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ORIGINAL PAPER

Surface water–groundwater interactions in the Matusagaratí wetland, Panama

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Abstract The Matusagaratí wetland in the Panamanian Darien is one of the largest and most biologically diverse wetland ecosystems in Central America. Despite this, no hydrological studies have been conducted in the area due to its remoteness and difficult access. The aim of this research is to define the relationship between surface water and groundwater through the field and laboratory data obtained from the first monitoring network installed in the Matusagaratí wetland. Variations registered in the isotopic relationships in surface water and groundwater show that the wetland receives contributions from rainfall as well as fluvial and estuarine water. There are areas of the wetland where one of these sources predominates, and others where they mix. In the wetland sector downstream the Tuira river, the groundwater presents a combination of freshwaters coming from Filo del Tallo and those coming from the Tuira river, whose high salinity reflects the estuary's influence. Meanwhile, in the upstream sector of the wetland, the groundwater is a mixture of river water and rainwater on the river´s levee but behind it, rainwater predominates. In all cases, groundwater has Rare Earth Elements patterns like those of the Tuira river, highlighting the importance of river flooding as a source and support system for the wetland groundwater. Hydrological research such as this, presents a valuable opportunity to provide sound scientific information to promote sustainable management and environmental conservation of this unique wetland that is rapidly being transformed to cattle pasture and palm and rice cultivation.

Keywords Environmental isotopes · Rare earth elements · Hydrochemistry · Groundwater salinity · Fluvial–estuary water

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Introduction

Wetlands cover about 5–8% of the Earth's surface but are disproportionately important in providing unique habitats for large numbers of plant and animal species, storing immense amounts of carbon, and providing ecosystem services such as flood mitigation, water quality improvement, and coastal protection (Melton

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2016). Despite their important role as provider of ecosystem services, they are particularly vulnerable to drivers of land-use change (Barbier et al. 2011; Ricaurte et al. 2017) and climate change (Deane et al. 2018; Cowood et al. 2018).

Groundwater interacts with surface water in nearly all landscapes, mainly in wetland environments (Winter 1999). The main sources of water in riparian wetlands come from flooding, groundwater discharge and direct precipitation (Brinson and Malvarez 2002; Scheliga et al. 2019). In estuarine wetlands, periodic flooding of the tidal flow induces another variable of relevance in the dynamics of surface water—groundwater interaction (Brinson 1993; Wolanski and Elliott 2015) conditioning, for example, the aquifers recharge (Santucci et al. 2019), physical properties of sediment (Mazda and Ikeda 2006); the salinization processes of water and soils (Carol and Alvarez 2016; Galliari et al. 2020a) and pollutants migration (Li et al. 2018). The area of tidal influence depends on the topography and morphology of the coast, and the amplitude of the tide (Mazda and Ikeda 2006; Carol et al. 2009), and likewise, the tidal asymmetry usually alters the duration of flooding (Seenath 2015; Serrano et al. 2020).

Interest in understanding the water inflow interactions and hydrological connectivity of wetlands has accelerated in recent years, largely in response to the need for scientific information to guide wetland management (Hayashi et al. 2016; Neri-Flores et al. 2019; Neff et al. 2020). The interactions and connections between surface water and groundwater flows produce a variety of eco-hydrological conditions that support and maintain diverse wetland ecosystems (Zhang et al. 2017). Therefore, a detailed understanding of the water flows as well as the origin of the water, is vital for the management and conservation of natural wetlands (Wolanski et al. 2004). Despite this importance, to determine the origin of the waters that enter a wetland it is not always an easy task. In this respect, research based on the study of stable water isotopes and rare earth elements (REE) offer a relevant and practical tool to further our understanding of wetland hydrology (Dia et al. 2000; Kerr et al. 2008; Siebert et al. 2012; Davranche et al. 2015, 2016; Galliari et al. 2020b). The stable isotopes of the water molecule are a useful tool to determine the origin of water (Clark 2015). In this way, its study allows to differentiate between contributions of rainwater, sea water or if there is a mixture, as well as evaporation processes. REE, constitute the group of lanthanide elements, which have common physicochemical properties, which determines that they often have a similar geochemical behavior (Noack et al. 2014). In aquatic systems, with regards to their slight solubility, REE concentrations are low compared to their concentrations in rocks or sediment. For the sake of convenience, the REE distribution in waters is usually illustrated by normalized REE patterns relative to the upper continental crust (e.g. Taylor and McLennan 1985; Rudnick and Gao 2003). The REE patterns result from the combination of several processes able to induce their fractionation and they are also important in water source or provenance analysis (Noack et al. 2014).

