Environ Earth Sci (2016) 75:520
DOI 10.1007/s12665-015-5141-9

THEMATIC ISSUE

Snowmelt contribution to the sustainability of the irrigated Mendoza's Oasis, Argentina: an isotope study

Hector Massone[1] · **Daniel Martinez**[1,2] · **Alberto Vich**[3] · **Mauricio Quiroz Londoño**[1,2] · **Darío Trombotto**[3] · **Sebastián Grondona**[1,2]

Received: 18 June 2015 / Accepted: 5 October 2015 / Published online: 18 March 2016

Abstract Mendoza is the province that has the largest irrigated area in Argentina where water resources depend mainly on snowmelt and glacier melting in the closed Andes Mountain. In this region the Blanco River Basin is one of the most important, covering about 300 km^2 flowing from the highest peaks to Potrerillos Dam (1300 masl). The objective of this work was to make a preliminary characterization of stable isotopes in surface and groundwater, ice and snowmelt to contribute to a better understanding of the hydrologic cycle in the region, using a Los Gatos DLT-100 analyzer. Hydrochemical analyses were performed on 157 samples. The isotopic composition of rain water is more enriched than streamwater, clearly indicating that the stream recharge sources are at higher altitude. The discharge regime of the streams indicates that snowmelt is the main water origin, and considering the theoretical evolution of isotopes in meltwater, the composition of streams corresponds to the first meltwater, without fractionation. Then, it is more depleted than the original snow. The ice isotopic composition is more enriched than streamwater, indicating that snowmelt is the main recharge source. The hydrochemical results indicate the importance of geology in determining streamwater composition, which is integrated with isotopic data to achieve a better comprehension of the hydrological system.

Keywords Isotopes · Groundwater · Surface water · Snowmelt

Introduction

Mendoza is the province having the largest irrigated area in the Central Andes of Argentina. Climate is arid and water resources depend mainly on snowmelt and glacier melting in the closed Andes Mountains. A significant economic activity is possible due to the existence of a network irrigation system 8100 km long, taking water from rivers with sources in the Andes ranges and from alluvial aquifers. There are two main rivers in the north of Mendoza province: Mendoza (50 m^3/s average) and Tunuyan (28 m^3/s average), both widely used for irrigation. Moreover, there are about 16,000 groundwater wells that are used for direct irrigation, or to complete irrigation with surface water, especially in poor hydrological years (Auge 2004). These agricultural areas are called Mendoza's and Tunuyan Oasis (2500 km^2). Agriculture is the most important activity in the province, where the main cultivated crops are grape, stone fruits, pome fruits, vegetables, trees and forage (Morabito et al. 2009). All this economic activity, together with the human supply depends on irrigation systems and dams. The precipitation as snow in the high peaks of the Central Andes is the main source of systems recharge; this makes it not possible to think about the sustainability of the hydric system and its relation to consumption without a better understanding of the hydrological cycle and how ice, snowmelt, surface water and groundwater interact.

This article is a part of a Topical Collection in Environmental Earth Sciences on "3RAGSU", guest edited by Daniel Emilio Martinez.

✉ Daniel Martinez
demarti@mdp.edu.ar

[1] Institute of Coastal Geology and Quaternary, National University of Mar del Plata, Mar del Plata, Argentina

[2] Institute of Marine and Coastal Research, CONICET-National University of Mar del Plata, Mar del Plata, Argentina

[3] Argentine Institute of Snow Research and Glaciology, CONICET, Mendoza, Argentina

Stable isotopic measurements have been widely used to study the water cycle (Clark and Fritz 1997; Aggarwal et al. 2005). Although the applications of water stable isotopes are very diverse, those related to groundwater recharge (Harvey and Sibray 2001; Blasch and Bryson 2007; Yeh et al. 2011; Qian et al. 2014), relationships between surface and groundwater (Edjah et al. 2015; Congjian et al. 2015), and relationships between water and snowmelt (Kurás et al. 2008; Lee et al. 2010) are particularly interesting for this work. In the Mendoza province, Panarello et al. (1993), Panarello and Dapeña (1996) and Dapeña (2008) made a regional isotopic characterization of surface water and groundwater; they identified recharge areas and sources of water pollution for the Mendoza and Tunuyan river basins. Zuluaga et al. (2008) and Drovandi et al. (2010) have previously characterized the chemistry of the surface water in the Rio Blanco catchment, analyzing also the pollution degree.

The objective of this paper was to develop a hydrogeochemistry, and isotopic characterization of the Blanco River basin, including samples of groundwater, surface water, ice and snow melt water was studied. The relationship between them and the individual contribution to the water resources of this area were analyzed.

Study area

Blanco River basin is in the north of Mendoza province (Fig. 1), lying on the eastern slope of the Andes Mountains (called "Cordón del Plata" mountains). Drovandi et al. (2010) divided the catchment into the main central branch of the Blanco River, and two sub-catchments, one to the south denominated Alto Las Vegas, and a northern subcatchment denominated Alto Manantiales (Fig. 1). The Blanco River is a tributary of the Mendoza river and is the main source of drinking water and irrigation of Mendoza Oasis. This river begins on the eastern slope of the Cordón del Plata (6100 masl) and flows eastward into the Potrerillos dam; it was built in 2005 to supply drinking water to the city of Mendoza (850,000 inhabitants). In the Blanco River basin (150 km^2) the altitudes range from 6300 to 1300 masl in a distance of just 20 km.

The area is located in the geological province of Cordillera Frontal and occupies two different geomorphological areas: The Cordillera Frontal sensu stricto occupies the western and northwestern sector, while the eastern sector, called "Cuyana Basin" (Heredia et al. 2012), is occupied by an alluvial fan. (Fig. 1)

The Cordillera Frontal contains a Paleozoic basement constituted by sedimentary, metamorphic an igneous rocks, which was strongly deformed during the Famatinian and Gondwananorogenic cycles (Ramos 1988) and is intruded by Upper Paleozoic granitoids. This bedrock supports unconformably the "Choiyoi Group" (Perm-Triassic volcanic rocks) and Cenozoic sediments related to the uplift of the Andes. Tertiary deposits consist of sandstones and conglomerates, while the Quaternary is represented by alluvial deposits (fanglomerates) described by Polanski (1963) and levels of pediment (Cortés 2000). This sedimentation originated large alluvial fans in whose apexes are born the main rivers and from which start an extensive floodplain.

