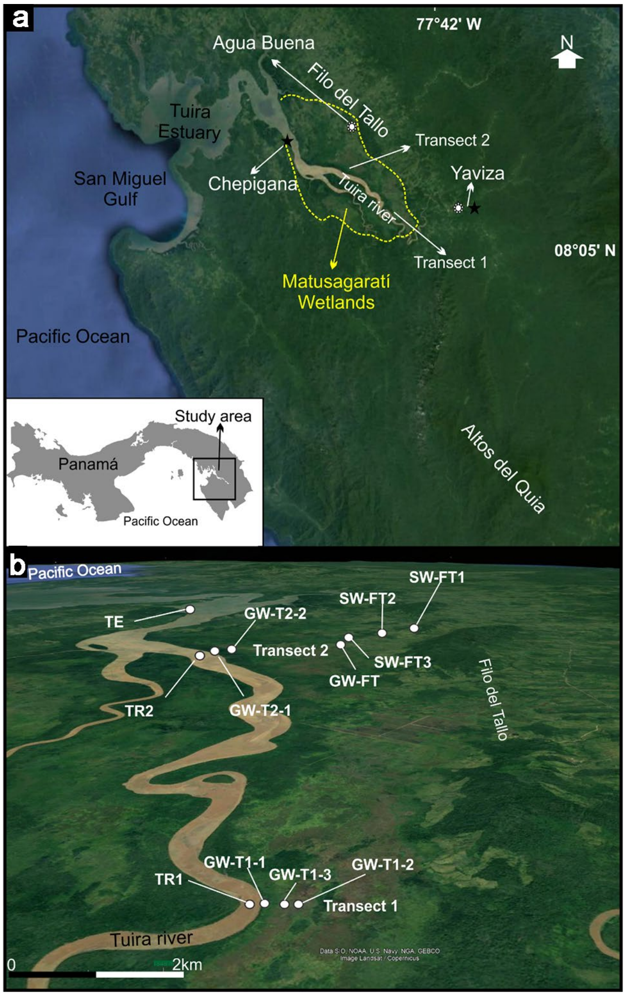

**Fig. 1** **a** Location of Matusagaratí Wetland (yellow dotted line), transects area, pluviographs (white circles), river level measurement sensors (black stars). **b** Location of monitoring points

## Study area

Matusagaratí Wetland is located in the tropical region of the Panamanian Darien, where rainfall reaches about 2800 mm per year. This wetland develops in fluvial environments associated with the Tuira River (Fig. 1). This river originates in the mountainous area of Altos de Quía and flows to the northwest, considerably increasing the width of the channel until it discharges into the San Miguel Gulf, in the Pacific Ocean. The Tuira River has a watershed area of 900,000 hectares, with extensive floodplains in the middle and lower parts. This wetland also receives freshwater from small streams draining from the Filo del Tallo and other nearby ridges. The Matusagaratí Wetland, that developed in these floodplains, covers approximately 56,000 hectares and recent studies have confirmed that there are at least nine different vegetation types ranging from mangroves in tidal areas to flooded forests in riverine areas and flooded grasslands (Baúles et al. 2020). This wetland is also the northernmost limit of several South American bird and plant species (Ibáñez and Flores 2020; Ortiz et al. 2020). Matusagaratí is legally protected by three reserves: Filo del Tallo-Canglon hydrological reserve, Chepigana Forest Reserve and Matusagaratí Wildlife Refuge. However, there is no wetland management in any of these protected areas and, during the last decade, almost a third of the wetland was illegally titled and part of it was drained and transformed into oil palm plantations and more recently into rice cultivation (CREHO 2015).

## Methodology

The interaction between groundwater and surface water in the wetland was studied through the measurement of water levels and chemical and isotopic characteristics of the water. A monitoring network of groundwater was designed in the form of transects perpendicular to the Tuira River, measuring different wetland environments. Transect 1 was located in the middle basin and transect 2 in the lower basin, both on the right margin of the river (Fig. 1). To define the location of the piezometers within the transects, the geomorphological characteristics defined in the field and the type of vegetation of each sector of the wetland were considered. The boreholes in each of these environments were made between 3 and 3.5 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.

Transect 1 intercepts three wetland environments defined as river levee (GW-T1-1), floodplain (GW-T1-3) and island environments associated with the latter (GW-T1-2), and also a water sampling point in the Tuira River is associated with this transect (TR1; Fig. 1b). The river levee comprises a raised strip that develops adjacent to the river margin and is composed of silty to silty-clayey sediments, where crab burrows abound. A mixed forest with a 20 m canopy and emergent trees of approximately 30 m develop within this environment. Cativo (*Prioria copaifera*) is the dominant specie together with barrigón (*Pseudobombax septenatum*), roble (*Tabebuia rosea*) and sangrillo (*Pterocarpus officinalis*), *Macrolobium* sp. Within the understory, the palm, locally known as corocita or American oil palm (Elaeis oleifera), dominates. The floodplain adjacent to the levee constitutes a topographically depressed zone composed of silty-clayey sediments and where at 2–3 m high grassland approximately 90% is dominated by *Typha domingensis*. This species was accompanied by *Elaeocharis* sp. and *Aeschynomene* cf. The island environment corresponds to small zones (10 m × 6 m approximately) topographically higher within the floodplain. Sediments have silty-clayey textures being *Typha* the dominant specie in the surrounding grassland. Species such as *Elaeis oleifera*, *Coccoloba* sp., *Pseudobombax septenatum*, *Ludwigia nervosa*, *Palicourea tryphylla*, *Machaerium capote* dominate this "island" area. There are also *Thalia geniculata*, *Typha domingensis*, *Calathea lutea*, *Blechnum serrulatum*, *Ludwigia sp*.

Transect 2 intercepts the levee environment (GW-T2-1) and the adjacent floodplain (GW-T2-2) on the right margin of the river, being associated with this transect a water sampling point in the Tuira River (TR2; Fig. 1b). In this lower basin area, the river levee is dissected by small sinuous tidal channels of a short length which end in the floodplain area. The levee, as in transect 1, constitutes a raised strip adjacent to the river composed of silty-clayey fluvial deposits, in which a 20–25 m high mangrove forest of *Rhizophora racemosa* develops. The understory was almost exclusively *Acrostichum aureum*, a mangrove fern locally known as negra jorra. The floodplain environment adjacent to the floodplain comprises a depressed area with fine-textured sediments. Within it a forest of mora tree (*Mora oleifera*) can be observed with trees ranging between 12 and 15 m high and occasionally mangrove trees (*Rhizophora racemosa*). Again, the understory of this forest was almost completely covered by mangrove fern (*Acrostichum aureum)*. In this sector numerous crab burrows were observed, mainly on the site, where mangrove forest dominates. In addition, and complementing transect 2, a water sampling point was defined in the Tuira River near the estuary (TE) and also three water sampling points in the streams that drain into the wetland from Filo del Tallo (SW-FT 1–3). A piezometer (GW-FT) was also installed in a sector of corocita palm (*Elaeis oleifera*) stands and where second growth vegetation predominates with species, such as *Vismia baccifera*, *Davilla sp*. and *Cissus microcarpa*. Approximately 5 m from the piezometer, the flooded area is located, where several species proliferate, such as *Pistia stratoites, Ceratopteris thalictroides, Spirodela polyrhiza, Azolla filiculoides, Typha dominguensis, Nymphoides indica* and *Nymphaea* sp., among others. Both the sampling points and this last piezometer were established to study the hydrodynamics of the wetland in the sectors furthest from the river, as well as the water inputs from the adjacent elevated areas.