The Matusagaratí wetland in the Panamanian Darien (Fig. 1) is one of the largest wetlands in Central America. This wetland covers approximately 56,000 hectares and is located along the margins and adjacent lowlands of the Tuira river which empties into the Pacific Ocean forming an extensive estuary. Wetland also receive freshwater from small streams draining from the Filo del Tallo and other 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 Matusagaratí Wildlife Refuge. However, there is no on-the-ground management on any of these protected areas and the wetland's herbaceous vegetation, is often burned by local cattle ranchers, at the end of the dry season, to expand their pastures. Furthermore, during the last decade, nearly a third of the wetland was illegally titled and part of it drained and transformed into oil palm plantations and more recently to rice cultivation (Ministerio de Ambiente 2016; CREHO 2015).

To this problem is added the lack of baseline studies that would allow for better management, and this is largely due to the fact that it is extremely difficult to access the wetland with the purpose of taking field data because of the wildness of the site. Scientific studies in the Matusagaratí wetland have focused on its rich plant and animal diversity (e.g. Grauel and Putz 2004; Ortiz et al. 2020; Ibañes and Flores 2020), but despite the importance of the water flows in creating the conditions for biodiversity development and maintenance (CREHO 2015; Ministerio de Ambiente de Panamá 2016), no hydrological studies have been

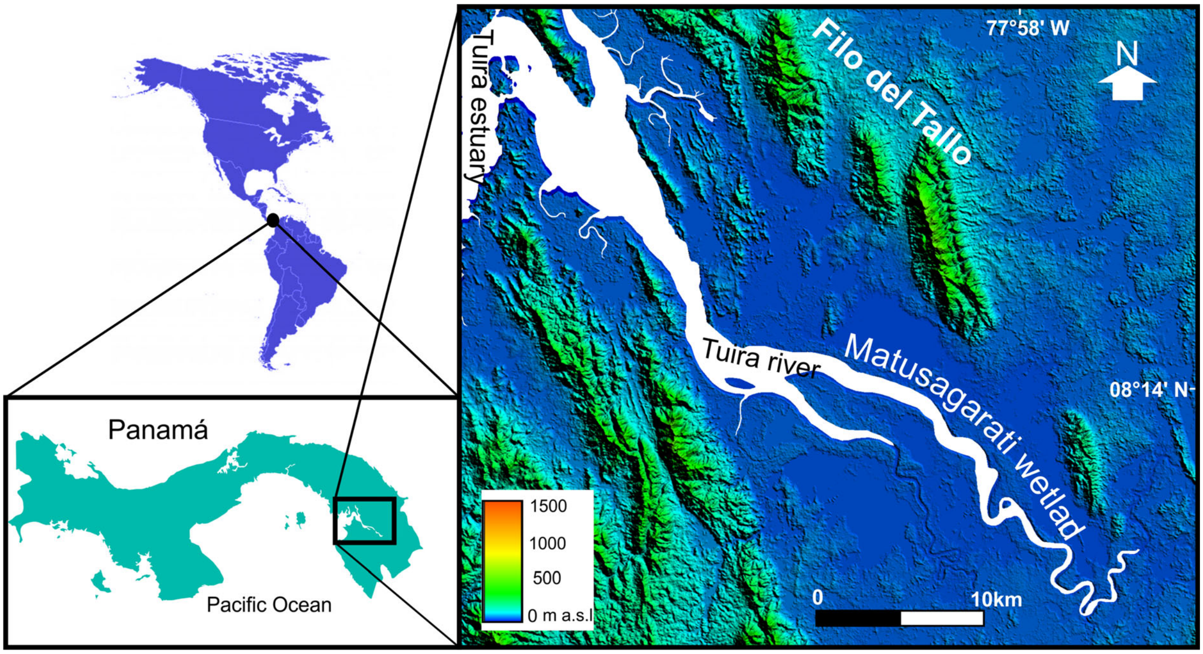

Fig. 1 Study area location

conducted in the area. The aim of this research is to define the relationship between surface water and groundwater through field and laboratory data which were obtained from the first monitoring network installed in the Matusagaratí wetland. It is hypothesized that there are changes in this relationship, as well as in the contributions of water from different sources (tidal, river, rainwater) and that these changes determine the existence of different environments within the wetland. The study of the stable isotopes and REE will allow us to identify the interaction between the different water sources that contribute to the wetland.

Methodology

A monitoring network was installed in order to analyze the physicochemical properties of the water in different wetland environments. Samples of surface water and groundwater were taken in March 2019 in two transects perpendicular to the Tuira river. The transect 1 located upstream and the transect 2 located downstream (Fig. 2). Sample sites were selected considering wetland vegetation types. In the transect 1 a sample was taken from the Tuira river (TR) and wetland groundwater was sampled in three zones. In the first zone located on the river levee (GW-T1 1) there is a mixed forest with a 20 m canopy and emergent trees of approximately 30 m. This forest is dominated by cativo (*Prioria copaifera*) along with other species such as barrigón (*Pseudobombax septenatum*), roble (*Tabebuia rosea*), sangrillo (*Pterocarpus officinalis*), *Macrolobium sp.* The palm locally known as corocita or American oil plam (*Elaeis oleifera*) is abundant in the understory. In this sector of the levee numerous crab burrows were observed. Behind the levee (GW-T1 2 and GW-T1 3) there is a 2–3 m high grassland approximately 90% dominated by cattail (*Typha domingensis*). This species was accompanied by *Elaeocharis* sp. and *Aeschynomene* cf. The last sample of these two, was taken in a very small (10 m × 6 m approximately) forest-shrub "island" higher than the surrounding grassland dominated by *Typha*. In this "island" there are species such as *Elaeis oleifera*, *Coccoloba* sp., *Pseudobombax septenatum*, *Ludwigia nervosa*, *Palicourea tryphylla*, *Machaerium capote*. There are also *Thalia geniculata*, *Typha domingensis*, *Calathea lutea*, *Blechnum serrulatum*, *Ludwigia* sp.