The main aquifers of this region are developed in the tertiary and quaternary sediments, formed by alluvial and fluvial deposits that were provided by the Mendoza and Tunuyán rivers. The hydrogeological basement consists of paleozoic and pre-paleozoic rocks (Auge 2004). The alluvial fans form a phreatic aquifer which is extended in the entire valley, having a thickness ranging between 700 and 800 m. Towards the center and downstream of the catchment this phreatic aquifer is underlied by confined or semi-confined aquifers (Alvarez 2008).

Groundwater recharge occurs through three processes: (a) infiltration in the Mendoza riverbed, (b) infiltration in irrigated fields and (c) infiltration from irrigation canals. The main recharge occurs in the unconfined aquifer area directly by infiltration into the bed of the Mendoza river, with prevailing directions of groundwater flow toward the northeast, east and southeast (Auge 2004).

Climate is semi-arid (North 1995), with a mean annual precipitation (rain and snow) in this area of about 240 mm. Precipitation is higher from May to October (snow), but during summer there are short and intense rains. The mean annual temperature is 12.5 °C (January: 21.3 °C and July: 3.6 °C). The incomplete records of Vallecitos meteorological station (2470 masl) provide a mean annual temperature of approximately 5 °C and a precipitation of approximately 450 mm.

Materials and methods

Analytical methods

Analyses were carried out at the Hydrogeochemistry and Isotope Hydrology Laboratory belonging to the "Instituto de Geología de Costas y del Cuaternario", Mar del Plata University. Total hardness was measured, and major ion concentrations were determined in all samples. The standard methods used (APHA 1992) were as follows: chloride following Mohr method, detection limit (DL) 0.1 mg/L using a titration solution of $AgNO_3 \cdot 0.01$ N; sulfate by turbidimetry, DL 1 mg/L, calibration solution of $BaCl_2$; calcium, DL 0.5 mg/L, and magnesium, DL 1 mg/L by complexometric titrations with EDTA 0.01 M; sodium, DL 0.02 mg/L; and potassium DL 0.1 mg/L by flame spectrometry using calibration solution of 30 mg/L of NaCl and

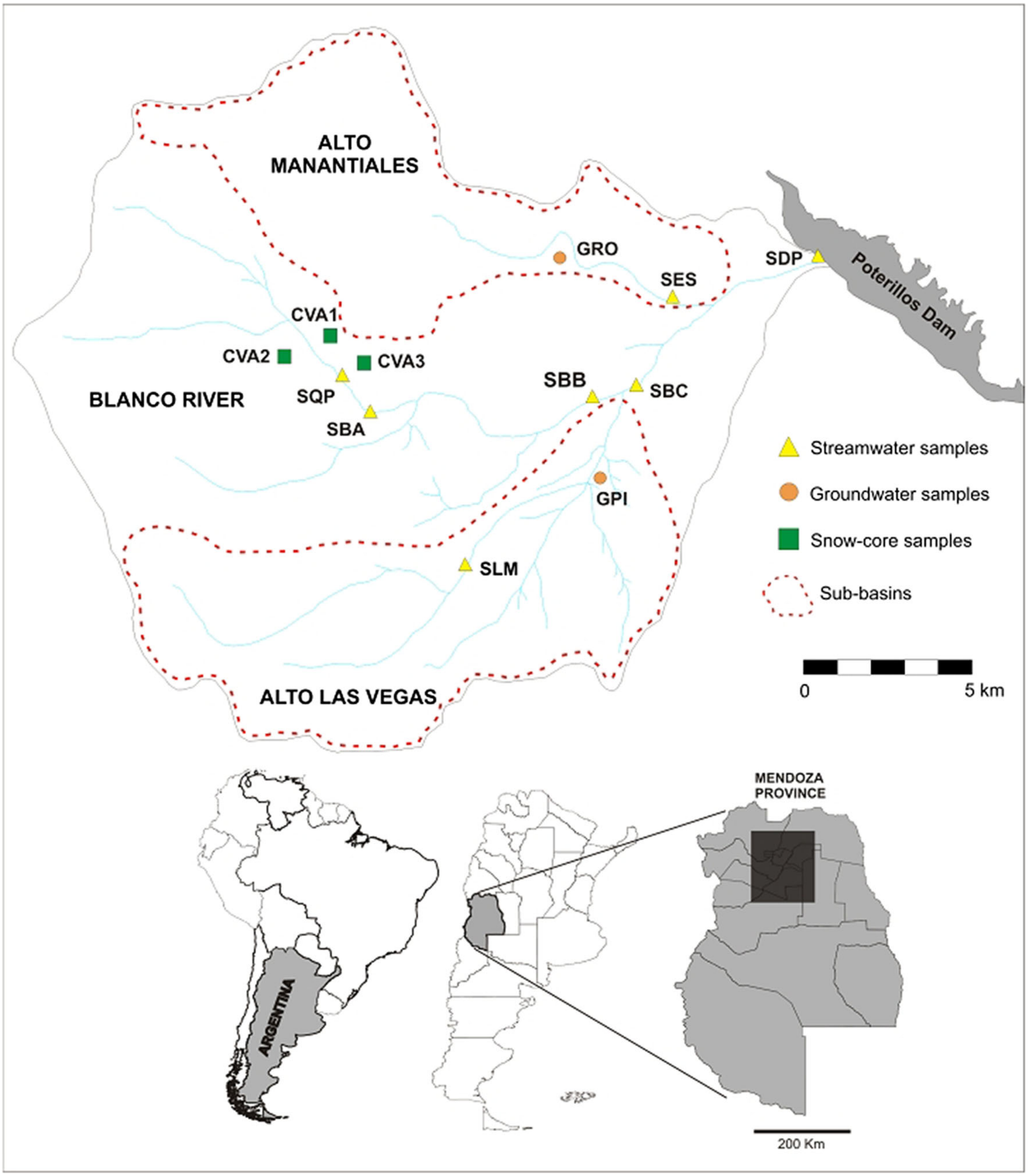


Fig. 1 Location map. Blanco River basin with subcatchments (from Drovandi et al. 2010) and sampling sites

3.8 mg/L of KCl; silica by means of silicomolybdate method; DL 0.2 mg/L and calibration solution of 50 mg/L of SiO_2; nitrate by a spectrophotometer Hach DREL 2800 method N°10.206 HR 5.0–155 mg/L; and bicarbonate–carbonate by potentiometric titration (DL 0.5 mg/L) with a solution of HCl 0.1 N. Furthermore, fluorine by the zirconyl chloride method (DL 0.01 mg/L) and total iron by spectrophotometry (HachDrel 2800 Ferrover1 method, DL 0.05 mg/L) were done.

