

# Origin of flooding water through hydrogeochemical identification, the Buenos Aires plain, Argentina

M. M. Alconada-Magliano · J. R. Fagundo-Castillo ·  
J. J. Carrillo-Rivera · P. G. Hernández

Received: 19 October 2010 / Accepted: 26 October 2010 / Published online: 19 November 2010  
© Springer-Verlag 2010

**Abstract** Hydrogeochemical behaviour of samples of surface and groundwater collected on a cross-section from Mendoza to the Buenos Aires provinces was studied based on chemical trends, mass balance and water mixing. Hydrogeochemical modelling included major, minor elements as well as stable isotopes (deuterium and 18-O). The area investigated is located in the “*Médanos Longitudinales*” (longitudinal dunes) of the northwest of Buenos Aires province, Argentina. The study area is subject to alternating flooding and drought. Rainfall and surface water subsequently transferred by rivers, canals and lagoons have been usually considered responsible for local flooding. For this study, origins of excess water were investigated using physical and chemical characteristics of the water involved. The prevalence of groundwater inflow to rainfall events was proposed based on data interpretation. Groundwater influence of flows of local and intermediate nature were defined and the importance of recharge, transit and discharge zones was highlighted. Lagoon floodwater, as well as groundwater from observation wells and production boreholes, show components of intermediate origin. Regional recharge water was identified in Mendoza

and San Luis provinces. Their discharge zone was inferred to be located beyond the Buenos Aires province.

**Keywords** Hydrogeochemistry · Hydrogeochemical modelling · Flooding · Groundwater flow systems · Stable isotopes · Argentina

## Introduction

The northwest territory of Buenos Aires (NWBA) called “*Pampa Arenosa*” (sandy plain) (6,000,000 ha), is composed of two basic regions: *Salado* (salty)-*Vallimanca* (9,900,000 ha) and *Lagunas Encadenadas* (linked lagoons) of the west (1,100,000 ha); they are located in the Salado River catchment which comprises a surface of 17,000,000 ha of the Buenos Aires province, Argentina. These regions were recently connected to the Salado River by a canal called *Jauretche-Mercante-República de Italia* which starts in the *Hinojo-Tunas* lakes complex and continues to the Bragado lagoon where it reaches the Salado River. The Salado starts in the *Mar Chiquita* and *Gómez* lagoons (Figs. 1, 2). Economic production is largely agricultural. Periods of alternating drought and flooding have been registered in the NWBA since 1576 (Moncaut 2003), affecting sustainability of the regions. The alternating behaviour of the floods has been blamed on natural and anthropic causes. Local rainfall increase is considered the major factor in flooding enhancement. A drought in the 1960s lowered the water level in the Encadenadas lagoons, and then a last humid cycle started in the 1970s due when annual mean rainfall increased from 700 a 1,000 mm (PMI 1999). The canal and related secondary constructed waterways experienced increased flooding in 1985 due to water transfers and as barriers to flow, resulting in costly economic losses.

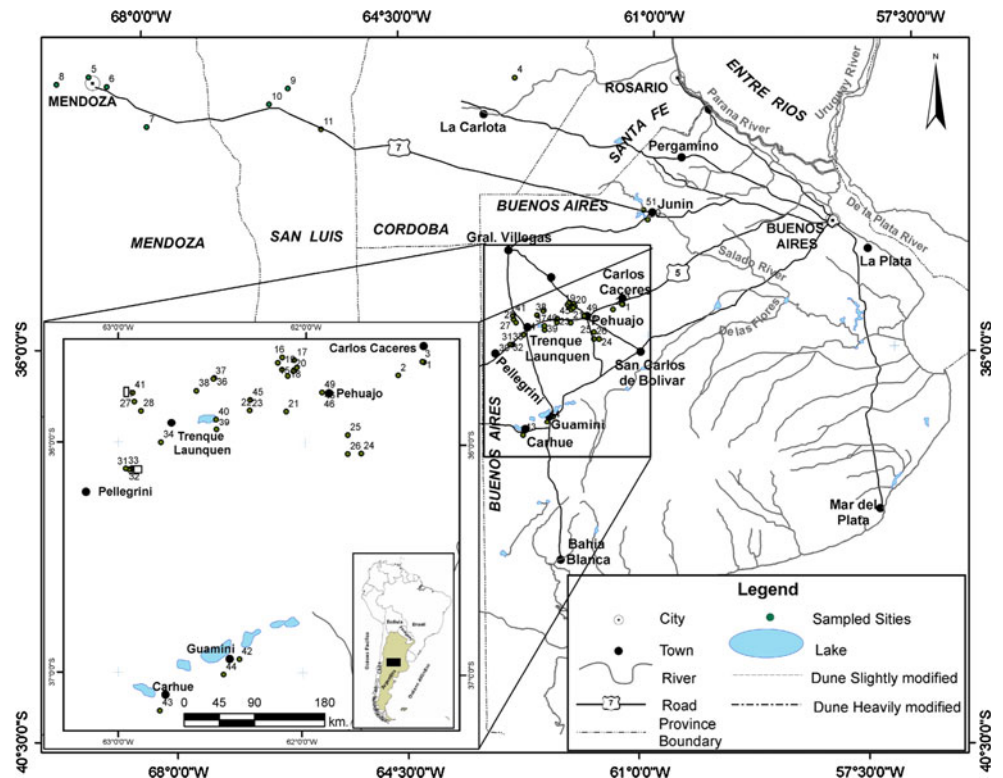
---

M. M. Alconada-Magliano  
CISAUA (MAA-UNLP) y FCAgFs,  
Universidad Nacional de La Plata, Buenos Aires, Argentina

J. R. Fagundo-Castillo · P. G. Hernández  
Centro Nacional de Medicina Natural y Tradicional,  
Havana, Cuba

J. J. Carrillo-Rivera (✉)  
Instituto de Geografía, Universidad Nacional Autónoma de  
México, México, Mexico  
e-mail: joeljcr@igg.unam.mx

**Fig. 1** Location of study area and provinces between the Andes Cordillera and Buenos Aires Province. It includes the main river network and location sites of water samples collected between Mendoza and Buenos Aires provinces



In general, international references are few concerning the application of hydrogeochemical procedures to define groundwater function related to identification of the origin of flooding water. In the case of the NWBA, flood concern has been related to only to surface water (PMI 1999). The hydraulic continuity of groundwater between the NWBA and neighbouring areas within and beyond the Salado River catchment (Fig. 1) has been neglected. Due to the slow velocity of lateral movement, groundwater has been considered to have negligible impact in observed flooding. The canals network has been constructed without much consideration for groundwater function. Consequently, the different components of the groundwater flow system have not been characterised as described by Tóth (2000), such as local, intermediate and regional flows and their zones of control (recharge-transit-discharge). Similarly, little attention has been given to related water–rock interaction studies. Investigations have pursued groundwater quality definition only regarding human consumption, geological characterization, aquifer type identification and the change in time of the main lagoons water chemistry. Recently, Alconada (2008) using climatology data and satellite imagery found a lack of favourable conditions that suggest flood water to be directly related to rainfall occurring on site or to the transfer of surface water among the various water bodies. This author in an independent analysis using Modflow modelling (McDonald and Harbaugh 1996) found that water table rising was only reproduced when head

boundaries (inflow of groundwater originated outside the study area) were incorporated in the analysed system.

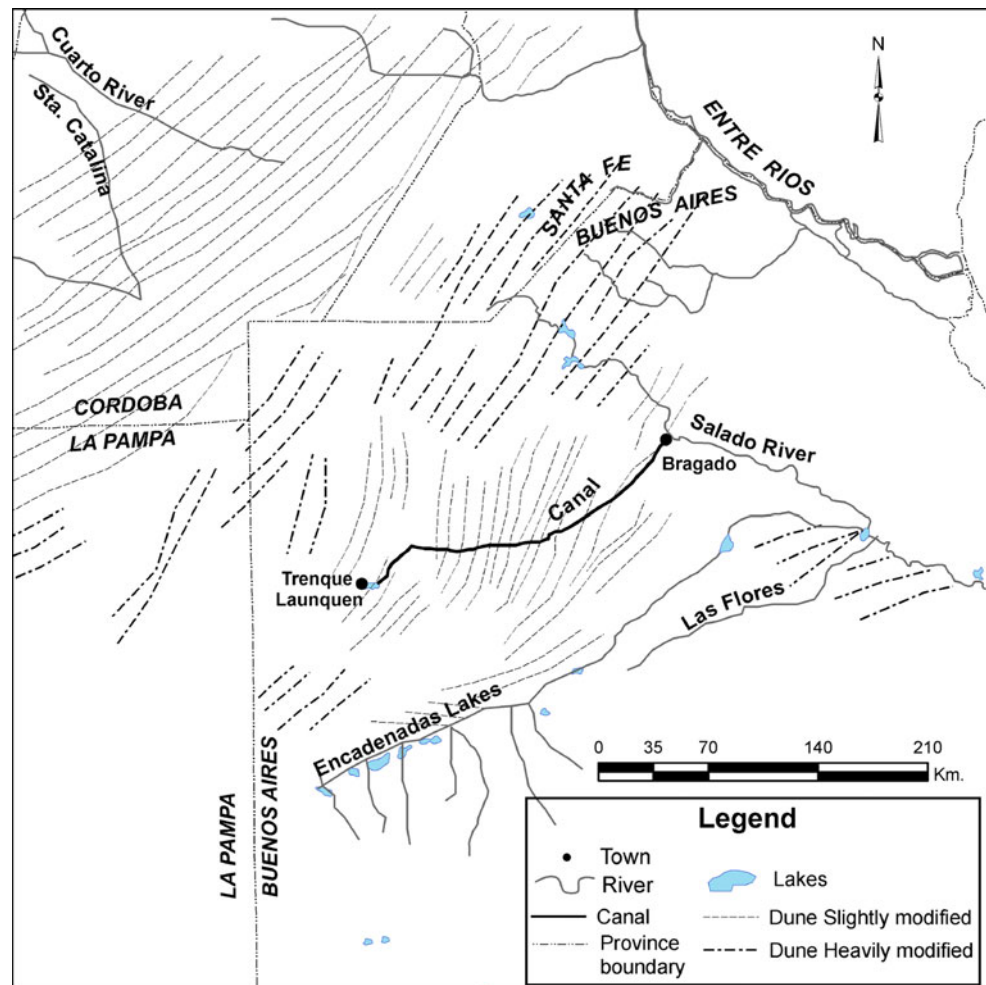
Good quality groundwater (<1,000 mg/l, total dissolved solids TDS) is commonly found in recharge zones, disregarding the flow system involved (local, intermediate or regional). However, as the groundwater surface in the longitudinal dunes of the NWBA (Fig. 2) is at shallow depth, it produces a water table subject to high evapotranspiration effects. This shallow water table condition incorporates a further hydrological control on the functioning of large discharge terrain surface (flooded), creating intermittent lagoons and increasing the size of permanent ones. The relation between inflows and outflows in the study area presents a response strongly suggestive of their hydrogeochemical behaviour, supported by the groundwater flow system theory (Tóth 2000).