Odyssey® Capacitance Water Level sensors (Odyssey, Christchurch, New Zealand) were installed in all the piezometers, and programmed to measure the level every 15 min. For measurement of Tuira River levels, similar continuous recording sensors were installed at the Yaviza and Chepigana docks (Fig. 1a). To evaluate the influence of rainfall, Odyssey® Recorder with Davis Tipping rain gauges (Odyssey, Christchurch, New Zealand) were installed, where daily rainfall was recorded in Yaviza and Agua Buena towns (Fig. 1a). The level data of the sensors installed in the piezometers were compared with the river levels and with the precipitation data. The comparison between river and groundwater levels will allow the analysis of flow exchanges between surface water and groundwater. Comparison of groundwater levels with rainfall data were be carried out to visualize the influence of rain infiltration towards the groundwater of the wetland.

On the other hand, surface water and groundwater samples were taken to determine stable isotopes of the water molecule ($\delta^2$H and $\delta^{18}$O), to establish the water origin in the different sectors of the wetland. The location of the water samples is indicated in Fig. 1 and the data presented in this work correspond to a sampling carried out in April 2019. Surface water samples in the Tuira River were taken from a boat using adequate bottles, and in the streams of Filo del Tallo surface water samples were taken directly from the centre of the water courses.

For groundwater sampling, the piezometers were cleaned by emptying the equivalent of three times their volume with a bailer. In all cases, the sampling bottles were cleaned three times with the sampled water before taking it, and at each point, pH and electrical conductivity (EC) were measured in situ using a portable multiparametric instrument (Lutron® WA-2017SD, Lutron Electronics, Coopersburg, PA, USA).

Stable isotopes were determined by mass spectroscopy (Thermo Finnigan MAT Delta Plus XL continuous flow mass spectrometer, Bremen, Germany) in the stable isotope laboratory of the University of San Luis (Argentina). The isotopic results are expressed as $\delta$‰, where $\delta = 1000\ (\mathrm{Rs} - \mathrm{Rr})/\mathrm{Rr}$ ‰; $\delta$ is the isotopic deviation, in ‰, in relation to the Vienna oceanic water standard mean (V-SMOW) (Gonfiantini 1978); $s$ is the sample; $r$ the international reference; $R$: isotopic ratio ($^2$H/$^1$H, $^{18}$O/$^{16}$O). The analytical precision of the determination is ± 0.05‰ and ± 0.5‰, for $\delta^{18}$O and $\delta^2$H, respectively. The origin of the different contributions of water that enter the wetland associated with rain, surface runoff and tidal water were studied. With the purpose of assessing the contribution of water whose origin derives from precipitation, the isotopic values were compared with the local meteoric line $\delta^2\mathrm{H} = 7.63\ \delta^{18}\mathrm{O} + 6.51$ which was defined for the Pacific coast in the central sector of Panama by Kern et al. (2016). To evaluate the contributions whose origin is related to the precipitations runoff that drains through the streams and the Tuira River and also the contribution of marine origin that enters with the tide from the estuary, a theoretical mixing line was drawn. One of the extreme members of this line corresponds to the rainwater composition based on the extrapolation of the isotopic values of the samples located in Filo del Tallo on the meteoric line, and the other extreme member corresponds to the average composition of seawater worldwide (Clark 2015). It should be noted that this line also represents a possible evaporation line of precipitation water, a process that occurs during surface runoff in streams and the river. Likewise, rainwater and marine water have contrasting values of EC and pH, which were measured in situ and also contributed to the analysis of the isotopic data.

## Results

### Hydrodynamics, chemistry and stable isotopes in fluvial environments associated with the wetland

Tuira River dynamics varies from the middle basin area to the lower basin area. This is clearly observed if the river water levels, which were registered in the Yaviza dock in the middle basin, are compared with those registered in the Chepigana dock located in the lower basin (Fig. 2a). Comparing these registers allows the visualization of two behaviours. On the one hand, at the Chepigana dock, the river water level responds to the propagation of the tide from the San Miguel Gulf, given by a meso-tidal regime (with maximum amplitudes close to 5 m). In the record of river levels, the alternation of neap tides (amplitudes close to 3 m) and spring tides periods (amplitudes between 4 and 5 m) is observed. Note in the record that at low tide the levels flatten out, showing the base level at which the river discharges into the estuary. In the records obtained at the Yaviza dock, it is observed that the water level of the river registers ascents and descents, mainly associated with the runoff of excess rainfall recorded in the same sector (Fig. 2a). However, the effect of the tide is also recorded in these river water levels as small oscillations. If these oscillations are analyzed in detail (Fig. 2b), a lag is observed between the high tides measured at the Chepigana dock and the rises in river level at the Yaviza dock. This is due to the delay time of the tidal propagation along the river from the estuary to the upper basin, which sometimes causes that high tides recorded in Yaviza coincide temporarily with low tides in Chepigana.

With respect to water levels of the river in the Yaviza dock, comparing with the precipitation from the corresponding meteorological station (Fig. 2), it is observed that, although a correspondence between precipitation events and level rises in the river exists, there are situations in which this relationship is not as direct. This is due to the fact that