Analytical quality control has been done through ionic balance, computing as percentage the difference in the sum of equivalents of cations minus the sum of equivalent of anions divided by the total sum of equivalents of each solution. Around 80 % of the samples fit into the acceptable <5 % error. Hydrochemical information was analyzed through a general statistical characterization and conventional Piper and Schoeller diagrams (Hem 1992) using AQUACHEM software (Calmbach and Waterloo

Hydrogeologic Inc. 2003). PHREEQC software (Parkhurst and Appelo 1999) was used for hydrogeochemical calculations.

Isotopic analyses were performed through laser spectroscopy (Lis et al. 2008) using a DLT-100 liquid water isotope analyzer, automated injection, developed by Los Gatos Research. The results were expressed as δ values in permil (‰), defined as: $\delta = 1000$ (Rs–Rp)/Rp %, where δ is the isotopic deviation in %; S is the sample, P is the international reference, and R is the isotopic ratio (^{2}H/^{1}H, ^{18}O/^{16}O). The standard is Vienna Standard Mean Ocean Water (V-SMOW; Gonfiantini 1978). The internal laboratory standards used for the determinations were std1 δ ^{18}O = −15.4, δ ^{2}H = −111.0; std2 δ ^{18}O = −4.78, δ ^{2}H = −25.7, std3 δ ^{18}O = −8.54, δ ^{2}H = −59.9. The analytical uncertainties were ±0.2 % for δ ^{18}O and ±2.0 % for δ ^{2}H.

Sampling design

Precipitation two collectors for precipitation samples were installed in November 2010 in Mendoza city (LCR, 826 masl) and in Colonia Suiza, a residential area near the mouth of the Blanco River (LCS, 1200 masl). Samples correspond to individual events and were kept preventing evaporation from the collector.

*Surface water s*ix surface water sampling sites were selected in the Rio Blanco basin (Fig. 1) and sampling was carried out one time per month. The sites selected were: a) four in the main central sub-catchment, labeled from upstream to downstream as SQP at 2786 masl, SBA at 2587 masl, SBB at 1660 masl, and SBC at 1645; b) a sampling point in the southern sub-catchment, SLM at 2307 masl, c) and one in the northern sub-catchment, SES at 1570 masl. Physico-chemical parameters temperature, pH and electrical conductivity (EC) were measured in the field.

Groundwater the dem1and for irrigation and drinking water in the Rio Blanco basin is mostly supplied by surface water. Therefore, just two boreholes have been located in the catchment (Fig.). Borehole GRO is located in "Alto Manantiales" subcatchment, and borehole GPI in "Alto Las Vegas" subcatchment. These two are used to irrigate a small vegetable production. During 2014 a new borehole began to operate at the mouth of the basin (GPO). Groundwater samples were taken using a bailer sampler with a seasonal frequency, since June 2011.

*Ice, Snowpack and snow*cores samples an ice sample was taken in the "Morenas Coloradas Glacier" at aprox. 3700 masl and 3.4 m depth (January 2011). Snowpack has been sampled at 3100 masl in September 2010 (NVA sample). After that, three sampling points were selected during 2011 and 2012 winters: *NQP* 2700 masl, *NCS* 1280 masl, *NLM* 2300 masl. These samples were taken from the upper 20 cm of the snowpack, after removing the first 5 cm of snow. Three snowcores were taken in August 2012, near the Vallecitos Ski center (CVA1, CVA2, CVA3, Fig. 1). This sampling device used was a stainless steel tube 1 m long with a diameter of 7.5 cm, which was buried until the bedrock, taking between 60 and 80 cm of snow.

Snowmelt

Three wick samplers (Frisbee et al. 2010) were prepared according to the design explained by Penna et al. (2014). They were installed during three consecutive winters: 2012, 2013 and 2014, and they were taken out at the end of each winter season, around October. The collected water was analyzed for isotope composition. The installation at sites are those denominated as FVA, FCA and FEM, placed at altitudes of 2800, 2700 and 2580 masl, respectively.

Results

Hydrogeochemistry

Groundwater

The statistical parameters of groundwater compositions of the sampling point in the northern sub-catchment (GRO) and in the southern sub-catchment (GPI) are shown in Table 1. The observed salinity is low, but some differences were observed when comparing both sites. Electrical conductivity ranges between 491 and 781 μS/cm for GRO samples, and between 292 and 308 μS/cm for GPI samples, so EC values were more variable in GRO. This difference was also observed in the ionic composition of both wells (Fig. 2). The most important difference is in cationic composition: GRO is formed by calcium-magnesium waters, while GPI is formed by sodium waters. The samples' anionic composition is more similar, being mostly bicarbonate water,

Streamwater

The chemical composition of streamwater is also variable; a general characterization of the parameters measured is included in Table 2. SLM site is the only located in the southern sub-catchment, where EC ranges between 100 and 200 μS/cm, being markedly lower than the other sampling sites. SES is the only point taken in the northern sub-catchment and placed at the lowest altitude. Its EC values

Table 1 Statistics summary of the Mendoza's oasis physicochemical parameters of groundwater

Parameter	Unit	Min	Max	Average	Standard deviation	Sample number
pH		7.00	9.27	7.71	7.56	15
EC	uS/cm	282.00	781.00	455.23	168.61	13
Ca	mg/l	2.00	100.00	34.00	31.95	15
Mg	mg/l	2.35	81.30	40.74	30.49	15
Na	mg/l	8.00	130.00	53.20	43.63	15
K	mg/l	0.80	13.00	3.68	3.22	15
Cl	mg/l	9.19	41.30	25.54	9.55	15
HCO_3	mg/l	119.00	462.00	230.36	95.27	15
SO_4	mg/l	14.00	320.00	109.39	83.17	15
NO_3	mg/l	0.00	13.80	3.94	5.06	7
F	mg/l	0.05	2.38	1.35	0.77	13
SiO_2	mg/l	0.18	16.10	6.90	6.25	15

