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Groundwater dynamics in a coastal aquifer in north-central Chile: Implications for groundwater recharge in an arid ecosystem

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Abstract

The understanding of the water cycle is one of the key elements to evaluate the present and long-term primary productivity in arid ecosystems. This study uses hydrogeological and isotope tools to evaluate the recharge mechanisms in a coastal unconfined gravel and sand aquifer located in the arid zone of north-central Chile. The main water sources in the study area, fog, rain and groundwater, were isotopically characterized over a decade. The isotope data confirm previous studies based on fog capture, that fog does not play any role in groundwater recharge. The water table and isotope data showed that during low water conditions (dry periods), the aquifer is maintained primarily by water recharged in the higher part of the Romeral basin. During high water table conditions (wet periods), recharge associated with local precipitation becomes a significant source of groundwater recharge. The water table data showed that the aquifer responded very fast to rains with amounts over the average level for precipitation and the fastest response was observed during the El Niño year of 1997. No recharge was detected with precipitation events lower than the average value for precipitation. The aquifer recharge pattern in the coastal area of the Romeral Basin has significant implications for functional groups of plants characterized by deep root systems that have low capacity to respond directly to precipitation and consequently use groundwater as their main water source for new plant

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growth and reproduction. The recharge pattern can also influence the behavior of other functional groups characterized by a dimorphic root systems than can perform hydraulic redistribution. Part of the fast recharge of the aquifer could be related to this water redistribution. This study also shows that wetlands near the coast are fed mainly by groundwater associated with regional groundwater systems linked to recharge areas located in the high part of the Elqui River Basin.

Keywords: Groundwater; Precipitation; Arid zone; Hydrogen isotope ratio; Oxygen isotope ratio; Water sources

1. Introduction

The understanding of the water cycle is one of the key elements to evaluate the present and long-term productivity in desert ecosystems (Ehleringer and Mooney, 1983; Hadley and Szarek, 1981; Le Houérou, 1996; Le Houérou et al., 1988; Southgate et al., 1996). Arid ecosystems are highly dependent on seasonal pulses of water contribution from different sources. Therefore rainfall variability can determine pulses in the development of vegetation (Agnew, 1997; Gutiérrez, 1993; Noble and Gitay, 1996; Noy-Meyr, 1973; Polis, 1991; Reynolds et al., 1999; Sala and Lauenroth, 1982; Smith and Nobel, 1986; Squeo et al., 1994). Available water for desert plants depends on the balance between the contribution from scarce rainfalls (in the form of rain and/or fog) and groundwater, as well as from water losses due to direct evaporation of the soil surface, from transpiration and from the deep percolation (Noble and Gitay, 1996; Torres et al., 2002). Finally, properties of the local soil determine the amount of water that infiltrates during a period of time and water runoff (Noble and Gitay, 1996) when rainfalls occur over a short period of time.

The ability of plants to use different water sources depends on their root systems. Plant species that exhibit superficial root systems are highly dependent on rain events compared with those with deep or dimorphic root sytems (Ehleringer et al., 1991; Olivares and Squeo, 1999; Squeo et al., 1999, 2000). In north-central Chile, El Niño Southern Oscillation (ENSO) has been associated with rainy winters and intense 24 h precipitation events, and can explain the interannual variation in precipitation observed in this region (Bullock and Le Houérou, 1996; Caviedes, 1984; Santibáñez and Uribe, 1994; Squeo et al., 1994). Furthermore, a clear decline in rainfall since the beginning of this century has also been identified in this region (Soto and Ulloa, 1997; IPCC, 2001), so rainfall water contribution for coastal desert ecosystems is decreasing. Because rainfall is scarce, the relative importance of the contribution of fog water in Chilean coastal-desert ecosystems has been studied (Cruzat-Gallardo, 2004; Dawson and Vidiella, 1998; Kummerow, 1966; Fuenzalida et al., 1989). The fog contribution to annual water budget in Fray Jorge forest, a temperate relict in the coastal desert (30°40′S, 71°40′W, 560 m a.s.l.), is near 1000 mm that correspond to over 75% of total water input (Cruzat-Gallardo, 2004; Kummerow, 1966). Similar findings were obtained in the Tofo area (northern La Serena) (Soto et al., 1985). These studies were performed at the top of the coastal range where fog is an important water source for vegetation. However, no evidence of an important contribution of fog as a water source were found in the lowland areas of this region. Annual fog collections are between 4.8 and 0.9 mm at Romeral (29°43′S, 71°15′W, 300 m a.s.l.) (Squeo, unpubl. data). Therefore, there is a little fog-water contribution to this coastal-desert ecosystem, but low water pressure differences between leaf and air during the diurnal fog events can be important in avoiding plant evapo-transpiration (Dawson, 1998; Field and Dawson, 1998).