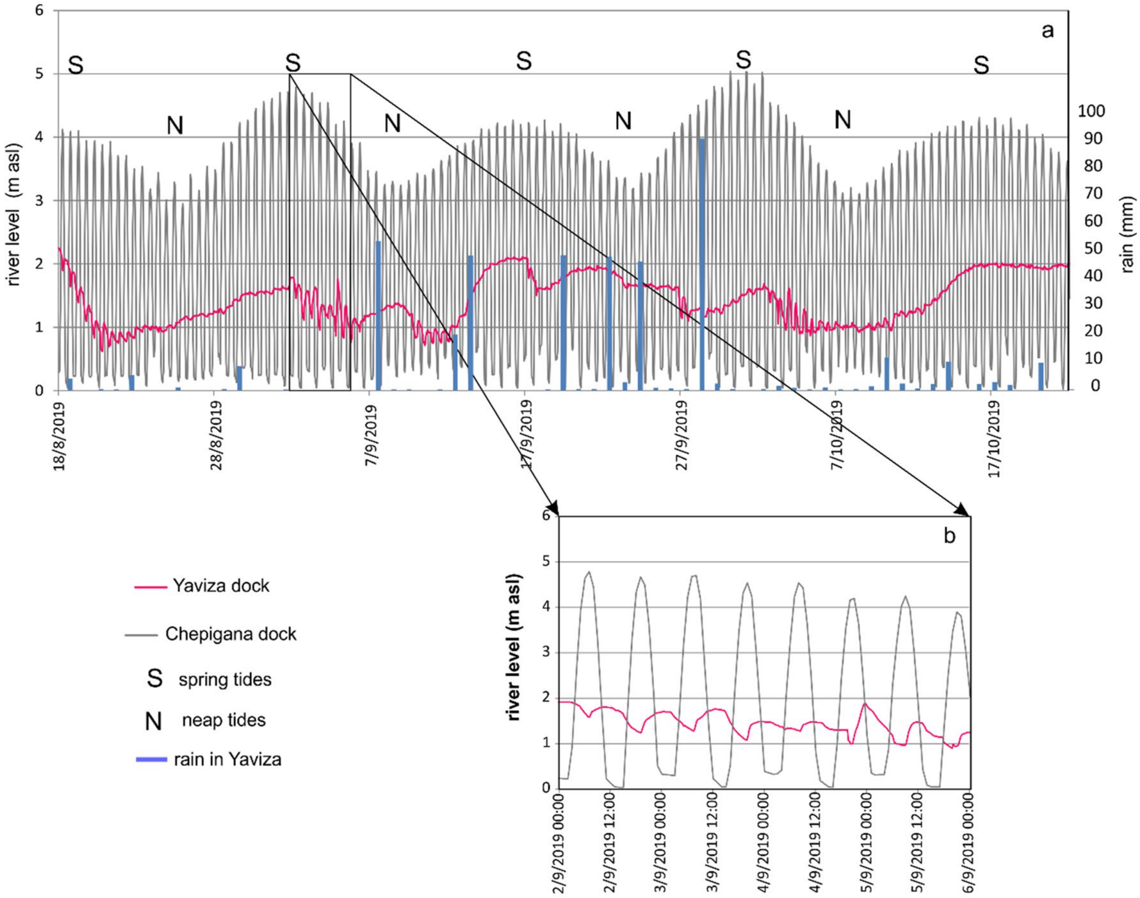

**Fig. 2** **a** Water levels in the Tuira River at the Chepigana and Yaviza docks. **b** Detail of the oscillation of the Tuira River at the Yaviza and Chepigana stations

the river level registered in Yaviza does not strictly depend on local precipitation, but is also determined by the precipitation that the basin upstream of this station captures, which may vary from that registered in Yaviza.

On the other hand, the EC values of the water in the different sectors of the Tuira River register spatial variations. In the middle basin sector (TR1), the EC is 4.85 mS/cm and increases to 29.2 mS/cm (TR2) in the lower basin sector, and to 33.10 mS/cm in the vicinity of the estuary (TE). The pH values recorded in the samples from the Tuira River showed neutral to slightly alkaline waters (between 7.0 and 7.8) without a tendency to spatial variation. Besides, the small streams that drain from Filo del Tallo towards this sector of the wetland show low EC values and pH values close to neutrality. The SW-FT1 and SW-FT2 water samples are very similar showing EC values close to 0.27 mS/cm and pH values close to 7.7; and the SW-FT3 water sample has a slightly higher EC of 0.29 mS/cm and a lower pH of 6.5.

Likewise, the increase in the EC of the Tuira River water from the middle basin (TR1) to the estuary (TE) is accompanied by changes in the isotopic signal. The

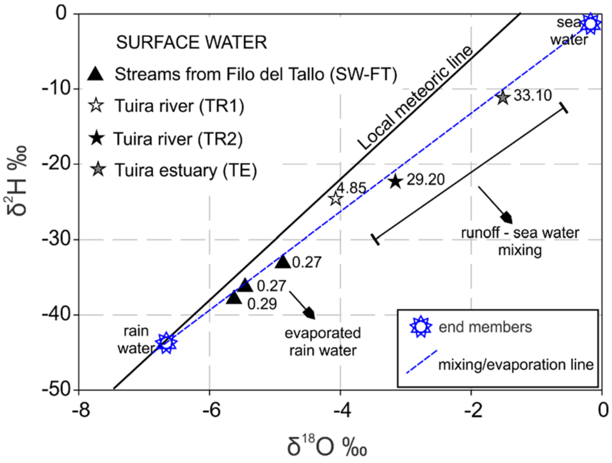

**Fig. 3** Relationship $\delta^2$H vs. $\delta^{18}$O for surface water samples. Local meteoric water line for the Pacific coast of central Panama taken from Kern et al. (2016). The value next to each sample corresponds to the EC value in mS/cm. The blue dotted line represents both the meteoric water evaporation line (in the case of the FT samples) and the mixture between rainwater and the global mean seawater composition

surface water sample near the estuary (TE) has values of $\delta^{18}O$ of – 1.50 and of $\delta^{2}H$ of – 11.5 which are isotopically more enriched than those of surface water in the middle basin (TR1) whose values are of – 4.05 for $\delta^{18}O$ and of – 24.5 for $\delta^{2}H$. In the relationship $\delta^{2}H$ vs. $\delta^{18}O$ (Fig. 3) the samples from the Tuira River are located around the mixing line between rainwater and seawater, indicating a mixture. The isotopic composition of the TR1 sample is more similar to that of rainwater and receives greater contributions of water from rainwater runoff. The TE sample is isotopically more similar to sea water and has a composition associated with higher inputs of seawater. The water samples that drain from the Filo del Tallo have low EC (values lower than 0.3 mS/cm) and have values of $\delta^{18}O$ between – 4.90 and – 5.65 and of $\delta^{2}H$ between – 33.0 and – 38.0 slightly isotopically enriched with respect to rainwater. Although in the graph $\delta^{2}H$ vs. $\delta^{18}O$ (Fig. 3) these samples are located on the mixing line, they have no spatial connection with inputs from the estuary. For this reason, the deviation from the local meteoric line is associated with an evaporation line (similar to the mixing line), showing the surface water of the streams an origin in the rainwater that evaporates during surface runoff.

## Hydrodynamics, chemistry and stable isotopes in middle basin wetlands

The comparison between groundwater levels of the piezometers of transect 1 and the data of levels of the Tuira River in Chepigana and also the rainfall of the Yaviza station (Fig. 4a), allows the analysis of the relationship between surface and groundwater flows, as well as its relationship with rainfall. First, if the groundwater levels between the three piezometers are compared, it is observed that the groundwater in the levee (point GW-T1-1) is located in a higher position than that of the piezometers placed in the area of floodplain (points GW-T1-2 and GW-T1-3). This shows that there is a flow of groundwater from the levee to the