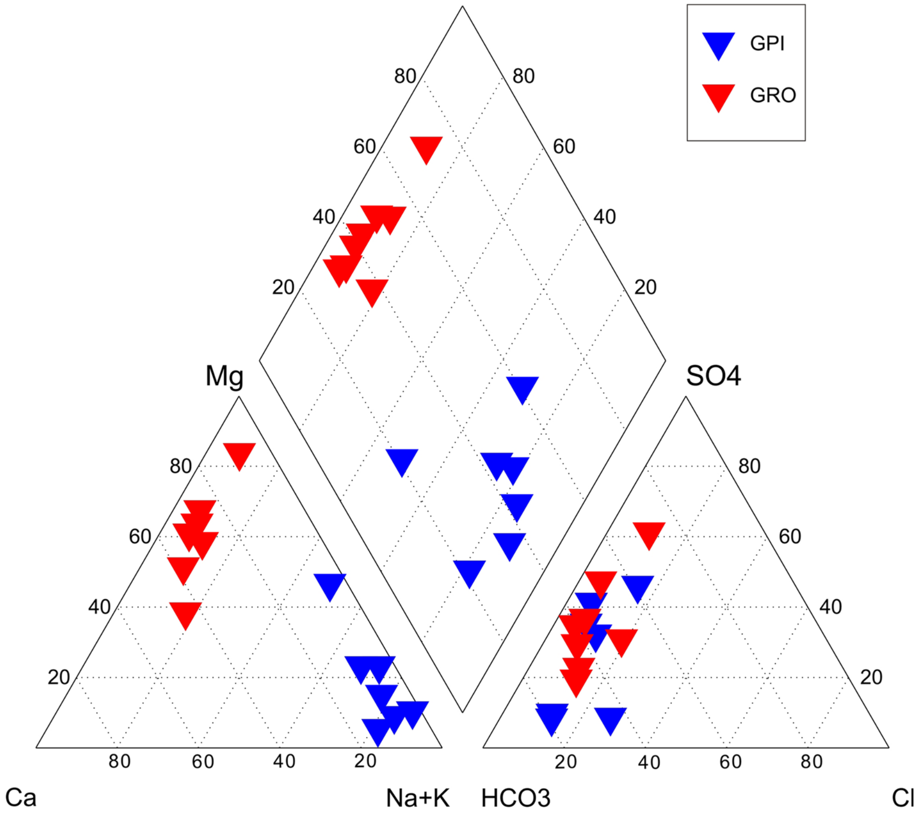


Fig. 2 Piper diagram of ionic composition of groundwater samples

are the more variable, also being the highest of all the sampling points.

The samples SQP, SBA, SBB and SBC are in the central sub-catchment, and ordered from highest to lowest level. The two highest sites, SQP and SBA, had a similar range of values for EC, approximately between 300 and 500 µS/cm, but with a different annual distribution. SQP is at the highest altitude in a minor creek tributary of the Blanco River and had lower EC values during summer months and the highest values during end of winter and spring months. SBA is in the main stream (Blanco River), has the lower EC values during the end of winter and spring months and the highest values during summer. SBB and SBC sites are in the main stream downstream SBA and had highest EC values between 400 and 550 µS/cm, thus demonstrating the higher influence of the Blanco river main course in their composition.

Two Piper diagrams have been plotted due the large number of streamwater samples analyzed (258). One for samples in the southern sub-catchment (SLM), the northern

Table 2 Statistics summary of the Mendoza's oasis physicochemical parameters of streamwater

Parameter	Unit	Min	Max	Average	Standard deviation	Sample number
pH		6.17	8.8	7.67	7.24	258
EC	uS/cm	114	568	390.97	126.26	258
Ca	mg/l	0.25	100	41.4	16.68	258
Mg	mg/l	4	100.4	48.22	18.01	258
Na	mg/l	0	118	10.78	12.21	258
K	mg/l	0.1	96.6	3.28	9.55	258
Cl	mg/l	0	136	20.47	12.91	258
HCO_3	mg/l	0	571.4	140.94	84.77	258
SO_4	mg/l	0	360	151.5	77.35	258
NO_3	mg/l	0.5	118.2	11.52	16.38	151
F	mg/l	0	18.6	1.55	1.68	214
SiO_2	mg/l	0	147	10.7	11.69	258

(SES) and the small tributary in the main stream (SQP) (Fig. 3a). The second Piper diagram includes the samples in the Blanco River (SBA, SBB and SBC, Fig. 3b).

SQP is mostly sulfate magnesium-calcium water type, SLM samples are bicarbonate magnesium-calcium type, and SES samples correspond to a wider range of compositions, with a higher participation of sodium and bicarbonate. The ionic composition of the three samples in the main branch of the Blanco River is in all the cases sulfate calcium-magnesium water, with few alkaline samples. SQP is also located at the main central sub-basin and had the same composition than SBA, SBB and SBC, so it is simple to differentiate calcium sulphate-magnesium waters of the Blanco River to the calcium-magnesium bicarbonate waters from the southern and northern sub-catchments.

Isotope hydrology

Isotopes in precipitation

A total of 299 samples of daily precipitation events were analyzed, 214 corresponding to LCS station and 85 corresponding to LCR station. The diagram of $\delta^{18}O$ vs $\delta^{2}H$ shows the wide dispersion of values of stable isotopes in precipitation (Fig. 4). Local meteoric water lines for both collectors are also included in the graph, which are quite close to the global meteoric water line. Deuterium excess is around 13–15 for LCS and LCR, respectively.

The weighted average values for the stations were LCS $\delta^{18}O$ −5.01 and $\delta^{2}H$ −23.7, LCR $\delta^{18}O$ −5.24 and $\delta^{2}H$ −26.1. Working on monthly composite samples, Dapeña

