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TRACING GROUNDWATER DISCHARGE IN THE FLOODPLAIN OF THE PARANA RIVER, ARGENTINA: IMPLICATIONS FOR ITS BIOLOGICAL COMMUNITIES

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ABSTRACT

Groundwater discharge can be an important determinant of the functioning of aquatic environments and their associated biological communities. However, the presence and the importance of groundwater have not been considered in the Parana River floodplain owing to the large quantity of surface water. The present study aimed to identify groundwater discharge conditions in a sector of the middle of the floodplain of the Parana River by studying groundwater flow systems. Eight piezometers were installed to record groundwater movement in the vertical plane weekly for 2 years. Water samples were collected in piezometers, domestic wells, the river and other water bodies to study the groundwater flow systems. Rising of the water level during piezometer installation and recording suggested that the study zone represents groundwater discharge conditions. Residence time proxy allowed identification of local flows and intermediate flows. Local rainfall (in Santa Fe) showed an isotopic signature (δD and $\delta^{18}O$) similar to some local flows detected in the study zone, and this suggested local recharge. The chemical characteristics of an intermediate flow suggest that water would have travelled from a recharge area ~30 km from the study zone. Local rainfall and the intermediate flow have different isotopic signature. Results suggest that the willow forest is associated with the recharge area of a local flow, which plurispecific-canopy forest is related to a transit area of a semi-intermediate flow, and that tall grassland and marshy community colonize discharge areas of local and intermediate flows, respectively.

KEY WORDS: surface water and groundwater interaction; flow systems; groundwater discharge; floodplain; ecosystems

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INTRODUCTION

The Parana River occupies the second place in importance among the fluvial systems of South America; its annual mean flow of 17 000 m^3/s and its hydro-sedimentological pulses have been identified as responsible for the existence, productivity and interaction of biota of the associated ecosystems (Bonetto *et al*., 1972; Junk *et al*., 1989; Neiff, 1990b). The variety of ecological conditions produced by the spatio-temporal dynamics of hydrological pulses has been suggested as the main modeller agent of the fluvial landscape (Neiff, 1990a). In this conceptual scheme, the active role of other components of this environment such as groundwater has been given less attention.

Despite the scarce consideration of groundwater, the literature provides at least two conceptual frameworks that emphasize its importance in landscapes of different types. The conceptual model of groundwater flow systems (Tóth, 1999) proposes the hierarchical identification in 3D of flow systems that are generated in any given territory, incorporating the recharge, transit and discharge area of each identified flow system. Other authors (Grimm and Fisher, 1984; Duff and Triska, 1990; Standford and Ward, 1993; Standford, 1998) consider groundwater in the context of hyporheic corridors as hydric ecotones where interaction between surface water and groundwater takes place in floodplains of lowland rivers.

It is estimated that more than 95% of unfrozen available water (fresh) on the continents is groundwater (Freeze and Cherry, 1979). The importance of incorporating the study of groundwater and its relation to ecosystems has been supported by numerous examples that have documented the relationship between groundwater and biological communities at different scales. At micro-scale, groundwater is important in nutrient input and the physical and chemical characteristics of ecosystems, determining, for example, microbial activity (Boulton *et al*., 1998), the presence/absence of benthic organisms (Creuzé des Châtelliers and Reygrobellet, 1990) and micro-invertebrate communities (Brunke *et al*., 2003). At landscape scale, groundwater affects ecosystems in general (Rosenberry *et al*., 2000; Carrillo-Rivera *et al*., 2007; Patten *et al*., 2008) and vegetation cover in particular (Lodge *et al*., 1989; Batelaan *et al*., 2003; Baird *et al*., 2005; Muñoz-Reinoso and García Novo, 2005; Schipper *et al*., 2007).

In Argentina, studies of the effect of groundwater dynamics on ecosystems are few (Jobbágy and Jackson, 2007; Jobbágy *et al*., 2008; Nosetto *et al*., 2008), and those related

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to the floodplain of the Parana River are even fewer (Fili, 1986; Marchetti, 2011). Although the Parana River has been extensively studied, the surface water has hidden the presence and function of groundwater and hindered the assessment of its contribution to related ecosystems.

The main objective of the present work is to identify groundwater discharge input by analysis of flow systems and to characterize at community level the associated vegetation in the floodplain of the Parana River.

STUDY ZONE

The study zone is a sector in the floodplain of the Parana River in its middle reach (Iriondo and Drago, 1972) between the cities of Santa Fe and Parana (Figure 1). The Parana River flows through La Plata river basin, which is among the largest fluvial systems in the world (3 100 000 km^2). A maximum yield of 60 000 m^3/s has been recorded for the Parana River (Giacosa *et al.*, 2000).

The middle reach of the floodplain of the Parana River is some 600 km long and 13–60 km wide. It covers approximately 7200 km^2 (Iriondo and Drago, 1972) and is represented in two of the geomorphological units recognized by Iriondo (2007): bars plain and meanders plain. The bars plain is a belt of elliptic bars of fine sand close to the main channel that are permanently modified by processes of erosion and sedimentation. It is formed by bars and islands inside the major channel, and sand bars developed at the channel margins. The meanders plain lies along the right margin of the floodplain. In this plane, the Colastine River, an important branch of the Parana River, has been shaping a meander plain composed, on the surface, of fine silty sand.

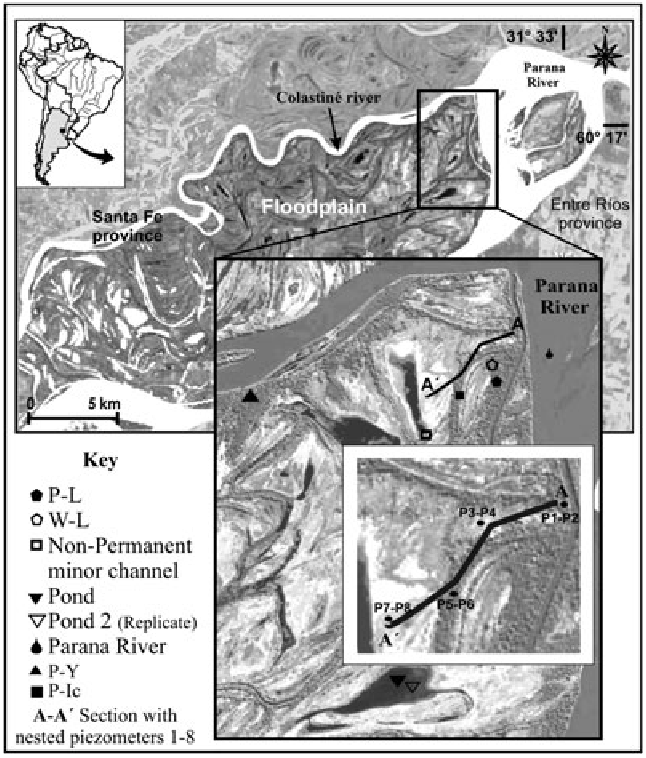

Figure 1. Study zone in a sector of the floodplain of the Parana River showing water sampling sites. P-L and P-Y are domestic boreholes, W-L is a shallow well, Non-Permanent minor channel is a secondary channel just active during annual flooding, Pond and Pond 2 represent two samples taken in a permanent pond and P-Ic is a piezometer built on a secondary channel bank. Piezometers 1 to 8 were built on sites located along Section A-A′

The soils comprise successive layers of sediment that are carried and deposited by the river during each flooding episode. Spatial distribution and thickness of each layer of sediment is heterogeneous as a result of flood dynamics and topography. According to definitions of soil taxonomy (Soil Survey Staff, 1999), these fluvial soils are *entisols* and belong to the sub-orders *Aquents* and *Fluvents* (Orellana and Bertoldi de Pomar, 1969). *Aquents* generally correspond to levees, and *Fluvents* correspond to the lowest topographic zones with high sedimentation rates.