Hydrogeochemical processes responsible for observed chemical composition of the NWBA waters, processes that could highlight the flooding and better understand its origin were studied. Such analysis is believed to assist in future feasible flood control management through forestry and farming measures.

### Geographic, geologic and hydrogeologic frameworks

When considering groundwater function in a study territory, the flow system theory (Tóth 2000) provides a

**Fig. 2** The Buenos Aires Province and canal *Jauretche-Mercante-Republica de Italia* that communicates the lake complex of Hinojo-Las Tunas between Trenque Lauquen (TL) and Bragado (B) crossing Pehuajó (Pe), Carlos Casares (CC) and 9 de Julio (NJ)



satisfactory framework to envisage its presence in 3D. The identification of recharge-discharge evidence of the various flows involved suggests their location and relation with the territory. Field evidence suggests the hierarchy of the various groundwater flows anticipated with prevailing geological and hydrogeological conditions. The presence of local, intermediate and regional flows may be acknowledged within the geographical, geological and hydrogeological location of their paths implicit in the chemical and physical characteristics of the water.

The geographical location of the study area implies the possibility of hydrological influence of regional groundwater that is recharged in the Andes Cordillera in the vicinity of Mendoza (+1,400 m amsl) and probably San Luis (+1,100 m amsl); it would be expected that these flows discharge in the NWBA plain. The Buenos Aires province (Cingolani 2005) includes the *Llanura Pampeana*, which is an extensive plain, with topographic heights below 100 m amsl. This plain lays on sediments of Cretaceous to Pleistocene age in variable thickness (1,000–6,000 m), depending on the site, which fills up an irregular structure formed by a Pre-Cambrian-Palaeozoic

undifferentiated basement (PMI 1999; González 2005). Zárata and Rabanese (2005) report a complex geological history including a fault system NW–SE.

The surface of the NWBA has a regional slope of 0.25% lacking a defined drainage system. Within this unit, two major geomorphological elements are recognised, the *Médanos (dunes) Longitudinales* to the north, and the *Médanos Parabólicos* to the south. The former shows NNE–SSW parallel to sub-parallel arcs, which cross (W–E) the regional topographic slope. From the perspective of surface and groundwater, these elements control the local hydrologic response. The water table is from few centimetres to 2–5 m deep, conditions that produce about 20,000 ha of water bodies distributed about dunes, which may be observed even in small-scale satellite imagery (Fig. 2).

The lagoons have had a different evolution, distribution, morphology and typology; they are closely related to climatic conditions, relief, lithology and geological structure; they represent shallow water bodies (with an average of 2–2.5 m and a maximum of 10 m in *Guaminí* and *Cochicó* lagoons). The largest continuous set of water bodies is

represented by the *Hinojo-Las Tunas* system (Fig. 2) (Dangavs 2005).

Each geological formations beneath the NWBA plain has different grain size fractions: fine sand to silt, clayey silt, volcanic ash, sandy to clayey silt, calcareous clay with gypsum, loess, clayey sand, gypsum, fine to medium sand with clayey matrix and mica, calcareous cementing material. This lithology consists mainly of minerals such as quartz, calcedonia, plagioclase, K-feldspar, calcite, halite, augite, hiperstene, hornblende, gypsum, kaolinite and muscovite (PMI 1999; González 2005). Etchichurry et al. (1988) report that deposits 0–12 m deep are mainly formed by quartz (20–28%) plagioclase (15–21%), K-feldspar (6–8%) and in small proportion, by augite, hiperstene, hornblende, and biotite.

These minerals were used in inverse geochemical modelling to obtain arguments about controls related to the origin of the chemical composition of sampled water as well as to infer related processes (Garrels and Mackencie 1967; Fagundo-Sierra et al. 2001). Natural water obtains its chemical composition by complex processes of chemical and physical interaction involving lithology, soil, hydrogeological, geomorphological, climatological, microbiological, and anthropic phenomena (Fagundo 1990).

Groundwater plays an active roll as a geological agent producing physical changes (lubrication and control of inter-granular pressure), chemical processes (dissolution, hydration, hydrolysis, oxidation–reduction, precipitation, ionic exchange) and kinetic adjustments (transport of water, aqueous and non-aqueous matter, heat) (Tóth 2000). In general, the chemical differentiation of water as related to the minerals found in the lithology along the flow path is more conspicuous in a local flow (of shallow and short travel distance) than in larger and deep travelling flow. The long the flow path the water chemistry becomes more homogeneous and independent of the particular rocks composition it has travelled through (Carrillo-Rivera et al. 2007). The presence of groundwater with contrasting mineralization is common in territories as the NWBA geologically complex (Shterev 2004; Vinograd 2004).

The regional distribution of sediments of the Araucana, Puelche, Pampeana Formations, and dunes of the Médano Invasor Formation (adding from 100 to 500 m thickness) provide conditions for the development of local and intermediate groundwater systems to develop. Below these strata, a sedimentary sequence 1,000–6,000 m thick presents conditions for the development of regional flow. In general, the TDS of groundwater at shallow depth is from 500 to 2,000 mg/l and >50,000 mg/l in the underlying sequence (PMI 1999; González 2005).

The NWBA is characterised by: (1) the lowest topographic position suggesting the presence of discharge

groundwater conditions, (2) a shallow water table configuration, (3) the geomorphology of nearby highlands which relates it to recharge zones in Mendoza and San Luis, (4) the presence of a large sedimentary sequence suggesting the possibility to develop local, intermediate and regional flows, and (5) vertical and lateral variability in water chemistry. It is feasible to apply the flow system theory as devised by Tóth (2000) from where elements to propose the origin of flooding water. A definition of the nature of local, intermediate or regional flows and their zones of recharge, transit or discharge would benefit from their chemical control on water, soil and vegetation type. Therefore, temperature, pH, Eh (redox potential), OD (dissolved oxygen), alkalinity, as well as the ionic and isotopic water composition, provides information on characteristics reflecting the flow type, as well as processes the rain has undergone after infiltration occurred. This analysis may be useful, among other things, for flood control definition from where suitable alternatives for farming and forest management policies may be proposed.

## Materials and methods

### Sampling and analytical procedures

A physical and chemical reference of groundwater in a high topographic zone of the study area was obtained in the provinces of Mendoza (Me) and San Luis (SL). Sampling collection was more dense in space for sites of Buenos Aires (BA), Trenque Lauquen (TL) and Pehuajó (Pe); density was low in Carlos Casares (CC), 9 de Julio (NJ), Junín (Ju), Guaminí y Carhué (Gu y Ca) (Fig. 1).

Standard sampling procedures included field measurements (Table 1) of temperature, pH, Eh, dissolved O<sub>2</sub> and electrical conductivity (APHA-AWWA-WPCF 1989). When possible, an in-line flow-cell was used to ensure exclusion of atmospheric interference and to improve measurement stability. Alkalinity was obtained through standard volumetric Gran titration method using HSO<sub>4</sub> with a digital titrator. All used equipment was in situ calibrated. Water samples were kept at 4°C before being sent to the laboratory. Chemical solutions used during field determinations were subject to quality control. All reported values have ionic balance error within 5%, except some samples of highly mineralized water, which show less than 10% error. Determinations of minor-trace elements, and major ions were determined with inductive coupled plasma mass spectrometry (ICP-MS) and by inductive coupled plasma optical emission spectroscopy (ICP-OES), respectively, by Activation Labs. Stable isotopes ( $\delta^{18}\text{O}$  and  $\delta\text{D}$ ) were analysed at the University of Arizona.