Isotopic studies in northern Chile have shown that groundwater plays a significant role as water sources for vegetation in this arid environment (Aravena and Acevedo, 1985; Aravena et al., 1989; Squeo et al., 1999, 2000). The isotope approach has also been used to evaluate the origin and groundwater residence time and role of fogs in groundwater recharge in the Northern Chile region (Aravena, 1995; Aravena et al., 1989; Magaritz et al., 1990). The purpose of the work presented in this paper is to understand the recharge mechanisms in an unconfined gravel and sand aquifer located in the arid coastal region of north-central Chile. This research, part of a major research program in vegetation ecology in north-central Chile, aims to apply the isotopic fingerprinting approach for evaluating the main water sources for coastal-desert vegetation.

2. Methods

2.1. Study site

The research was carried out for 7 years (fall 1996 to December 2003) and a detailed evaluation of seasonal patterns was performed during the last 3 years of the study. The study site is part on a coastal-desert ecosystem located at Quebrada El Romeral (29°43′S, 71°15′W, 300 m a.s.l.), 10 kilometers from the coastal border, and 21 km northeast of the city of La Serena (Fig. 1a). The upper part of the El Romeral basin is the Papilones Mount (1881 m a.s.l.) (Fig. 1b). Di Castri and Hajek (1974) classified this area as Mediterranean arid type with summer aridity having frequent morning cloudiness and fog, while Novoa and Villaseca (1989) consider the area under the influence of the Mediterranean subtropical semi-arid type, and Amigo and Ramírez (1998) identify the area as meso-Mediterranean arid type.

The climate of La Serena is characterized by a mean annual temperature of 13.5 °C, with a mean maximum temperature of 21 °C during the warmest month, while the mean minimum temperature reaches 7.0 °C during the coldest month. The mean annual rainfall is 114.4 mm, being June the wettest month, while the dry season lasts 9 months. The average annual evaporation is 1220 mm, reaching a monthly maximum in January (172 mm) and a monthly minimum in June (47 mm) (Novoa and Villaseca, 1989). Our study site is located in the southern border of the agroclimatic district of Choros Bajos-Romeral (Caldentey, 1987). A mean maximum temperature of 20–21 °C during January and a mean minimum temperature of 8–10 °C characterize this last district during July, without frost occurrences and no vegetative recess period. Annual rainfalls reach 67.4 mm, with a dry period lasting 11–12 months; the annual potential evapotranspiration is 824.3 mm, and the annual hydric deficit reaches 756.9 mm. Annual precipitation at Minas El Romeral (1956–2003) show an average value of 82.9 mm (76.5 mm in the last 30 years), with rainy years associated to ENSO events (Fig. 2).

All local soils are highly stony. Soils located in the bed of ravines are sandy, while the ones located on slopes are clayey and silty. The area is characterized by the presence of shrubs such as *Heliotropium stenophyllum*, *Senna cumingii*, *Encelia canescens*, *Flourensia thurifera*, *Haplopappus parvifolius*, *Pleocarphus revolutus*, *Ephedra chilensis*, *Balbisia peduncularis* and *Bridgesia incisifolia*, among others (Olivares and Squeo, 1999; Squeo