In the transect 2 a sample was taken from the surface drainage discharge to the Tuira river (TR-T2) and to the estuarial zone (TE), and groundwater

Fig. 2 Location of sample sites. Box 1 shows transect downstream and Box 2 shows transect upstream the Tuira river. *GW* groundwater, *SW* surface water, *TR* Tuira river, *TE* Tuira estuary, *T1* Transect 1, *T2* Transect 2, *FT* Filo del Tallo

samples in the wetland were taken in a transect that started in a 20–25 m high mangrove forest of *Rhizophora racemosa*. The understory was almost exclusively *Acrostichum aureum*, a mangrove fern locally known as negra jorra. The last sample was collected in a forest of mora tree (*Mora oleifera*) with trees ranging between 12 and 15 m high and occasionally mangrove trees (*Rhizophora racemosa*) (GW-T2 2). 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, surface water samples were taken from the streams that drain from Filo del Tallo (SW-FT1, FT2 and FT3).

Surface water samples in the Tuira river were taken directly with bottles from the boat and in the streams of Filo del Tallo within the streams. In all cases, the sampling bottles were cleaned three times with river water before taking the sample. To take groundwater samples, 3 m deep boreholes were drilled with a manual auger. The boreholes were fitted with a 5.1 cm PVC casing, with grooved filter and a siliceous gravel prefilter located in the lower 1.5 m, and the annular space of the upper section was sealed to prevent the ingress of flood water. For water sampling, the wells were cleaned by emptying them three times with a bailer. The sampling bottles were also rinsed three times in each point, pH, Eh and salinity were measured in situ using a portable multiparametric instrument (Lutron® WA-2017SD). Samples were filtered and stored in polypropylene bottles for the isotopic analysis, and nitric acid (1%) was added to samples for REE analysis.

Stable isotopes in water (δ^2H and $\delta^{18}O$), were measured using mass spectroscopy (Thermo Finnigan MAT Delta Plus XL continuous flow mass spectrometer) at the Stable Isotopes Laboratory of San Luis University (Argentina). Isotopic results are expressed as δ‰, defined as $\delta = 1000(Rs - Rr)/Rr$‰, where δ is the isotopic deviation in ‰ relative to Vienna Standard Mean Ocean Water (V-SMOW) (Gonfiantini 1978); s: sample; r: International reference; R: isotopic ratio ($^2H/^1H$, $^{18}O/^{16}O$). The analytical accuracy is ± 0.05‰ and ± 0.5‰, for $\delta^{18}O$ and δ^2H, respectively. Isotopic values were compared with the local meteoric line which corresponds to $\delta^2H = 7.63\ \delta^{18}O + 6.51$ for the Pacific coast of Central Panama (Kern et al. 2016). This allows to identify whether the groundwater receives contributions from rainwater, as well as evaporation processes. Isotopic data were also contrasted with salinity data to evaluate trends associated with salt dissolution processes.

In the case of the transect located in the estuarine area, a theoretic mixing line was calculated using, as end members, the average value of the samples taken closer to Filo del Tallo (SW-FT 1 and SW-FT 2) and the Tuira estuary water samples (TE). Similarly, to analyze the tidal spread into the riverbed, a theoretical mixture of two end member mixing model was made from the isotopic values considering as extreme members the sample of the Tuira river (TR-T1) and that of the water of the sector of the estuary (TE). For this purpose, the following equation was used:

$$C_x = y * C_1 + (1 - y) * C_2$$

where Cx is the isotopic composition of the mixture, C_1 the isotopic value of the end member 1, C_2 the isotopic value of the end member 2 and y the percentage of the end member 1.

The analysis of REE was made in the laboratory at the Centro de Investigaciones Geológicas (Geological Research Center, Argentina) using ICP-MS with an analytical accuracy of ± 0.001 µg/L. Samples were measured by triplicate and during the measurements Merck certified reference standards were interleaved, and the relative SDs of the replicate samples were $<$ 5%. The REE results were normalized to the upper continental crust (UCC) values (concentration in sample/concentration in UCC) according to the concentrations in UCC indicated in Rudnick and Gao (2003).