**Table 1** Field (and laboratory) of pH, OD, Eh, STD, CE, in different sampling sites

Sample	Site (depth of extraction, m)	pH	pH Lab	OD (mg/l)	Eh (mV)	T (°C)	CE <sub>field</sub> (μS/cm)	CE <sub>Lab</sub> (μS/cm)	STD (mg/l)
1	Borehole (13) M	7.04	8.14	2.7	496	16.40	1,697	1,884	1.571
2	Borehole (6) M	7.01	8.75	1.2	1,556	16.30	3,820	3,500	2.303
3	Borehole (30) M	6.98	8.12	4.7	1,445	18.30	18,500	18,300	8.839
4	Borehole (200) M	7.43	7.35	9.7	912	15.10	516	854	583
5	Borehole (flowing, 120)	7.29	7.65	4.4	788	15.70	943	1,557	1.151
6	Borehole (200–300) M	7.89	7.50	6.7	1,054	17.80	819	746	505
7	Borehole (300) M	7.79	7.45	0.2	1,957	28.60	2,510	2,400	1.733
8	Potrillo, River (M)	8.15	7.63	9.7	1,551	26.20	991	898	653
9	Dam Florida SL	8.64	6.83	9.9	1,576	21.10	252	213	151
10	Borehole (10) SL	6.93	7.70	2.3	1,944	16.10	1,370	1,269	1.003
11	River Quinto, SL	8.20	7.48	11.1	630	25.80	1,189	1,157	760
13	Lagoon temp, P	9.02	8.19	11.6	−92	25.20	4,220	4,190	2.663
14	Borehole silos, P	7.03	7.29	ND	−1	19.10	5,400	5,150	3.311
15	Piezometer, P	ND	7.65	ND	ND	27.00	ND	7,690	3.122
16	Piezometer, P	ND	7.36	ND	ND	ND	ND	1,510	930
17	Piezometer, P	ND	7.21	ND	ND	19.00	ND	1,536	1.805
18	Piezometer, P	ND	7.25	ND	ND	19.50	ND	568	531
19	Piezometer, P	6.98	7.04	ND	−3	17.70	6,980	1,819	141
20	Lagoon El tostado, P	9.87	8.26	9.6	−28	21.00	9,870	10,420	7.296
21	Piezometer, P	6.92	7.26	0.5	−74	16.80	7,730	8,010	5.095
22	Borehole, P	7.92	7.88	3.5	−86	23.50	9,060	9,350	6.274
23	Borehole, P	8.29	8.03	2.6	−93	21.70	3,500	3,420	2.539
24	Borehole, P	7.70	8.02	2.5	−89	18.50	2,480	3,660	2.958
25	Borehole, P	8.11	8.13	3.7	−86	22.30	3,250	3,200	2.772
26	Borehole, TL	8.25	7.81	2.0	−74	17.80	4,300	4,180	2.830
27	Piezometer, TL	ND	7.44	ND	ND	ND	ND	1,618	1.108
28	Lagoon La Vidaña, TL	ND	6.69	ND	ND	ND	ND	8,950	5.082
29	Borehole, TL (40)	8.12	7.94	3.5	−75	18.20	3,110	3,010	1.928
30	Borehole, TL (20)	no	7.60	ND	ND	18.60	ND	646	530
31	Borehole, TL (40)	7.60	7.90	2.3	−52	18.20	4,760	4,860	3.897
32	Borehole, TL (28)	8.04	7.60	2.1	−88	18.10	1,090	1,015	636
33	Borehole, TL (molino)	ND	7.67	ND	ND	ND	ND	6,510	4.201
34	Borehole, TL (6)	7.23	7.30	4.9	−87	19.10	18,360	ND	22.850
35	Borehole-tanque TL	ND	7.58	ND	ND	ND	ND	11,850	7.543
36	Borehole, TL (10)	ND	7.63	ND	ND	18.60	ND	11,850	1.533
37	Piezometer, TL	ND	7.90	ND	ND	ND	ND	868	762
38	Lagoon Murphy, TL	ND	6.83	ND	ND	ND	ND	19,800	14.133
39	Lagoon Tunas TL	ND	8.31	ND	ND	23.00	ND	22,900	16.531
40	Lagoon Hinojo, TL	ND	8.25	ND	ND	23.00	ND	18,100	12.653
41	Lagoon Cuero Zorro, R	ND	7.60	ND	ND	25.50	ND	10,410	7.593
42	Lagoon Cochicó, G	ND	9.07	ND	ND	23.00	9,750	10,270	7.099
43	Lagoon Epecuén, C	9.53	8.88	8.2	−65	21.40	FE	75,600	67.356
44	Lagoon del Monte, G	ND	9.02	ND	ND	ND	ND	17,730	11.767
45	Lagoon El Recado, P	ND	7.73	ND	ND	20.00	ND	36,400	15.904
46	Lagoon La Salada, P	ND	7.31	ND	ND	21.00	ND	8,610	5.478
47	Borehole, City P	8.33	8.19	6.9	0	19.70	1,555	1,481	1.138
49	Borehole, 9 de Julio	8.18	8.14	1.2	−1	17.20	1,106	1,060	895
50	Lagoon. Gómez, J	ND	9.20	ND	ND	ND	ND	9,370	6.450
51	Lagoon Mar Chiquita, J	ND	8.09	ND	ND	ND	ND	5,240	3.512

M Mendoza, SL San Luis; y en Buenos Aires, P Pehuajo, TL Trenque Lauquen, CC Carlos Casares, NJ Nueve de Julio, J: Junín, G Guamini, C Carhué, R Rivadavia, ND non determine

## Processing of analytical information

Available data on physical and chemical behaviour of water flowing through different lithology of the NWBA was interpreted based on the flow system theory (Tóth 2000) from where the hierarchy of different flow systems was defined with the combined use of soil and topographic data suggesting the existence of discharge, transit or recharge conditions. Chemical constituents in groundwater provide valuable information on the history of flow path in related environment. Consequently, analyses of groundwater collected from rivers, natural and artificial lakes, boreholes and observation piezometers were assessed to outline a flow description. Isotope data were used as direct means to define evaporation processes affecting obtained samples, and to propose a relative recharge characterisation.

Analytical results were divided into groups and sub-groups by standard Piper-Hill and Stiff (1951) diagrams. Considering the objective and prevailing hydrogeological setting, two main questions were examined from chemical data of obtained samples: (1) which is the theoretical hierarchy for the various flows systems in terms of their local, intermediate and regional length of path, and (2) which flow mixture might be defined at surface. The use of advanced hydrogeochemical modelling PHREEQ-C (Parkhurst et al. 1980), MODELAGUA (Fagundo-Sierra et al. 2001) was performed to evaluate water–mineral equilibrium and mixture among different identified flows.

Hydrogeochemical pattern (HP) was used to define stoichiometric relationships such as Na + K:Ca:Mg and Cl:HCO<sub>3</sub>:SO<sub>4</sub> represented in a combination between 1 and 9, according to “percentage” of cation and anion content in solution rounded into one digit (Kurlov, in Fagundo 1998). The HP and geochemical processes were used to explain origin for the chemical composition of sampled water; the definition of processes was also assisted by mass balance and flow mixing computations (Garrels and Mackenzie 1967; Fagundo-Sierra et al. 2001).

For modelling *flow mixing* two end-members were used, one that represents local flow (sample 17) with 19.0°C and 1,805 mg/l TDS; and another representing an intermediate flow (sample BA2) of the Buenos Aires province (Pesce and Miranda 2003) with a temperature of about 35.5°C and a mineralization as STD of 8,286 mg/l.

The chemical equilibrium of water regarding the minerals that form the aquifer units was calculated as a saturation index, SI (Back et al. 1966):

$$SI = \log \frac{K_{IAP}}{K_{eq}}$$

where  $K$  is the ionic activity product, and  $K_{eq}$  is the thermodynamic equilibrium constant of the mineral. If the

SI = 0, the water is in equilibrium in respect to a mineral. If SI < 0, the water is sub-saturated (ready to dissolve the mineral in question). If SI > 0, the water has an excess of the mineral in regard to its solubility product so the mineral would tend to precipitate. This calculation was based on the PHREEQ-C code (Parkhurst et al. 1980), it is important to indicate that in carried out modelling the mineral sepiolite was included instead of biotite.

An interpretation of minor elements reported in the chemical analysis (concentration <1 mg/l) may assist for the interpretation of weathering processes of water–rock interaction which may be affected by microorganisms activity in the hydrosphere, or by human action. In weathering processes, guest components in the crystal lattice of minerals move into solution depending on their abundance and relative solubility, this provides information on the presence of minerals that hold such minor elements, which might be a proxy suggesting water origin. Minor and trace elements were evaluated comparing mineral composition of various rock units (granite, shale, sandstone, limestone) and seawater, as reported by Drever (1988).

Stable isotopes ( $\delta^{18}\text{O}$  and  $\delta\text{D}$ ) were used to define evaporation processes and to evaluate a comparative altitude effect of samples collected in regard to the *Global Meteoric Water Line* (GMWL) (Mook 2001) showing a  $\delta\text{D}$  and  $\delta^{18}\text{O}$  linear relation ( $\delta\text{D} = 8\delta^{18}\text{O} + 10\text{‰}$ ). This tool is useful due to the resulting isotopic fractionation registered in the water molecule when it is subject to evaporation or condensation produces an isotopic enrichment in the heavy isotopes in the liquid phase. In general fractionation is temperature dependent; at low temperature (high latitude or topographic elevation) heavy isotope content is lower in rainfall that at high temperature (low latitude or topographic elevation). When water is subject to evaporation, there is a slope reduction. Water travelling underground keeps its isotopic composition stable unless it is affected by exchange with oxygen in rock units, which is not the case in the study area.

