

Interaction of water components in the semi-arid Huasco and Limarí river basins, North Central Chile

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Abstract. For sustainable water resource management in semi-arid regions, sound information is required about interactions between the different components of the water system: rain/snow precipitation, surface/subsurface run-off, groundwater recharge. Exemplarily, the Huasco and Limarí river basins as water stressed river catchments have been studied by isotope and hydrochemical methods for (i) the origin of water, (ii) water quality, (iii) relations of surface and groundwater.

Applying the complex multi-isotopic and hydrochemical methodology to the water components of the Huasco and Limarí basins, a differentiation of water components concerning subsurface flow and river water along the catchment area and by anthropogenic impacts are detected. Sulphate and nitrate concentrations indicate remarkable input from mining and agricultural activities along the river catchment.

The ²H-¹⁸O relations of river water and groundwater of both catchments point to the behaviour of river waters originated in an arid to semi-arid environment.

Consequently, the groundwater from several production wells in the lower parts of the catchments is related to the rivers where the wells located, however, it can be distinguished from the river water. Using the hydrological wa-

ter balance and the isotope mixing model, the interaction between surface and subsurface flows and river flow is estimated.

1 Introduction

In the Coquimbo and Atacama regions the vulnerability of the natural water resources is increasing by the water requirements of the agricultural and mining industry and of the urban development which requires a sustainable water resource management. An increasing demand of sound information about the origin of water resources, their quality, the groundwater recharge conditions, surface and subsurface run-off, rain/snow precipitation and water use is required for a proper management of water resources. A water quality data base was established for several important catchment areas in semi-arid zones by the CADE-IDEPE in 2004 (CADE-IDEPE, 2004a, b). These data were evaluated according to sustainable water resource management by Ribbe et al. (2008) due to the water quality and monitoring practice for requirements of water policy and legislative measures. Because of increasing demand of water for agriculture, mining, and domestic use, groundwater abstraction gains importance in river catchments, but needs a better understanding about its interaction with surface water in semi-arid watersheds. Groundwater resources in two relevant



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and water stressed river catchments of the Atacama and Coquimbo Regions – the Huasco and Limarí river basins – are associated to shallow sediments of the flood plains in direct interaction with the river surface discharge, and to fractured rock aquifers (Rojas et al., 2008). The groundwater source is currently used in small proportion for domestic consumption and irrigation purposes by local suppliers. According to a study at the Elqui basin using combined multi-isotope and hydrochemical methods, the groundwater dynamic to the river basin and its origin from the fractured basement could be estimated (Strauch et al., 2006).

Applying this methodology exemplarily to the catchments of the Huasco and Limarí basins, we aimed on an improved understanding about the origin of water components, water quality, and the interaction of surface and groundwater in those catchments.

2 Geological settings, sampling and analytics

The geology of the both watersheds is characterized by a variety of rock units ranging in age from Palaeozoic to Quaternary whereas the high-altitude domain of the region comprises a volcanic series of the Doña Ana Formation (Upper Oligocene-Lower Miocene) with important metallogenic provinces (Maksaev et al., 1984; Bissig et al., 2002).

Groundwater in the Huasco and Limarí catchment is present in (i) a gravel-sand dominated aquifer formed by shallow sediments of the flood plains of valleys and gulches, and in (ii) fractured rock aquifers corresponding to both granitic batholiths and volcanic and sedimentary beds (Rojas et al., 2008). The shallow aquifer is influenced by the high run-off dynamic of the rivers during either direct precipitation or snow melting in the Andes. Run-off data between 0.79 and 2.14 m³ s⁻¹ for the Huasco river (at Algodones, DGA station), and for the Limarí catchment Rio Grande (at Puntilla San Juan) between 3.75 and 5.62 m³ s⁻¹ and the Rio Limarí (at Ovalle, Panamericana) with 1.07 and 1.73 m³ s⁻¹ point to the remarkable dynamic of the watershed (Table 1; DGA data).