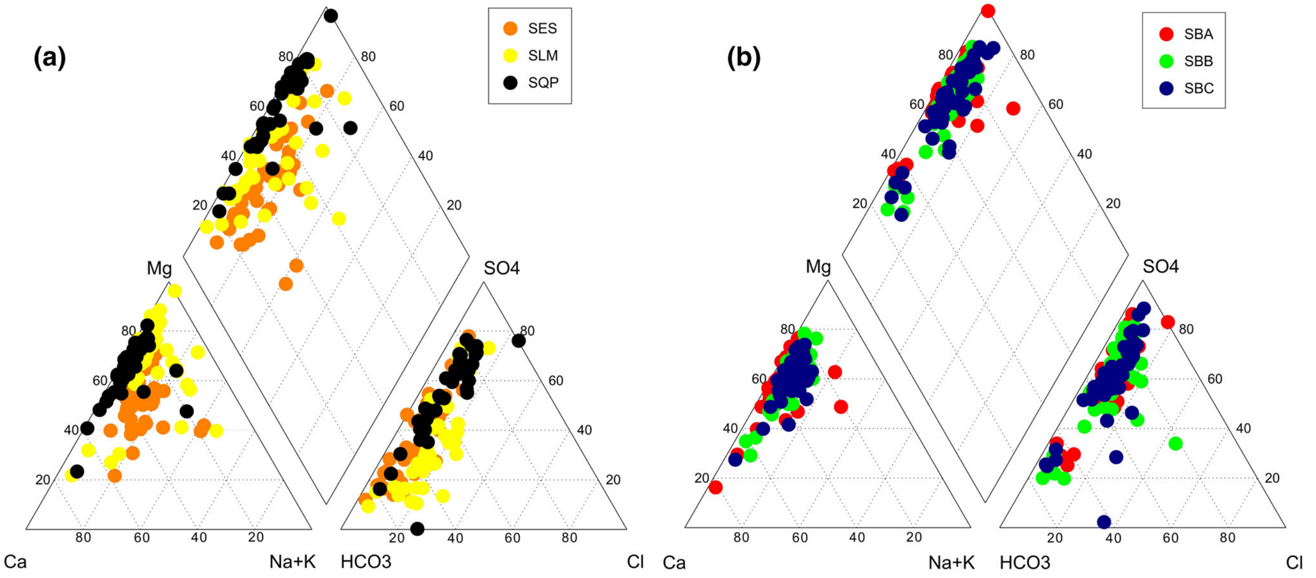


Fig. 3 Piper diagrams showing the ionic composition of streamwater sampling points: **a** sites SQO, SLM and SES; **b** sites SBA, SBB and SBC

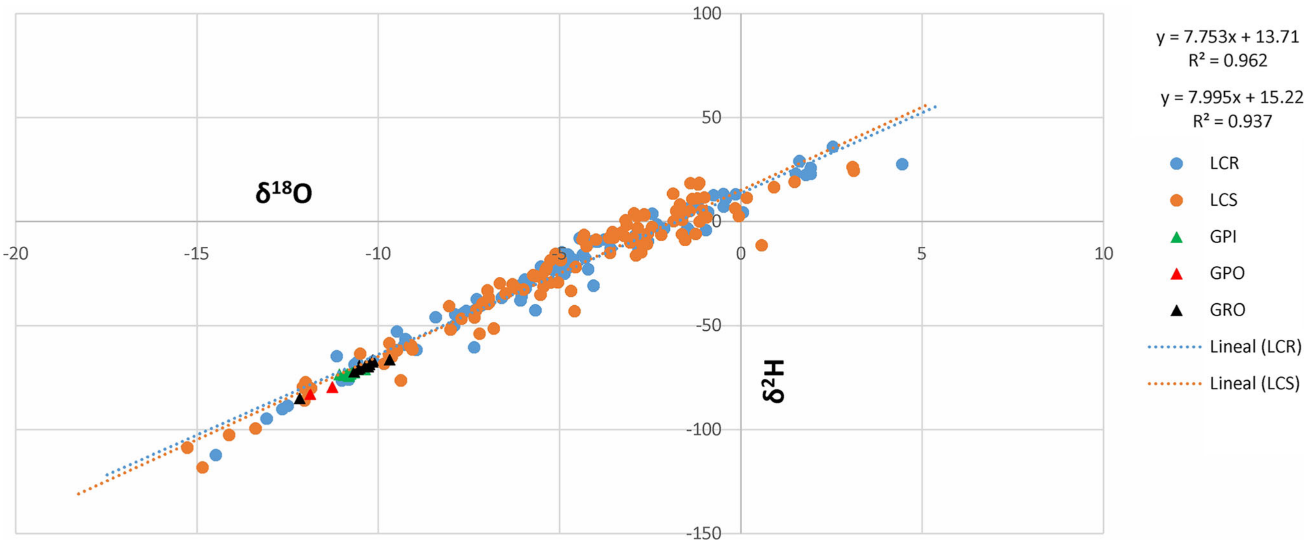


Fig. 4 $\delta^{18}O$ vs $\delta^{2}H$ diagram of daily rain precipitation samples and groundwater samples

(2008) determined that average values in precipitation in Mendoza city are $\delta^{18}O$ −5.6 ‰ and $\delta^{2}H$ −42 ‰.

Groundwater

Twelve samples were taken from the well GRO placed in the sub-catchment Alto Manantiales, nine from the well GPI located in the sub-catchment Alto Las Vegas, and two from GPO in the lower basin. GRO samples are more enriched than GPI samples (Fig. 4). GPO samples are more depleted than the others from GRO and *GPI.*

Streamwater

The isotopic composition of surface water (Fig. 5) shows a gradient from depleted to enriched samples with the following order: SQP, SBA, SBB-SBC, SLM, SES. The samples are disposed along the LMWL, following a general trend where the highest sampling points (SQP and SBA) are the most depleted and the lowest sampling point (SES) samples form a separate more enriched group of samples. The average value for SLM (2307 masl) is more enriched than those for SBB and SBC stations (around 1650 masl).

Snow and ice isotope characterization

The isotopic composition of snow and snowmelt characterization was considered through three different sampling procedures: snowpack samples, snowcore samples, and composite samples taken using passive wick samplers.

The composition is plotted in a diagram in Fig. 6. In this figure the average composition of the snowpack samples and the average composition of the highest streamwater site (SQP) are also included.

Discussion

The hydrology of catchments where snow is an important component of precipitation requires specific analysis because of the different sources of runoff and the temporal variability of water inputs (Kurás et al. 2008). The complexity of the identification of streamwater sources and its relationship with geochemical tracers have been discussed by different authors (Kirchner 2003; Mcdonell 2003). The application of stable isotopes in streamflow studies has been exposed in different contributions, such as the classic book by Kendall and McDonnell (1998) or in recent papers form Tekleab et al. (2013), Klaus and McDonnell (2013).

In the Río Blanco Catchment, the streamwater samples showed a clear trend in different parameters from upstream (higher altitude) to downstream (lower altitude). Temperature, pH and EC increase in the sense of flow. EC shows a normal evolution in the flow sense in the main branch of the Blanco River, increasing its values, but showing differences in different months. There is a big difference between low EC values at the three sampling points above 2500 m and the medium EC values below 1600 m of altitude. Nevertheless, SLM site, at 2037 masl, showed the lowest EC values all along the year.