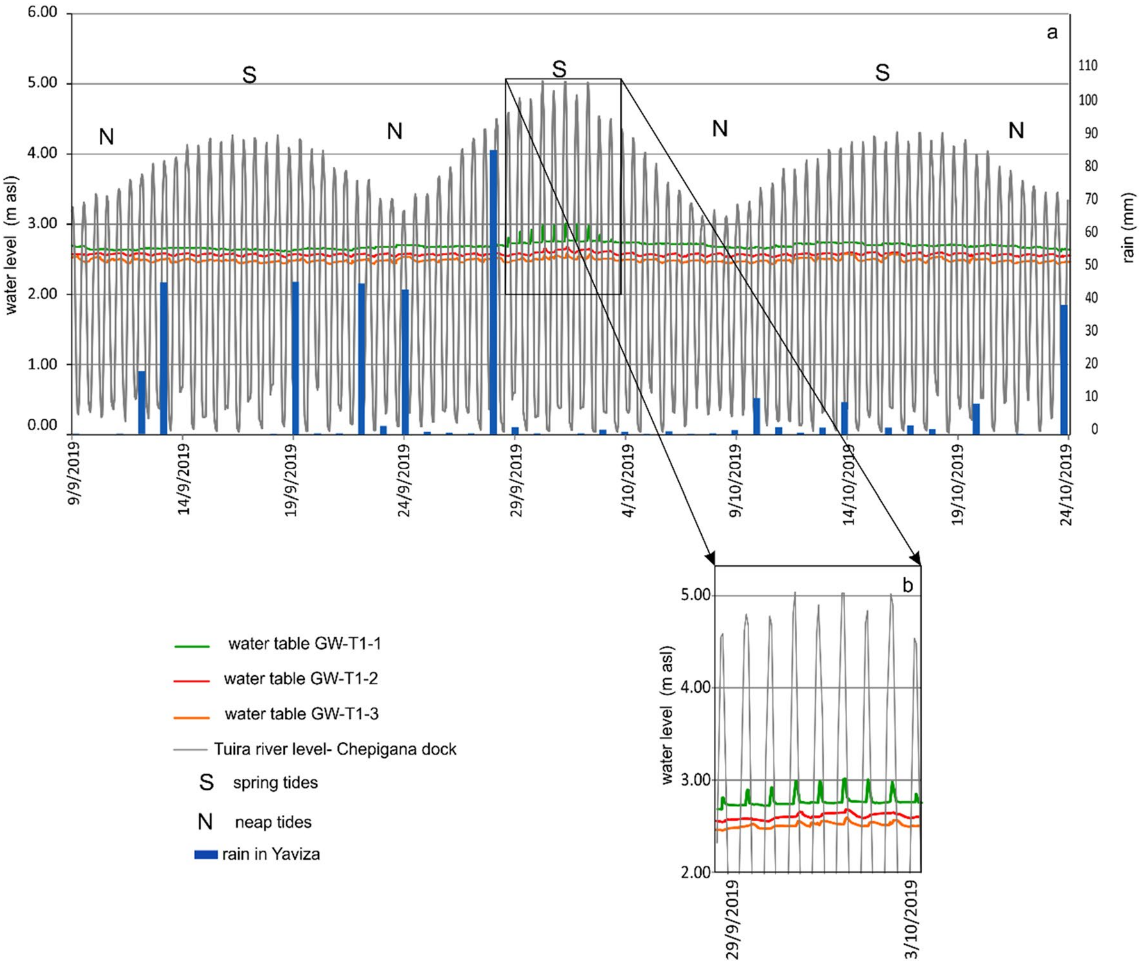

**Fig. 4** **a** Comparison between precipitation data from Yaviza station, Tuira River water levels in Chepigana station and groundwater levels in piezometers of transect 1. **b** Detail of the spring high tides effect on the groundwater levels of the levee

flood plain within the wetland. In addition, the water table of the island located within the floodplain (point GW-T1-2) displays a higher position than that of the floodplain itself (point GW-T1-3). The lowest position of the water table in the flood plain with respect to the levee and the islands indicates that this environment receives the discharge of groundwater from the adjacent environments that are topographically higher. In turn, if the groundwater levels of the three piezometers are compared with the water level in the river, it is observed that at spring high tides that exceed 4.5 m asl (meters above sea level), an oscillation in the water table occurs in the area of the levee that follow the tidal oscillation of the river (Fig. 4b). This shows a modification in the relationship between surface and groundwater flows in the levee area of the wetland. During low tide or at high tides with levels below 4 m asl, groundwater discharges into the river. When the high tide exceeds 4.5 m asl, part of the levee area is flooded and the river water enters the sediments, constituting a source of recharge towards the groundwater. Although an oscillation with a similar period to that of the tide is also observed in the piezometers located in the flood plain area, this is very slight and could be related to a mechanical effect exerted by the mass of water coming from the tide. In all the cases there is a lag between the tidal peaks in the river and those in the groundwater, which can be attributed to the delay time of the tidal propagation between the Chepigana dock (measured river level) and the site, where transect 1 is located. Finally, if groundwater levels data are compared with those of the rainfall recorded in Yaviza (Fig. 4a), it is observed that there are no clear increases in the water levels associated with the rain events.

In transect 1, the groundwater in the levee (GW-T1-1) registers a value of $\delta^{18}O$ of $-3.10$ and of $\delta^{2}H$ of $-20.0$ and an EC of 13.99 mS/cm (a higher value than that registered in the Tuira River in this sector of the wetland, TR1). Groundwater in floodplain (GW-T1-3) has $\delta^{18}O$ of $-2.80$ and $\delta^{2}H$ of $-18.5$ and the EC decreases to 3.06 mS/cm. In the island sectors (GW-T1-2) these values are lower, registering $-3.70$ in $\delta^{18}O$ and $-26.5$ in $\delta^{2}H$ and EC values of 1.33− mS/cm. In all cases the groundwater pH is acidic with values between 4.3 and 4.8. In the graph of $\delta^{2}H$ vs. $\delta^{18}O$ (Fig. 5) it is observed that groundwater samples are located both close to that of the Tuira River in the middle basin, and around the evaporation line of rainwater evidencing these two possible origins. The most enriched values (indicative of evaporation processes) were recorded in the floodplain sample and the least enriched in the island sector.

## Hydrodynamics, chemistry, and stable isotopes in lower basin wetlands

In transect 2, the groundwater levels were compared with Tuira River level data in Chepigana station and the rainfall from the Agua Buena station (Fig. 6a). The comparison of groundwater levels shows that the piezometer located in the levee (point GW-T2-1) has a higher level than the piezometer located in the flood plain (point GW-T2-2). As in the transect described above, this shows that there is a groundwater flow from the levee toward the floodplain. The comparison of the groundwater levels with those of the Tuira River in Chepigana, shows that in both piezometers the water table is influenced by the spring tides whose high tides exceed 4.5 m asl. The tidal influence on the plain sectors located behind the levee would be associated with the fact that, in these sectors of the lower basin of the wetland, there are tidal channels that cross the levee and enable the propagation of tidal water to the more distant floodplain sectors. If levels during the days of spring tides above 4.5 m asl are analyzed in detail, it is observed that the phreatic levels rises register asymmetric peaks, with abrupt ascents and less marked descents (Fig. 6b). Regarding the rainfall, note that only the piezometer located in the plain registers ascents after precipitation events (e. g. 10/13/19), showing that the infiltration of rainwater occur and consequently the groundwater recharge (Fig. 6a).

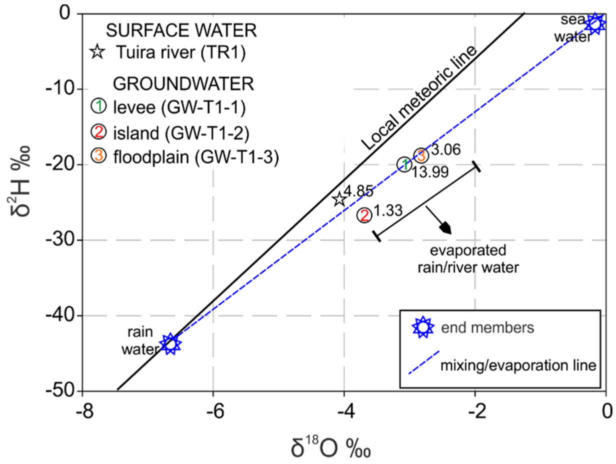

**Fig. 5** Relationship $\delta^{2}H$ vs. $\delta^{18}O$ for water samples from transect 1. Local meteoric water line for the Pacific coast of central Panama taken from Kern et al. (2016). The value next to each sample corresponds to the EC value in mS/cm

