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Groundwater Origins and Circulation Patterns Based on Isotopes in Challapampa Aquifer, Bolivia

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Abstract: Aridity and seasonality of precipitation are characteristics of the highland region in Bolivia. Groundwater becomes an important and safe source of water when surficial bodies are intermittent and affected by natural and anthropogenic contamination. Decades of exploitation of the Challapampa aquifer, combined with lack of information required to understand the groundwater circulation, represent a challenge for reservoir management. This study analyzes isotopic compositions of deuterium and oxygen-18 in different stages in the hydrologic cycle to assess flow patterns in the aquifer, especially in the alluvial fan of River Paria, where records are more extensive in space and time. Interpretations are based on existing and new data. Some implications, such as the age of water, the evaporation effect in groundwater and some thermal intrusions are supported by stable isotopes, tritium, radiocarbon, and electrical conductivity records. New results confirm that modern precipitation over the mountains surrounding the study area is the most important origin of water for shallow aquifers until exploited depths, 100 m below surface. The origin of water in deeper depths, 400 m, seems related to infiltration at higher altitudes and longer residence times.

Keywords: stable isotopes; groundwater; highland; Andes; Bolivia

1. Introduction

In the Bolivian Altiplano, as in other arid and semi-arid regions over the world, groundwater is an important component of the available water resources [1]. The region has a long history of mining activities since pre-colonial times [2], promoting the growth of cities like Oruro, where the most important water reservoir is the Challapampa aquifer system. The identification of the recharge areas, estimation of the inlet volumes, and general understanding of the circulation patterns are crucial for the management of this and any reservoir. For these purposes, various types of data and techniques can be used to study groundwater systems [3], among them, the environmental isotopic approach.

Previous studies proposed general theories about the circulation patterns in the Challapampa aquifer system, e.g., the most productive porous aquifers are contained in Quaternary sediments, which fill the flat and lower lands in the region. The main recharge originates in the annual rainfall over the mountain range, at the eastern and northern limits of the study area. It runs off and reaches the aquifer system mainly through alluvial fans. The regional groundwater flows towards Lake Poopo, the lowest and predominant discharge zone in the enclosed catchment, though high extraction rates may be causing some shallow systems to flow towards a well-field in the middle of the study area [4–7]. Even if the conceptual description above has been established in previous basic studies, the region has been scarcely researched in the last decades. Earlier attempts, analyzing isotopes, considered different stages in the hydrologic cycle like only precipitation [8,9] or only groundwater [10–12]. Also, increased demand for water and changes in climatic conditions over the last thirty years have not been taken into account in the circulation models.

This study presents an updated and combined analysis of environmental isotopic data in precipitation, surface water, and groundwater, in order to elucidate and verify hypotheses about origins, circulation patterns, and flow systems in the Challapampa aquifer. The investigation is based on all available isotopic information, in order to propose a conceptual circulation model. Furthermore, new data provided so far by this research enhances novel interpretations and results.

2. Study Area

The Altiplano is a high plateau about 150 km wide and 1500 km long [13]. Bolivia has a third of its territory located in that region (Figure 1a). This land has distinctive characteristics in terms of geomorphology, climate, and resources. The Bolivian Altiplano hosts a substantial part of the biggest enclosed catchments in the continent, called the TDPS system. Its name is an acronym of the four sub-systems of which it is comprised, Lake Titicaca, River Desaguadero, Lake Poopo, and the salt flats (Figure 1a,b) [14,15].

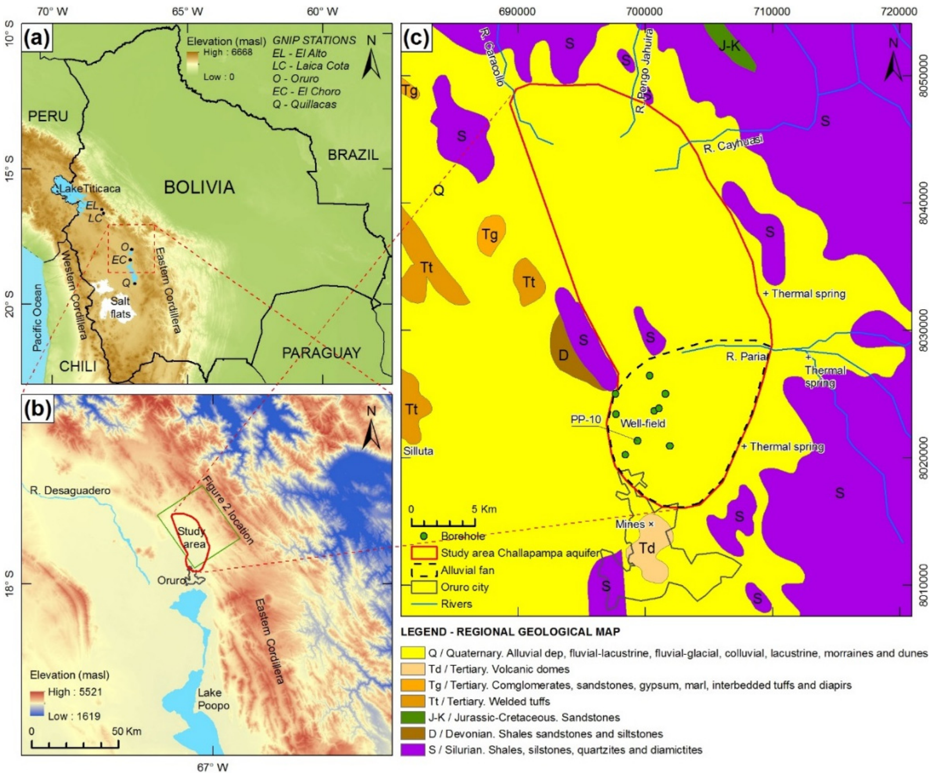


Figure 1. Location of the study area. (**a**) The Bolivian Altiplano and TDPS system; (**b**) Northern part of the Lake Poopo enclosed catchment; (**c**) Regional geological map. Modified from Geobol & Swedish Geological AB (1992) [16].