Less important due to the amount of water, the fractured rock aquifer discharges in natural springs in the mountains and used on a small scale for domestic consumption and irrigation purposes by local farmers.

Sampling was performed at the end of austral spring in November 2006, localities and relevant features are displayed in Table 2 and Fig. 1. Surface water sampling was scooped from different tributaries of the catchments starting at altitudes of 1890 m a.s.l. along the river courses down to the main cities of the catchments Vallenar and Ovalle, respectively (Fig. 1).

Groundwater was sampled from operating wells of the local water suppliers in Vallenar, Ovalle, and Monte Patria. Hydrochemical parameters as pH and electric conductivity (EC) were directly measured during sampling, alkalinity was

Table 1. Run-off data from the catchment areas investigated at DGA-Stations in November 2006 (DGA, 2007).

Catchment	Station	Lat/Long	Flow (m ³ s ⁻¹)		
			Mean	Min	Max
Rio Huasco	Algodones 3820001	28.44/70.33	1.263	0.788	2.141
Rio Limarí/ Rio Hurtado	Samo Alto (Ang)		1.14	0.73	1.77
Rio Limarí/ Rio Grande	Puntilla San Juan 4523002	30.42/70.55	5.62	3.75	7.02
Rio Limarí	Panamericana		1.36	1.07	1.73

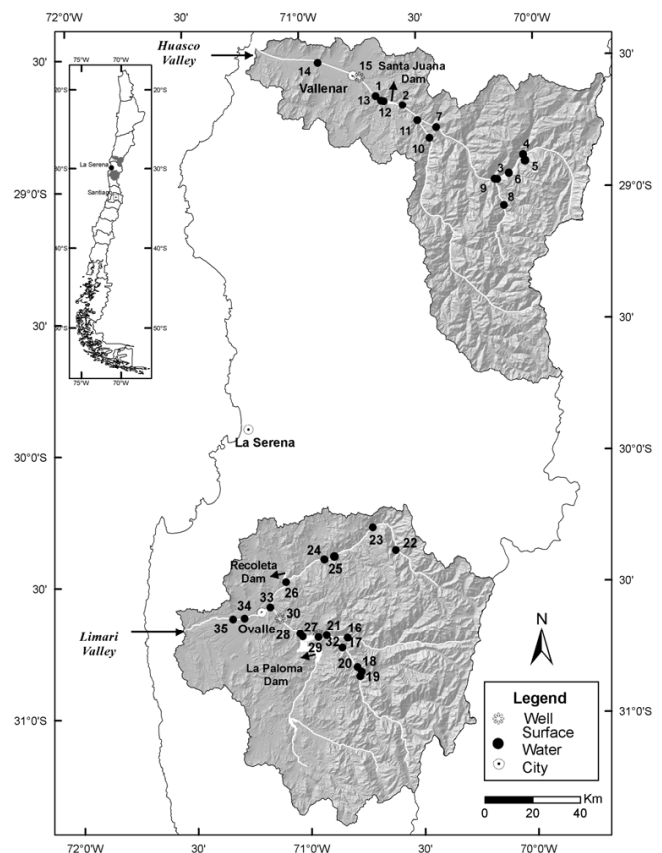


Fig. 1. Investigation areas and sampling locations in the catchments of Rio Huasco (above) and Rio Limarí (below).

titrated in the field. Samples for hydrochemical analysis were filtered with 0.45 μm cellulose acetate filters. Anions were analysed using the ion chromatograph system D120 from Dionex with a reproducibility of 5% for each anion. Major cations were performed by ICP-AES (Varian) with an accuracy of 5%.

H- and O-isotopes were on-line measured by the XL-Plus Continuous flow IRMS (Thermo Electron Corporation)

Table 2. Sampling location characteristics, hydrochemical and isotope data including water flux estimations during sampling. The sampling was from 11 to 15 November, 2006.