The groundwater in the levee (GW-T2 1) has an EC of 18.90 mS/cm and a pH of 6.6, while in the floodplain (GW-T2 2) the EC of the groundwater is slightly lower, being 15.60 mS/cm, with a similar pH value. In both cases the EC of the groundwater is lower than that registered in the river in the same sector of the wetland (29.2 mS/cm in TR2). In the graph of $\delta^{2}H$ as a function of $\delta^{18}O$ (Fig. 7) it is observed that groundwater samples are located close to that of the Tuira River and over the mixing line between rainwater and seawater. Groundwater sample from the levee (GW-T2-1) is located towards the seawater end, close to that of the Tuira

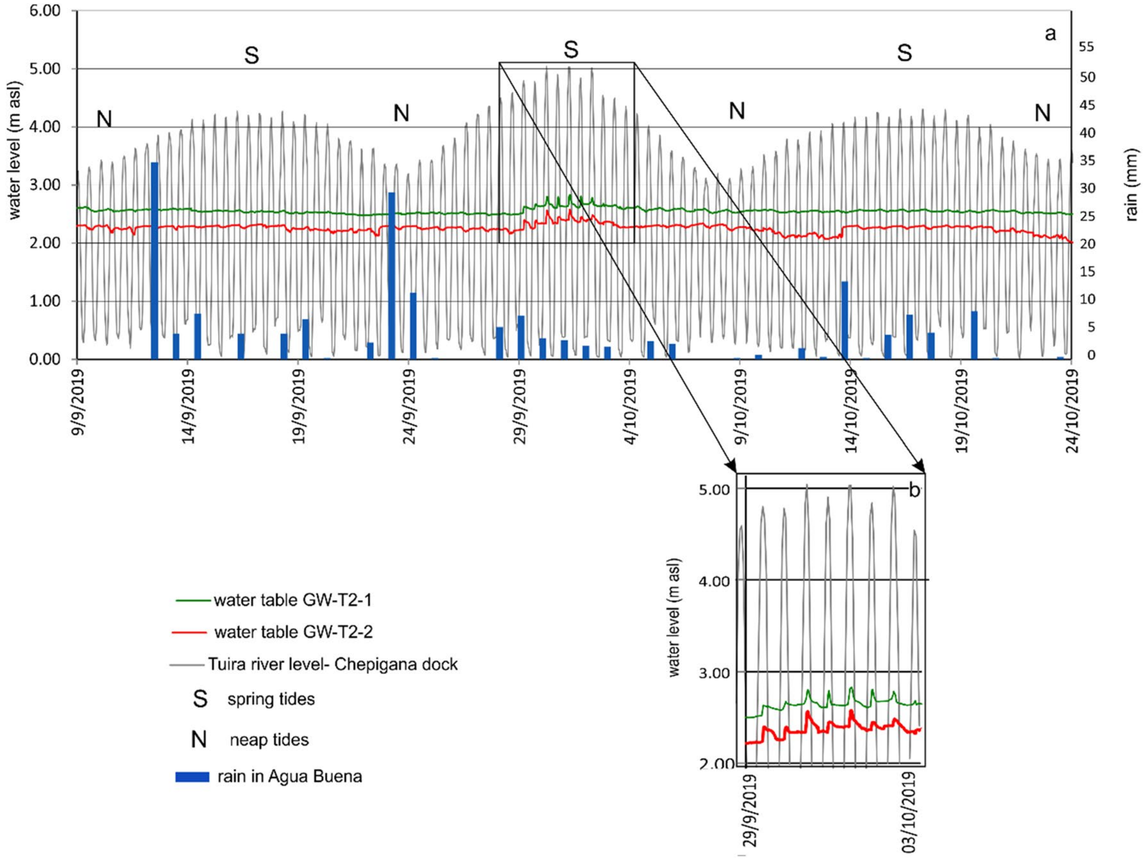

**Fig. 6** **a** Comparison between precipitation data from the Agua Buena station, Tuira River water levels in Chepigana station and groundwater levels in piezometers of transect 2. **b** Detail of the tidal influence on groundwater levels in the levee when the tide exceeds 4.5 m asl

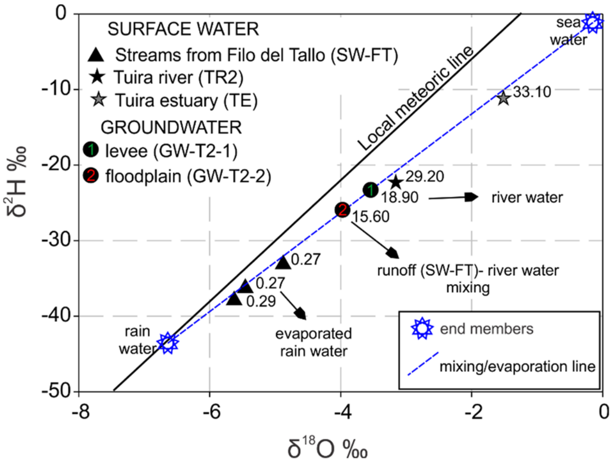

**Fig. 7** Relationship $\delta^2H$ vs. $\delta^{18}O$ for water samples from transect 2. Local meteoric water line for the Pacific coast of central Panama taken from Kern et al. (2016). The value next to each sample corresponds to the EC value in mS/cm. The blue dotted line represents both the meteoric water evaporation line (in the case of the FT samples) and the mixture between rainwater and the global mean seawater composition

River, while floodplain groundwater sample moves along the line towards the rainwater end. This indicates that the origin of the groundwater in both wetland environments derives from the infiltration of rainwater and floodwater from the river, with greater contributions from rain in the floodplain.

Finally, the piezometer located in the Agua Buena area (GW-FT), within a sector of the wetland far from the river, registers clear rises in the water table associated with rainfall (Fig. 8). Note that these ascents occur up to a level close to 1.8 m asl and decrease after a period in which there is little or no precipitation.

## Discussion

The joint analysis of surface water and groundwater levels and rainfall data allowed the understanding of the water flows dynamics in the wetland. The isotopic signal registered in the surface water and groundwater displayed the origin of the water contributions that enter the wetland. Likewise, knowing the electrical conductivity and pH water values also contributed to the understanding of the water

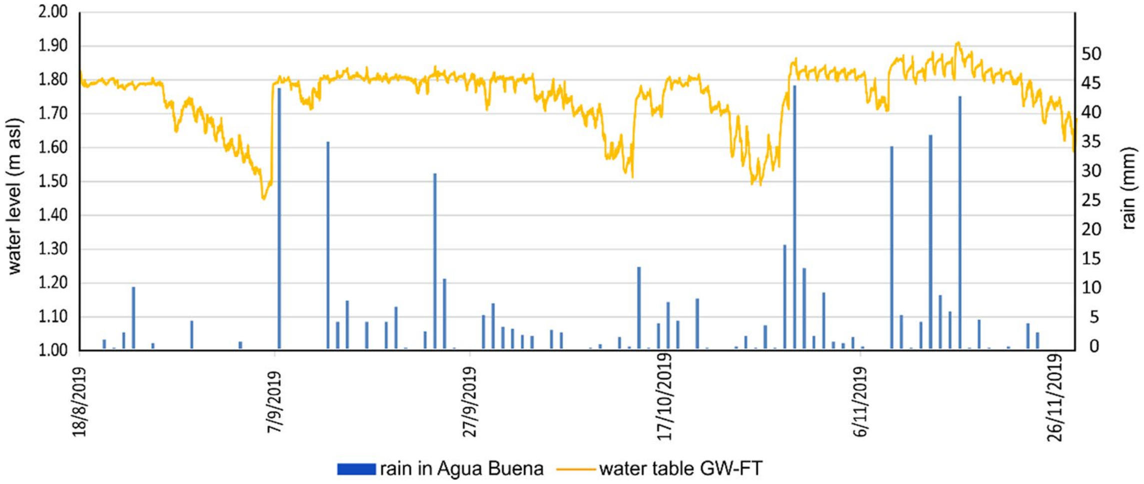

**Fig. 8** Comparison of precipitation data from Agua Buena station and groundwater levels in Agua Buena (GW-FT)

flows dynamics. The results obtained in the different sectors studied in the Matusagaratí Wetland, by applying these methodologies, show the spatial and temporal hydrological variations that exist in the Tuira River and in the different environments of this wetland.