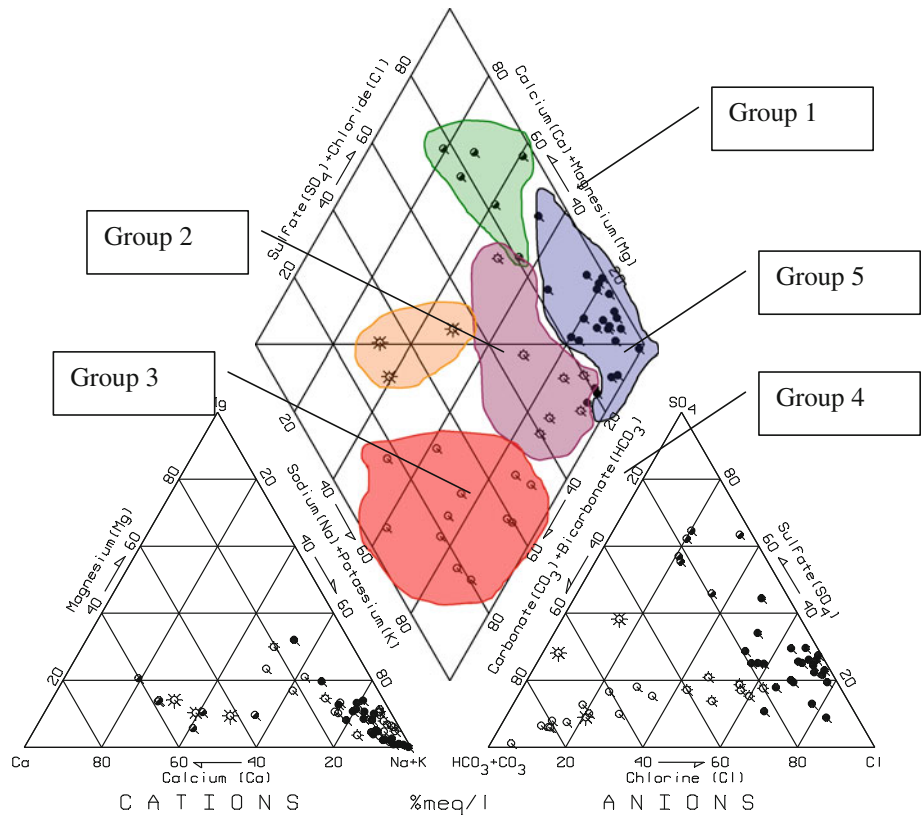
## Results and discussion

### Water characterization

Figure 3 shows a Piper–Hill diagram with the hydrochemical data. Samples gathered are in agreement with five main groups as defined with the Kurlov method that incorporates the average concentration of each element present in the sample; they follow a general tendency to an increase in chloride and sodium. Each group has a particular water type, HP and TDS conditions as follows:

*G1* sulphate–calcium (some with a tendency to chloride and sodium) with a HP 361–316. TDS values are between

**Fig. 3** Piper–Hill diagram with main ions data distribution, and five water groups whose tendency is linked to a general increase in Cl and Na concentrations



505 and 1,733 mg/l. The trace element whose presence was anomalously in a relative high concentration was Sc (0.001–0.008 mg/l). Boreholes 4, 5, 6, 7 (Me); dam 8 (Me) and river 11 (SL) represent this group.

G2 bicarbonate and has a tendency to sulphate, with some calcium and sodium, its HP is 451-163. TDS values are between 141 and 1,003 mg/l. No specific concentration of trace elements was found. Dam 9, borehole 10 (SL) and observation well 19 (Pe, BA) represent this group.

G3 bicarbonate-sodium with a tendency to chloride-sulphate, its HP is 811-361. TDS values are between 530 and 3,897 mg/l. Vanadium (0.006–80.0 mg/l) and As (0.01–0.45 mg/l) were found in abnormal high concentration. This group is represented by boreholes 1, 20, 24, 25, 30, 31, 40, 49; and observation wells 27 and 37 (BA: TL, Pe, CC, NJ).

G4 chloride–bicarbonate, mainly sodium, its HP is 811-631. TDS values are between 531 and 4,201 mg/l. Relative high concentration of V (0.026–70.0 mg/l) were found in this group. Boreholes 2, 22, 23, 26, 32; and observation wells 15, 18, 33 (BA: Pe, CC y TL) represent it.

G5 chloride–sodium with a tendency to chloride-sulphate, its HP is 811-712. TDS values are between 930 and 67,356 mg/l. Relative high concentrations of Sr, Ba, Zn, Ni, Cd, Cr, Co, Al, Ti, Pd, Rb, Sb, Cs, and rare earths where found (La, Pr, Nd, Sm, Dy, Er). It is represented by boreholes 3, 14, 29, 34, 35, 36; observation wells 16, 17,

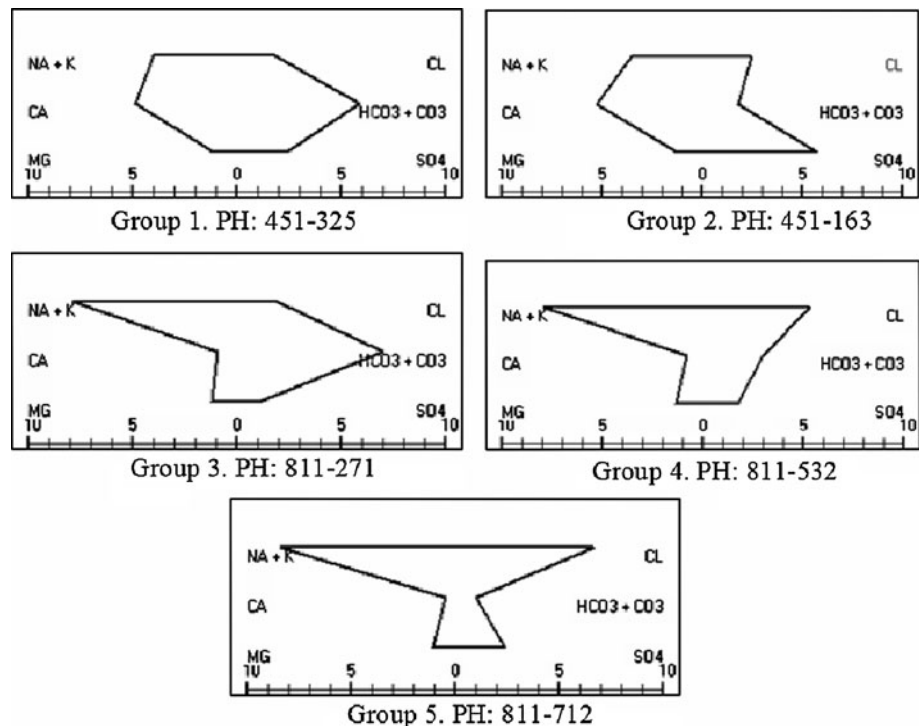
18, 21; lagoons 13, 20, 28, 38, 39, 40, 41, 42, 43, 44, 45, 46, 50, 51 (BA: TL, Pe, CC, Ri, Gu, Ca, Ju) Fig. 4

G1 is mainly reported by samples of Mendoza. G2 is characteristic of San Luis. Samples collected in La Florida dam (9) and in Villa Mercedes (11) both and SL belong to G2 and G1, respectively; both sites are located along the Quinto River catchment, which receives flows from other surface streams along its path. In La Florida dam (9) several streams emerge. G5 prevails in the Buenos Aires region where is represented by different manifestations; this province has a number of samples from G4 followed in importance by samples from G3. The presence of trace elements in recharge zones is suggested by chemical weathering processes, the relative increase of these elements towards discharge areas further suggest that the salinity of sampled water is not solely related to evaporation process. Table 2 ratios further propose a similarity between water from the lagoons to that of boreholes in the Buenos Aires area, suggesting the origin of water in the former.

**Chemical evolution of water composition**

The chemical evolution of sampled water was inferred based on the groups that were defined; this was also supported by hydrogeochemical modelling. Analysed data for the various geographical sites suggests the following:

**Fig. 4** Individual staff representation of each hydrochemical group in the study area



**Table 2** Chemical ratios for selected chemical constituents in water samples (*N*, numbers of samples considered)

Sampling site	Location	<i>N</i>	Sr/Ca	Li/Sr	Ca/Mg	Ba/K
Boreholes	Mendoza	4	0.010	0.044	8.698	0.015
Boreholes	San Luis	1	0.006	0.079	7.342	0.117
Boreholes	Buenos Aires	18	0.030	0.031	0.882	0.068
Rivers, dams	San Luis, Mendoza	3	0.008	0.058	6.380	0.098
Piezometers	Buenos Aires	8	0.014	0.057	2.628	0.133
Lagoons	Buenos Aires	14	0.047	0.022	0.421	0.042

*Trenque Lauquen*, TDS water in boreholes has concentrations from 530 to 22,850 mg/l and there is a chemical evolution of G3 to G4 and eventually to G5 as indicated below:

- Boreholes: (a) sample 30: G3, TDS 530 mg/l,  $\text{HCO}_3\text{-Na} > \text{Ca} > \text{Mg} \Rightarrow$  (b) sample 26: G4, TDS 2,830 mg/l,  $\text{Cl} > \text{HCO}_3\text{-Na} \Rightarrow$  (c) sample 34: G5, TDS 22,323 mg/l,  $\text{Cl} > \text{SO}_4\text{-Na} > \text{Mg}$ .
- Observation wells and lagoons: (a) sample 37: G3, TDS 762 mg/l,  $\text{HCO}_3 > \text{Cl-Na} > \text{Ca} > \text{Mg} \Rightarrow$  (b) sample 33: G4, TDS 4,201 mg/l,  $\text{Cl} > \text{HCO}_3\text{-Na} \Rightarrow$  (c) sample 39: G5, TDS 16,531 mg/l,  $\text{Cl} > \text{SO}_4\text{-Na}$ .