Results

Sample analysis shows variations in the physicochemical parameters of surface water and groundwater samples taken in different wetland areas (Table 1). The salinity of the surface water varies from 3100 ppm in upstream sector (TR) to 18,700 ppm (TR T2) and 21,200 ppm (TE) in downstream sector. This indicates that there is a salinity gradient along the Tuira river, with brackish water in the sector of transect 1 and brackish -saline water in the sector of transect 2. On the other hand, the registered pH indicated neutral to slightly alkaline values, and Eh values were in all cases close to 200 mv.

Table 1 Physical and chemical parameters measured in situ, isotopic and REE values

Sample	Salinity (TDS, ppm ± 5)	pH (± 0.1)	Eh (mv ± 1)	δ^{18}O‰ (± 0.05)	$\delta\ ^2$H‰ (± 0.5)	Σ REE (ppb ± 0.001)
Groundwater						
GW-T1 1	8950	4.8	180	− 3.10	− 20.0	20.684
GW-T1 2	850	4.3	180	− 3.70	− 26.5	28.010
GW-T1 3	1960	4.3	212	− 2.80	− 18.5	90.413
GW-T2 1	12,100	6.6	− 30	− 3.55	− 23.5	7.922
GW-T2 2	9980	6.7	183	− 3.95	− 26.0	3.542
Surface water						
TR-T1	3100	7.5	229	− 4.05	− 24.5	2.617
TR-T2	18,700	7.0	178	− 3.15	− 22.5	27.086
TE	21,200	7.8	214	− 1.50	− 11.5	28.125
SW-FT 1	175	7.4	270	− 4.90	− 33.0	0.803
SW-FT 2	175	7.7	283	− 5.45	− 36.0	1.404
SW-FT 3	185	6.5	231	− 5.65	− 38.0	1.334

TDS total dissolved solids, *GW* groundwater, *SW* surface water, *TR* Tuira river, *TE* Tuira estuary, *T1* transect 1, *T2* transect 2, *FT* Filo del Tallo

In the transect 1 (upstream), the groundwater in the levee with mixed forest (GW-T1 1) presents high salinity (8950 ppm), while in the depression behind, with high grassland dominated by cattail, it diminishes to 1960 ppm (GW-T1 3) and 850 ppm (GW-T1 2). In all cases, pH is acid showing values between 4.3 and 4.8, and Eh close to 200 mv. In the transect 2 (downstream), groundwater among the mangroves (GW-T2 1) shows higher salinity (12,100 ppm) with pH of 6.6 and Eh of-30 mv. In the mangrove-alcornoque sector (GW-T2 2) the groundwater salinity is slightly lower (9980 ppm), with similar pH but with Eh oxidant values (183 mv) (Table 1).

On the other hand, the small streams that drain from Filo del Tallo (samples SW-FT in Fig. 2) shows general low salinity values (175 and 185 ppm), pH between 6.5 and 7.7 and oxidant Eh (283mv). Interesting to note that, even though samples SW-FT1 and SW-FT2 are very similar, sample SW-FT3 (nearer to the river) has slightly higher salinity and lower pH and Eh that the other surface water samples (Table1).

The δ^2H vs. δ^{18}O graph shows that, even though the samples are close to the local meteoric water line described for the Pacific coast of Central Panama (Fig. 3a), there are small deviations. The Surface water and groundwater in the transect 2 is particularly close to the theoretical mixing line between SW-FT and TE. This mixing trend registered in the isotopic values can also be seen in the graph δ^{18}O as a function of salinity (Fig. 3b). Similarly, the groundwater samples from the transect 1 area tend to move slightly away from the meteoric line showing two behaviors in the graph δ^{18}O as a function of salinity (Fig. 3b). The samples taken from the depression behind the levee (GW-T1 2 and GW-T1 3), present a slight isotopic enrichment associated to low salinity variations, trend associated with evaporation processes prior to infiltration. In contrast, the sample from the levee (GW-T1 1) shows an increase in the salinity value, possibly associated to dissolution/alteration of minerals and/or towards the mixing line of waters from the Tuira river and estuarine waters.

The standardized REE graph (Fig. 4) shows that the groundwater in both areas of the wetland shows similar patterns to the Tuira river, with no variation in the pattern between river samples both in the transect 1 and 2 sectors. In all cases, the patterns are flat and there is a slight decrease in the light REE (LREE). Among the groundwater samples, those of the transect 1 sector have higher LREE contents than those of the transect 2 sector. On the other hand, the river shows an increase in the REE content towards the estuary (Table 1; Fig. 4).