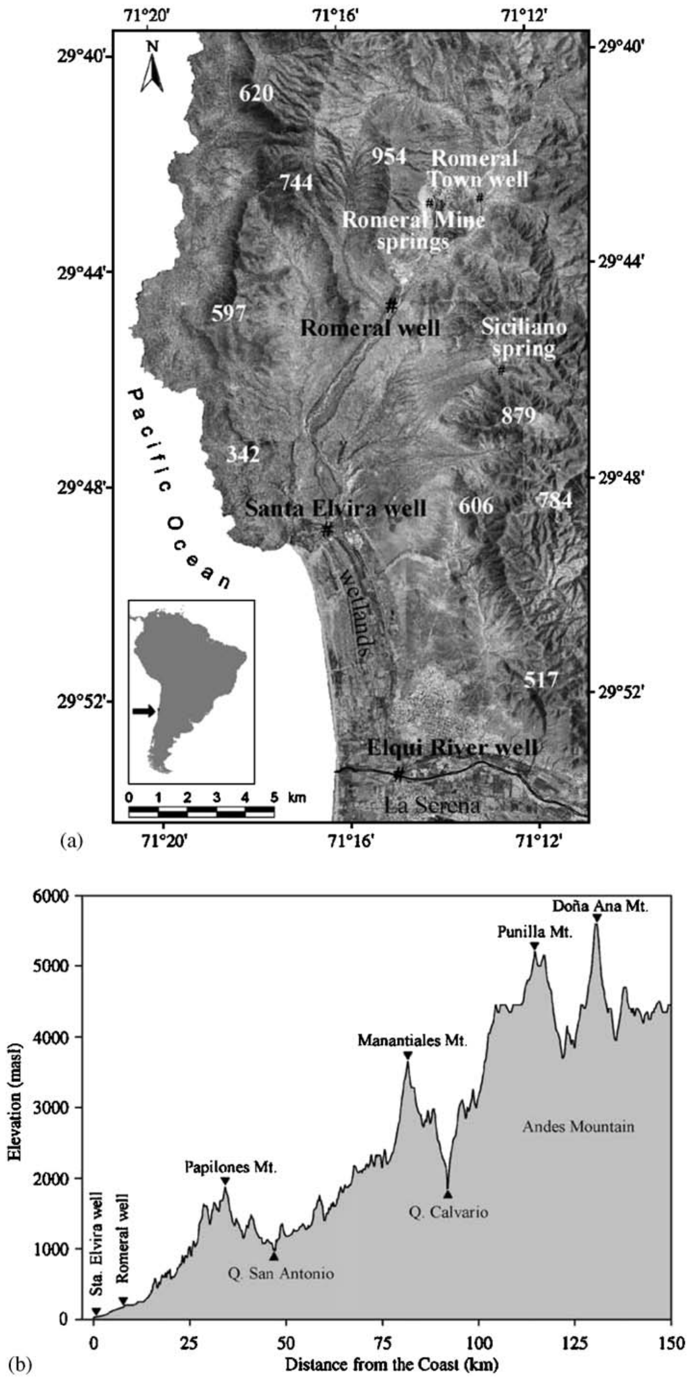

Fig. 1. (a) Location of study site and sampling locations, Quebrada El Romeral, north-central Chile. Principal elevation (in m a.s.l.) are shown. (b) Altitude transect from the coast to the west side of the Andes near at 29°45′S (71°20′–69°55′W).