Nr	Sampling locations Location	Altitude m a.s.l.	Hydrological parameter				Hydrochemistry						Water flux Q m ³ s ⁻¹	Stable isotopes			
			T °C	el. Cond. μS cm ⁻¹	pH	Na ⁺	K ⁺	Mg ⁺⁺	Ca ⁺⁺	Cl ⁻	SO ₄ ⁻	HCO ₃ ⁻		NO ₃ ⁻	δ ¹⁸ O	δ ² H	d-excess o/oo
Catchment Huasco: Rio Huasco/Tránsito/Carmen,																	
8	Pascua Lama gate door	1888	15.8	382	8.18	6.7	0.9	10.7	51.4	2.0	132.6	93	1.71	0.77	-13.59	-98.7	10.0
4	Caceo village	1859	18.6	315	9.18	17.2	1.6	6.5	38.3	6.1	45.1	121	0.61	0.106	-10.47	-83.8	0.0
5	Valeriano Bridge	1827	17.3	573	8.29	22.8	1.6	11.7	72.1	18.7	190.3	66	2.04	1.54	-13.25	-99.7	6.3
3	Conay Bridge	1384	21.6	497	8.14	8.6	1.4	12.0	71.4	2.8	182.0	41	1.00	1.8	-13.10	-96.7	8.1
9	after confluence Conay	1436	23.1	537	8.03	15.6	1.4	11.7	75.2	8.9	179.6	72	1.13	2.16	-12.97	-96.2	7.5
6	Malaguin Bridge	1198	17.5	545	8.44	22.3	1.6	10.9	70.2	16.7	164.0	79	1.77	1.18	-12.72	-96.6	5.2
7	Puente Negra	864	19.3	722	8.68	30.7	2.1	16.2	99.0	14.7	196.0	160	2.30	2.25	-11.99	-91.6	4.2
10	Retamo Village	902	19.2	792	8.60	23.3	2.0	20.4	116.0	8.3	265.2	157	1.77	0.93	-13.20	-100.7	4.9
11	Confluence after Alto d Carmen, near Algodones	790	23.8	766	8.43	28.3	2.3	19.3	105.2	12.8	251.4	137	1.41	1.8	-12.25	-94.4	3.6
2	St Juana Dam inflow	643	22.9	778	8.54	27.0	2.2	19.0	107.6	12.5	239.3	152	1.67	2.3	-12.36	-95.2	3.7
12	Surface St Juana Dam	650	20.9	644	8.60	23.3	1.8	16.2	86.7	11.0	211.4	102	0.76	n.e.	-11.59	-90.0	2.8
13	St Juana Dam outflow	618	15.7	649	8.50	22.8	1.8	15.7	90.1	18.3	209.2	117	1.18	n.e.	-11.98	-92.2	3.6
1	Vallenar, upstream	448	17.0	652	8.62	22.0	1.7	15.4	87.8	13.0	204.8	115	1.11	n.e.	-11.91	-91.9	3.3
14	Rio Huasco, downstream Val	242	16.1	2040	8.66	247.8	4.9	38.9	201.0	198.5	586.9	331	6.17	10	-10.96	-85.7	2.0
Catchment Limarí: Rio Grande																	
18	vill. Carén, Pte Mostazal	703	19.6	410	8.34	12.1	1.1	9.5	62.0	4.5	64.1	173	1.73	1.4	-11.88	-87.2	7.9
19	vill. Carén	700	18.7	186	8.40	7.1	0.6	2.7	26.6	4.7	16.6	82	0.25	6.8	-12.43	-89.6	9.8