The dynamics of the water in the Tuira River is determined by the runoff of excess rainfall, which is overlaid by a tidal regime resulting from the propagation of the Pacific Ocean tide from the estuary. This determines that different hydrodynamic behaviours exist along the river, as observed when comparing the temporal variation of the river levels in Yaviza and Chepigana stations (Fig. 2). The propagation of the tide from the San Miguel Gulf towards Tuira River upstream reaches an extension of close to 100 km, modifying the hydrological dynamics in the middle and lower basin of the river and, consequently, in the associated wetlands. The influence of tidal water along the course is recorded in the isotopic signal of the water (Fig. 3), where the samples which correspond to the river are aligned around the mixing line of rainwater and seawater in the $\delta^2$H vs. $\delta^{18}$O graph. Likewise, this propagation also causes changes in the salinity of the water in the river, as observed in the diverse wetland sectors, where salinity of the surface water recorded varied from 4.85 mS/cm in the middle basin sector (TR1) to 29.20 mS/cm in the lower basin sector (TR2) and 33.10 mS/cm in the sector near the estuary (TE). Although in this work the data which integrate the water column salinity values are analyzed, it is important to highlight that there is a saline stratification in these environments owing to the propagation of the tidal wave in rivers due to the difference in density that occurs in the form of a saline wedge (Carol et al. 2012).

These variations in the river salinity also lead to changes in the wetland environments associated with the river from the middle basin sector to the lower basin sector. In addition, the salinity variations associated with the different water flows and the geomorphology reflect changes in the vegetation in each wetland environment along the river. In the wetlands area associated with the middle basin of the Tuira River (transect 1, Fig. 1), the records of surface water and groundwater levels, rainfall and salinity and also stable isotopes values indicate that the three environments studied display different water contributions and hydrodynamic behaviours. In the levee sector there is a clear exchange of water flows between the river and the groundwater which is evidenced by the relationship between the water levels in the river and the groundwater levels. During the neap and spring tides with high tide levels lower than 4.0–4.5 m asl, the groundwater of the levee discharges to the Tuira River. In the spring tides with levels higher than 4.5 m asl, the river water partially floods the levee and infiltrates causing a rise in the groundwater levels (Fig. 4b). Despite the entrance of the river water can also occur in the river gullies due a tidal lateral propagation through the sediments, it is expected that, given that the sediments have low permeability, this process will only affect a narrow strip of the levee (Carol et al. 2009). Contrary to the low permeability of the sediments, the burrows of the crabs give the soils a secondary permeability and constitute preferential routes for the entry of water into the levee sediments when the river water floods it (Susilo et al. 2005; Carol et al. 2011). This exchange between groundwater and surface water has also been reported in similar rivers that have forested levees (Santucci et al. 2019).

The infiltration of rainwater also constitutes a contribution to the groundwater of the wetland which can be registered in the water levels. Although there is no abrupt rise in the water table associated with rainfall, there are slight rises in the levels after a rain period. However, despite the significant rain events in the area, it is expected that the abundant vegetation will intercept the rainwater and reduce its infiltration. The $\delta^{18}$O and $\delta^2$H values recorded in the groundwater of the levee also indicate that the origin of the groundwater in this sector of the wetland derives from the water contributions from the rain and from the Tuira River water (Fig. 5). However, from the point of view of water isotopes, the groundwater in the levee has a more enriched signal than the river water and the precipitation, which would indicate evaporation processes prior to the infiltration and/or infiltration of isotopically more enriched and more saline water. It is expected that the latter will occur at spring high tides greater than 4.5 m asl, since the entry of water from the estuary at high tide is greater.

In the floodplain areas and islands located behind the levee, no variations in groundwater levels associated with the spring high tides recorded in the river were observed (Fig. 4). The isotopic values of the groundwater in this sector present values of $\delta^{18}$O and $\delta^{2}$H (Fig. 5) that can be attributed both to an origin related to the infiltration of rainwater previously evaporated, and to a fluvial origin from the Tuira River. However, since the groundwater levels do not register rises associated with high tides in the river (Fig. 4), the contribution of fluvial origin is discarded, being the infiltration of rainwater the main contribution source to the groundwater of the wetland. Given that the floodplain is a topographically depressed area, the rain accumulates on the surface and infiltrates slowly as a result of the medium to low permeability of sediments. This implies that, prior to infiltration, the accumulated water can evaporate, which would explain the slight isotopic enrichments observed in the groundwater samples from this sector (Clark 2015). In these depressed areas, the groundwater has low salinity (lower than the river water), a characteristic that also indicates the contribution of rainfall to the groundwater that sustains this sector of the wetland. However, in extraordinary river flood events it is expected that the floodplain will also receive water inputs from the river. In all cases, groundwater pH values in the wetland are acidic, a common characteristic in environments with a high rate of decomposition of organic matter and slow water flows (McLatchey and Reddy 1998; Clark 2015; Robertson and Paul 2000). Figure 9 outlines the processes described above, indicating the interaction between the surface water of the Tuira River and the groundwater of the wetland, and also the sectors with rains contributions.

In the sector of the wetland associated with the lower basin of the Tuira River (transect 2, Fig. 1), both in the area