The climate in the floodplain of the Parana River is subtropical humid with an average annual temperature of 19 °C. Yearly rainfall ranges from 900 to 1000 mm with 70% falling between October and April (Rojas and Saluso, 1987).

The surface hydrology is characterized by a succession of high and low water phases (Figure 2) that have an ordinary regime (every 1, 2 or 3 years) and an extraordinary regime (every 8 to 10 years) (Neiff, 1996; Neiff *et al.* 2000). The groundwater hydrology of the study zone is poorly understood; two hydrogeological systems, one of shallow water and one of deep water, have been proposed (Fili, 1986) but with little detail of their hydraulic relationship. The water table is shallow, from 10 cm to 4–5 m deep.

From a geological perspective, the study zone belongs to the Chaco-Paranaense basin (Ramonell, 2005). It lies on a thick (>5500 m) sedimentary-volcanic sequence with regional distribution. These materials cover a regional crystalline hydrogeologic basement consisting of igneous and metamorphic rocks of the Precambrian and a low undifferentiated Palaeozoic sequence (1516 Ma to 5500 Ma in age). From bottom to top, this material is represented by 2000 m of sediments beneath Upper Carboniferous deposits; above these lies 1500 m of clay and black shale, interspersed with white sandstone, as well as diamictite, grey shale, sandstone and limestone, representing the Upper Carboniferous and Lower Permian. Lying on the Palaeozoic sequence, there is a thickness of ≈1000 m from the Upper Jurassic to Lower Cretaceous; the older is sedimentary (sandstone of mid grain size interbedded with a thick sandstone conglomerate of fluvial origin), and the younger is volcanic (tholeiitic basalt) interdigitized with layers of sandstone. Above this material, there is a 300 m stratum of fine-grained

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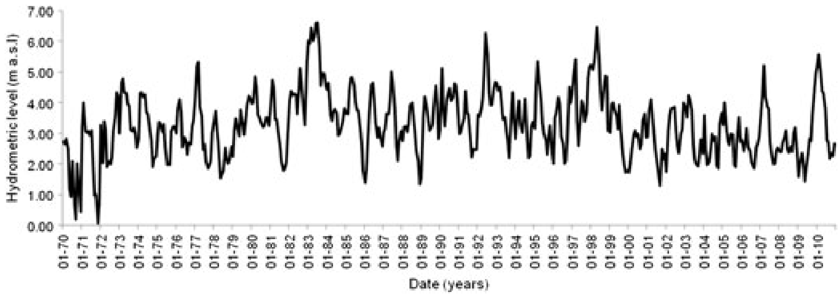

Figure 2. Seasonal variation of the Parana River hydrometric level in the last 40 years. This period represents a homogeneous behaviour of the river in the last century

marine sandstone of Upper Cretaceous to Palaeocene age. Eocene to Lower Miocene (Chaco Formation) sediments are composed of sandstone and shale interbedded with gypsum with a thickness of about 300 m. On top, there are materials belonging to the Middle Miocene (Parana Formation) represented by a marine transgression, 280 m thick, of fine grey sand and interbedded green clay lenses, which has been identified over the whole Chaco-Pampa region in Argentina, northern Paraguay and Bolivia. Current deposits of possible Upper Miocene to Holocene age are represented by 50 m of fluvial silt, sand and clay deposited in a floodplain by successive floods, and these are the dominant landforms of the study zone.

This sedimentary fill of >5500 m thickness has been reported (Pesce and Miranda, 2003) to form a complex stratigraphic column of different texture. It is fully saturated with water of a salinity that differs according to the site and depth. In general, water salinity from shallow to deep varies from fresh with 500–1000 mg/L of total dissolved solids, through brackish (<10 000 mg/L) to saline (~60 000 mg/L). Some direct explorations (boreholes) have reached basement rock (Pesce and Miranda, 2003), but most of these were outside the study zone.

METHODS AND MATERIALS

Conceptual method of work

The concept of gravitational systems of groundwater flow (Tóth, 1999), which recognizes groundwater as a geologic agent, helps to throw light on the behaviour of groundwater as a common element in a variety of natural phenomena in the study zone.

This model uses direct and indirect evidence that results from the interaction of groundwater with various elements of the environment, including the hierarchical nature of flow in a three-dimensional movement within the prevailing geological framework. Hence, local, intermediate and regional flow systems can be identified, each with its areas of recharge, transit and discharge (i.e. water seeping out from below ground) (Figure 3). In general, the water of each flow has an isotopic content according to the altitude and location of its recharge; as water travels, its chemical content depends on lithology, travelling depth and distance. A local flow has a short and shallow path, so its characteristics will be closer to recent rainfall, and it will be influenced by dissolved minerals from geologic units through which groundwater has flowed. A regional flow travels the deepest and longest path underground, with its recharge area in the highest continental region and its discharge in the lowest topographic area. A local flow recharges and discharges in top neighbouring topographic places; a local flow is superimposed on intermediate flows. Intermediate flows circulate between those of local and regional type, showing physical and chemical characteristics intermediate between those flows. Although water quality of different flows evolves along their path, their paths do not mix. The water in a regional flow, as it approaches its discharge area, becomes chemically homogeneous whatever the composition of the geological units through which it has travelled (Carrillo-Rivera *et al*., 2007b).

Recharge and discharge areas can be identified by indicators at surface level. Recharge areas have a water table level ranging from metres to tens of metres deep, whereas discharge areas have a water table level ranging from a few metres to groundwater springing out on the soil surface; discharge areas are generally in the lowest topographic positions (Tóth, 1999).

A recharge area is characterized by an absence of saline soil, soil moisture deficiency and mainly woody vegetation; the groundwater has low pH and salinity and has high oxygen content and a downward vertical movement. In contrast, in a discharge area, there could be springs and phreatophyte vegetation, soil moisture content is high, and saturation water has higher salt content, more alkaline pH and reducing conditions; the direction of groundwater movement is upward (Tóth, 1999). The water-level response during drilling has received little attention: as the depth of drilling progresses in an area of recharge, the water table will be deeper; conversely, in a discharge area, as the depth of drilling progresses, the level will be increasingly shallow. In a transit area, the water