20	Semita Bridge	674	18.1	221	8.28	7.9	0.7	3.6	31.6	4.8	22.1	93	0.41	6.8	-12.35	-89.2	9.6
16	Rio Rapel	619	19.9	535	8.25	17.4	1.4	13.8	78.5	4.3	73.9	244	3.75	0.23	-11.86	-87.1	7.8
17	vill. Chilecito, Pte Mialqui	516	20.9	235	9.11	8.4	0.7	4.0	33.8	5.1	24.3	35	0.24	6.17	-12.24	-88.9	9.0
21	Rio Grande, before La Paloma Dam	444	20.3	287	8.31	10.7	0.8	5.8	41.2	5.8	30.4	127	0.50	5.6	-12.00	-87.3	8.7
27	Rio Grande, direct input La Paloma Dam, Pte Patria	383	19.9	318	7.64	12.3	1.0	6.7	48.5	12.9	31.4	162	0.11	7.6	-11.91	-86.8	8.4
28	La Paloma Dam, surface water	386	19.4	305	8.81	14.5	1.5	7.7	39.4	7.3	38.1	131	0.35	n.e.	-8.71	-67.9	1.7
29	Outlet La Paloma Dam	305	16.1	318	8.33	15.0	1.5	8.0	41.1	7.3	38.0	134	0.51	2.9	-8.87	-68.8	2.2
Catchment Limarí: Rio Hurtado																	
22	Rio Hurtado, Las Breas	1540	13.3	263	8.31	6.6	1.0	4.5	36.8	3.5	74.3	48	1.01	3.2	-13.73	-100.8	9.1
23	downst Hurtado, upstr Fundina, Puente	1531	16.3	345	8.33	10.7	1.3	7.4	49.1	4.4	79.1	97	1.68	n.e.	-13.44	-98.9	8.6
24	Samo Alto, Pte Samo Alto	606	22.7	446	8.90	15.2	1.2	9.4	68.1	6.4	90.6	163	0.55	1.8	-13.01	-96.7	7.3
26	Recoleta Dam, surface water	421	21.0	436	8.72	16.9	1.7	10.0	62.7	8.6	92.3	146	0.17	n.e.	-10.02	-79.3	0.9
Catchment Limarí: Rio Limarí																	
34	Rio El Ingenio, tribut. Rio Limari	177	25.3	3370	8.44	344.8	5.8	153.2	289.9	811.6	630.9	277	14.55	n.e.	-7.42	-59.6	-0.3
33	Rio Grande, input Los Peniones, Ovalle	374	21.5	464	9.00	33.2	1.8	12.5	52.9	19.5	54.9	194	0.20	n.e.	-8.24	-65.1	0.8
35	Rio Limari, vill Trapiche	115	24.5	1045	9.52	111.3	3.1	21.7	94.0	121.4	112.5	293	3.16	n.e.	-7.59	-60.9	-0.2
Groundwater																	
15	Waterworks Vallenar	259	19.6	895	7.70	87.8	3.6	16.7	76.7	42.0	204.9	226	8.51	n.e.	-11.80	-90.1	4.3
30	Well Ovalle, Aguas del Valle Ovalle	277	18.5	641	7.07	50.2	1.7	17.2	65.6	29.1	62.9	268	15.09	n.e.	-8.50	-65.2	2.8
32	Well Monte Patria, Aguas del Valle Ovalle	401	19.3	631	7.09	39.6	1.5	14.8	79.3	15.0	71.4	273	14.90	n.e.	-10.63	-78.8	6.2