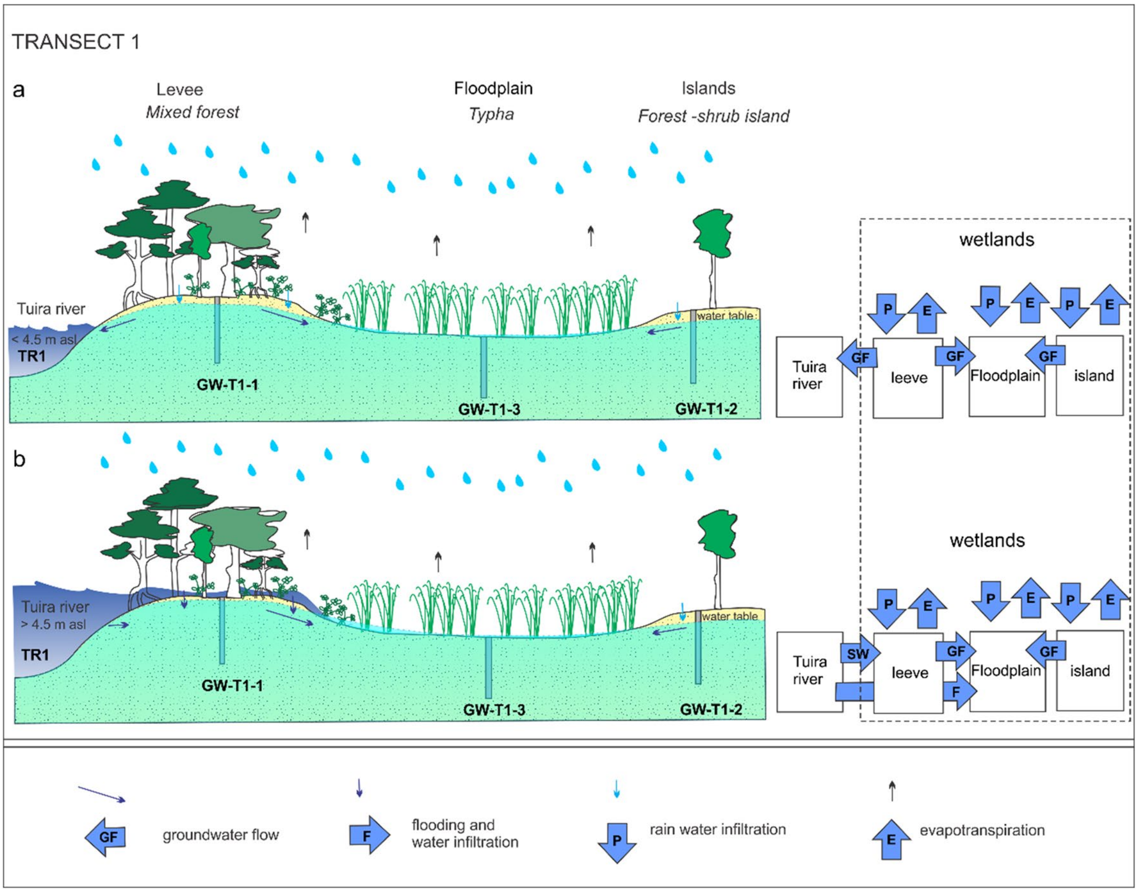

**Fig. 9** Diagram of the hydrological functioning for transect 1. **a** Situation with high tide levels below 4.5 m asl. **b** Situation when the tide exceeds 4.5 m asl

of levee and in the floodplain located behind it, there is an exchange between surface water and groundwater flows. As described in transect 1, during neap and spring tides with high tide levels lower than 4–4.5 m asl, the groundwater from the levee discharges into the Tuira River. During spring tides with levels higher than 4.5 m asl, the river water partially floods the levee and infiltrates, causing a rise in groundwater levels. Likewise, during high tide, the river water also enters through the tidal channels that develop in this area of the wetland and reaches the flat areas located behind the levee, also causing a rise in groundwater levels in this sector. Although in these wetland environments the sediments are fine, the numerous crab burrows facilitate the infiltration of floodwater. In particular, within the floodplain the infiltration of rainwater is a process that also influences the groundwater dynamics, being these contributions evidenced in increases in the water table after rain events (Fig. 6). The water that enters this area of the wetland not only comes from the precipitation that occurs over the sector, but can also be associated with the superficial runoff of precipitation from the higher areas of Filo del Tallo.

The hydrodynamic characteristics described above are reflected in the chemistry and isotopic signal of the water. The groundwater samples show intermediate isotopic values between the surface water that runs off from Filo del Tallo and that of the river near the estuary (Fig. 7). Although this indicates the existence of two origins in the main water sources, the high salinity recorded in the groundwater suggests that the main source of groundwater recharge in this area of the wetland has an origin in the infiltration of tidal water from the Tuira River. The water inputs from the river are not reflected in the pH values, since the river water is neutral to slightly alkaline and the pH of the groundwater in both the levee and the floodplain is slightly acidic. This decrease in pH would respond to the decomposition processes of organic matter accumulated in the soils of the wetland that acidifies the groundwater that flows slowly (Clark 2015). Figure 10 summarizes the processes described above, indicating the interaction between surface water and groundwater, the sectors with contributions from rains and from Filo del Tallo streams.

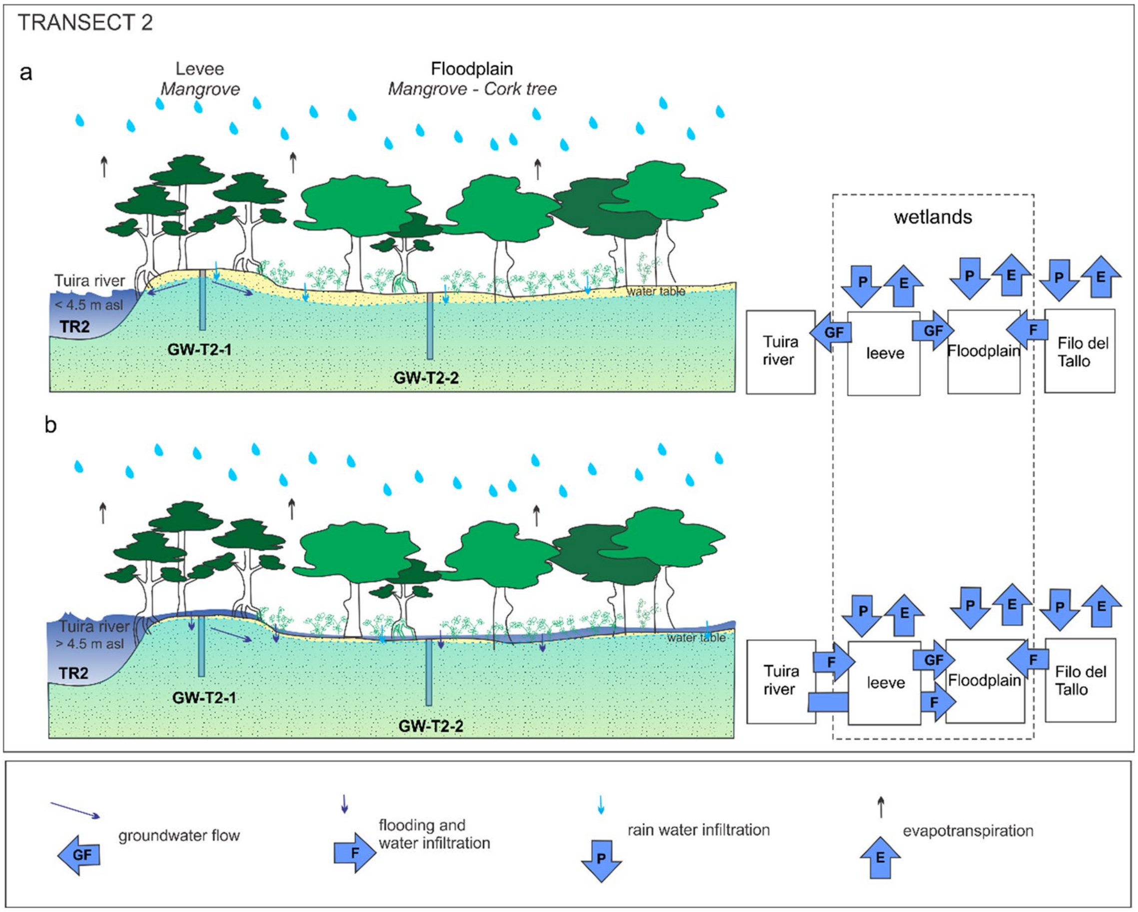

**Fig. 10** Diagram of the hydrological functioning for transect 2. **a** Situation with high tide levels below 4.5 m asl. **b** Situation when the tide exceeds 4.5 m asl

Finally, the piezometer located in the wetland sector away from the Tuira River has a strong dependence on rainfall water. In this sector, groundwater levels are strongly associated with infiltration of rainwater, which saturates the entire soil. Under these conditions the water table rises to the surface and surface runoff and flooding of depressed areas occur. This characteristic can be observed in the records of groundwater levels, which rise to a level close to 1.8 m asl, after which they remain slightly variable even with precipitation events (Fig. 8).