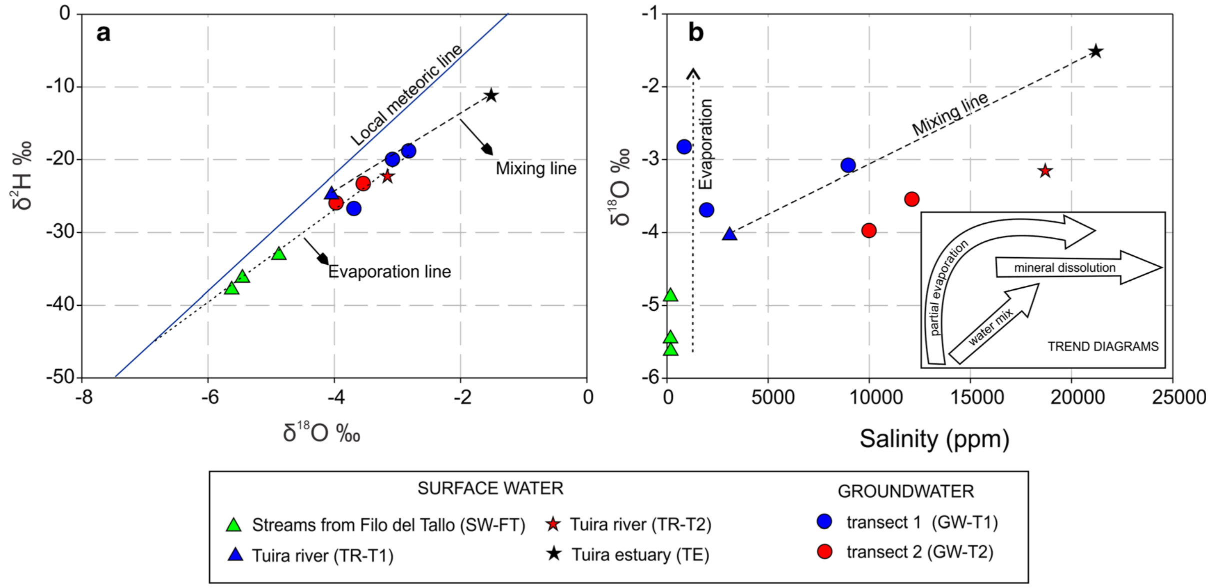

Fig. 3 **a** Values of δ^2H as a function of δ^{18}O, **b** relation between δ^{18}O and salinity (TDS in ppm). Local meteoric water line for the Pacific Coast of Central Panama from Kern et al. (2016)

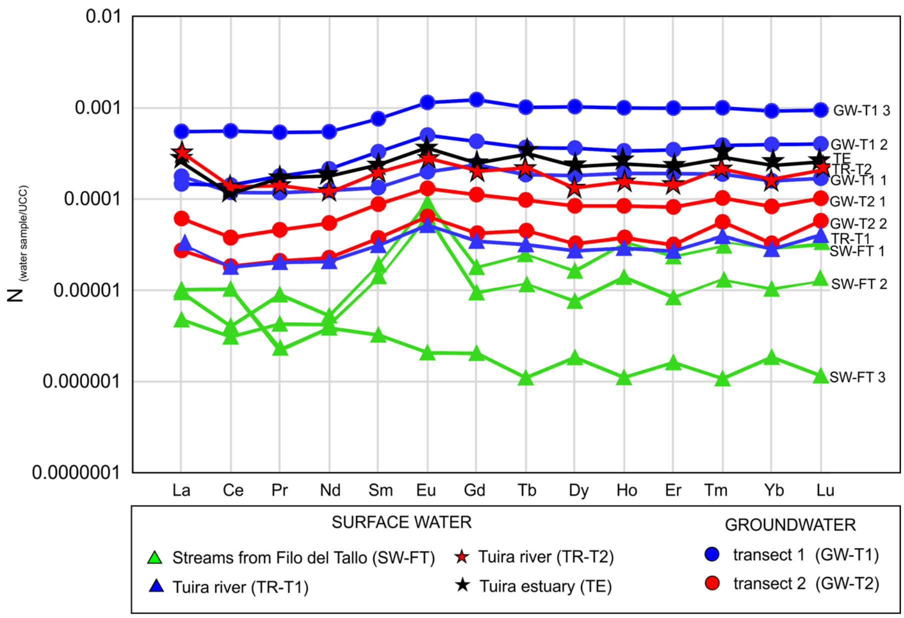

Fig. 4 Multielement graph of normalized REE according to the average composition of the Upper Continental Crust (Rudnick and Gao 2003)

Different patterns and concentrations of REE were found in the samples taken from the streams that drain from Filo del Tallo. These differences are also appreciated in the chemical and physical analysis previously presented (Table 1; Fig. 4). Samples from SW-FT1 y SW-FT2 show patterns with a slight enrichment of heavy REE (HREE) and marked anomaly in Eu, while the sample SW-FT3 presents even less enrichment of LREE.

Discussion

The study of the physical and chemical parameters, as well as the isotopic values and REE patterns in surface water and groundwater in different environments of the Matusagaratí wetland, provides a more integrated understanding of water inflows that support the wetland's functions and ecosystem services.