The study area is bounded by latitudes 17°35′ S–18°00′ S and longitudes 66°59′ W–67°12′ W, and it covers about 500 km^2 (Figure 1b,c). The average elevation in the plateau is about 3700 m above sea level (masl). The surrounding landscape is mountainous, divided with ridges parallel to each other in NW–SE direction, reaching 5500 masl in high peaks [5]. The region is characterized by semiarid climate; the average temperature is about 10 °C and the rainfall is in the range of 300 to 500 mm/y with a markedly wet summer, from December to March, during which the high-reaching anticyclones over the subtropical Andes produce about 80% of the annual precipitation. The potential evaporation in the region is around 1.5 m/y [13,15].

The delimitation of the study area is based on geological features and outcrops which enclose a substantial part of the aquifer system; nevertheless, as the sedimentary deposits cover greater areas in the region, some flow systems could cross the assumed limits. The regional geological features are dominated by two units; the first composed by outcrops of Silurian rocks and the sporadic presence of Tertiary and Devonian sediments (purple and brown colors in Figure 1c); and the second by Quaternary deposits controlled by glacial, lacustrine, and fluvial processes (yellow color in Figure 1c). Sedimentary units were the result of weathering and erosion of rocks in the mountain range, where the action of water led to the formation of terraces and alluvial fans. Those Quaternary deposits, commonly including colluvium, colluvium-fluvial, fluvial, fluvial-lacustrine, fluvial-glacial, and terraces, composed by coarse to fine grained sediments (pebbles, gravel, sand, silt, and clay) cover most of the flat study area.

Fluvial-lacustrine deposits, composed of clay and silt, cover large areas in the plain and prevent direct infiltration of surface water, causing floods during the rainy season [4,5,10]. Water retained at the surface evaporates by intense radiation, high temperatures during daylight hours, and high vapor pressure deficit, leaving salts encrusted in the soil matrix. Furthermore, isotopic analysis reveals that evaporation occurs prior to infiltration in those areas [10]. The average groundwater velocity in the aquifer was estimated as 1 m/y [11], though this value rises to 10 m/y in recharge areas [17]. The occurrence of thermal waters is also important in the groundwater circulation systems. Gitec & Cobodes (2014) [7] identified 16 thermal springs in the Lake Poopo basin, three of them at the eastern limit of the study aquifer. The influence and patterns of thermal activity in the aquifer system is still unknown. However, some boreholes in the southern part of the study area appear to be in contact with thermal intrusions (e.g., PP-10 in Figure 1c), probably through fault systems [6,11] (Figure 2).

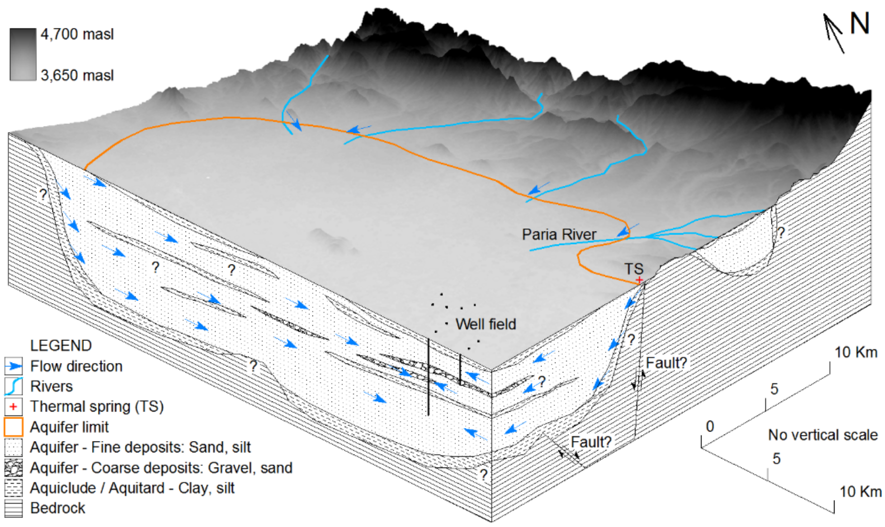


Figure 2. Schematic hydrogeological model of the Challapampa aquifer system (location in Figure 1b).

Lizarazu *et al.* (1987) [11] proposed the distinction of circulation patterns at different depths. However, their interpretation refers to a small area around the well field shown in Figure 2. The aquifer system is assumed to be a complex sedimentary unit, with horizontal and vertical continuity [2,4,6,7,12,17]. However, lenses with low hydraulic conductivity, mainly comprised of clay, exist in the stratification, but they are not large enough to isolate individual aquifers. Banks *et al.* (2002) [4] also proposed that the regional and deepest flow might be limited by a transition to a less permeable silty clay unit (Figure 2).