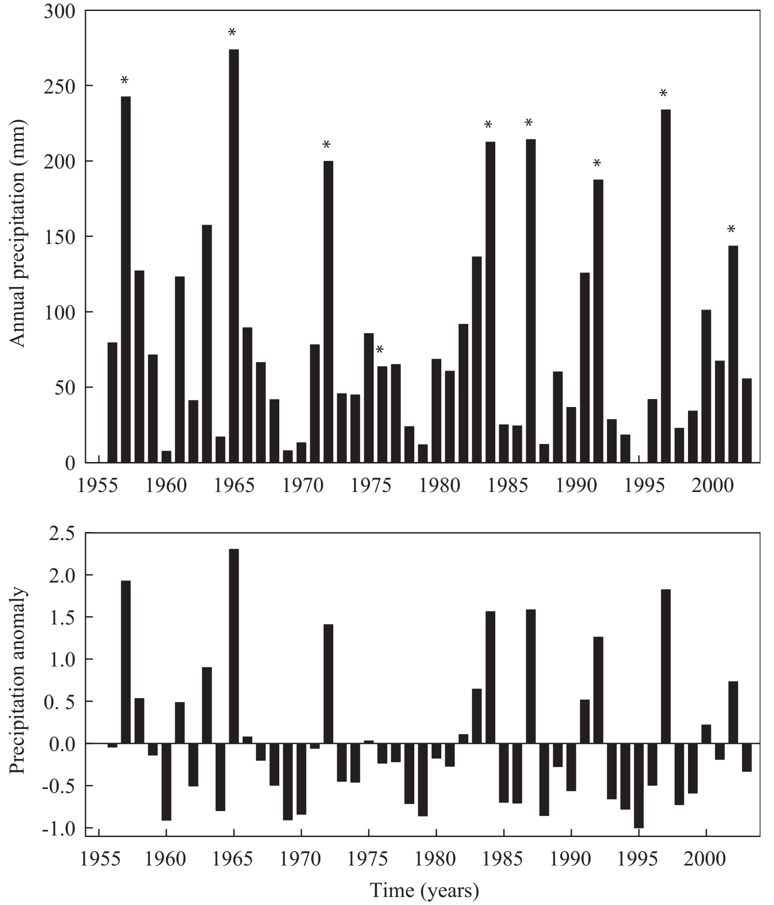

Fig. 2. Annual precipitation and precipitation anomaly recorded at Romeral Meteorological Station between 1956 and 2003. (* = ENSO years)

et al., 1999). The aquifer is under unconfined conditions and is composed of gravels and coarse sands, which are part of the alluvial deposits of the Quebrada El Romeral.

2.2. Sampling of water sources

Fog was collected using 50%-Rashel double-net vertical collectors measuring 3 m wide and 1 m high, which were placed between 0.5 and 1.5 m above the surface, and oriented perpendicular to west. The height of our fog collector took into account the mean plant height, and differed from most studies where they are usually installed over 2 m. The collectors were distributed in different topographical locations (bed of ravine and hillside—polar and equatorial facing slopes). Both, rain and fog water were stored in a 2 l bottle with a mineral oil layer to avoid evaporation and isotopic enrichment (Friedman et al., 1992).

Groundwater samples were collected from wells located in the middle and lower part of the El Romeral basin (Fig. 1). The Elqui river aquifer in the lower part of the basin was also sampled for isotope analysis. A full sampling program was conducted in 1996, and two selected wells (El Romeral and Santa Elvira) were used to monitor seasonal changes in the isotope composition of the groundwater. Water level was also monitored at the well at Romeral. The depth of this well is 13 m and is tapping the alluvial deposit of the Quebrada El Romeral. The Santa Elvira well has a depth of about 14 m and is tapping the sand deposits of the coastal area of La Serena.

2.3. Environmental isotopes

Oxygen-18 and deuterium analyses were performed on rain, fog and groundwater samples. Tritium analysis was only performed on groundwater samples collected during 1996 and 1998 sampling events.

Hydrogen and oxygen isotope ratios on water samples were measured using a Finnigan MAT 252 isotope ratio mass spectrometer at CCHEN (Chilean Nuclear Energy Commission). Both isotope ratios were expressed in δ‰ units using the following expression:

$$\delta^2\mathrm{H}\ (\text{or } \delta^{18}\mathrm{O}) = (R_{\text{sample}}/R_{\text{standard}} - 1)1000‰,$$

where R refers to the ^{2}H/ ^{1}H (or ^{18}O/ ^{16}O) ratio of sample and standard, respectively. The standard used for δ ^{2}H and δ ^{18}O was SMOW and analytical errors were 0.2‰ and 2‰ for ^{18}O and ^{2}H, respectively (Squeo and Ehleringer, 2004).

Tritium analyses were conducted at the Environmental Isotope Laboratory, University of Waterloo (Canada) by liquid scintillation counting. The tritium data is expressed in tritium units (TU) with an analytical error of 0.8 TU.

3. Results and discussion

3.1. Isotopic composition (δ ^{2}H, δ ^{18}O) of water sources

A wide range in isotope composition that varies between −13‰ and −1‰ for δ ^{18}O and −100‰ and −1‰ for δ ^{2}H was observed on the different waters that are part of the water cycle in the study area (Fig. 3). Fog waters are the more isotopically enriched waters ranging between −3‰ and −1‰ for δ ^{18}O, and −2‰ and −18‰ for δ ^{2}H. These values are similar to data reported for fogs in coastal areas located south of the study area (Aravena et al., 1989). Precipitation varies between −9‰ and −2‰ for δ ^{18}O and −77‰ and −10‰ for δ ^{2}H. The weighted mean isotope composition for the precipitation at the Romeral station is −28.1‰ and −4.8‰ for δ ^{2}H and δ ^{18}O, respectively, which is very similar to the long-term weighted mean isotope composition of the precipitation collected at La Serena (GNIP, 2004). The overall data for precipitation in the study region is in the same range that isotope precipitation data reported for coastal areas in Chile (Moser et al., 1975; Aravena et al., 1989). The rain isotopic data collected at the Romeral precipitation station define a linear relationship δ ^{2}H = 7.7 δ ^{18}O + 9.6‰ ($r^2 = 0.91$). This local meteoric water line is close to global meteoric water line δ ^{2}H = 8 δ ^{18}O + 10‰ reported by Craig (1961).