n.e.=not estimated; No. 25 not sampled.

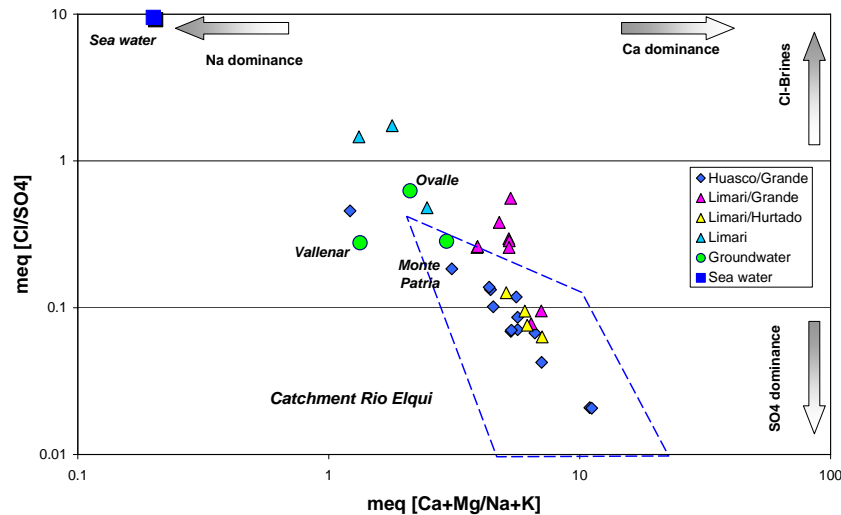


Fig. 2. Hydrochemical characteristics of river and groundwater from the Rio Huasco and Rio Limarí catchments in relation to the Rio Elqui catchment (dotted area).

(Gehre and Strauch, 2004). Isotope ratios of hydrogen and oxygen are reported in the δ -notation

$$\delta = ([R_{\text{sample}}/R_{\text{standard}}] - 1) * 1000,$$

with values expressed in ‰ vs. VSMOW (Vienna Standard Mean Ocean Water) with $R = [^{18}\text{O}/^{16}\text{O}]$ and $[^2\text{H}/\text{H}]$, respectively. The accuracy of the isotope analysis is 0.8‰ for hydrogen and 0.1‰ for oxygen. All analyses were performed at the laboratories of the UFZ-Departments Hydrogeology and Isotope Hydrology in Halle/Saale, Germany.

Table 2 presents the data of the field measurements and the hydrochemical and isotope analyses.

3 Results and discussion

3.1 Hydrochemistry

The river waters from the Huasco watersheds, the northern and more arid area, are generally characterized by increasing mineralization along the tributaries Rio Conay/Chollay, Rio El Tránsito, Rio Del Carmen downstream to the Rio Huasco. The surface water for the Huasco watershed is Ca-, Na- and sulphate stressed resulting in a Ca-(Na)-SO₄-(HCO₃) water type. Downstream of Vallenar (14), the highest load of mineralization was analysed including nitrate which reflects clearly the agricultural and urban input of the Vallenar area. River water from the Rio Chollay (samples 3, 8) has a remarkable load of sulphate (Fig. 2) discharging the high mountain mining area (Pascua Lama District). Similar ion ratios were observed in the upper part of the Elqui catchment influenced by gold-copper mining (Strauch et al., 2006).

Along the Limarí watershed, located more in a semi-arid environment, river water is less mineralized than that of the

Huasco catchment: it concerns the main tributaries Rio Hurtado and Rio Grande. Downstream Ovalle at Trapiche, a significant urban and agricultural impact can be observed, and is evidently in the high mineralized stream water of the El Ingenio with particularly high nitrate concentration. Generally, the water type of the mountain controlled Limarí watershed upstream Ovalle is Na-(Ca)-HCO₃-SO₄.

Groundwater, the second important water resource in the catchments, confirms its origin from the catchment runoff (Fig. 2), but is affected by anthropogenic activities. In Vallenar, the groundwater signature follows the Huasco river water type, but changes its character to Na-Ca-SO₄-(HCO₃) similarly to the polluted river water downstream Vallenar (14). The groundwater in the important agricultural region of Monte Patria (Limarí catchment) is of Ca-(Na)-HCO₃-(SO₄) type. The abstracted groundwater (32) is consequently nitrate polluted in relation to the receiving water in this part of the Limarí catchment. Interaction of surface (river, La Paloma reservoir) and subterranean water (bank filtration, groundwater) can influence the type of groundwater near Monte Patria (Figs. 2, 3, Table 2). Downwards near Ovalle, river water (33) and groundwater (30) have the same Ca-(Na)-HCO₃-(SO₄) water signature, but anthropogenic based with likewise high nitrate concentration in the groundwater.