The Challapampa aquifer system is used to provide water for domestic consumption, agricultural and mining activities, and has hosted a well-field operated by SELA (a local public water supply company in Oruro) for the last 50 years. Domestic water demand has doubled in the last 15 years. The average annual abstraction is 8,600,000 m^3 in this period [18]. The occurrence of groundwater in the region is related to the past and present climatic conditions over the TDPS system and the sedimentation processes that shaped the most important and extended porous aquifers. In the modern TDPS system, Lake Titicaca feeds by overflowing the lower Lake Poopo through the River Desaguadero (Figure 1a,b). During the Quaternary, the central Altiplano valley was the site of several lacustrine transgressions and regressions. Tauca was the earliest palaeolake covering the region, between 13,000 and 16,000 years BP. Some characteristics of that time, like high precipitation rates and melting of glaciers, are mentioned in previous studies [13,19–21]. Therefore, it is expected that hints of those characteristics will be found in groundwater at the deepest levels if it was recharged during that time.

3. Data, Sampling and Methods

Isotopic data used in this study is comprised of records of series and single measurements in different hydrologic cycle stages. Although stable isotopes of hydrogen and oxygen have been widely used in several climate and paleoclimate studies in the Bolivian Altiplano, the scarcity of data, gaps in series, and lack of consistent sampling methods are common problems reducing accuracy of the results [8,22]. This study includes records of oxygen-18 (^{18}O), deuterium (^{2}H), tritium (^{3}H), carbon-13 (^{13}C), and carbon-14 (^{14}C). However, besides the aforementioned issues, a substantial part of the sampling sites do not have clear position references or coordinates. Consequently, just part of the data is included on the maps and spatial analysis in this study.

Compositions of isotopes in precipitation were obtained from the International Atomic Energy Agency's (IAEA) Global Network for Isotopes in Precipitation (GNIP), which includes ^{18}O, ^{2}H, and ^{3}H records [9]. This study refers to five GNIP stations with similar characteristics as in the study area, regarding, for example, elevation and precipitation regimes. Those are Laica Cota, El Alto, Oruro, Quillacas and El Choro (Figure 1a). Sampling methodology for isotopes in precipitation follows the IAEA's procedures and recommendations; monthly precipitations were captured, stored, and transported to specialized laboratories to be analyzed (Laica Cota to IAEA laboratory Vienna, Austria; El Alto to Laboratoire de Geochimie et d'Hydrologie Isotopique, Université de Paris-Sud, Orsay, France; Oruro, Quillacas and El Choro to University of Michigan, Department of Earth and Environmental Sciences, USA) [8,9]. To estimate isotopic compositions, methods based on gas-source mass-spectrometry were applied (Oruro, Quillacas and El Choro using Picarro Cavity Ringdown Spectrometer L2120; Laica Cota and El Alto not reported) [3,8].

The isotopic data of surficial water and groundwater used in this study is comprised of data reported in three articles [7,11,12] and new data generated between 2014 and 2015 for this study (Table 1). The latter was analyzed at the Geological Survey of Denmark and Greenland's (GEUS) laboratory, applying the technique described before.

Table 1. Surficial water and groundwater isotopic data. Data from the present study are found in last line.

Reference	Sampling Year	Sampling Sites Reported	Sampling Sites Located	Isotopes Reported	Types of Sampling Sites
Lizarazu *et al.* (1987) [11]	1984–1985	61	25	^{18}O, ^{2}H, ^{3}H, ^{13}C, and ^{14}C	Boreholes, dug wells, springs, rivers, and mines
Swedish Geological AB (1996) [12]	1996	23	0	^{18}O	Boreholes and dug wells
Gitec & Cobodes (2014) [7]	2013	6	6	^{18}O, ^{2}H, ^{3}H and ^{14}C	Boreholes and rivers
Present study	2014–2015	17	17	^{18}O and ^{2}H	Boreholes, dug wells, and rivers

Stable isotopic compositions are reported in δ units as the per mil (‰) deviations with respect to the Vienna Standard Mean Ocean Water (VSMOW). No uncertainties were reported in previous studies, only in the present study the uncertainty is reported, ± 0.15 for ^{18}O and ± 1.51 for ^{2}H.

Tritium compositions are expressed in tritium units (TU) that corresponds to an abundance of 1 ^{3}H per 10^{18} ^{1}H atoms [23]. ^{13}C compositions are reported as the per mil (‰) deviations with respect to the Pee Dee Belemnite standard (PDB). Finally, ^{14}C activity refers the relation $^{14}C/^{12}C$, it is reported as percentage of Modern Carbon (pMC) with respect to the Oxalic Acid II standard [24].

4. Results and Discussion

4.1. Isotopic Compositions in Precipitation

The most intense rainy events occur from December to March (DJFM) [25], during the summer. In this season, precipitation over the region typically occurs when air masses from the Atlantic cross a large part of the continent, the Amazon, and pass over the Andes' Eastern Cordillera. That adiabatic transport promotes progressive reduction of heavy isotopes. Also, the elevation of the Altiplano promotes similar reduction. As a result, an inverse relation between stable isotopes and elevation is observed [8,26]. The rest of the year, with smaller precipitation, the atmospheric moisture source is the Pacific. This source is closer than the Atlantic. Consequently, the isotopic signature of precipitation from the Pacific is heavier. This study adopts the summer precipitation as the onset of the modern recharge process.

As shown in Figure 3a, the more depleted isotopic compositions are registered during DJFM in the selected GNIP stations. Four of them have $\delta^{18}O$ and $\delta^{2}H$ pair records used to obtain the Local Meteoric Water Line (LMWL) by linear regression (Figure 3b). The slopes of the LMWL and the Global Meteoric Water Line (GMWL) are similar. The later, estimated by Craig (1961) [27], follows the line $\delta^{2}H = 8 \times \delta^{18}O + 10$. However, the intercept of the LMWL in the $\delta^{2}H$ axis is higher. This tendency has been observed in precipitation at high altitudes across the continent [22,28]. This deuterium excess likely results from additional moisture promoted by fast evaporation of inland water bodies and movement of vapor in the upper troposphere down to the ground surface, both enriched in deuterium due to kinetic fractionation processes [8].