The different schemes of hydrological functioning proposed show the great spatial and temporal variability of the water flows in these wetlands. The isotopic and salinity results obtained indicate that the water that enters the wetland has different origins. There are some sectors of the wetland which depend on the contribution of the Tuira River, others depend on rainwater, and in other sectors the contribution of water to the wetland is mixed. Based on this, although isotopic and salinity data of the analyzed water provide useful information to analyze the origin of the water flows, they only represent the hydrological situation at the time of sampling. This suggests the need for a sustained monitoring over time that can include at least different hydrological situations allowing a better quantification of the different water inputs entering the wetland (Sanchez Murillo et al. 2020). However, this shortcoming is supported by the data obtained from the continuous water level sensors, which cover a prolonged period that enables to analyze the temporary changes that occur in the water flows of the wetland. In this way, based on the hydraulic gradients differences displayed by the surface water and groundwater in the different sectors of the wetland, the hydrological dynamics could be studied in detail. The latter constitutes a novel contribution that irrefutably shows the exchanges that exist between river water and groundwater, which had been partially addressed in previous works (Carol et al. 2020).

Understanding the contributions and flows of water within the wetland acquires not only hydrological but also ecological significance. Flood events due to the overflow of the Tuira River contribute to the accumulation of sediments and the transport and dispersal of seeds and fish larvae, playing an important role in the wetland ecosystems (Koerselman et al. 1990; Chen et al. 2018). Accordingly, the vegetation along the river shows a great diversity which is controlled by the different environmental characteristics associated with the geomorphology and water flows of the sector (Salinas and Casas 2007). Water flow dynamics is of prime importance for riparian vegetation, because it has a great effect on soil wetting, and germination and establishment of many species (Stromberg et al. 2005).

Within the variability of environments that exist in river wetlands, it is important to consider that they are not static entities, and their dynamic nature must also be taken into account for the management of their water resources (Björk 2010). Agricultural activities are one of the main causes of the deterioration of river wetlands around the world (Hassan et al. 2005; Gordon et al. 2010; Mondal and Pal 2018). Within the Matusagaratí Wetland, several canals, embankments and reservoirs for the accumulation of water that drains from the adjacent slopes have been built for large scale rice and oil palm cultivation. The expansion of oil palm crops since 2007 in the Matusagaratí Wetland area is a common trouble throughout the Darien region (Ocampo Peñuela et al. 2018). Oil palm production has been scrutinized for its environmental impact, specifically with respect to forest destruction, greenhouse gas emissions, and the lost of tropical biodiversity (Savilaakso et al. 2014). These impacts have been reported from Malaysia and Indonesia studies (Aratrakorn et al. 2006; Carlson et al. 2012; Gaveau et al. 2016). Although no specific studies that analyze the hydrological impact of oil palm plantations have been carried out in Matusagaratí Wetlands, it is expected that canals, embankments and reservoirs that were built for the expansion of these crops will modify the water flows entering the wetland and affect their ecosystems (Brinson and Malvarez 2002). Canals within floodplain areas drain the accumulated rainwater and also constitute preferential routes for the entry of tidal water during high tides. This not only modifies the dynamics of the water flows, but also determines the salinity of the water, consequently modifying the environmental conditions of the vegetation. Soil salinization and loss of vegetation are frequent problems in fluvial wetlands, where drainage and tidal influence are modified by canalizations and embankments (Carol et al. 2016, 2017).

The protection of sensitive biological communities (Poff and Zimmerman 2010) and compensating the needs of ecological and human uses of water (Lane et al. 2014) are important in the management of disturbed hydrological environments. The hydrological, ecological and social aspects of the environmental flow assessment (Poff et al. 2010) are strongly linked through the relationships between the flow alteration and the ecological characteristics for different natural hydrological regimes. Given the growing expansion of agriculture that currently exists towards the Matusagarati wetland area, it is essential to have hydrological data that allow defining the functioning of the wetland prior to agricultural activity. These data are part of the baseline of the hydrological characteristics (Lane et al. 2018) and for the studied wetland they are still scarce to null. In this sense, the data provided in this work are of utmost importance for the generation of basic information to establish guidelines for the management of water, the wetland and the protected areas of this environment. Likewise, understanding the origin and exchanges in water flows within each wetland environment contributes to a better understanding of environmental processes that sustain ecosystem services, biodiversity distribution patterns and also to foresee potential impacts that may occur if hydrological patterns are modified.

## Conclusions

Within the Matusagaratí Wetland, different environments associated with the levee and floodplain sectors of the Tuira River were recognized, with variations within the plain depending on the presence of topographically higher islands and on the proximity to the river. Spatial variations also occur as a result of the saline gradient that presents the water of the Tuira River, which registers an increase in the EC from the middle basin to the lower basin and isotopic values indicative of water originating from the mixture of water coming from the rains and sea water entry. This mixed origin in the river water is due to the propagation of the tide from the estuary through the main course of the Tuira River, which not only determines its chemistry and isotopic signal, but also its hydrodynamics.

The joint study of groundwater levels, water levels in the Tuira River and rainfall data allowed the recognition of the groundwater hydrological dynamics of the wetland and the interactions of water flows between the different environments. Likewise, the isotopes of the water molecule made it possible to recognize the origin of the water inputs that enter each sector of the wetland. In the levee sectors, the relationship between water levels shows that the groundwater mainly receives water input from the Tuira River during large floods, while when river levels are low, the groundwater discharges into the river. The isotopic similarity between the water of the Tuira River and the groundwater of the levee in each studied sector also confirms that the recharge of groundwater in this wetland environment has its origin mainly in the infiltration of river water. Although the infiltration of rainwater is not ruled out, the contribution of water of this origin in the levee area would be considerably less than the contribution of fluvial origin. In the floodplain sectors, rises in groundwater levels recorded after rain events and the lower salinity of the groundwater compared to that of the Tuira River indicate that in this environment, rainwater infiltrates the soils, recharging the groundwater of the wetland. The isotopic signal and the low EC values of the groundwater in the floodplain in the middle basin indicate that in this sector of the wetland the origin of the groundwater is mainly associated with the infiltration of rainwater. In the lower basin, however, the EC of the groundwater increases and the isotopic signal is interpreted as water from the Tuira River and from the rain events. These two origins are also recorded in groundwater levels, which rise both due to river flooding and rain events. In this way, there are environments within the wetland, where the origin of the groundwater is mainly fluvial, others where the contribution of rain dominates and others with mixed origin.

The results reported in this work provide hydrological data in non-anthropized sectors of the wetland. This contribute the generation of hydrological baselines in a wetland of ecological relevance for which there is no previous information. These data not only contribute to the understanding of the hydrological functioning of the wetland, but are also a valuable tool for generating management guidelines in view of the advance of anthropic activities that affect some sectors of the wetland.

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**Data availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of 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.

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