The major ion composition also differentiates clearly the samples from the central main sub-catchment which is

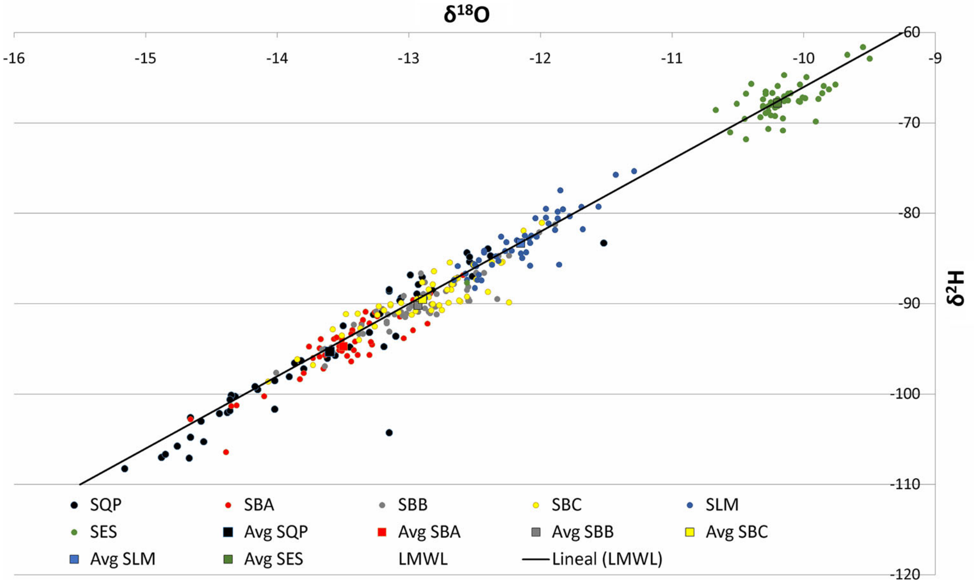
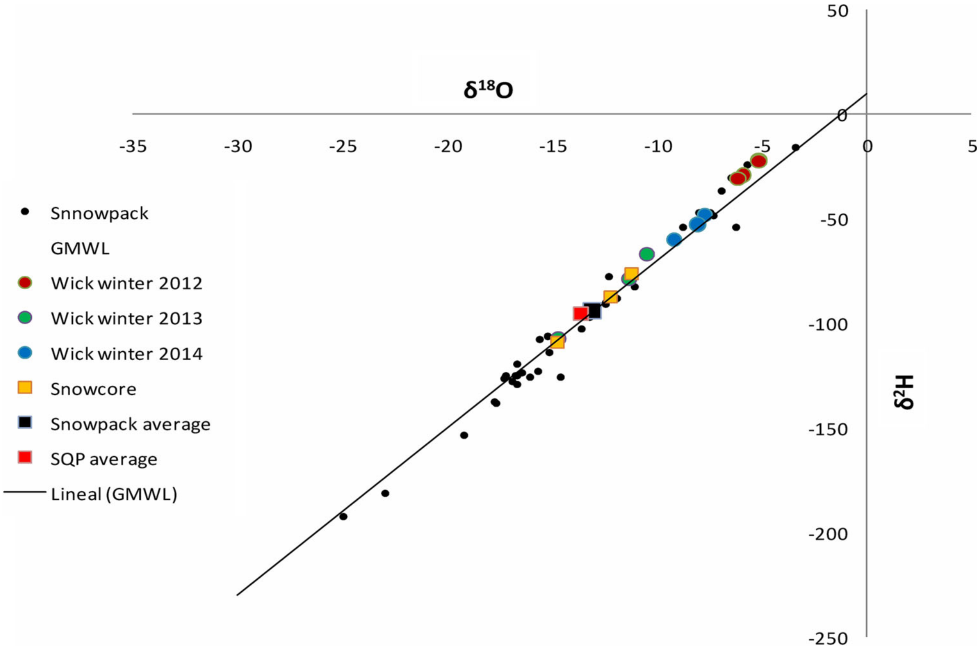


Fig. 5 δ18O vs δ2H diagram including streamwater samples and the average of each sampling site

Fig. 6 Isotope composition of different types of snow samples and the average of SQP streamwater



calcium-magnesium sulfate type, from those of the northern sub-catchment SES or Southern sub-catchment SLM which trend to sodium-bicarbonate members. The same pattern can be observed in groundwater, where GRO well waters are of calcium-magnesium sulfate type, having EC values around 500 µS/cm, and GPI well waters are of sodium-bicarbonate type with EC values around 300 µS/cm.

The origin of groundwater and streamwater can be addressed through the isotope composition. Rain water composition in precipitation events at the collectors placed in Colonia Suiza (LCS 1200 masl) and Mendoza City (LCR 816 masl) show a composition ranging from −0.3 and –8.3 ‰ to δ^{18}O and –45.0 and 0.0 ‰ for δ^{2}H. The general composition of rain isotope composition is quite enriched, probably because of the extremely low humidity of the air; the enrinchment takes place during precipitation (Dansgaard 1964). As it has been shown, rain precipitation values are more enriched than groundwater and stream water samples.

The isotopic composition of the streamwater shows a variation from −16.0 to −11.0 ‰ for $\delta^{18}O$ and from −110.0 to −75.0 ‰ for $\delta^{2}H$. It seems to be an altitude effect affecting also the streamwater samples, being the samples fom SQP (2786 masl) the more depleted, and the samples from SBC (1645) the most enriched. Nevertheless, the samples from SLM at 2307 masl present most enriched values than SBA and SBC points. This apparent inversion is actually due to the fact that in the drainage network the altitude effect should be analyzed considering the water divide altitude for each sub-catchment. In fact maximum altitude in the Blanco river sub-catchment (main central) is 6300 masl, in Alto Manantiales sub-catchment (Northern) is 5700 masl, and in Alto Las Vegas sub-catchment (Southern), 4800 masl.

The snowmelt as the source of surface water is a widely known phenomenon from hydrological observations (Zuluaga et al. 2008). Also some previous studies on the adjacent plain area of the province indicated the infiltration of Mendoza River as the main recharge source for the aquifers (Alvarez et al. 2011). Nevertheless, a more precise insight into the processes can be obtained analyzing the isotope results.

Snowmelt composition has been characterized through different sample types. Snowpack showed a high range of variation considering samples taken from different places and dates, with an average value of $\delta^{18}O = -13.05$ and $\delta^{2}H = -94$. The snowcore samples showed values of −12.18, −14.76 and −11.16 for $\delta^{18}O$ and −87.7, −109.3 and −76.5 for $\delta^{2}H$. Isotopic values in wick passive samplers were not constant and generally were more enriched samples than of snowmelt and snowpack. Samples of different winters resulted in different isotope value range: 2012 was the most enriched, 2013 was the most depleted and 2014 had intermediate values.