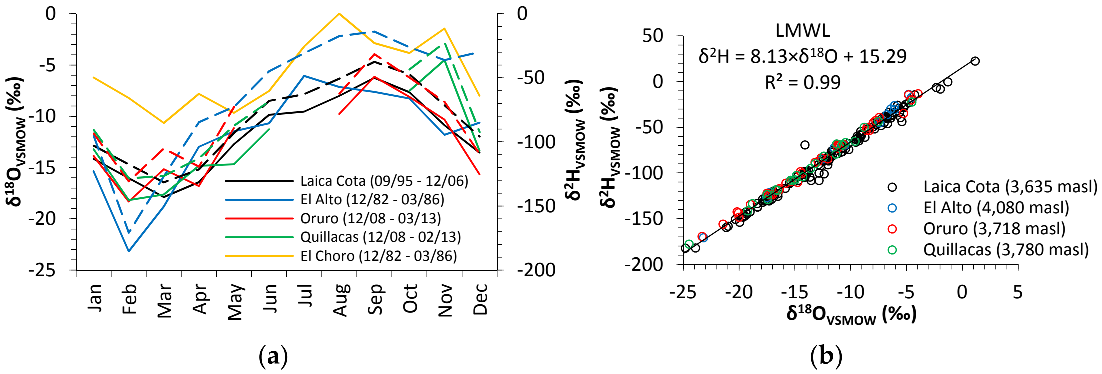


Figure 3. GNIP stations data. (**a**) Average isotopic compositions of precipitation by month ($\delta^{18}O$ in continuous lines and $\delta^{2}H$ in dashed lines. Nonexistent $\delta^{2}H$ records in El Choro) during indicated period (month/year); (**b**) LMWL [9].

Taking into account only the DJFM data, the isotopic relation is adjusted to $\delta^{2}H = 8.09 \times \delta^{18}O + 15.04$, which is comparable to the LMWL. A similar attempt was made for the rest of the months and the resulting equation is $\delta^{2}H = 8.24 \times \delta^{18}O + 16.06$. Consequently, a continuous correlation along the year is observed; the deuterium excess and the slope do not change significantly despite drastic seasonal changes in rainfall intensity. However, the GNIP data correspond to elevations between 3635 masl and 4080 masl (Figure 3b). In comparison to the high peaks of about 5500 masl in the surrounding tributary catchments (Figure 1b), the data exhibit insufficient information to identify signatures of rainfall at higher elevations.

4.2. Isotopic Compositions in Surface Water and Groundwater

Some studies in the Chilean Altiplano established gradients between −0.4‰ to −1.0‰ per 100 m height for $\delta^{18}O$ in precipitation [28,29]. Hence, the most depleted isotopic values in groundwater would represent recharge at higher altitudes. Conversely, water retained in the surface and shallow aquifers are significantly affected by evaporation [10,30]. As a consequence, the most enriched isotopic compositions are expected in samples of the aforementioned sites. Finally, $\delta^{18}O$ data corresponding to DJFM is assumed as the signature for the recharge process, the range between −12.6‰ and −17.5‰, defined by 25th and 75th percentile, respectively.

Isotopic data of surface water and groundwater in the study area and vicinity are scarce and a substantial part of it lacks complementary information like site locations, depths, sampling methods, and analysis procedures. Single $\delta^{18}O$ records are the largest available isotopic data. They are shown in Figure 4 *vs.* electrical conductivity (EC) as salinity parameter. Although just part of this data was located in the study area, most of the groundwater and surface water samples correspond to the range suggested as the typical signature of precipitation in the rainy season, dashed line range in Figure 4. Samples marked with "x" are different from those enclosed in a dashed rectangle. Although both groups correspond to the same place and the same mining activities at the southern limit of the study area. The first one represents groundwater pumped from deeper levels (400 mbs) to facilitate mineral extraction and the second one represents shallow levels where contaminants have been leaked after mineral refinement processes [12].

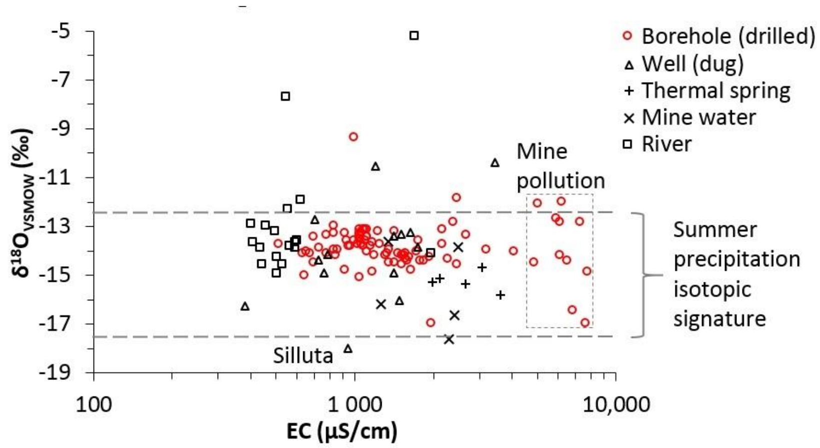


Figure 4. Isotopic data of all kinds in the region of Challapampa. EC (log) *vs.* $\delta^{18}O$. Modified from Gitec & Cobodes (2014), Lizarazu *et al.* (1987) and Swedish Geological AB (1996) [7,11,12].