A very distinct isotope pattern is observed in the groundwater. Groundwater collected in the Romeral basin is much more enriched isotopically than the groundwater collected in

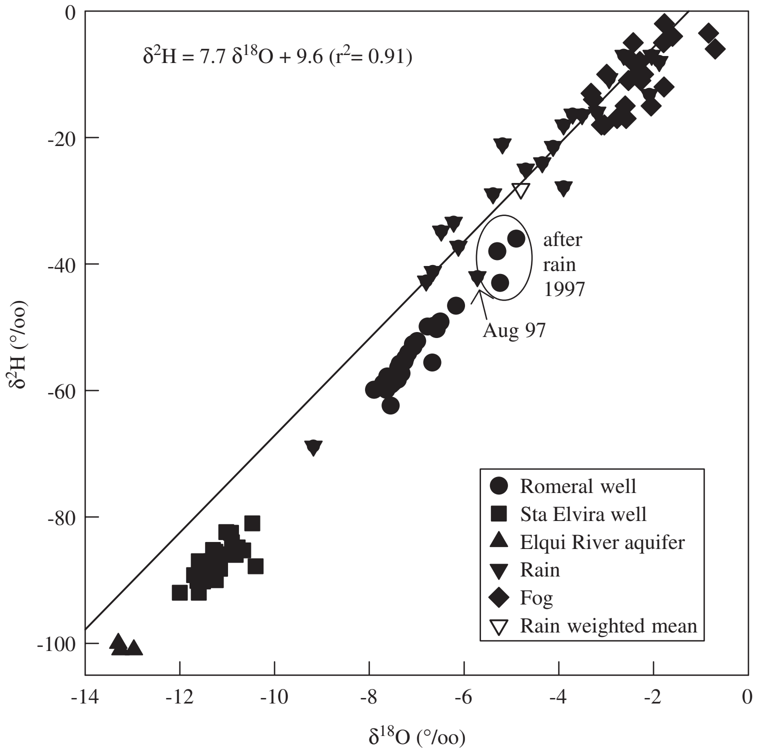

Fig. 3. Relationship between δ ^{18}O and δ ^{2}H for fog, rain and groundwater collected in this study (1996–2003). The local meteoric water line is shown.

the lower part of the basin (well Santa Elvira) (Fig. 3). In general, the Romeral groundwater is also more depleted isotopically than the isotope composition of the precipitation collected at the Romeral station (Fig. 3), which can be explained by the input of more isotopically depleted precipitation recharging the aquifer in the higher part of the Romeral basin. The groundwater seems to plot below the local meteoric water, which could be explained by the effect of evaporation in the recharge areas. However, it is worth noting than the local meteoric water mainly represents the rain in the lower part of the basin. The isotope data showed that coastal fogs do not play any major role in groundwater recharge of the Romeral aquifer. The groundwater collected in the Santa Elvira well with δ ^{18}O values ranging between −10.5‰ and −12.0‰ does not seem to receive a significant contribution from the groundwater flow system of the Quebrada El Romeral alluvial aquifer, even this well is located at the mouth of the Quebrada El Romeral. The aquifer tapped by the Santa Elvira well is clearly part of a discharge zone that has a major contribution of water recharged at higher altitude than the headwater of the Romeral basin. This water is represented by groundwater from the regional aquifer of the Rio Elqui Basin, which is characterized by an isotope composition of around −13‰ and −100‰ for δ ^{18}O and δ ^{2}H, respectively (Fig. 3). The coastal areas of the La Serena Region are characterized by a series of wetlands (Fig. 1) and based on the isotopic pattern of the Santa Elvira well, it can be postulated that these wetlands are located on a groundwater discharge zone of the regional aquifer recharged in the higher part of the Elqui basin.