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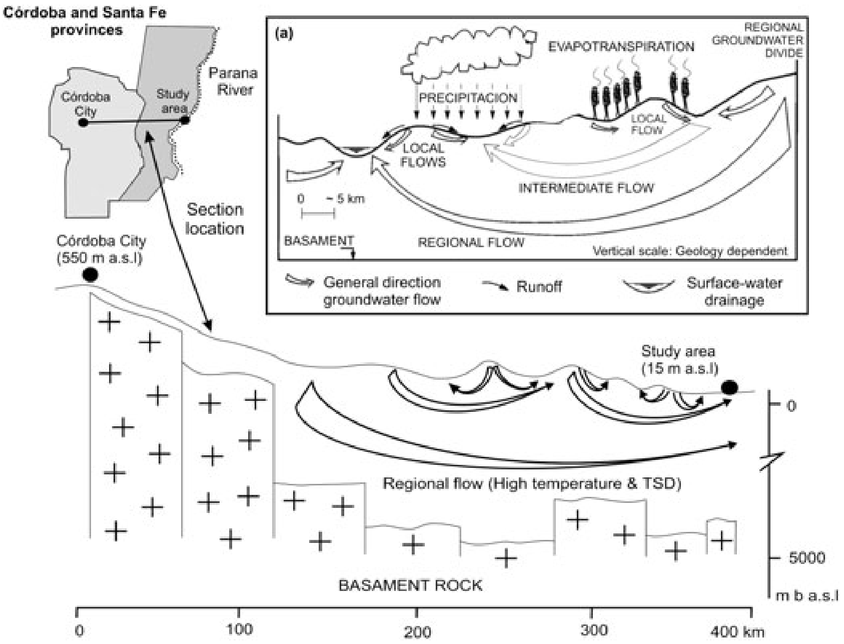

Figure 3. (a) Diagram of groundwater flow systems with light adaptations to the one proposed by Tóth (1999). Note that in the region related to the study zone, the vertical scale represents about 5500 m, so the size of the Parana River is considerably small

table depth will be basically the same, regardless of investigation depth (Freeze and Cherry, 1979)

Owing to the origin of a local flow, its discharge quickly responds to relatively abundant local rainfall. On the other hand, because the recharge areas of intermediate and regional flows are far away from their discharge areas, the hydraulic response of these discharge areas usually cannot be linked to local rainfall.

The characteristics of groundwater differ according to whether it is in a recharge area [low salinity and temperature, positive Eh, acid pH and high dissolved oxygen (DO) content] or a discharge area (high salinity and temperature, more negative Eh, alkaline pH and low DO content). In general, the altitude of recharge may be predicted according to climatic (temperature) conditions at the time of recharge by using historical data for several stations relating δ^{18}O in rainfall to station altitude; this results from an application of isotopic fractionation of ^{18}O and ^{2}H. Groundwater will have more positive values (implying a decrease in the fractionation factor; Criss, 1999) when the flow comes from a recharge area in a place with high temperature (i.e. away from a mountainous location). Water in a transit area has characteristics of the recharge water chemically evolving to the quality of water in the discharge area and a horizontal flow (Figure 3).

Groundwater discharge of flows of different hierarchy, together with factors such as the influence of surface water and wind (erosion/deposition), gives a particular chemical (and isotopic) quality to the soil through several complex processes that influence not only the natural biota of the site but also its prevailing structure. Each groundwater flow system in a region can be identified by its chemical and isotopic characteristics; these may determine the availability of a specific groundwater (e.g. brackish water) and thereby influence the presence of a specific soil-biota structure. An understanding of groundwater flow systems requires not only analysis of groundwater dynamics but also incorporation of information on other components of the environment (Carrillo-Rivera *et al*., 2007b).

Geologic and flow system models. The geological framework in the study zone has several implications to identify groundwater discharge in the floodplain of the Parana River. According to Figure 3, the underlying thickness of ~5500 m of sediment implies the following: (i) there are conditions for the development of regional flows with recharge areas in high topographic regions, for example, in Sierras of Córdoba (~400 km distance), circulating at depth in the thick stratigraphic column; (ii) owing to the distance and depth of the expected water pathway, these flows will have contrasting physical and chemical characteristics (i.e. temperature, salinity); (iii) the study zone has potential for the development of extensive intermediate flows; (iv) levees, a typical landform caused by geomorphologic dynamics, allow the formation of local flow systems; (v) local flows will be contained by intermediate flows and (vi) the stratigraphic thickness, low hydraulic conductivity and flat geomorphology force

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regional flows to travel deeply and thereby prevent the manifestation of thermal water in the region.

Materials and data collection

Piezometer installation. Eight piezometers were built in adjacent pairs (P-1 and P-2, P-3 and P-4, P-5 and P-6, P-7 and P-8) in a transverse section A-A′ of the study zone (Figure 1). The section started from the main channel (Parana River) and extended into the floodplain, thereby including a variety of landforms and vegetation units. To study the groundwater movement on the vertical plane, the water level was recorded at each pair of adjacent piezometers, these having been constructed at different depths (Table I, Section A-A′ in Figure 1). Recording of the relative difference of hydraulic head as reported from piezometric readings at different adjacent depth allows the identification of recharge to groundwater, or of the opposite process, discharge conditions. Piezometers were between 1 and 6 m deep and had a diameter of 2.5 in.; total depth was ~0.50 m below the detected water level during their installation. Piezometers were constructed using PVC casing, slotted for the final 0.30 m and fully immersed in a gravel filter. A helical shovel without lubricant was used to bore the cavity of the piezometer.

Hydraulic response. The vertical movement of the water table was recorded in each piezometer during its construction. These data are a useful indicator of discharge, transit or recharge conditions and provide an additional element in defining the hydraulic response conditions of existing flows.

Groundwater movement in the vertical plane. The groundwater level was recorded manually in each pair of piezometers of Section A-A′ (Figure 1), weekly from December 2007 to 2009. To have a reference level according to the altitude of the water at the Parana River, the altitude of the top of the casing of each piezometer was measured. In this way, the groundwater head was recorded in relation to the level of the Parana River; results are shown as metres above mean sea level. According to the mean level recorded (14.62 m a.m.s.l.), the Parana River level was in a low water phase (13.89 m a.m.s.l.) during the studied period.

Groundwater sampling and analyses. Twelve samples were collected: from five piezometers and also one in a non-permanent minor river channel, a pair in a permanent pond (two samples collected simultaneously in order to test the laboratory accuracy), one in a shallow well, two from domestic boreholes and one from the Parana River.

Sampling was according to APHA, AWWA, WPCF (1989) international protocol. During water collection, field measurements of physical and chemical parameters were recorded, taking four readings at 10-min intervals for electrical conductivity, temperature, pH, Eh and DO. Field determinations were made with equipment pre-calibrated in the laboratory. The pH metre was re-calibrated in the field with buffer solutions at 4, 7 and 10 pH; the containers with the buffer solutions were immersed in the water to be sampled, to allow the buffer solution to reach water temperature. Bottles were new and previously washed with a detergent solution, rinsed with tap water, immersed in a solution of 10% HNO_3 and finally rinsed three times with distilled water. Immediately before samples were collected, bottles were rinsed three times with water from the sample site. All piezometers were purged 24 h prior to sampling. In each sampling site (Figure 1), five 60 ml bottles were filled: (i) to analyse anions (filtered through a cellulose acetate membrane of 0.45 μm); (ii) to analyse heavy metals (filtered and acidified by adding nitric acid to take content to a pH of ~2); (iii) to determine stable isotopes ^{18}O and D (only filtered); (iv) control sample and (v) for alkalinity determination (filtered). All air bubbles were removed

Table I. Piezometer pairs (P-1 and P-2, P-3 and P-4, P-5 and P-6, P-7 and P-8) showing their altitude (m a.s.l.), total depth (m) and mean observed water level recorded from December 2007 to 2009

Piezometer			Registered level (depth to water table)		
	Altitude	Total depth	Mean	Minimum	Maximum
P-1	16.64	5.80	13.41 (−3.23)	12.47 (−4.17)	15.75 (−0.89)
P-2	16.37	3.60	13.62 (−2.75)	12.94 (−3.43)	15.58 (−0.79)
P-3	14.76	2.20	13.61 (−1.15)	12.94 (−1.82)	14.61 (−0.15)
P-4	14.79	1.20	(nwl)	(nwl)	(nwl)
P-5	16.62	4.50	13.57 (−3.05)	12.77 (−3.85)	15.79 (−0.83)
P-6	16.44	4.00	13.56 (−2.88)	12.86 (−3.58)	15.84 (−0.60)
P-7	13.95	2.00	13.64 (−0.31)	13.06 (−0.88)	13.95 (0.00)
P-8	13.89	1.30	13.51 (−0.36)	13.00 (−0.89)	13.89 (0.00)

nwl, means the water table was below the total depth for most of the study period.