In the transect 1 area (Fig. 2), the Tuira river water have an isotopic signal associated to the local meteoric line, and the groundwater δ^2H and δ^{18}O values similar to those of the river. This shows that the groundwater, that supports wetland's functions, has inflows from the Tuira river as well as from rainfall (Fig. 4a). In the flooded lowlands behind the levee, rainfall is accumulated, and the observed slight isotopic enrichments could be attributed to evaporation before infiltration (Clark 2015). In these depressions, groundwater has low salinity (lower than that of the river), which underlines the contribution of precipitation as a source of water in this part of the wetland. On the other hand, groundwater in the levee presents isotopic contents like those of the river but also shows higher salinity (Table 1). In this area, adjacent to the riverbed, contributions from the river waters are more important than those of the rainfall. The higher salinity in the levee´s groundwater, without a significant variation in the isotopic content, reflects dissolution processes or mineral alterations during the subterranean inflows (Clark 2015). Similarly, the increase in salinity seems to be related to isotopic values in the mix of Tuira river water and estuarine water (Fig. 3b). This would also indicate that the water that infiltrated the levee in the last flood before the monitoring date corresponds to a mixing composition between that of the river and that of the estuary. When the river overflows and its waters flood the levee, it gets infiltrated in its sediments. This infiltration is facilitated by crab burrows that act as macropores (Fig. 5a, b), providing higher secondary permeability to surface sediments (Susilo and Ridd 2005; Carol et al. 2011). When the river presents a low water level (base flow or low tide), groundwater from the levee discharges towards the river as observed on the river ravines sediments (Fig. 5c). This exchange between groundwater and surface water has also been reported in similar rivers that have forested levees (Santucci et al. 2019). Flooding due to the river overflow determines the chemical characteristics of the water and creates the environmental gradients in the wetland but also contributes to sediment accretion and seed and fish larvae transport and dispersal (Koerselman et al. 1990; Chen 2019).

The REE patterns in the groundwater samples are similar to those of the Tuira river (Fig. 4). This again corroborates the importance of river water flooding into the wetland as a source of recharge to groundwater. The lower pH level in the groundwater compared to the river water could be due to the decomposition of organic material. These acid pH conditions facilitate the release of REE from the sediments to groundwater (Gruau et al. 2004), resulting in higher concentrations of REE in the groundwater. Figure 6 summarizes the previously described processes, indicating the interaction between the surface water of the Tuira river and the groundwater, the sectors with contributions from the rains and the chemical contrasts that exist in each sector in relation to the salinity, pH and Eh.

In the transect 2 area with, groundwater samples present isotopic contents that reveal a mix of surface water draining from Filo del Tallo on one hand and rainwater and estuarine water on the other. This indicates the existence of two main sources of water. However, the high salinity registered in groundwater suggests that the infiltration of tidal waters from the Tuira river is the main source in this area of the wetland. Note that in this sector of the river the salinity is much higher than that of transect 1 due to the propagation of seawater from the estuary. On the other hand, here too the infiltration of tidal water is favored by the numerous crab burrows. This contribution from the river is also evident in the similarity observed between the REE patterns of the groundwater and those of the Tuira river. Regarding the contribution of waters from Filo del Tallo, it is important to consider that the patterns and concentrations of REE of these waters are very different from those of groundwater. These streams present low flows so their contribution to the wetland is limited and, therefore, they do not leave a mark in the groundwater REE patterns. Figure 7 summarizes the previously described processes indicating the interaction between surface water—groundwater, the sectors with contributions from the rains and from the streams of Filo del Tallo and the chemical contrasts that exist in each sector in relation to salinity, pH and Eh.

The relationships between surface and groundwater and the water inputs in the two transects studied show the variability in the hydrological functioning of the

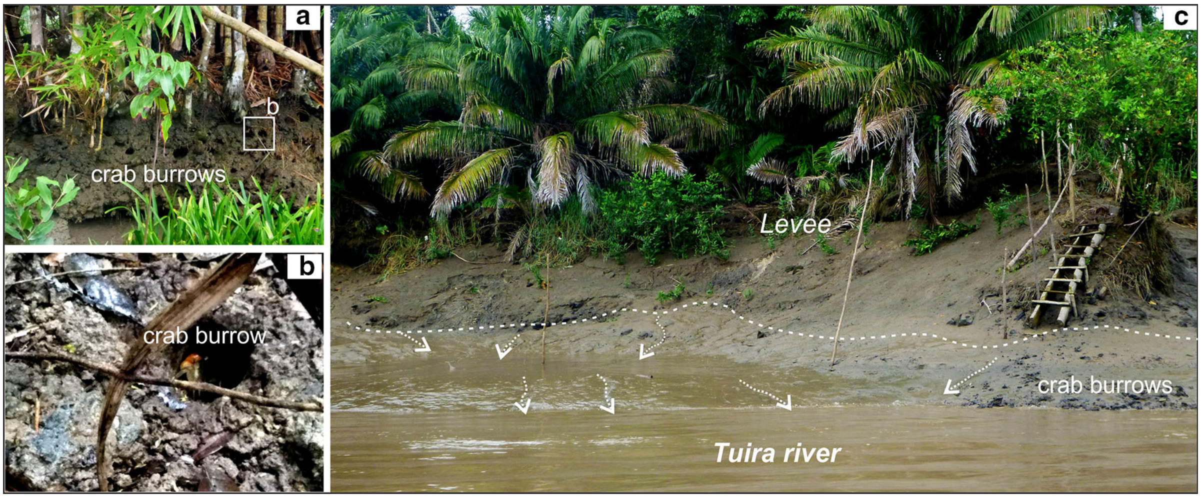

Fig. 5 **a** River levee and crab holes, **b** Crab burrow detail, **c** The dotted line shows the groundwater discharge from the levee towards the river. Surrounding forest to the borehole GW-T1 1