3.2. Regional vs. local recharge

A first approximation for the evaluation of aquifer recharge can be inferred from the seasonal data on precipitation and water level in the aquifer measured at the Romeral well and seasonal data on the isotope composition of groundwater collected at the Romeral and Santa Elvira wells (Fig. 4). During the monitoring period (November 2000 to December 2003), significant water table changes are observed in the Romeral aquifer (Fig. 4b). A high water table is observed in the period November 2000 and June 2001. Then

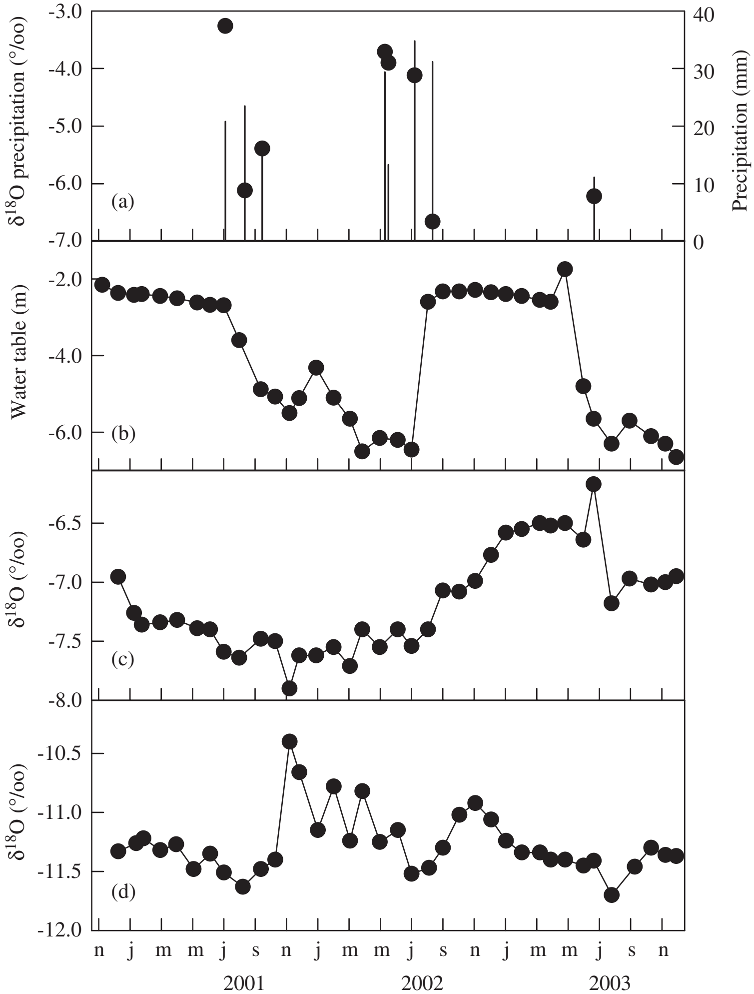

Fig. 4. Precipitation (a), water level Romeral well (b) and δ ^{18}O for Romeral (c) and Santa Elvira (d) groundwater (2000–2003).

a huge decline in water table is observed between July 2001 and July 2002 followed by a significant increase between August 2002 and May 2003 and a subsequent drop after May 2003. This water table pattern has to be related to a recharge cycle, which is controlled by the precipitation regime in the study area (Fig. 4a). The high water level of 2000 and 2002 could be explained by recharge linked to precipitation fell during the winter of 2000 and 2002, respectively. The amount of precipitation during this time was higher than the average value for precipitation for the study area (Fig. 2). The precipitation fell during the winter (July–September) of 2001 (65.8 mm, Fig. 4a) was lower than the average value (Fig. 2), then it seems it did not contribute to recharge and explains the significant drop in the water table observed during the period July 2001 to July 2002. (Fig. 4b). The significant water table drop observed after May 2003 can also be explained by the absence of aquifer recharge due to the dry winter of 2003 (Fig. 4a).

It is possible that the variability observed in the aquifer recharge pattern could be also imprinted in the isotope composition of the groundwater. During the period of significant water table decline (July 2001 and July 2002) the Romeral groundwater showed a trend toward more depleted $\delta\,^{18}$O values reaching a value −7.9‰ on November 2001 and most of the values remains at a value of −7.5‰ during July 2001 and July 2002. The isotope data suggest that during low water table condition, the aquifer is mainly maintained by the groundwater recharged in the higher part of the basin. This trend is reversed after August 2002 reaching $\delta\,^{18}$O values as high as −6.2‰ in July 2003. This trend coincided with the trend of water table recovery observed during the same period. The enrichment trend associated with an increase in water table indicated that the aquifer recovery is partially due to more groundwater recharge in the middle and lower part of the basin. During the winter of 2002, the amount of precipitation was significantly higher than the average value (Fig. 2). The $\delta\,^{18}$O of precipitation in the lower part of the basin is −4.8‰. The role of ground water recharge in the middle and lower part of the basin is also supported by isotope data collected on November 1997 that produced the most enriched isotope values for the Romeral groundwater, which was related with an unusual rain event in August 1997 (89.8 mm in 2 days) characterized by an isotopic composition of −5.7‰ and −42‰ for $\delta\,^{18}$O and $\delta\,^{2}$H, respectively (Fig. 3). It is expected that groundwater recharge during this time was much higher than post 1997 since this year was the wettest year of the last 38 years and was associated to an ENSO event (Fig. 2). The enriched isotopic trend started to change toward a depleted pattern after July 2003 that seems to coincide again with a drop in water table similarly to the pattern observed between July 2001 and July 2002.