The sampling sites which were located in the study area are shown in Figure 5. Part of the data presented in Figure 4 is excluded because it lacks location and coordinates, e.g., deep mine waters, dug wells, and thermal springs. The stable isotopic pair records of boreholes describe an evaporation trend line (Figure 5a), whose slope is less steep than that of the LMWL. The scattered point cloud fits with the water circulation conceptual model in the study area, along the arrow in Figure 5b. Summer precipitation over the catchments forms rivers (EC 500 µS/cm) running to the plain and recharging the aquifers. After infiltration, water travels throughout the Quaternary deposits, some flow systems are captured by boreholes in the range of 35–100 m below surface (mbs). The isotopic composition in these boreholes does not change significantly despite their increased salinity (EC 2000 µS/cm) due to mineral dissolution processes. As is shown in the potentiometric surface in Figure 5c, the lowest area is the well-field and some circulation systems flow towards it. Nevertheless, as this feature is based on potentiometric levels in wells and boreholes ranging from the surface until 100 mbs, deeper flows might cross this abstraction area and stream towards Lake Poopo, with NE–SW flow direction.

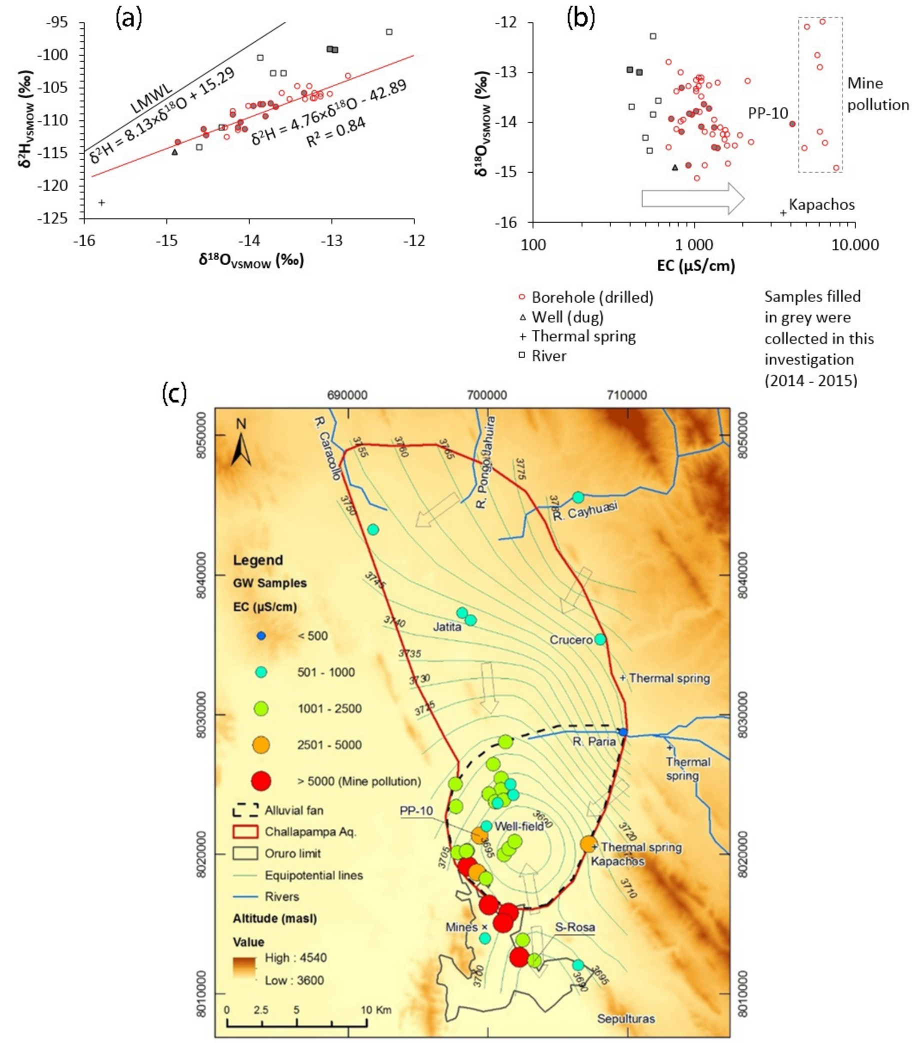


Figure 5. Isotopic data located in the Challapampa aquifer. (**a**) LMWL and the evaporation trend alignment for boreholes (red line); (**b**) EC (log) *vs.* δ^{18}O scatter plot. The arrow represents the increasing salinity along groundwater flows in the aquifer; (**c**) Location of groundwater samples, EC distribution, and the potentiometric surface. Red circles (shallow samples affected by pollution) and PP-10 (thermal intrusion) might not follow the increasing salinity arrow in (**b**). Modified from Gitec & Cobodes (2014) [7].

The range of δ^{18}O concentration is very broad in precipitation (Figure 3b); it is narrower taking into account surficial water and shallow groundwater in the study area (Figure 5a); and finally it is even narrower in borehole samples (red circles in Figure 5a). The more enriched values correspond to water affected by evaporation in rivers, shallow wells, and some boreholes where the average groundwater potential is 15 mbs in the alluvial fan. On the other hand, the more depleted values correspond to thermal springs (Kapachos) and deep groundwater samples in mines. Very depleted δ^{18}O values are also found, in some shallow wells near to Silluta village, 20 km west of the alluvial fan (Figure 1c). The depleted δ^{18}O values might indicate recharge at higher altitudes and even longer residence times. Glacier ice-cores from the peak of Sajama, 190 km to the east of the study area, preserve depleted δ^{18}O compositions; values of about −17‰ correspond to the last 11,000 y BP [31]. This isotopic fingerprint also hints at ancient recharge processes, when paleolakes flooded the area. The stable isotopic data of groundwater and rivers were updated in this investigation (Table 2).