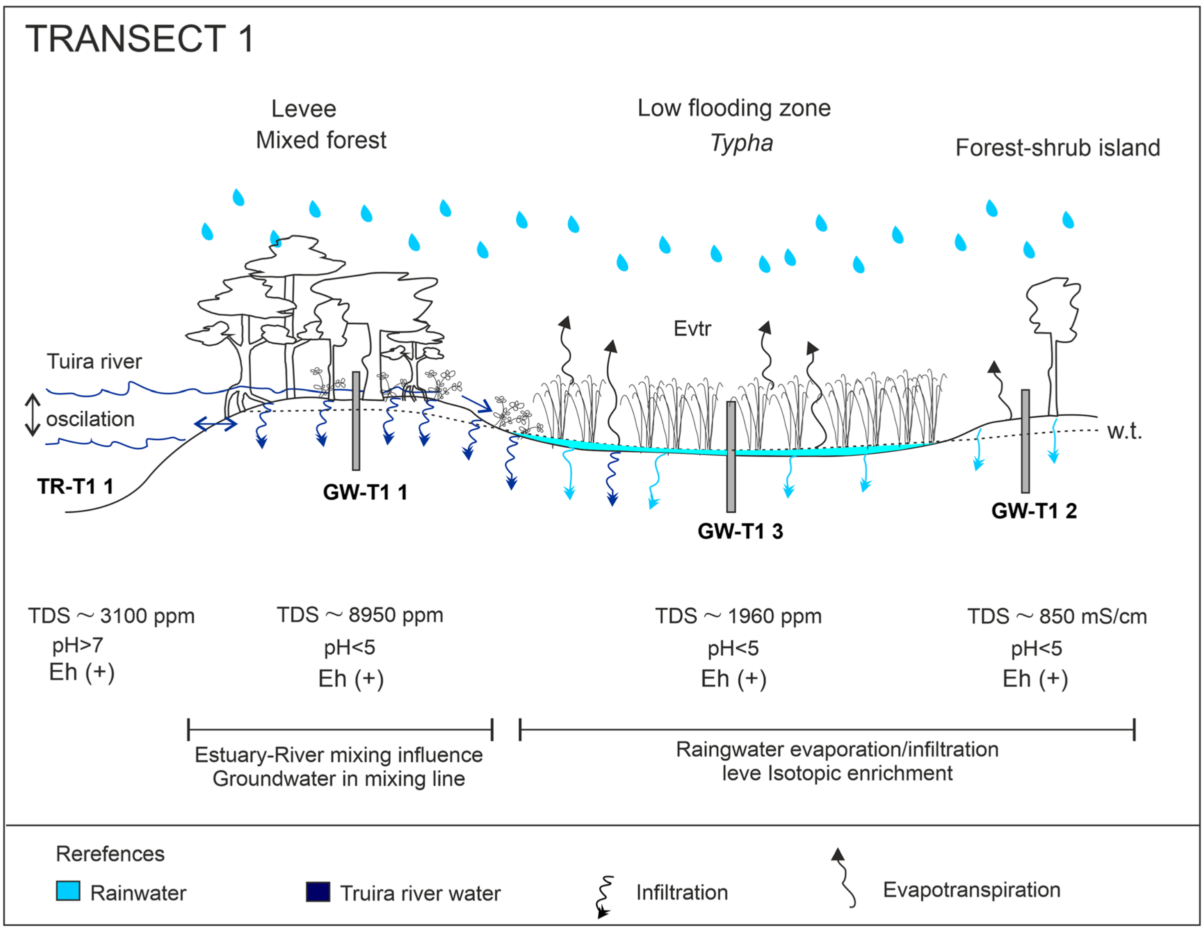

Fig. 6 Conceptual model showing the hydrologic and geochemical processes that creates the environmental conditions in the wetland area of transect 1