*Pehuajó*, TDS values in boreholes are rather constant disregarding that there are different groups involved. There is a general tendency of chemical evolution in the sampled water in observation wells and lagoons as follows:

- Boreholes: (a) sample 25: G3, TDS 2,772 mg/l,  $\text{HCO}_3 > \text{Cl-Na} \Rightarrow$  (b) sample 23: G4, TDS 2,539 mg/l,  $\text{Cl} > \text{HCO}_3\text{-Na} \Rightarrow$  (c) sample 14: G5, TDS 3,252 mg/l,  $\text{Cl-Na} > \text{Mg}$
- Observation wells and lagoons: (a) sample 19: G2, TDS 141 mg/l,  $\text{HCO}_3 > \text{Cl-Ca} > \text{Na} \Rightarrow$  (b) sample 15: G4, TDS 3,122 mg/l,  $\text{Cl} > \text{HCO}_3\text{-Na} \Rightarrow$  (c) sample 45: G5, TDS 15,904 mg/l,  $\text{Cl} > \text{SO}_4\text{-Na}$ .

*9 de Julio y Carlos Casares*, here TDS concentration in the water is from 894 to 12,239 mg/l, the water type is from  $\text{HCO}_3 > \text{Na}$  (G3) to  $\text{Cl} > \text{SO}_4\text{-Na}$  (G5).

Table 3 suggests a general evolution of anions from bicarbonate to sulphate, ending in chloride water. Concerning cations, the evolution is from calcium to sodium water. These results seem to be in agreement with the chemical evolution as proposed by Tóth (2000) where recent water, such that in a local flow, is of the type  $\text{HCO}_3 > \text{SO}_4 > \text{Cl}$ . The final composition of a water flow that has travelled for long distance, time and depth such as an intermediate or regional flow attains a type represented by  $\text{Cl} > \text{SO}_4 > \text{HCO}_3$  with a high salinity load.

Observed evolution is mainly the result of chemical evolution of local and intermediate groundwater flow from a recharge to a discharge zone; in this case, resulting lagoons include the mixture of water from intermediate flow circulating at depth. It may be postulated that the chemical composition of water in lagoons changes significantly due different natural processes: lost of  $\text{CO}_2$  linked to an ionic recombination of mineral precipitation, change



**Table 3** Example of general evolution of water chemistry along the flow path, from recharge to discharge zones, starting on an elevation close to the Andes and ending on the Buenos Aires plain (concentrations in mg/l)

Sample	Sampling site	Group	TDS	HCO <sub>3</sub>	Cl	SO <sub>4</sub>	Ca	Mg	Na	K	Type
9	Dam	2	151	78.2	2.7	25.6	23.5	3.7	13.7	3.6	HCO <sub>3</sub> > SO <sub>4</sub> -Ca > Na
4	Borehole (200 m)	1	583	78.2	60.6	263.0	107.0	107.0	56.1	3.2	SO <sub>4</sub> > Cl-Ca > Na
23	Borehole	4	2,539	860.5	534.0	534.0	24.0	49.1	755.0	26.8	Cl > HCO <sub>3</sub> -Na
45	Lagoon	5	15,904	286.8	4480.0	1,740.0	230.0	670.0	8,240.0	257.0	Cl > SO <sub>4</sub> -Na
43	Lagoon	5	67,356	1,382.0	28,600.0	14,100.0	15.0	119.0	22,800.0	340.0	Cl > SO <sub>4</sub> -Na

of pH from acid to basic, variation in redox potential (i.e. soluble Fe<sup>2+</sup> and Mn<sup>2+</sup> are oxidised to Fe<sub>2</sub>O<sub>3</sub> and MnO<sub>2</sub> respectively, also SO<sub>4</sub><sup>-2</sup> is changed into H<sub>2</sub>S, producing S-coloidal). Finally, evaporation processes are responsible of the high concentration of the aqueous solution and mineral precipitation, initially, of the more insoluble (aragonite, dolomite, calcite, silica) followed by the more soluble (gypsum, halite).

Origin of water composition

*Minerals and associated geochemical processes*

Based on the minerals considered in materials and methods for the study area, and through mass balance modelling (Garrels and Mackenzie 1967; Fagundo-Sierra et al. 2001) the chemical composition of sampled water was obtained. Halite, gypsum, calcite, quartz, plagioclase (albite and anortite), K-feldspar, biotite and clay minerals were incorporated. The suggested plagioclase to be present due to Na<sup>+</sup>/Ca<sup>2+</sup> ratio in the water has the formula: Na<sub>0.96</sub>Ca<sub>0.041</sub>Al<sub>1.04</sub>Si<sub>2.96</sub>O<sub>8</sub>. The geochemical reactions to reproduce the weathering processes were selected as suggested by chemical analytical results from sampled water, the applied criteria is incorporated in Fagundo-Sierra et al. (2001) and Fagundo-Castillo et al. (2008), results are discussed as follows.

*Mass balance modelling*

Table 4a–d shows some results obtained from mass balance modelling application. Similar geochemical processes may explain the chemical composition of water resulting from the interaction with aquifer lithology because the minerals composition involved in the aquifer material is comparable, but the expected proportion of weathering processes might differ under actual conditions. Therefore, it might be postulated that water travelling from regional (and intermediate) recharge zones in San Luis and Mendoza acquires its dissolved constituents, mainly through mineral dissolution processes, with precipitation of calcite possibly by the effect of common-ion resulting from gypsum dissolution.

In Trenque Lauquen there is a general tendency to a significant precipitation of calcite when TDS > 1,500 mg/l due to common-ion effect. When TDS > 7,500 mg/l a cation exchange process between Ca<sup>2+</sup> and Na<sup>+</sup> is developed. Therefore, sample 34, from a 6 m deep borehole in Berutti, shows the process of inverse ionic exchange between Ca<sup>2+</sup> and Na<sup>+</sup> (increase in Ca<sup>2+</sup> by Na<sup>+</sup> decrease). At regional level, this site is located in an environment with the lowest altitude in the region (96 m amsl) with a soil of the *Hapludol ácuico* type, which is characterised by hydromorphic features (i.e., Fe and Mn reduction) associated to a water table two metres deep.

In Pehuajó, data from the observation wells suggest calcite precipitation and inverse ionic exchange; the exchange is inferred to be produced with clay at soil level.

Water in 9 de Julio and Carlos Casares acquires its chemical composition similarly to above cases, here, calcite precipitation process is involved when TDS > 1,000 mg/l.

Concerning the boreholes of Buenos Aires calcite precipitation processes occur in all cases but ionic exchange is rarely observed.

*Mixing modelling*

The analysis made of acquired water chemistry has been pursued inferring an inflow from recharge zones only; a more precise interpretation could be made incorporating the mixture between each particular local and intermediate flows involved. González (2005) reports that groundwater in the sand dune units is under water table conditions being a water supply unit with the lowest salinity content; this author also indicates the presence of deep semi-confined aquifer units and suggests the presence of ascending flow from depth. The nature of this inflow following the theory of Tóth (2000) may be coincident with discharge conditions of an intermediate flow. PMI (1999) suggests that surface water receives salts from the groundwater system, from evaporation, from water imports beginning in other catchments, and from mineral dissolution of Post-Pampeano material along fluvial channels. This publication also reports that Canal Mercante (Fig. 2) acquires a salinity that varies in time

**Table 4** Concentrations in mmol/l resulting from geochemical processes with the application of balance mass modelling to water samples