Similarly than the El Romeral groundwater, the groundwater collected in the Santa Elvira well seems to show seasonal changes in its isotope composition but not as well defined as the Romeral groundwater. First, a slight trend toward depleted values of $\delta\,^{18}$O is observed between September 2000 and August 2001 then a clear trend toward more enriched isotope values starting from −11.4‰ and reaching values as high as −10.4‰ was observed between October and December 2001. This trend is reversed tending to −11.6‰ in July August 2002. Then, an enriched trend is observed after August 2002 reaching −11‰ in November 2002 and reversing toward −11.8‰ after this date. It is important to remember that the groundwater in the part of the coastal aquifer tapped by the Santa Elvira well is a mixture of groundwater associated to the Elqui aquifer (major contributor) and the Romeral aquifer. Then, the enrichment pattern observed in the period October–December 2001 could be explained by an increase in the groundwater contribution by the Romeral aquifer, which is characterized by 7.5‰ $\delta\,^{18}$O and then during low water period observed in the Romeral aquifer, the isotope composition of the Santa Elvira groundwater is mainly controlled by the contribution of the regional aquifer linked to the Elqui basin, which is characterized by 13.5‰ $\delta^{18}O$ in the lower part of the basin. The changes after August 2002 are much more subtle indicating the interaction between groundwater discharge of the Romeral basin and the regional aquifer in the coastal areas is quite complex.

3.3. Tritium values in ground waters

Tritium data collected in 1996 and 1998 in the Romeral basin also provide information about the dynamics of groundwater recharge in the study area (Table 1). The data collected in December 1996 after four dry years showed the groundwater was devoid of tritium. The precipitation in coastal areas in Chile should have tritium values in the range of 4–6 TU. The groundwater tritium data suggested that groundwater in the Romeral aquifer was at least 40 years old. The November 1998 data show 1.5–1.8 TU in some wells indicating the recharge of recent water probably associated with the heavy rains of 1997 linked to an ENSO year. The tritium data agreed with the stable isotope data that showed the Romeral aquifer responded very fast to recharge events associated with rains over the average value for precipitation in the study area. The lack of tritium in the Santa Elvira groundwater and the Elqui River aquifer agreed with the stable isotope data that showed the coastal aquifer tapped by the Santa Elvira well is receiving mainly groundwater linked to the Elqui regional aquifer.

3.4. Addressing implications for vegetation water use

In desert ecosystems, it has been proposed that plants can use different water sources that can differ in the space and time (seasonal and inter-annual) for different functional groups (Canadell et al., 1996; Ehleringer, 1985; Ehleringer and Mooney, 1983; Ehleringer et al., 1991; Mooney et al., 1974). In continental deserts of North America important water sources for plant growth are precipitation as rain (convective precipitation mostly in summer), snow or rain linked to polar fronts (in winter), and ground water (mostly recharge with winter precipitation) (Flanagan et al., 1992; Lin et al., 1996). In coastal desert in the Mediterranean Climate regions, fog, winter rain and groundwater change in

Table 1
Tritium values by groundwater from Quebrada El Romeral and Elqui river

Locations	December 1996	November 1998
Romeral Town well	< 0.8	1.5
Romeral Mine (6 m a.s.l spring)	0.9	—
Romeral Mine (80 m a.s.l spring)	< 0.8	—
Romeral Mine (265 m a.s.l spring)	< 0.8	—
Romeral well	—	1.8
Siciliano spring	< 0.8	—
Santa Elvira well	—	<0.8
Elqui river well	< 0.8	—

The sampling locations can be found in Fig. 1a. Analytical error ± 0.8 TU.

importance in different ecosystems (Friedman et al., 1992; Noble and Gitay, 1996; Olivier, 1995; Southgate et al., 1996). While in coastal mountain range fog could contribute more than 75% of the total water budget (Cruzat-Gallardo, 2004; Kummerow, 1966; Squeo et al. 2004a, b), in coastal areas the main source is ground water and rain (León and Squeo, 2004; Olivares and Squeo, 1999; Squeo et al., 1999; Torres et al., 2002).