Table 2. Isotopic composition of surficial water and groundwater samples collected in this study (2014 to 2015).

Sample	Depth * (mbs)	Type **	EC (μS/cm)	δ^{18}O (‰)	δ^{2}H (‰)	^{3}H *** (TU)	^{13}C *** (‰)	^{14}C *** (pMC)
PP-07	48–80	B/WF	979	−13.86	−107.72	1.0	−9.04	72.8
PP-09	38–71	B/WF	1172	−13.67	−108.05	BDL	−9.89	38.1
PP-10	39–84	B/WF	4130	−14.05	−111.46	0.4	−9.47	25.9
PP-11	36–84	B/WF	956	−13.83	−107.72	0.2	−8.63	40.5
PP-14	–	B/WF	1043	−13.80	−109.44	–	–	–
PP-17	22–79	B/WF	1339	−14.13	−111.18	–	–	–
PP-20	–	B/WF	1130	−14.09	−110.43	–	–	–
PP-21	–	B/WF	850	−14.19	−109.21	–	–	–
PP-22	–	B/WF	844	−13.32	−105.84	–	–	–
PP-23	32–97	B/WF	1251	−13.73	−107.47	–	–	–
Sela-2	38–53	B/WF	1357	−14.52	−112.50	0.2	−9.27	30.5
Crucero	–	B	932	−14.86	−113.51	–	–	–
Sta-Rosa	–	B	1432	−14.55	−111.39	2.4	−9.04	79.3
Jatita-I	65	B	760	−14.91	−114.85	–	–	–
Jatita-II	<10	D	734	−13.94	−107.85	–	–	–
Cayhuasi	0	R	460	−13.01	−99.24	9.3	–	–
Paria	0	R	407	−12.95	−99.34	7.4	–	–

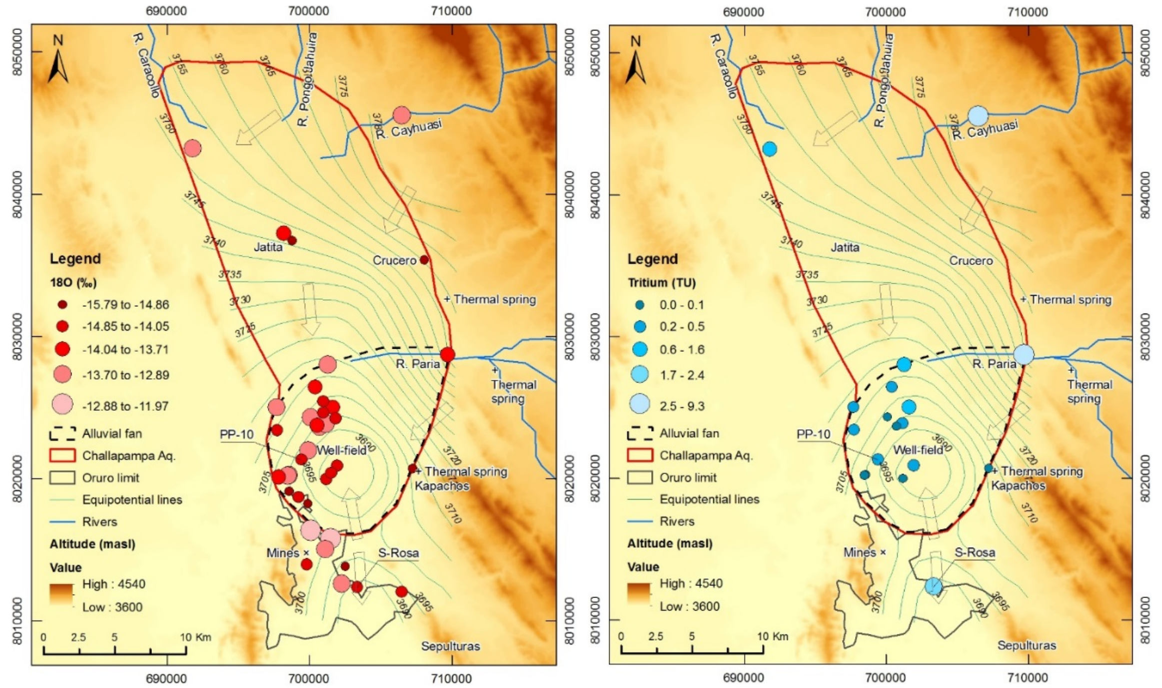
Notes: * Obtained from drilling reports [7]; ** B = borehole (deep); WF = well-field; D = dug-well (shallow); R = river; *** Samples collected in 1984 and 1985, reported by Lizarazu *et al.* (1987) [11]. BDL = below detection limit.

The distribution of isotopic compositions over the study area is shown in Figure 6a,b. Some depleted values of δ^{18}O are located in the middle part of the aquifer, in the villages of Jatita and Crucero, those samples correspond to levels about 40 mbs. A sample collected from a shallow well in Jatita displayed a more enriched composition. The origin of groundwater at 40 mbs in the middle part of the aquifer seems not to be directly related to the infiltration of the rivers Cayhuasi or Pongo Jahuira, whose flows reduce after DJFM period. The origin of water in boreholes located in the alluvial fan has a more evident correlation with the isotopic signature of River Paria. In the southernmost region of the study area, samples of boreholes monitoring mine pollutants expose enriched compositions affected by evaporation. Most of the flow systems circulating from shallow levels until 100 mbs might have been recharged by modern precipitation following the circulation pattern described before.