Table II. Physico-chemical parameters recorded during field sampling and laboratory analyses

	Parameters recorded in field					Stable isotopes		Major ions											Minor and trace elements					
		mv	°C	µS	mg/L			mg/L											[µg/L (ppb)]					
Sample	pH	Eh	T°C	EC	DO	δD	$\delta^{18}O$	Cl	NO_2	Br	NO_3	PO_4	SO_4	Ca	Mg	K	Na	HCO_3	As	F	Li	Be	B	Al
Intermediate flow																								
Pond	8.2	66.5	21.1	826.0	6.1	−3.2	−1.72	174.0	<0.02	0.21	0.04	<0.04	15.6	39.6	17.6	4.1	77	22.0	5	<0.02	8.55	<0.05	66.20	5.1
Pond 2 (replicate)	8.2	66.5	21.1	826.0	6.1	−5.3	−1.59	166.0	<0.02	0.21	<0.02	<0.04	10.5	39.8	17.7	4.3	78	18.3	8	<0.02	8.61	<0.05	65.84	2.1
P-L	6.4	−139.4	19.5	500.0	0.2	−29.5	−4.53	10.7	<0.01	<0.03	0.04	<0.02	0.23	41.6	17.2	2.5	23	27.5	17	0.02	6.23	<0.05	63.13	2.7
Non-permanent minor channel	6.2	94.8	21.3	189.8	3.4	−23.5	−2.90	20.5	<0.01	<0.03	0.20	<0.02	5.58	7.8	3.5	12.7	6	14.0	2	0.05	6.22	<0.05	34.29	46.8
Local flow																								
W-L	6.7	−6.5	18.2	505.5	2.2	−28.8	−4.64	10.5	0.02	<0.03	0.14	<0.02	0.34	43.3	16.0	2.3	19	41.5	4	0.02	2.80	<0.05	64.00	4.6
P-Y	7.0	−146.0	21.1	202.5	0.4	−28.0	−4.77	4.9	<0.01	<0.03	<0.01	<0.02	0.64	14.1	6.5	1.1	5	27.5	7	0.02	2.99	<0.05	15.65	0.4
P-1	6.6	−136.3	19.1	730.5	2.3	−28.1	−4.85	9.8	<0.02	5.63	0.03	<0.04	2.53	78.8	32.0	5.4	17	83.0	4	0.40	1.60	<0.05	48.82	51.3
Parana River	7.5	106.5	22.7	110.7	6.5	−33.8	−5.09	11.5	0.29	0.63	0.05	0.36	11.2	7.9	2.2	1.9	4	8.5	3	0.50	1.88	<0.05	15.34	329.5
P-Ic	6.0	−56.0	19.3	420.0	4.5	−29.3	−3.74	14.5	<0.01	<0.03	0.06	<0.02	17.4	37.1	11.8	6.0	19	47.0	4	0.51	1.62	<0.05	48.24	43.1
Mixed flows																								
P-5	6.2	125.8	19.9	435.3	5.4	−29.1	−4.78	15.5	0.11	<0.03	0.37	<0.02	1.84	41.9	16.9	4.2	16	47.0	8	0.37	5.54	<0.05	52.28	260.0
P-6	6.0	−56.0	19.3	420.0	4.5	−27.8	−4.40	14.9	<0.02	<0.06	0.11	<0.04	0.19	52.0	23.4	6.2	28	72.0	7	0.53	5.74	<0.05	47.50	8.1
P-7	7.0	92.0	22.0	592.8	5.0	−28.1	−4.49	31.2	0.10	<0.06	0.31	<0.04	28.2	49.6	16,0	22.0	17	44.0	5	0.13	3.96	<0.05	59.33	63.6
P-8	6.3	67.8	19.6	674.3	3.9	−32.2	−3.64	27.2	0.13	<0.06	0.19	<0.04	63.1	49.3	24.5	1.2	23	44.0	8	0.19	4.59	<0.05	62.44	32.7

Isotopic data are reported in delta (δ) unit per thousand (‰) that is defined by R_{sm} in the sample and in the standard. Grey type represents evaporated water.

EC, electrical conductivity; DO, dissolved oxygen.

Pond and Pond 2 represent two samples taken in a permanent pond, P-L and P-Y are domestic boreholes, Non-Permanent minor channel is a secondary channel active solely during annual floods, W-L is a shallow well, P-Ic is a piezometer built on the secondary channel bank and P1, 5, 6, 7, 8 are piezometers in section.

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before the bottles were closed. All samples were preserved on ice at 4 ° C until they arrived at the laboratory. Metals were analysed (Table II) in the Laboratory of the Faculty of Chemical Sciences of the Autonomous University of San Luis Potosí, Mexico; anions, F, Li, Br, NO_3, PO_4, As and B were analysed in Activation Labs, Toronto, Canada, by ion chromatography. Other trace elements were analysed by ICP-MS, and As by ICP-AES. Alkalinity was assessed in the *Laboratorio Integral de Análisis Químicos Industriales y Agropecuarios* in Parana City, Entre Ríos, Argentina, using the Standard method 2320 (Rice *et al*., 2012). Stable environmental isotopes, reported as $\delta^{18}O$ and δD, were analysed by mass spectrometry (VG Micromass 602C) in the heavy isotopes laboratory, LUGIS, of the Geophysics and Geology institutes of the National Autonomous University of Mexico (UNAM), which is certified by the International Atomic Energy Agency. The analytical error of $\delta^{18}O$ and δD determination was 0.02‰ and 2‰, respectively.

Associated vegetation communities. The presence of zones of homogeneous vegetation was identified along Section A-A′ (Figure 1) from satellite images Landsat 5 TM Path 227/Row 082 and field observations. Ten sample units were located within each zone identified. The minimal area of each sample unit was determined in the field by considering the surface occupied by each homogeneous zone; this was achieved by applying the species–area curve for the vegetation to be sampled (Chytrý and Otýpková, 2003). Each sample unit covered an area of $400\,m^2$ (20×20 m quadrants) for woody vegetation and $25\,m^2$ (5×5 m quadrants) for herbaceous vegetation. Within each sample unit, the abundance/cover of all species, from herbaceous to woody, was recorded according to the abundance/cover scale of Mueller-Dombois and Ellenberg (1974). Results yield a visual estimation of the importance of each species according to the following categories: r = only one individual is detected, and it covers less than 5% of the sample surface, + = 2–20 individuals are detected, and they cover less than 5% of the sample surface; 1 = more than 20 individuals covering less than 5% of the sample surface; 2 = 5–25% cover, 3 = 26–50%, 4 = 51–75%, 5 = 76–100%. The species that could not be identified in the field were collected for later taxonomic determination. Botanical nomenclature of all species followed Zuloaga *et al*. (2008a, 2008b, 2008c).