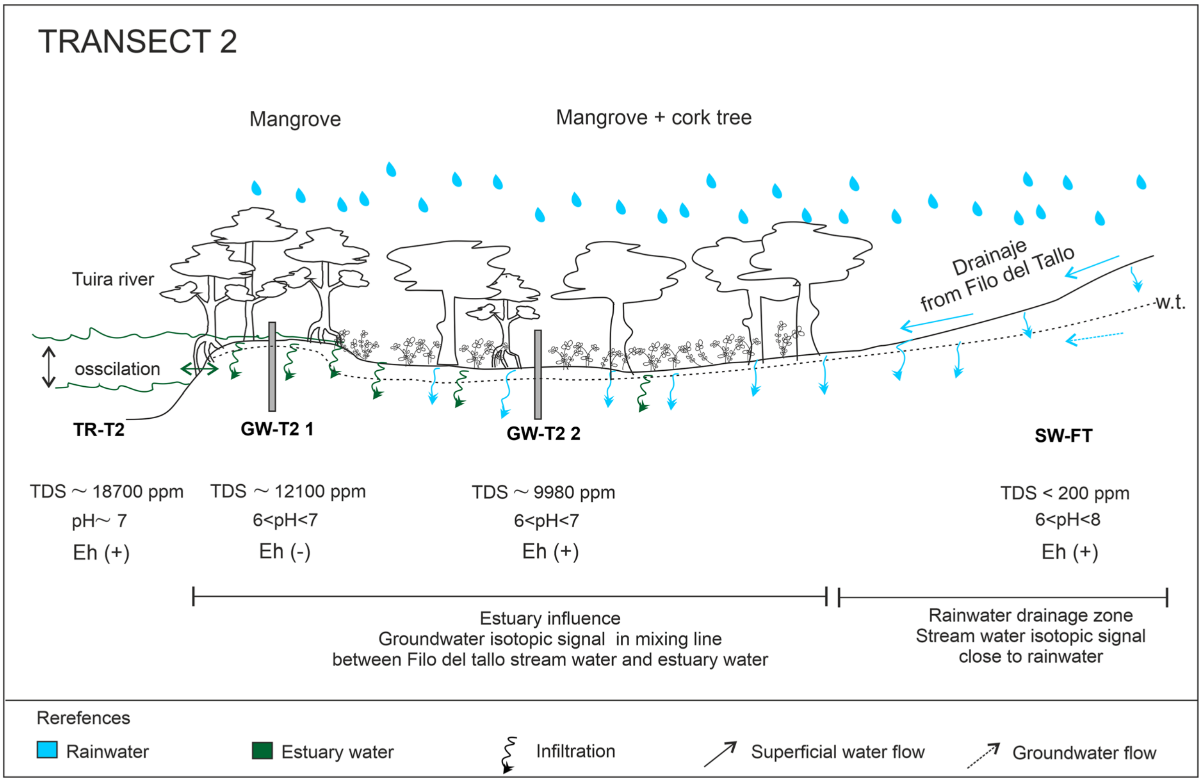

Fig. 7 Conceptual model showing the hydrologic and geochemical processes that creates the environmental conditions in the wetland area of transect 2

wetland that occurs along the river. Added to this variability in hydrodynamics is that associated with changes in the salinity of the Tuira river. This salinity gradient influences the salinity of groundwater in wetland environments where the contribution of water from the river is more important than that of rainfall.

The findings presented here, provide some valuable information that could be used for wetland management and conservation. The wetlands hydrologic alteration through human interventions for farming and agricultural uses, such as embankments, ditches and drainage channels for land reclamation, produced the loss and degradation of this environment (Portnoy and Giblin 1997; Brinson and Malvárez 2002; Bruland et al. 2003; Godet and Thomas 2013; Carol et al. 2017).

The results obtained indicate that there are sectors in the wetland that depend on the contribution of the Tuira river, others that depend on rainwater, and other sectors where the water supply is mixed. Those sectors that depend mainly on the river water inflow, such as the zone of the levees, have also groundwater reduced conditions due to the permanently saturated soils. If these sectors were drained, their hydric conditions would change from a reducing environment to an oxidizing one, generating irreversible acidification of the soil (Sammut et al. 1996; White et al. 1997; Karimian et al. 2018). On the other hand, in those sectors of the lowlands behind the levee, where the inputs are mainly rainwater, if they are channeled to drain them, these channels will not only drain the excess water drying up the wetland, but will also be preferential routes for the entry of water from the river, generating changes in salinity (Moorhead 1991; Carol et al. 2014).

Conclusions

Variations registered in the isotopic relationships in surface water and groundwater show that the wetland receives contributions from rainfall as well as fluvial and estuarine water. There are areas of the wetland where one of these sources prevail and others where they mix. Different water inputs create different hydrological conditions within the wetland and these hydrological differences are recorded in the environmental isotopes.

In the wetland area downstream the Tuira river, the groundwater presents a mix of waters that combine those that drain from Filo del Tallo and those that are brought by the river, whose high salinity reflects the influence of the estuary. On the other hand, in the wetland area upstream the Tuira river, the groundwater in the levee presents a mix of river water and rainwater but in the depression behind the levee, rainwater predominates. Regardless of salinity variations and isotopic tendencies, in all cases the wetland's groundwaters and the Tuira river show similar REE patterns.

Hydrological research such as this presents a valuable opportunity to provide sound scientific information to promote sustainable management and environmental conservation of this unique wetland.

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