Most of the boreholes in the well-field have similar characteristics with the exception of PP-10 (Figures 5 and 6), which is more saline and hot. The isotopic signature here is similar to those in the vicinity. Some deeper flows ascending and mixing with shallow and modern groundwater might explain the characteristics found in this borehole.

The distribution of tritium might confirm the regional circulation pattern. Higher values are recorded in river samples, Paria and Cayhuasi. Along the movement of water throughout the sediments, tritium concentrations display decay, diminishing to even nonexistent contents in boreholes at the middle and the distal part of the alluvial fan. However there are exceptions, the composition of a sample taken inside the city limit (Sta-Rosa) suggests a different origin of water for that specific area, not related to the infiltration of River Paria.

The age of groundwater in the study area can be estimated using tritium and radiocarbon concentrations. Tritium in the atmosphere had maximum records originating in the open-air nuclear weapon tests during 1955–1964 [9]. Nevertheless, the presence of the isotope was significantly lower in South America during the same peak-period. Of the five closest GNIP stations, only Laica Cota has tritium records in precipitation for the period 1995–2006. However, there are some gaps in the series. The average composition in that station was estimated to be 4.9 TU [9]. Although surficial water and groundwater samples in the study area were collected about 10 years earlier, it is possible to observe the decay of the isotope along the movement of water, from rivers (7.4 TU in Paria), to distant and deeper outlet points like boreholes where the tritium content is lower than the average in precipitation, as is shown in Figure 7. However, the circulation systems at intermediate levels seem to have residence times longer than the active life of tritium. As a consequence, values below the detection limit (close to zero) are common in boreholes.



(**a**) (**b**)

Figure 6. Distribution of isotopic data over the study area. (**a**) $\delta^{18}O$ (‰); (**b**) Tritium (TU), compositions in 1984–1985. Arrows mark main groundwater flow directions. Modified from Gitec & Cobodes (2014), and Lizarazu *et al.* (1987) [7,11].

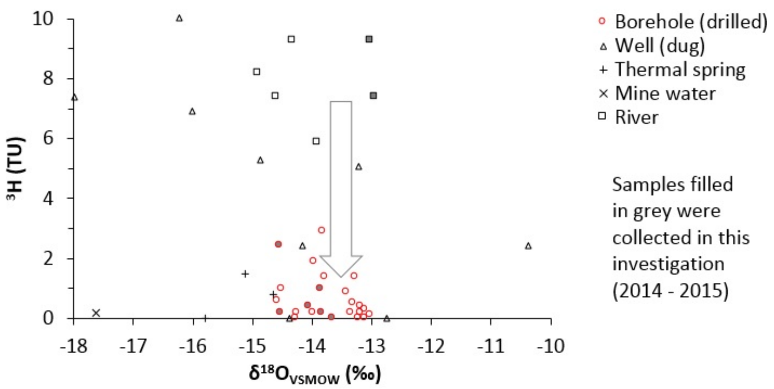


Figure 7. Tritium content in surficial water and groundwater samples between 1984 and 1985. The arrow indicates the decay of ^3H along the intermediate circulation flow system. Modified from Lizarazu *et al.* (1987) [11].

Isotopic compositions of ^{13}C and ^{14}C were also used to estimate groundwater ages from modern until 10,000 y BP in the region [7,11]. In the study area, the well-field shows dispersed ages, from modern in PP-07 until 7200 y BP in PP-10 [11]. In the latter borehole, the age agrees with the high salinity, exposing some deep flow patterns, probably ascending through faults. The modern age in the Sta-Rosa borehole, reported by Lizarazu *et al.* (1987) [11], might confirm the water divide in the south of the study area.

The analysis in this study is restricted by the sampling depth, ranging from the surface until about 100 mbs. Deep flow systems and their analyzes were compiled from previous studies [4,11].

The following interpretations are valid for the area of the alluvial fan of River Paria, where most of the sampling sites are located. As is shown in Figure 8, four circulation systems are proposed to distinguish origins, patterns, and characteristics: the first of these systems is on top, inluding local sub-systems from the surface until about 20 mbs. This system also enclose the unsaturated zone. The water here is infiltrated from surface after being retained by clay layers and part of it is evaporated. This process causes shallow groundwater to be saline (EC 1000 µS/cm) and enriched in heavy isotopes. Information about dug wells support this assumption (Figure 4). The residence time in the uppermost part of the groundwater flow system might be short, probably less than a year considering that the ponds and floods disappear some weeks after the rainy season. However, further investigations are needed to know this residence time more accurately. The second system, situated below the latter and reaching abstraction levels (100 mbs) is the intermediate one. A substantial part of the groundwater originates in modern precipitation over the mountains surrounding the aquifer system, transported by rivers and infiltrated in the alluvial fans. The constant abstraction in the well-field may create a depression cone of about 5 km radius around it, which is the main outlet for this system. The EC may vary from 600 to 2000 µS/cm. The $\delta^{18}O$ compositions are similar to those in rivers. The residence times might be some decades, according to the low or even nonexistent tritium compositions. Most of the samples collected in this study belong to this system. The results confirm the isotopic signature range identified in previous studies [4,7,11]. The third system is assumed as a transition between the modern flow system and an older, deeper one. This system might reach depths of 300 mbs or more. Although there are no boreholes pumping from this depth, resistivity and seismic tests suggest that the sediments might still be present at this level [4,12]. The geological units might include both the Quaternary sediments and the bedrock. Also, its salinity and isotopic characteristics might be a result of mixing between the overlying and underlying flows. The fourth and the deepest flow system is the regional one. Just a few samples reported by Lizarazu *et al.* (1987) [11] refer to characteristics at 400 mbs (see Figure 4, samples with "x"). Infiltration at high altitudes or recharge during the last paleolake event might be the origin of water in this level. The most depleted $\delta^{18}O$ values in groundwater correspond to this system, as well as high salinities far away from the pollution fingerprint. This system is likely flowing through the bedrock.