All vegetation sample units were organized in a primary matrix made of abundance/cover data for each species. Symbols ‘r’ and ‘+’, included in the Mueller-Dombois and Ellenberg abundance/cover scale, were transformed to values of ‘0.20’ and ‘0.50’, respectively, to include them together with the rest of the values (1–5) in the analyses. The main matrix was classified by cluster analysis using Euclidean distance as dissimilarity measure and Ward’s method as linkage criterion. The floristic analyses were carried out with PC Ord 4.1 software (McCune and Mefford, 1999).

RESULTS AND DISCUSSION

Groundwater movement in the vertical plane

During piezometer construction, the water level ascended at piezometers P-3, P-4, P-7 and P-8, descended at piezometers P-1 and P-2 and moved only slightly at piezometers P-5 and P-6. These observations suggest discharge, recharge and transit (horizontal) conditions, respectively, at the time of construction.

Groundwater variations at piezometers P-1 and P-2, P-5 and P-6 and P-7 and P-8 were associated with variation in the Parana River hydrometric level during most of the recording period (Figure 4) until early 2009. After that, the river level fluctuated more abruptly and markedly than the water levels recorded in the piezometers. The difference in water level response among piezometer pairs increased in 2009.

Dates on which the water level in piezometers (Figure 4) appeared to remain constant (P-4: 3/08, 7/08, 1/09, 3/09), (P-7 and P-8: 5/08, 7/08) are those on which the water level was below the total depth of piezometer P-4, or on the soil surface in the case of piezometers P-7 and P-8. On these dates, the water level could not be recorded. Nevertheless, the water table in piezometers P-3 and P-4 was higher than the Parana River hydrometric level during several periods, suggesting groundwater discharge conditions. This implies a groundwater head higher outside the study zone.

Figure 4 shows little difference in the water level head of piezometers P-5 and P-6 or of P-7 and P-8, whereas there were inter-pair differences for P-1 and P-2 and for P-3 and P-4. The water level in piezometer P-6 was an average of 0.045 m higher than in piezometer P-5 during 45% of the recorded time. For the remaining time, the water evel was 0.047 m higher in piezometer P-5 than in piezometer P-6. The slight difference between the water level in these two piezometers suggests a horizontal movement of groundwater (the low vertical component) typical of transit areas. In contrast, the water level in piezometer P-2 was between 0.08 and 0.47 m shallower than in piezometer P-1 during 90% of the recorded period. The downward movement from P-2 to P-1 suggests recharge conditions (from 09/09 to 12/09); for the remainder of the time, the water level in piezometer P-1 was 0.17 and 0.68 higher than piezometer P-2, showing discharge conditions. Both situations showed the importance of defining the groundwater movement in the vertical plane. Similarly, the water level in piezometer P-3 (set deeper than piezometer P-4) was higher than in piezometer P-4, indicating discharge conditions. The water level in piezometers P-7

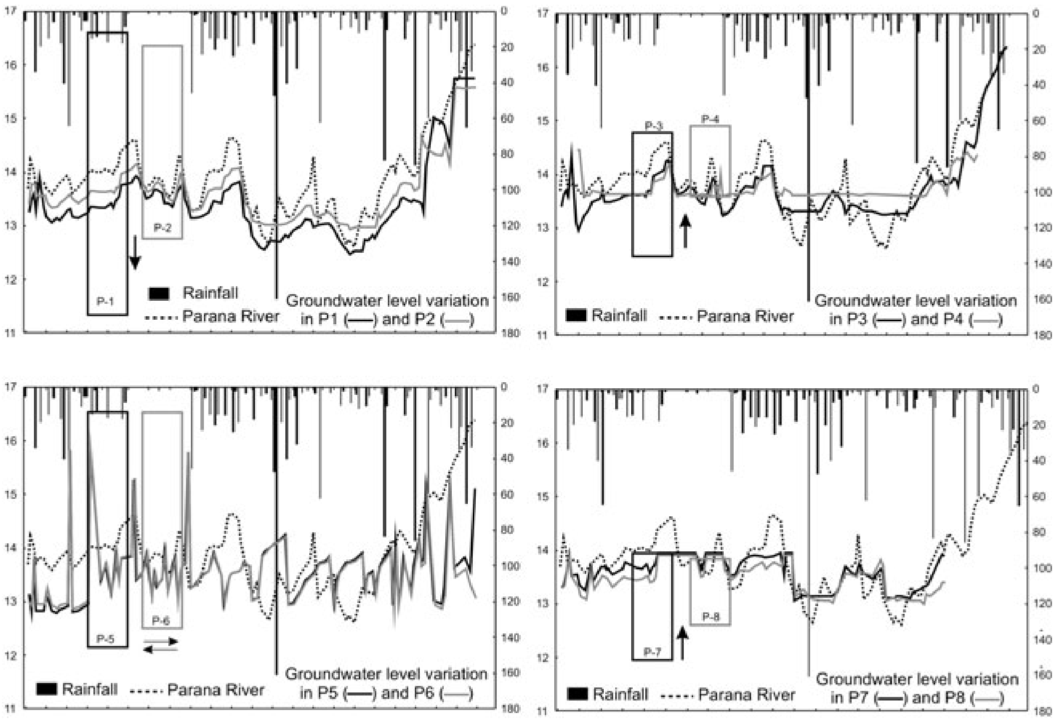

Figure 4. Variation of water level in the Parana River and in groundwater during the studied period (December 2007–2009) in adjacent piezometers (black and grey boxes). Bars represent the rainfall recorded *in situ* during the same period. Downward arrow represents descending vertical movement of the water level during piezometer construction; upward arrow represents ascending vertical movement of the water level during piezometer construction; horizontal arrows represent slight movement of ascending/descending water level for piezometers during piezometer construction

and P-8 also showed discharge conditions because piezometer P-7 (set deeper than piezometer P-8) showed a higher water level for most of the studied period. Further, Figure 4 shows the absence of any relationship of water table to rainfall in most of the piezometers.

Groundwater physical–chemical characterization

The physical–chemical parameters of surface water and groundwater in the 12 samples (Figure 1) are shown in Table II (note that ‘Pond 2’ sample is a control replica of sample ‘Pond’). A stoichiometric difference between cation and anion concentration suggested an inconsistency in alkalinity determination, so alkalinity results were not incorporated in any interpretation; however, other results were considered reliable.

Isotopic signature analysis. Stable isotope determination is an important tool in groundwater studies (D’Elia *et al*., 2008; Panarello and Dapeña, 2009). For example, the isotopic signature can define temperature conditions (altitude) to which the sampled water was exposed during its recharge. Moreover, evaporation processes to which the groundwater could have been exposed during its pathway can be identified because evaporated water is progressively enriched faster in δ^{18}O than in δD (Clark and Fritz, 1997).

Evaporation can be identified from the position of the water sample in relation to the Global Meteoric Water Line (Figure 5) as is the case of samples of piezometers P-8 and P-Ic, and Minor Channel (Table II). If a flow has local hierarchy, the isotopic signature of the groundwater sample will be similar to local rainfall. If the signatures differ, the recharge source will be other than present local rainfall.