No of sample	9	19	10	6	4	8	11	5	7		
Sampling site	Dam	Pz	BH (10 m)	BH (250 m)	BH (200 m)	Dam	River	BH (13 m)	BH (300 m)		
						Potrerillos	Quinto				
<b>(a) From Mendoza and San Luis (depth)</b>											
Location	SL	Pe, BA	SL	Me	Me	Me	SL	Me	Me		
Group	2	2	2	1	1	1	1	1	1		
TDS	164	141	957	508	648	685	918	1,176	1,722		
Halite	0.240	0.243	1.854	1.310	1.547	1.826	3.699	3.586	8.629		
Gypsum	0.267	0.087	2.615	2.281	2.740	2.740	2.552	4.740	8.396		
Calcite	0.268	0.246	-0.148	-0.019	-0.166	-0.053	-0.719	0.394	-1.427		
Albite	0.146	0.000	4.371	1.340	0.682	0.536	2.134	0.000	1.292		
Anortite	0.013	0.000	0.393	0.121	0.061	0.048	0.192	0.000	0.116		
Biotite	0.125	0.052	0.628	0.368	0.603	0.649	0.541	1.766	0.745		
K-Feldspar	0.040	0.176	0.022	0.056	0.000	0.000	0.123	0.000	0.421		
Ionic exch Na–Ca [Ca]	0.000	0.022	0.000	0.000	0.000	0.000	0.000	0.322	0.000		
No of sample	30	32	37	27	36	29	26	31	33	35	34
Sampling site	BH	BH	Pz	Pz	BH	BH	BHo	BH	Pz	BH	BH
<b>(b) From Trenque Lauquen (Buenos Aires)</b>											
Group	3	4	3	3	5	5	4	3	4	5	5
TDS	530	551	762	1,108	1,533	1,928	2,830	2,404	4,201	7,543	22,323
Halite	0.536	4.094	1.795	0.637	12.206	16.826	22.967	17.925	38.150	90.826	295.615
Gypsum	0.218	0.9658	0.474	0.091	2.729	3.615	3.469	4.021	5.427	13.958	36.979
Calcite	0.426	-0.484	0.084	0.656	-2.641	-3.417	-4.709	-6.560	-6.378	-9.766	-29.377
Albite	2.741	2.479	4.776	0.970	9.106	8.747	17.562	33.605	22.510	0.000	0.000
Anortite	0.247	0.223	0.430	0.087	0.819	0.784	1.581	3.024	2.026	0.000	0.000
Biotite	0.828	0.703	1.258	0.649	1.916	1.745	1.070	1.849	2.741	12.958	39.512
K-Feldspar	0.000	0.000	0.281	2.774	0.434	0.354	0.805	0.000	0.440	0.518	0.000
Ionic Exch Na–Ca(Ca)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.608
No of sample	18	16	17	23	25	24	15	14	21	22	
Sampling site	Pz	Pz	Pz	BH	BH	BH	Pz	BH	Pz	BH	
<b>(c) From Pehuajó (Buenos Aires)</b>											
Group	4	5	5	4	3	3	4	5	5	4	
TDS	531	930	1,805	2,539	2,772	2,958	3,122	3,252	5,095	6,274	
Halite	4.460	12.291	23.502	14.882	8.094	11.530	20.150	35.051	73.925	64.085	
Gypsum	0.779	1.833	2.000	3.021	3.010	3.615	2.760	4.833	3.979	5.260	
Calcite	-0.419	-4.733	-2.531	-4.057	-5.066	-5.287	-4.590	-3.088	-10.880	-6.685	
Albite	0.026	0.000	0.000	17.734	25.392	23.695	28.771	0.000	0.000	20.942	
Anortite	0.002	0.000	0.000	1.596	2.285	2.133	2.589	0.000	0.000	1.885	
Biotite	0.093	0.337	0.970	2.016	1.124	2.378	3.112	5.553	10.012	3.245	
K-Feldspar	0.000	0.112	0.903	0.005	0.810	0.000	0.000	0.000	0.000	0.139	
Ionic Exc Na–Ca(Ca)	0.000	3.207	1.291	0.000	0.000	0.000	0.000	1.239	15.111	0.000	
No of sample	49	1	2	3							
Sampling site	BH	BH	BH	BH							
<b>(d) From 9 de Julio and Carlos Casares (Buenos Aires)</b>											
Location	9 de Julio	Carlos Casares	Carlos Casares	Carlos Casares							
Group	3	3	4	5							
TDS	894	1,517	2,303	8.839							
Halite	1.215	3.502	21.361	140.122							

**Table 4** continued

No of sample	49	1	2	3
Sampling site	BH	BH	BH	BH
Gypsum	0.335	1.302	2.750	26.354
Calcite	-0.704	-1.111	-1.453	-21.046
Albite	8.314	10.853	0.000	11.134
Anortite	0.748	0.977	0.000	1.002
Biotite	0.466	1.374	5.553	15.637
K-Feldspar	0.189	0.524	0.000	0.000
Ionic exch Na–Ca(Ca)	0.000	0.000	2.438	0.000

BH borehole, Pz piezometer

and space from 7,800 to 17,600 mg/l; water of the Salado River has between 5,400 and 10,600 mg/l. Alconada (2008) applying Modflow modelling (McDonald and Harbaugh 1996) was able to reproduced a water table rising only when Head Boundary conditions incorporated groundwater inflows from beyond the study area. This intermediate flow discharge and mix with locally recharged water. Recharge scenarios with up to half of current rainfall (1,000 mm/annum) fail to show observed water table rise and flooding increase. A plausible process responsible for such water enhancement appears to relate to groundwater discharge from local and intermediate systems in variable proportions.

The fraction of local water in the evaporated water in the lagoons was established (Table 5) with a water-mixing model. The proposed end-members are water from a local flow (sample 17 with 19°C, TDS of 1,805 mg/l, Cl of 840 mg/l) and an intermediate flow (sample BA2 with 34°C, TDS of 8,286 mg/l, Cl of 4,434 mg/l) (Pesce and Miranda 2003). Results using Garrels and Mackencie (1967) as well as Fagundo-Sierra et al. (2001) are presented in Table 5 where the Lagoon of/Mar Chiquita/(sample 51) has an inflow of 85% of local flow and 15% of an intermediate flow; the water composition is explained by the dissolution of gypsum, albite and biotite; with calcite precipitation. Similarly, water in other lagoons have a groundwater inflow derived from an intermediate flow in the range of 9.2, 39.0, 43.9, 49.0, 56.1, 57.7, 62.9, and 95.1% for the lagoons of Temporal, La Vidaña, La Salada, Gómez, Cuero Zorro, Cochicó, El Tostado, and El Recado, respectively. The lagoons: Del Monte, Hinojo, Tunas and Epicuen have a groundwater inflow of 100% derived from an intermediate flow.

The origin of the chemical composition of other lagoons may be explained by evaporation of water of similar composition to the Mar Chiquita; Table 6 shows results of proposed evaporation processes that are currently taking place in the lagoons.

**Table 5** Mixing model results showing minerals in mmol/l resulting of chemical processes that reproduce the water quality of Mar Chiquita lagoon using end-members represent by local flow (sample 17) and an intermediate flow (sample BA2)

MAR CHIQUITA	51
Location	Junín
Group	5
TDS (mg/l)	3,512
Cl <sup>-</sup> (mg/l)	948
% R1 (AC 17)	85.2
% R2 (BA 2)	14.8
Halite (Cl)	-11.976
Gypsum (SO <sub>4</sub> )	4.831
Calcite (Ca)	-7.474
Albita (Na)	23.423
Anortite	2.100
Biotite	0.464
Dolomite	0.000
K-Feldspr	0.000
Ionic exch Na–Ca(Ca)	0.000

Rankama and Sahama (1964) indicate that the production of gypsum, sodium sulphate or calcium carbonate is feasible in some salty lakes by precipitation due to evaporation. Generally, aragonite and calcite are the first minerals to precipitate, with the molar relation of alkalinity/calcium, defining the preferential precipitation of one or the other mineral. This corresponds with saline deposits observed in several of the lagoons, that include halite, quartz, and calcite crystals as well as clayey dark sulphate mud, iron sulphate, disperse organic matter and microalgae. Lagoons with high TDS concentration (Table 6) associated salts and related deposit, indicate that the original salt concentration of the water was higher than that determined by the chemical analysis due to evaporation processes and salt precipitation.

**Table 6** Geochemical modelling results (mineral concentrations in mmol/l, TDS in mg/l) of anticipated evaporation processes that are proposed to be taking place in the lagoons on the Buenos Aires plain

Sample	13	20	45	46	50	28	38	39	40	41	42	44	43
Location	Pe	Pe	Pe	Pe	J	TL	TL	TL	TL	TL	Gu	Gu	Ca
Group	5	5	5	5	5	5	5	5	5	5	5	5	5
TDS	2,663	7,296	15,904	5478	6,450	5,082	14,133	16,531	12,653	7,593	7,099	11,767	67,356
CF (Cl <sup>-</sup> )	1.08	2.80	4.73	2.27	1.84	2.36	6.21	7.13	5.19	2.08	2.15	4.77	30.17
Calcite (Ca <sup>2+</sup> )	-8.25	-20.71	86.85	-18.02	2.14	-22.27	-52.46	-58.37	-42.23	4.00	-1.52	-38.05	-319.74
Calcite-Dolomite (Mg)	0.34	0.48	20.22	1.84	0.73	1.69	4.41	2.01	1.67	3.07	0.31	-5.43	-44.22
SO <sub>4</sub> <sup>2-</sup> (reducing)	-2.46	-3.23	-16.75	-5.59	-1.15	-7.79	-13.98	-20.13	-7.68	0.0	-2.86	-17.27	-75.80
Pirita	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.18	0.0	0.0	0.0
Ionic exchange Na-Ca <sup>2+</sup> (Ca)	8.38	18.55	-65.08	17.99	-3.32	23.11	57.34	53.18	40.25	-1.37	-0.25	27.24	232.43
Ionic exchange K-Ca <sup>2+</sup> (K)	-1.60	-4.44	-4.33	-3.80	0.02	-3.97	-12.72	-11.75	-8.50	-2.79	-2.91	-7.56	-60.98

Pe Pehuajó, TL Trenque Lauquen, Gu Guaminí, Ca Carhué, FC Concentration Factor for Chloride