Snowmelt is then the water input for fluvial system, and it was isotopically characterized through different sampling methods. As could be observed from Fig. 6, snowpack samples have a large variability, which depends not only on the altitude but also on it is changing on different dates. The isotopic composition of the three snowcores is similar to the average values for snowpack and streamwater. On the other hand, the determined composition in the integrated samples, obtained from the wick samplers, showed to be variable among the different winters, but in all the cases more enriched than streamwater at SQP point.

It is important to hghligth that the composition of the points at the headwaters, SQP and SBA, is close similar to that of the average snowpacks value and snowcores. From this point of view it can be said that snowcores are a quite good representative of snowmelt composition forming headwaters.

The results from wick samplers are until this moment not well understood. In a comparative study (Penna et al. 2014) it has been observed that in semi-arid climate environments this devices result in enriched isotope compositions. In the observed period just the integrated samples of winter 2013 are approximately coincident to the headwaters'' average composition. No clear reason is yet assigned as the cause for these divergences. The different degrees of enrichment can be a result of sampling problems not identified, or some differential fractionation due to different degrees of snow sublimation.

In this study, and accepting that points SQP and SBA are the most representative of water sources due to snowmelt, the isotope composition of snowmelt is probably well characterized from the isotope composition of snowcores integrating the whole profile. Also, a good characterization of melt water by using "cumulative snow pack samples" has been obtained by Abbott et al. (2000).

The hydrochemical results indicate the importance of geology in determining streamwater composition, which can be integrated with isotopic data to achieve a better comprehension of the hydrological system. The presence of sulfate in the streamwater of the Blanco River may be explained by the process of pyrite oxidation, and the isotopic fingerprint of water with sources at altitudes up to 6000 masl, with the most depleted values. Pyrite is a common mineral in the Formation El Plata, which outcrops at the headwater area in the central sub-catchment. On the other hand, the streamwater of its tributaries coming for the sub-basin Alto Las Vegas has a Calcium Bicarbonate composition, more characteristics of recharge in low reactive rocks.

Groundwater isotope composition is clearly different from the precipitation average values, indicating that groundwater recharge is also from snowmelt direct infiltration, or due to river water infiltration. GPI samples are more depleted than GRO samples and it is not coincident with the effect of maximum altitude observed for streamwater samples, but can be indicative of the altitude of the main recharge zones. The Ca-SO_4 water type of GRO suggests main control of pyrite oxidation and cation exchange on water composition and supports the theory of river bed water infiltration as the groundwater recharge dominating process. Gypsum dissolution appears to be the easiest explanation for this hydrochemical facies, but the presence of the gypsum-bearing formations in the Cordillera Frontal (Fm. Divisadero Largo, Fm. Auquilco) has not been mentioned outcropping in the study area.

Conclusions

The isotopic composition of rain water at LCS and LCR is more enriched than that of streamwater, clearly indicating that the stream recharge sources are at higher altitude. The discharge regime of the courses indicates that snowmelt is the main water origin, and considering the theoretical evolution of isotopes in meltwater, the composition of streams (SQP as example), corresponds to the first meltwater, without fractionation. Then, it is more depleted than the original snow. The ice isotopic composition is more enriched than streamwater, indicating that snowmelt is the main recharge source. The dependence of the isotopic composition to the maximum altitude for each subcatchment was demonstrated, but the isotope enrichment of the Blanco River along the downstream flow indicates that it is receiving the discharge of small tributaries with sources at lower atitudes. The different subcatchments present different geochemical features, helping to identify the water sources in each case.

Groundwater recharge is not from rain infiltration and according to its isotopic signature the main source is riverbed infiltration. The same geochemical differentiation in different subcatchments than that for streamwater is observed in groundwater samples.

A final important conclusion of the study refers to the best way to characterize snowmelt water. The observations indicate that the isotope composition of the streamwater points located closer to the sources (SQP and SBA) is similar to the average composition of snowpack samples, and also to the snowcore results. Snowcores seem to be a good characterization of the snowmelt composition. The results of the wick samplers need more study in this site. The samples corresponding to winter 2013 seem to be representative of the snowmelt composition forming the drainage system headwaters, but the winters 2012 and 2014 give more enriched values.

Acknowledgments The authors wish to thank the International Atomic Energy Agency (IAEA) for the financial support (CRP 16202/RO) and specially thank Eng. Enrique Montero from "Departamento General de Irrigación" of Mendoza province for the sampling of wells.

References

Abbott MD, Lini A, Bierman PR (2000) δ^{18}O, δD and ^{3}H measurement constrain groundwater recharge patterns in an upland fracture bedrock aquifer, Vermont, USA. J Hydrol 228:101–112

Aggarwal PK, Gat JR, Froehlich KFO (2005) Isotopes in the water cycle: past, present and future of a developing science. International Atomic Energy Agency (IAEA), Netherlands

Alvarez A, Fasciolo G, Barbazza C, Lorenzo F, Balanza ME (2008) Impactos en el agua subterránea de un sistema de aprovechamiento de efluentes para riego. El sistema Paramillo. Lavalle Mendoza. Rev Fac Cienc Agrar 40:61–81

Alvarez A, D'Elía M, Paris M, Fasciolo G, Barbazza C (2011) Evaluación de la contaminación de acuíferos producida por actividades de saneamiento y re-uso de efluentes en el norte de la provincia de Mendoza. Rev Fac Cienc Agrar 43:19–39

APHA (American Public Health Association) (1992) Standard methods for the examination of water and wastewater, 18th edn. American Public Health Association, American Water Works Association, Water Environment Federation, Washington

Auge MP (2004) Regiones hidrogeológicas. República Argentina y provincias de Buenos Aires, Mendoza y Santa Fe. La Plata. http://sedici.unlp.edu.ar/bitstream/handle/10915/15909/Documento_completo.pdf?sequence=1. Accessed 22 May 2015

Blasch K, Bryson J (2007) Distinguishing sources of ground water recharge by using δ^{2}H and δ^{18}O. Ground Water 45:294–308

Cambalach and Waterloo Hydrogeologic (2003) Water quality data analysis, plotting and modeling; Aquachem user's manual v.4.0, Co. Developed by Lukas Calmbach and Waterloo Hydrogeologic Inc., USA

Clark ID, Fritz P (1997) Environmental isotopes in hydrogeology. CRC Press/Lewis Publishers, Boca Raton

Congjian S, Weihong L, Yaning C, Xingong L, Yuhui Y (2015) Isotopic and hydrochemical composition of runoff in the Urumqi River, Tianshan Mountains, China. Environmental Earth Sciences, in press. doi: 10.1007/s12665-015-4144-x