The δD and δ^{18}O values used are based on the fact that the isotopic composition of groundwater reflects the weighted average of the isotopic composition of rainfall in the recharge area. Precipitation is depleted of heavy isotopes as the mass of air moves inland from the coast (continental effect; Clark and Fritz, 1997), or when an air mass rises in altitude (altitude effect), or when there are long storms, particularly, at the end a storm with abundant rainfall (quantity effect). It is well known (Freeze and Cherry, 1979) that the rain on the coast is much more enriched in δ^{18}O and δD than rainfall towards the continent and mountains. Delta values are more negative towards the poles than towards the Equator. Because the isotopic composition of groundwater is expected to remain the same along its flow pathway because there are no geothermal sources that might produce chemical reactions

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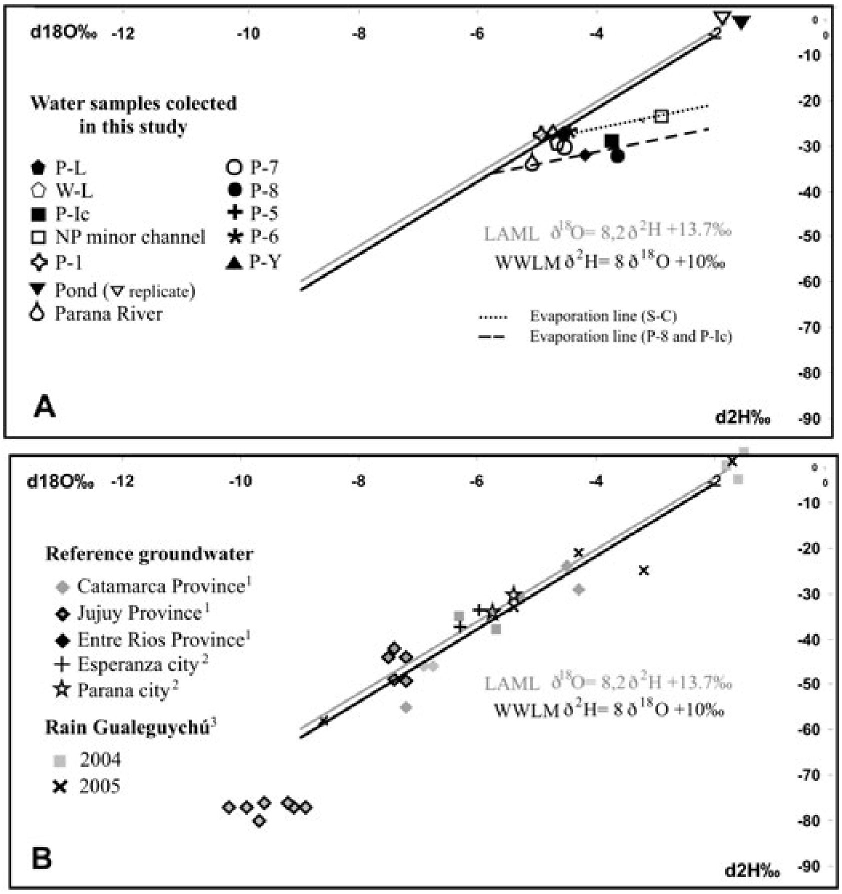

Figure 5. (A) Shown here is the relationship between δ18O and δD for samples collected in the study zone. (B) Reported reference data is from (i) Pesce and Miranda 2003, (ii) D'Elia *et al*. 2008 and (iii) Institute of Geochronology and Isotopic Geology, CONICET, Argentina. LMWL, Local Meteoric Water Line (D'Elia, 2006); GMWL, Global Meteoric Water Line

(Freeze and Cherry, 1979) in this study, δ^{18}O and δD may be used to estimate conditions and processes occurring in the recharge area.

Isotopic values in the water samples in the present study ranged between −1.7‰ and −5.1‰ for δ^{18}O and between −3.2‰ and −32.2‰ for δD (Figure 5 A). The more enriched isotopic value corresponds to the Pond sample. Local inhabitants recorded that this pond had always contained water, even when river water was low or during drought. With NO_3 at 0.04 mg/l and NO_2 at <0.02 mg/l, there was no evidence of contamination in the pond and the isotopic content gave no evidence of evaporation (Figure 5). The Pond sample suggests a flow that was recharged by water precipitated at a lower altitude than the rest of the water samples, or during warmer weather conditions, which seems to be the more plausible explanation.

The stable isotopes were most depleted in the sample from the Parana River. This would be expected as it collects water precipitated at high altitudes in the Andes, the Brazilian Shield, as well as regions subject to penetration of wet air-vapour masses from the Atlantic that cause rainfall in large areas of Brazil (Panarello and Dapeña, 2009). Those authors reported a significant variation in the isotopic content of the Parana River over a 10-year period related to the amount of precipitation associated with the inter-tropical convergence zone: δ^{18}O varied between −7‰ and −3‰ and δD varied between −44‰ and −15‰. Considering the seasonal variability of the Parana River during the 10 years, even the most positive values are lower than the values recorded in the Pond sample. This precludes any association of the sampled water in the Pond with the Parana River water.

Data in D'Elia *et al*. (2008) for rainfall in Santa Fe and two other cities less than 40 km from the present study zone propose a weighted annual mean isotopic composition for Santa Fe of −5.3‰ for δ^{18}O and −30.2‰ for δD. Regarding groundwater, δ^{18}O varied between −6.3‰ and −5.9‰ in Esperanza City and between −5.7‰ and −5.3‰ in Parana City; δD varied between −37.0‰ and −32.3‰ in Esperanza City and −32.8‰ and −30.2‰ in Parana City (Figure 5 B). Those authors suggested that groundwater responds to local rainfall in the two cities.

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In the present study, all values were higher than those reported by D'Elia *et al*. (2008); they even differed from local rainfall average and from the lowest value recorded for spring-season rainfall. These values support the inference that Pond water does not derive from local rainfall.

Isotopic signature data of groundwater samples from different Argentinean provinces as well as rainfall from Gualeguaychu (provided by *Instituto Nacional de Geocronología y Geología Isotópica*, CONICET, Argentina) (Figure 5B) suggest the following: (i) local water (piezometers P-1 and domestic borehole PY) in the study zone is similar to samples from Catamarca, Entre Ríos and Gualeguaychú-2005; (ii) the Pond sample is similar to Gualeguaychú-2004, which reinforces the suggestion of a different and contrasting origin to the rest of the samples; and (iii) in relation to evaporation processes, piezometers P-8 and P-Ic would represent evaporated water of the Parana River, whereas the non-permanent minor channel would represent evaporated water of all grouped samples.

Major ions and minor and trace elements. The chemical composition of groundwater is the result of continuous processes of interaction between rainfall water that infiltrates into the soil and the lithology it moves through as well as residence time (Price, 2003). Dissolved cations are related to lithology as well as to physical–chemical characteristics of the initial rainwater at the infiltrated site location at high altitude and to the tendency to achieve a chemical balance. The relationship between Ca^{2+}/Mg^{2+} and Na^{+}/K^{+} (Figure 6) of the water in the study zone suggests different flows that might be identified from their different geochemical characteristics. According to this perspective, the Na/K ratio shown by the Pond sample suggests a longer pathway (Domenico, 1972) that could be classed as an intermediate flow. In contrast, in Parana River, piezometer P-1 and domestic borehole P-Y suggest local water flow. Three classes (local flow, intermediate flow and semi-intermediate flow) can also be proposed in Figure 6. These groups suggest that related water samples have been exposed to different physical–chemical processes; that is, after infiltration, rainwater followed a different pathway that determined the difference in its chemical quality.