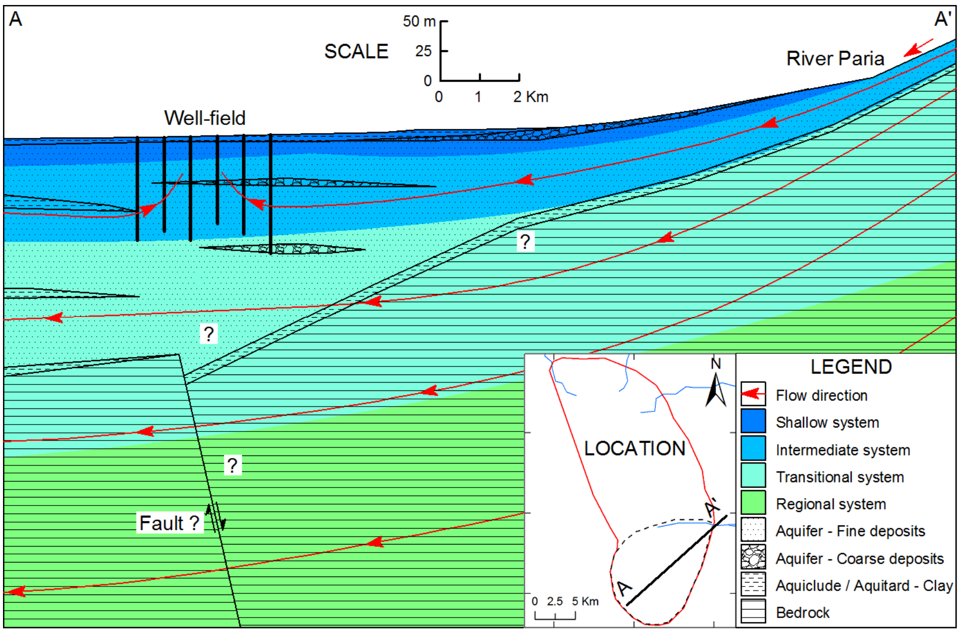


Figure 8. Schematic cross section (A–A') of the proposed four flow systems in the alluvial fan of River Paria.

5. Conclusions

The study of environmental isotopes in the Challapampa aquifer system aids understanding about the circulation patterns in the region. Nevertheless, due to the complexity of the geological settings, scarcity of data, and size of the study area, it is difficult to assess a simplified circulation model combining all criteria extracted from individual isotopic analyzes. The well-field, where the records are more abundant, exposes characteristics of the intermediate flow system. These characteristics are increased salinity, similar values regarding to stable isotopes, and tritium concentrations. Nevertheless, the same area shows some anomalies linked with thermal intrusions and even artesian conditions in at least one borehole (PP-10).

Summer precipitation represents 80% of the annual rainfall over the study area. It is comprised of the most depleted stable isotopic values along the year and this fingerprint remains similar in groundwater samples. The LMWL has a similar slope as the GMWL but with greater deuterium excess, as an effect of the site characteristics, e.g., altitude, amount of precipitation, and continental effect. The linear trend of stable isotopic compositions in groundwater samples expose the effect of evaporation.

The combination of the potentiometric surface, the degree of salinity, and the isotopic compositions reveal the circulation patterns flowing towards the well-field in the central part of the alluvial fan, owed in great part to the constant pumping in the area. Nevertheless, the latter is valid for systems until 100 mbs. The natural discharge zone of regional flow might be located outside the limits of the study area, perhaps in Lake Poopo.

Isotopic compositions in different stages of the hydrologic cycle hint at circulation patterns in the Challapampa aquifer system. This study differentiates four circulation systems. Most of the water exploited for consumption and irrigation is assumed as modern, originating in precipitation, transported by rivers, and recharged into the aquifers at the foothills and alluvial fans. Modern precipitation is the most important recharge source until about 100 mbs. Conversely, deeper levels seem to be recharged by different processes, possibly at higher altitudes or ancient times. Furthermore, it is recommended to extend the sampling of isotopes and hydrochemical parameters in precipitation over the entire elevation range to obtain the local gradient for stable isotopes, which should aid in the process of distinguishing recharge at higher elevations. Such extended sampling would also include groundwater at deeper levels, sampling stable isotopes to differentiate origins and radiocarbon isotopes to enhance the analysis regarding the age of water. Furthermore, some specific characteristics like thermal intrusion, artesian conditions, and migration of mining contaminants can be elucidated with isotopic techniques in the area.

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Abbreviations

The following abbreviations are used in this manuscript:

DJFM	December, January, February, and March
EC	Electrical conductivity
GMWL	Global Meteoric Water Line
GNIP	Global Network for Isotopes in Precipitation

IAEA	International Atomic Energy Agency
LMWL	Local Meteoric Water Line
PDB	Pee Dee Belemnite
PMC	Percentage of modern carbon
SELA	Servicio Local de Acueductos y Alcantarillado Oruro
TDPS	Titicaca, Desaguadero, Poopo, and the salt flats
VSMOW	Vienna Standard Mean Ocean Water

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