Cortés JM (2000) Fallas cuaternarias oblicuas al frente montañoso en la Cordillera Frontal de Mendoza (34°–34°30′S). Revista Cuaternario y Ciencias Ambientales Special Paper 4:57–62

Dansgaard W (1964) Stable isotopes in precipitation. Tellus 16:436–468

Dapeña C (2008) Isótopos Ambientales Livianos: su aplicación en hidrología e hidrogeología. PhD Tesis, University of Buenos Aires

Drovandi A, Zuluaga J, Filippini M, Cónsoli D, Valdes A, Nacif C, Dediol C, Morsucci A (2010) Evaluación de la calidad del agua en el Embalse Potrerillos y Cuenca del Río Blanco, Provincia de Mendoza. III Congreso Internacional sobre Gestión y Tratamiento Integral del Agua. Córdoba, Argentina. Proceedings: 1–39

Edjah AKM, Akiti TT, Osae S, Adotey D, Glover ET (2015) Hydrogeochemistry and isotope hydrology of surface water and groundwater systems in the Ellembelle district, Ghana, West Africa. Appl Water Sci, in press. doi: 10.1007/s13201-015-0273-3

Frisbee M, Phillips F, Campbell A, Hendrickx J, Engle E (2010) Modified passive capillary samplers for collecting samples of snowmelt infiltration for stable isotope analysis in remote, seasonally inaccessible watersheds 2: field evaluation. Hydrol Process 24:834–849

Gonfiantini R (1978) Standards for stable isotopes measurements in natural compounds. Nature 271:534–536

Harvey FE, Sibray SS (2001) Delineating groundwater recharge from leaking irrigation canals using water chemistry and isotopes. Groundwater 39:408–421

Hem J (1992) Study and interpretation of the chemical characteristics of natural water, 3rd edn. USGS, Water Supply paper, Virginia, p 2254

Heredia N, Farias P, García-Sansegundo J, Giambiagi L (2012) The basement of the Andean frontal cordillera in the Cordón del Plata (Mendoza, Argentina): geodynamic evolution. Andean Geol 39:242–257

Hernández J, Martinis N (2006) Particularidades de las cuencas hidrogeológicas explotadas con fines de riego en la Provincia de Mendoza, Instituto Nacional del Agua-Centro Regional Andino, Mendoza. http://www.riegoyfertirriego.com.ar/III_Jornadas/Trabajospresentados/Hernandez.pdf. Accessed 23 May 2015

Kendall C, McDonnell JJ (1998) Isotope tracers in catchment hydrology. Elsevier Science BV, Amsterdam

Kirchner JW (2003) A double paradox in catchment hydrology and geochemistry. Hydrol Process 17:871–874

Klaus J, McDonnell JJ (2013) Hydograph separation using stable isotopes: review and evaluation. J Hydrol 505:47–64

Kurás P, Weiler M, Alila Y (2008) The spatiotemporal variability of runoff generation and groundwater dynamics in a snow-dominated catchment. J Hydrol 352:50–66

Lee J, Feng X, Faiia A, Posmentier E, Kirchner J, Osterhuber R, Taylor S (2010) Isotopic evolution of a seasonal snowcover and its melt by isotopic exchange between liquid water and ice. Chem Geol 270:126–134

Lis G, Wassenaar LI, Hendry MJ (2008) High-precision laser spectroscopy D/H and $^{18}O/^{16}O$ measurements of microliter natural water samples. Anal Chem 80:287–293

Mcdonell JJ (2003) Where does water goes when it rains? Moving beyond the variable source are concept of rainfall runoff response. Hydrol Process 17:1869–1875

Morabito JA, Hernandez R, Salatino SE, Mirabile CM (2009) Calculo de las necesidades de riego de los principales cultivos del oasis Sur. Mendoza, Argentina. INA Papers. http://www.ina.gob.ar/pdf/CRA-RYD-22_Morabito_ETc_zona_sur.pdf. Accessed 26 May 2015

Panarello H, Dapeña C (1996) Mecanismos de recarga y salinización en las Cuencas de los Rios Mendoza y Tunuyan, República Argentina. Proceedings of XII Congreso Geologico de Bolivia 2:1–18

Panarello H, Dapeña C, Garcia E, Alvarez, A (1993) Estudio isotópico e hidroquímico de los acuíferos de la Cuenca Norte mendocina, Rios Mendoza y Tunuyan. Proceedings of XII Congreso Geologico Argentino, Mendoza

Parkhurst DL, Appelo CAJ (1999) User's guide to PHREEQC (version 2)-A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Water-Resources Investigations Report 99-4259

Penna D, Ahmad M, Birks SJ, Bouchaou L, Brenčič M, Butt S, Holko L, Jeelani G, Martínez DE, Melikadze G, Shanley J, Sokratov SA, Stadnyk T, Sugimoto A, Vreča P (2014) A new method of snowmelt sampling for water stable isotopes. Hydrol Process 28:5637–5644

Polanski J (1963) Estratigrafía, neotectónica y geomorfología del Pleistoceno pedemontano entre los ríos Diamante y Mendoza. Revista de la Asociación Geológica Argentina 17:127–349

Qian H, Wu J, Zhou Y, Li P (2014) Stable oxygen and hydrogen isotopes as indicators of lake water recharge and evaporation in the lakes of the Yinchuan Plain. Hydrol Process 28:3554–3562

Ramos VA (1988) The tectonic of the Central Andes: 30–33̊ S latitude. In: Clark S, Burchfiel D (ed) Processes in continental litospheric deformation, Geological Society of America, Special Paper 218:31–54

Tekleab S, Wenninger J, Uhlenbrook S (2013) Identifying residence times and streamflow generation processes using ^{18}O and ^{2}H in meso-scale catchments in the Abay/Upper Blue Nile, Ethiopia. Hydrol Earth Syst Sc Dis 10:10333–10377

Yeh HF, Lee CH, Hsu KC (2011) Oxygen and hydrogen isotopes for the characteristics of groundwater recharge: a case study from the Chih-Pen Creek basin, Taiwan. Environ Earth Sci 62:393–402

Zuluaga J, Filippini M, Drovandi A, Berrmejillo A, Morsucci A, Valdés A, Cónsoli D (2008) Caracterización de lo contaminantes del Río Blanco previo a su descarga en el Embalse Potrerillos. Proceedings of V Congreso Argentino de Embalses y Aprovechamiento Hidroelectrico, Tucumán