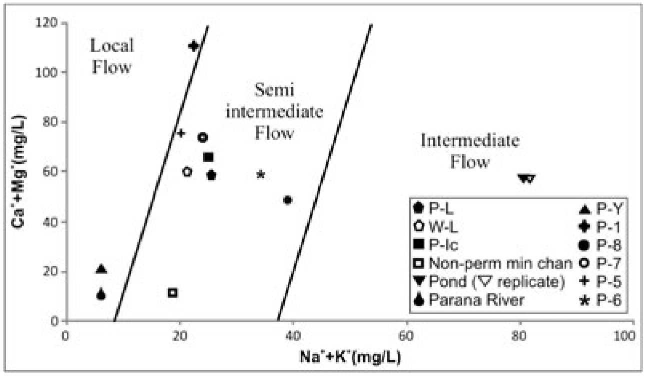

Figure 6. Relationship between $Ca^{2+} + Mg^{2+}$ and $Na^{+} + K^{+}$ in depicting local and intermediate groundwater flow systems

Because the HCO_3 results were not reliable and inorganic carbon could not be analysed, it was not possible to define the relationships among $HCO_3^- > SO_4^- > Cl^-$ and to propose a comparative distance pathway of the samples. Nevertheless, Li^+ concentration in groundwater can be useful as a reliable indicator of residence time (i.e. suggesting that the time groundwater has been circulating underground). The presence of Li^+ is considered as conservative, meaning that additional chemical reactions do not alter its natural concentration. In general, the higher the Li^+ concentration, the longer the residence time (Edmunds *et al*., 1986; Edmunds and Smedley, 2000). In this sense, Figure 8 confirms the aforementioned interpretations; the Pond sample presents the highest Li^+ concentration, a value that is in agreement with the highest value of Na^++K^+. Both results suggest that Pond water has been circulating for a longer time than the other collected samples. The relationship of $Cl^- + SO_4^{2-}$ to $Na^+ + K^+$ (Figure 7) suggests a local flow, a conclusion supported by the Li^+ concentrations (Figure 8) and the presence of at least three groups of water. The first includes the Parana River, piezometers P-1 and P-Ic and domestic boreholes P-L and P-Y samples, with these representing a local flow with the shortest residence time. The second represents the Pond water sample with the longest residence time. The third group consists of samples that have been circulating for a time and distance intermediate between the other two groups. The reported Cl^- concentration (15 to 30 mg/l) for the water samples in the third group suggests a ~30 km average pathway from the recharge area (Edmunds and Smedley, 2000).

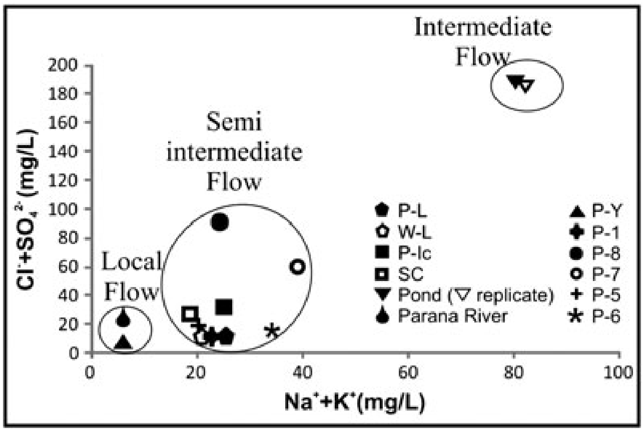

Figure 7. Relationship between $(Cl^- + SO_4^{2-})$ and $(Na^+ + K^+)$ in depicting local and intermediate groundwater flow systems

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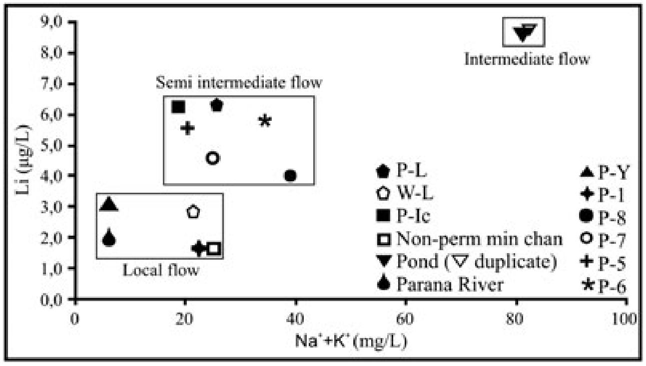
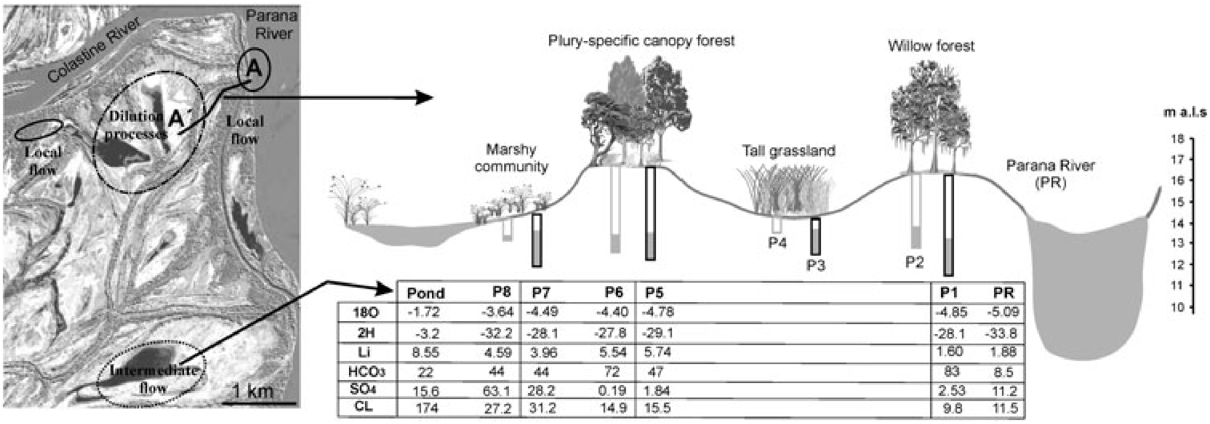


Figure 8. Relationship between ($Na^+ + K^+$) and Li^+ concentration. Li + concentration is used as an indirect indicator of groundwater residence time; it suggests three groundwater groups

Vegetation coverage as related to groundwater conditions. The influence of groundwater on the landscape in the study zone was reflected in the organization of biological communities. Where piezometers were constructed, dissimilarities were detected among vegetation communities that could be related to different groundwater quality and direction of movement. Floristic composition was used to identify four vegetation communities: willow forest, plurispecific-canopy forest, tall grasslands and marshy community (section A-A′ in Figure 9).