### Degree of saturation

Rainwater along the subsurface flow path increases its ionic content with travel distance achieving sub-saturation ( $SI < 0$ ) in the recharge zone and during rainy events; saturation ( $SI = 0$ ) and over-saturation ( $SI > 0$ ) is reached towards the discharge zone and during dry climatic periods. The values of the SI for halite, gypsum, quartz amorphous ( $SiO_2$ ), fluorite, pirolusite ( $MnO_2$ ), celestite ( $SrSO_4$ ),  $Zn(OH)_2$ ,  $CdSO_4$ , K-feldspar and anortite are negative, indicating that related water is sub-saturated in respect to these minerals. The calculated SI corresponding to halite ( $SI_H$ ), gypsum ( $SI_G$ ), calcite ( $SI_C$ ), dolomite ( $SI_D$ ) and quartz ( $SI_Q$ ) yielded the following results:

- *Halite*, the degree of sub-saturation in water of the lagoons is lower (-4.7 to -2.0) than in rivers and dams (-8.9 and -6.3), observation wells (-8.4 to -4.2), and boreholes (-7.5 to -3.0). The degree of sub-saturation tends to be low in agreement with the amount of TDS.
- *Gypsum*, the values obtained are: boreholes -3.8 to -0.4; observation wells -3.1 to -1.0; rivers and dams -2.5 to -1.1; and lagoons -2.0 to -1.0.
- *Calcite*, in this regard values indicate sub-saturation in about 62.5% of observation wells, 23% of boreholes, 25% of surface water, and 3 (21.4%) of the 14 samples of lagoons. Results on the degree of saturation in respect to dolomite are similar to those for calcite.
- *Quartz*, sub-saturation was found in 7.7% of the water from boreholes, in 25% of the water samples from observation wells, in 50% of rivers and dams, and in 93% of the lagoons.

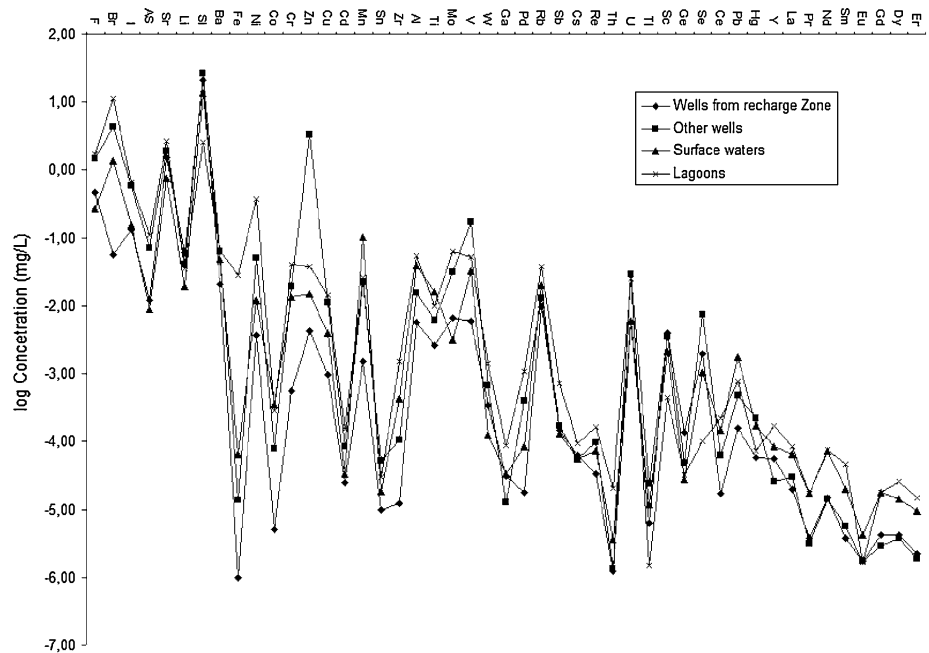
There are an outstanding number of samples with positive SI value or low negative value (close to saturation or chemical equilibrium) in lagoons. This may be interpreted

that lagoons correspond to discharge zones. This is in agreement with the identified presence of intermediate groundwater inflow in the mixing water in the lagoons and therefore with the influence of groundwater to the flooding areas. It also implies limited influence of local rainwater, which is in agreement with results obtained through the application of mass balance and mixture modelling.

### Minor elements

Figure 5 shows analytical results for analysed water samples where most elements (F, Br, I, As, Sr, Ba, Fe, Ni, Co, Cu, Cd, Cr, Zn, Zr, Al, Ti, Mo, V, W, Ga, Pd, Rb, Sb, Cs, Re, Th, U, Y) have a tendency to increase from the recharge zone of intermediate (and regional) flows (Mendoza Province) to discharge zones (lagoons). The concentration of these elements increases markedly, to ten fold or more (Br, As, Fe, Mn, Ni, Co, Cu, Cr, Zn, Sn, Zr, Al, Mo). This increase is reported for all sampling sites, high concentration is found in boreholes of Trenque Lauquen, Pehuajó, Carlos Casares, 9 de Julio. Regarding observation wells in Buenos Aires Mn, Pb, and Hg are exceptionally high. Boreholes in Buenos Aires have the highest concentration values in Mo and V. Surface water in San Luis (Quinto River) presents an increase in observed concentrations when compared to Mendoza samples. On the other hand, components as Li, Si, Ge, Se, Tl and Sc are in higher concentration in boreholes in the Mendoza province than in Buenos Aires lagoons. This suggests that groundwater and lagoon water in Buenos Aires lack direct connection to Mendoza boreholes whose flow possible continues at depth below the Buenos Aires plain. Lithium concentration is higher in groundwater in Mendoza and neighbouring localities than in the lagoons, as this element is conservative and adequate as residence time indicator (Edmunds and

**Fig. 5** A log graphical representation of chemical analytical results of for analysed water samples (concentration in mg/l)

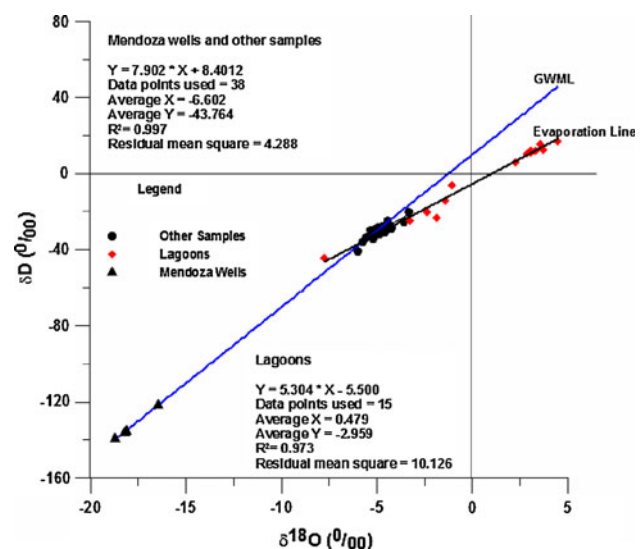


Smedley 2000) this is interpreted that sampled flows developed in the highlands limiting the Buenos Aires plain to the east have negligible influence in the lagoon and flooding water. This suggests that flows generated in Mendoza travel at depth (as regional flows) beneath the intermediate flows that affect the flooding areas, and discharge beyond the Argentinean Atlantic coast.

Stable isotopes

The content of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in sampled water was used to characterise water sources, comparative recharge origin and processes involved. Table 7 shows the values for  $\delta^{18}\text{O}$  and  $\delta\text{D}$  for the sampling sites and Fig. 6 their correlation along with the GMWL. Samples from San Luis, the dam, Quinto River, observation wells and Buenos Aires boreholes associate along the GMWL, as well as the Mendoza samples. Graph in Fig. 6 further suggests that the negative groundwater from Mendoza is not identified in the samples of the Buenos Aires plain; this also proposes the possibility that its discharge zone is located beyond the Buenos Aires province. The position of the samples from the lagoons (squares) showing a low  $\delta^{18}\text{O}$ - $\delta\text{D}$  slope indicates significant evaporation process to have occurred to most lagoon water, water whose origin is proposed to be related to local and intermediate flows as depicted from the samples that have negligible evaporation effect. This is in agreement with results from the application of groundwater hydraulic modelling (Alconada 2008) which confirms that discharged water is produced by local and intermediate flows.