The main conclusion of the present study is that during wet years and especially during ENSO events, the water table recovered very fast and local precipitation plays a significant role in groundwater recharge. This pattern has implications for a functional group of plant species, characterized by a deep root system, that have low capacity to respond directly to precipitation events (Squeo et al., 1999; Torres et al., 2002). However, the fast response of the aquifer to precipitation events, larger than the average value, after a long dry period makes it possible that this functional group can use groundwater as a main water source for new plant growth and reproduction (Olivares and Squeo, 1999; Torres et al., 2002). In Romeral basin, the plant phenology of 14 native shrub species was evaluated during two contrasting rainfall years (Olivares and Squeo, 1999). Vegetative growth in deciduous species are strong related with the winter precipitation while most of the evergreen shrub species are more dependent on groundwater (Olivares and Squeo, 1999; Squeo et al., 1999). In a field experiment with three shrub species with dimorphic (*Balbisia peduncularis* and *Senna cumingii*) or deep (*Haplopappus parvifolius*) root systems, Torres et al. (2002) showed that these three species used two water sources (shallow water coming from rainfall and a greater proportion of subterranean water). The species with dimorphic roots are able to reduce their water deficits after the artificial watering in fall, winter and spring, while the deep-rooted species only was able to use a proportion of the rain in winter.

The response of the aquifer can also be linked to another functional groups characterized by a dimorphic root systems than have the possibility to perform hydraulic redistribution (i.e., the movement of water through the root system from deep to shallow soils in dry periods, and shallow-wet soil to deep-dry soil in very rainy periods) (Squeo et al., 1999; León & Squeo, 2004). Part of the fast recharge of the aquifer could be related to this water redistribution as it has been shown in other desert ecosystems (Burgess et al., 2000a, b; Caldwell et al., 1998; Espeleta et al., 2004; Scholz et al., 2002; Schulze et al., 1998). However, the magnitude of the contribution of the plants in the recharge of this coastal aquifer still needs to be quantified. The other effect of fast water table rebound in the study area could be on seedling recruitment of deep-rooted species. Most of the seeds of shrubs species germinated with precipitation lower than 20 mm (Baskin and Baskin, 1998; Dodd and Donovan, 1999; Maldonado et al., 2002; Moreno et al., 1990), but the survival of the new springs of deep-rooted plants required a shallow water table during the next summer to be established.

4. Conclusion

This study used hydrogeological and isotope tools to evaluate the main water sources involved in the water cycle of a coastal desert near La Serena. The isotope data showed these water sources are characterized by very different isotope compositions indicating a complex history. The more isotopically enriched water are fogs and coastal rains, and the more isotopically depleted water are groundwaters that are part of the regional groundwater system of the Elqui River basin, which is recharged in the higher part of the basin. The isotope data confirms results of previous studies, based on fog capture, that showed fogs do not play any role in groundwater recharge in the Romeral aquifer. The relative long-term seasonal evaluation of the aquifer dynamic showed a strong correlation with the precipitation regime. This is in agreement with the geographical location of the Romeral Basin that does not have precipitation as snow in the high part of the Basin. The seasonal evaluation of the water table showed that during dry periods, significant drops were observed in the water table and the isotope data showed the groundwater is mainly associated to recharge areas located in the high part of the Romeral basin. These data also showed that no recharge occurs with amount of precipitation lower than the average value. Otherwise, during wet years and especially during ENSO events, the water table recovered very fast and the isotope data showed local precipitation plays a significant role in groundwater recharge. This study also showed that the groundwater in the coastal areas of the La Serena is linked to a regional more stable groundwater flow system, which is mainly recharged in the high part of the Elqui River Basin. This pattern made possible the establishment and long-term survival of wetlands in a coastal environment characterize by arid conditions. The understanding of the groundwater dynamics, based on isotope and hydrogeological tools used in this study, provide critical information for a more comprehensive evaluation of plant–water relations in aridland ecosystems.

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