Willow and plurispecific-canopy forests were in the highest topographic position. Associated piezometers (P-1 and P-2 and P-5 and P-6, respectively) showed different groundwater behaviour. The willow forest showed mainly recharge conditions (downward vertical movement) suggesting that associated vegetation depends on the water quality provided by rainfall input. The piezometers in the plurispecific-canopy forests showed transit conditions (horizontal groundwater movement) that could imply that this forest receives water derived from recharge other than local. These differences seem to be related to physiognomy, structure and floristic composition between the two forests (Figure 9). Tall grasslands, located between willow and plurispecific-canopy forests, represent one of the most frequent herbaceous communities in the fluvial landscape, and this community occupies intermediate topographic positions. The marshy community (herbaceous) appeared at the lowest topographic position (end of section A-A′) that is usually found in areas with high hydrological dynamics. Tall grassland showed an association with groundwater with chemical quality related to a flow of local origin (Figure 9). The marshy community was associated with discharge areas of local/intermediate flow system.

Importance of groundwater discharge in lowland river floodplains. Groundwater discharge is important in relation to the ecosystem. As the nature of expected flows to discharge is of different hierarchy (i.e. local, intermediate), their water quality can determine the physical–chemical characteristics of a water body and therefore to influence the presence of specific biological communities. The recognition of the presence of discharge conditions in a large floodplain helps to assess groundwater-dependent ecosystems and to predict their potential relationship to certain chemical constituents in the water and soil. The floodplain of the middle Parana River has a shallow water table suggesting discharge conditions over an extensive surface (approximately 7200 km^2). The floodplain also has a large land surface covered by water bodies with a range of salinities; most of this water is expected to be from rainfall accumulation. However, groundwater input causes a direct effect on the expected local water balance, because this input is manifested as discharge of a flow that has originated



	Pond	P8	P7	P6	P5	P1	PR
18O	-1.72	-3.64	-4.49	-4.40	-4.78	-4.85	-5.09
2H	-3.2	-32.2	-28.1	-27.8	-29.1	-28.1	-33.8
Li	8.55	4.59	3.96	5.54	5.74	1.60	1.88
HCO3	22	44	44	72	47	83	8.5
SO4	15.6	63.1	28.2	0.19	1.84	2.53	11.2
CL	174	27.2	31.2	14.9	15.5	9.8	11.5

Figure 9. Spatial distribution of detected groundwater flows showing their main physical and chemical characteristics as well as their relation with vegetation communities. Intermediate flow refers to the discharge of a flow of this hierarchy; local flow refers to recharge discharge process defines for this flow, and dilution process refers to the mixing of intermediate and local flows

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outside the boundary considered. Results of hydrological modelling using Visual-Modflow™, which incorporated the geological sequence described earlier in the second section, suggest that groundwater discharge into the study zone is ~445 000 $m^3\ day^{-1}$.

This interaction between surface water and groundwater has been identified in most landscapes, wetlands and floodplains (Winter, 1999). It has been equally accepted that surface water and groundwater represent linked elements of a hydrological continuum (Standford and Ward, 1993; Sophocleous, 2002) and that surface water represents in most cases a mixture of groundwater and rainfall.

Several studies have shown the close relationship between groundwater and biological communities. The presence of invertebrate species as well as the spatial changes in the composition and abundance of their assemblages (Malard *et al*., 1996) has allowed groundwater biomonitoring and the definition of direction and intensity of water flows between a river and its underflow. In addition, groundwater input in aquatic ecosystems can determine the presence and organization of some aquatic plant species in wetlands as described for the Rhône River, France (Bornette *et al*., 1998) and Minnesota lakes, USA (Rosenberry *et al*., 2000).

Whereas Wassen *et al*. (1992) linked vegetation zoning on the floodplain of the Biebrza River (Poland) to a gradient of physical–chemical characteristics of the groundwater, in the present study, such a gradient was not detected; here, vegetation and the physical–chemical gradient of groundwater from the Parana River to its floodplain were not detected. However, the present results agree with those reported by Schipper *et al*. (2007) for wetlands in Siberia where groundwater was diluted by rainwater.

In relation to water bodies, there were some notable differences. Water samples from the Parana River and a non-permanent minor channel differed markedly from those from Pond and piezometers P-7 and P-8. The sample sites of piezometers P-7 and P-8 were close to a topographic low (about 1.5 m), below the Perennial Pond. Piezometer P-7 was connected to an abandoned channel system that is annually reactivated when the Parana River level rises. This temporal connection could have mixed the water in the pond close to piezometers P-7 and P-8 (Figures 6 and 7) obscuring the groundwater discharge as detected in the perennial Pond. The Pond that is at a higher topographical position is not connected to any drainage system and is perennial in nature; these and its contrasting isotopes are in agreement with a discharge of groundwater belonging to an intermediate flow. The chemical composition of Pond water (Figures 6 and 7) could also suggest P-7 and P-8 water to be in a chemical evolution between local flow and intermediate flow or to be a mixture of Pond water and local flow.

Physical–chemical characteristics and hydrological response suggest a spatial distribution of the processes involved in groundwater manifestation in the floodplain of the Parana River (Figure 9). The levees of the Parana and Colastiné Rivers are mostly associated with recharge areas of local flows (piezometers P-1 and P-2 and the borehole P-Y). Intermediate flows would discharge in sites according to local characteristics (lithology, topography, etc) and could appear to be diluted by rainfall and flood water.

FINAL CONSIDERATIONS

These new data confirm the theory of Tóth (1999) as applied to the study zone. Results suggested the presence of a discharge area, in this case, of local and intermediate flows. In local flows, the residence time of Li as main indicator (~2.0 mg/L) produced differences in physical–chemical characteristics (Figures 6–8) in the water, making it possible to recognize these flows (by their low Na and Cl content). The intermediate flow identified in the perennial Pond lacks agreement with the topographically lowest site. This suggests both an important hydraulic distant connection and specific stratigraphic conditions that require further investigation, a topic beyond the objective of the present work. In a low site, the annual flooding and rainwater could obscure the intermediate flow detected in the perennial Pond sample.

In relation to the recharge area of the detected flows, the local rainfall (Santa Fe) showed an isotopic signature similar to some local flows identified in the study zone. The intermediate flow system showed chemical characteristics that suggested that water would come from a recharge area >30 km from the study zone. On the other hand, the isotopic signature of local rainfall was completely different from that of intermediate flow. The isotopic signature of the intermediate flow is similar to the average rainfall in Gualeguaychu in 2004 (230 km due S-W of the study zone).

Chemical and isotopic evidence suggests that the recharge area of the intermediate flow lies outside the study zone. Topographic altitude suggests that groundwater would be generated in the highest locations and would flow towards the lowest places and, in general, to discharge in the sea or the Parana River. It is likely that the recharge area of the intermediate flow is in a place with weather and altitude conditions similar to Gualeguaychú.

Because groundwater is important in the definition of physical–chemical characteristics in soil and aquatic environments, a proper identification of the presence and hierarchy of groundwater flow systems is an essential complementary tool in interpreting fluvial systems dynamics as well as the characteristics (and dynamics) of associated biological communities. These preliminary results suggested a relationship among groundwater and vegetation communities, whereas the willow forest was associated with the recharge area of a local flow; the plurispecific-canopy forest was linked to a transit area of a semi-intermediate flow. Herbaceous communities, represented by tall grassland and marshy community, colonize discharge areas of local and intermediate flows, respectively. Finally, the importance of identifying the actual discharge conditions also confirmed the need for a conceptual model of hydrological functioning of the territory in agreement with field conditions. In addition, other hydrological studies in a large river floodplain should incorporate discharge conditions in the hydrological balance because water taken by vegetation and by other evapotranspiration processes is not derived solely from local rainfall.

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