Obtained results propose that the chemistry of the study area is a potential tool to differentiate flow systems (local



**Fig. 6** Correlation between  $\delta^{18}\text{O}$  and  $\delta\text{D}$  for sampled waters as related to the GMWL

or intermediate) and their control zones (recharge or discharge). The local flow is characterised by 15–17°C; 9–1 mg/l DO; 9–1 mv Eh; 850–1,000  $\mu\text{S}/\text{cm}$ . The intermediate flow has a 18–23°C; 2.5–3.7 mg/l DO; -9 to 1 mg/l DO; 9–1 Eh; 3,200–3,600  $\mu\text{S}/\text{cm}$  EC. Recharge conditions are usually observed where salinity and temperature are the lowest (i.e.,  $\approx 600 \mu\text{S}/\text{cm}$ , and  $\approx 16^\circ\text{C}$ , respectively), and DO and Eh are high (i.e.,  $\approx 7$ , and  $\approx 1,000$  mv). Discharge conditions are represented by emerging water table together with high salinity. Identified hydraulic and chemical situation define contrasting practices for forestry and agricultural management to establish

**Table 7** Average values for  $\delta^{18}\text{O}/^{16}\text{O}$  and  $\delta\text{D}/\text{H}$  content in samples collected

Site	Average value				
	$\delta^{18}\text{O}\text{‰}$	$\delta\text{D}\text{‰}$	$\delta\text{D}/\delta^{18}\text{O}$	$\delta\text{D}/^{18}\text{O}_{\text{GMWL}}$	$\delta\text{D}/^{18}\text{O}_{\text{GMWL}}/\delta\text{D}$
Mendoza (boreholes)	-17.94	-133.69	7.45	-133.52	1.00
San Luis (borehole, 10 m)	-4.37	-2.29	6.25	-24.93	0.91
Dam & River Quinto, SL	-4.15	-24.49	5.93	-23.215	0.93
Buenos Aires (boreholes)	-4.86	-29.85	6.17	-28.87	0.97
Piezometers	-4.93	-30.65	6.20	-29.42	0.96
Buenos Aires (piezometers)	-5.16	-32.39	6.26	-31.291	0.97
Lagoons	0.59	-2.72	5.59	14.73	2.17

potential flooding control policies. Due to the water quality involved, there is a marked difference when a flooding situation affects a discharge zone related to a local flow whose soil productivity characteristics would have a higher possibility to be recovered than a soil related to a discharge zone affected by flooding resulting from a saltier intermediate flow.

Hydrogeochemical modelling interpretation in conjunction with major and minor ions, and stable isotopes suggest the presence of flooding water is derived from the inflow of groundwater that was not recharged locally. The inflow of intermediate flow water that has travelled from outside the catchment is in agreement with: (1) hydraulic modelling of the groundwater flow regime; (2) the rise of the water table rise disregarding the prevailing drought conditions, (3) the lack on surface communication among the surface water bodies as identified in satellite imagery in the flooding area (Alconada 2008). These results are considered to be valuable in flood land management such as bio drainage and related forestry and farming practices (Alconada-Magliano et al. 2009).

## Conclusions

Surface water (dams, rivers) and groundwater from Mendoza and San Luis provinces are related to regional recharge zones that show little chemical influence in the flooding water of the Buenos Aires area, as well as in observation wells and boreholes. The composition of sampled groundwater in Buenos Aires belongs to intermediate and local flows; there is a lack of chemical and physical (i.e., presence of thermal springs) evidence of regional discharge zones forming lagoons or wetlands in the study area or neighbouring sites. This is considered additional evidence on the flooding process that occurs, mainly, by the discharge of intermediate flow systems.

Geochemical results for Mendoza, San Luis, and Buenos Aires imply processes such as the dissolution of halite, gypsum, biotite, albite, anortite and K-feldspar; the precipitation of calcite is defined. The difference between

halite and dolomite precipitation in the lagoons, occasionally is explained by additional diffuse groundwater inflow from depth, which is originated from intermediate flow. The geochemical processes that affects sampled water for observation wells and boreholes are similar, the proportion in which weathering occurs in each of them is different.

The changes in composition observed along the flow path for the studied water, start with sulphate-bicarbonate and bicarbonate-sulphate type water in the regional recharge zone in Mendoza and change into bicarbonate-chloride type, following a chloride-bicarbonate type. Observed final evolution represented by chloride and chloride-sulphate water indicates a large flow path, which advocates that flooding water is not related directly to rain water resulting from an increase in precipitation. The condition of intermediate (and local) flow discharge may be postulated by the low value of lithium in lagoon water as compared to its concentration in Mendoza water. Similarly, a final prevalence in sodium as related to calcium and magnesium content is coherent with such lengthy path.

The joint application of mass balance, mixing and saturation index modelling provided information to define hydrogeochemical processes related with the functioning of flooding water that is proposed to be mainly related to groundwater discharge of intermediate and local flow systems.

## References

- Alconada MMM (2008) Flooding processes in the longitudinal dunes of the northwest of the Buenos Aires Province, Argentina, its relation to vegetation, soil and water: developing options (in Spanish). Thesis for the degree of Doctor in Geography, UNAM, pp 650
- Alconada-Magliano MM, Bussoni A, Rosa R, Carrillo-Rivera JJ (2009) El bio-drenaje para el control del exceso hídrico en la Pampa Arenosa, Buenos Aires, Argentina. *Investigaciones Geográficas* 68:50–72
- APHA-AWWA-WPCF (1989) Standard methods for the examination of water and wastewater, vol 17. Washington, DC

- Back W, Cherry RN, Hanshaw BB (1966) Chemical equilibrium between the water and minerals of a carbonate aquifer. *Nat Speleol Soc Bull* 28(3):119–126
- Carrillo-Rivera JJ, Varsányi I, Kovács LÓ, Cardona A (2007) Tracing groundwater flow systems with hydrogeochemistry in contrasting geological environments. *Water Air Soil Pollut* 184:77–103
- Cingolani CA (2005) Unidades morfoestructurales y estructurales menores de la provincia de Buenos Aires. XVI Congreso Geológico Argentino, Chapter II 21–30
- Dangavs N (2005) Los ambientes acuáticos de la provincia de Buenos Aires. XVI Congreso Geológico Argentino, La Plata. Chapter XIII: 219–236
- Drever JY (1988) *The geochemistry of natural water*, 2nd edn. Prentice Hall, Englewood Cliffs, p 437
- Edmunds WM, Smedley PL (2000) Residence time indicators in groundwater: the East Midlands Triassic sandstone aquifer. *Appl Geochem* 15:6737–6752
- Etchichurry MC, Tofalo OR, Forzinetti ME (1988) Composición de la fracción psamítica de sedimentos actuales de la provincial de Buenos Aires y su significado tectónico. *Seg Tour Geol Bon, Bahía Blanca*
- Fagundo JR (1990) Evolución química y relaciones empíricas en aguas naturales. Efecto de los factores geológicos, hidrogeológicos y ambientales. *Hidrogeología (Granada)* 5:33–46 (ISSN 0214-1.248)
- Fagundo JR (1998) Patrones hidrogeoquímicos y relaciones matemáticas en aguas naturales. *Ingeniería Hidráulica* 19(2):62–78 (ISSN 0253-0678)
- Fagundo-Castillo JR, Carrillo-Rivera JJ, Antigüedad-Auzmendi I, González-Hernández P, Leláes-Díaz R, Hernández-Díaz R, Cáceres-Govea D, Hernández-Santana JR, Suárez-Muñoz M, Melán-Rodríguez C, Rodríguez-Piña M (2008) Chemical and geological control of spring water in eastern Guaniguanico mountain range, Pinar del Rio, Cuba. *Env Geol* 55(2):247–267
- Fagundo-Sierra J, Fagundo JR, González P, Suárez M (2001) Modelación de las aguas naturales. *Contribución a la Educación y la Protección Ambiental*, vol VII. ISCTN, La Habana. 959-7136-13-9
- Garrels R, Mackenzie FT (1967) Origin of the chemical composition of some springs and lakes. Equilibrium concepts in natural water systems. *Am Chem Soc Adv Chem Ser* 67:222–242
- González N (2005) Los ambientes hidrogeológicos de la provincia de Buenos Aires. XVI Congreso Geológico Argentino, La Plata. Cap XXII. pp 359–374
- McDonald MG, Harbaugh AW (1996) A modular three-dimensional finite-difference ground-water flow model US Geological Survey, *Techniques of Water-Resources Investigations*, Book 6, Chapter A1
- Moncaut CA (2003) Inundaciones y sequías tienen raíces añejas en la pampa bonaerense (1576–2001). Capítulo 1: 27–48. *En O. Maiola, Gabellone, N. y M. Hernández (ed) Inundaciones en la región pampeana*. Ed. UNLP, Argentina
- Mook WG (2001) Environmental isotopes in the hydrological cycle, principles and applications. V.1 Centre for isotope Research, *Croningen UNESCO/IAEA series*
- Parkhurst DL, DC Thorstenson, LN Plummer (1980) PHREEQC. A computer program for geochemical calculations. *US Geol Surv Water Resour Inv* 90–92, 210 pp
- Pesce H, F Miranda (2003) Catálogo de manifestaciones termales de la República de Argentina. Vol. I-II Región Noroeste. SEGEMAR, Buenos Aires. 1666–3462
- PMI, Plan Maestro Integral Cuenca del Río Salado (1999) Ministerio de Economía de la Provincia de Buenos Aires-Halcrow-Banco Mundial. Volumen principal y 14 Anexos en CD. 1300 p
- Rankama K, Sahama THG (1964) *Geoquímica*. ed. Aguilar, España. 861 pp
- Stiff HA (1951) The interpretation of chemical water analysis by means of pattern, *Jour. Petrol Technol* 3(10):15–17
- Tóth J (2000) Las aguas subterráneas como agente geológico: causas, procesos y manifestaciones. *Boletín Geológico y Minero*, 111 (4):9–25. Instituto Geológico GeoMinero (España) (ISSN 0366-0176)
- Vinograd NA (2004) Formation of mineral and thermal waters of some artesian basins in Russia. *Env Geol* 46:675–679
- Zárate M, J Rabanesse (2005) Geomorfología de la Provincia de Buenos Aires. XVI Congreso Geológico Argentino, La Plata. Capítulo VIII: 119–138