3.2 Stable isotopes of water

As reported above, river and groundwater in both watersheds correlate in their hydrochemical signature. Anthropogenic pollutants, however, can influence the water types and thus the clear distinction between the origins of the water components. That's why the application of stable water isotopes

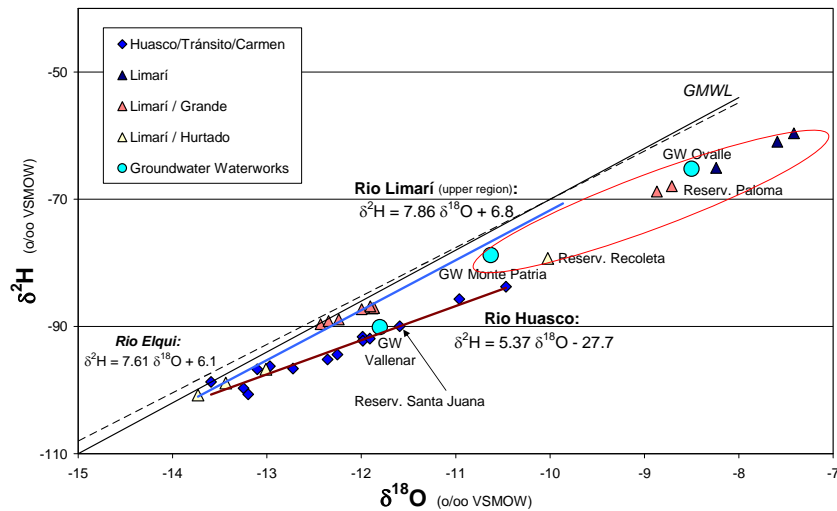


Fig. 3. Isotopic signature of the water components of the both catchments within the $\delta^2\text{H}$ - $\delta^{18}\text{O}$ diagram. The water line of the Huasco catchment comprises all tributaries. For the Limarí catchment, only run-off of the mountain tributaries forms the water line (blue line). Lower region is evaporation influenced (red area). To compare: Global Meteoric Water Line (GMWL $\delta^2\text{H}=8\delta^{18}\text{O}+10$) and Rio Elqui water line (dotted) are added (see Strauch et al., 2006).

^2H and ^{18}O can be used to understand the origin and the interaction of river and groundwater within the watersheds.

The ^2H - ^{18}O signature of both water catchments follow the meteoric water relation (Fig. 3) and point to precipitation controlled river waters originated under arid environment in the high Andes Mountain. For the mountain controlled Huasco catchment (Rio El Tránsito, Rio Del Carmen), the river water corresponds the run-off of the winter precipitation following the meteoric water relation. Evaporation processes along the river course affect the surface water shown by the smaller slope of the ^2H - ^{18}O relation compared to the GMWL (Fig. 3).

Likewise, the deuterium excess d decreases $<10\%$ as consequence of dry and arid conditions. Those climatic conditions are responsible for the isotope variations at the high mountain glacier fields, the source region of the river run-off (see Stichler et al., 2001).

The groundwater signature at Vallenar correlates clearly with the river and dammed water of the Santa Juana reservoir located in the river basin upstream of Vallenar. Bank filtration from the river seems the main recharge process for the groundwater resource.

The Limarí catchment shows larger isotope variations due to the different catchments of the tributaries Rio Hurtado, Rio Grande with the region of Monte Patria, and Rio Limarí downstream of Ovalle. River water of both tributaries (Rio Hurtado, Rio Grande) corresponds to high altitude sources and fast transport downstream. Therefore, river water of both mountain tributaries keeps its meteoric origin down to the reservoirs as the ^2H - ^{18}O relation shows (Fig. 3). The lake water of the reservoirs Recoleta (Rio Hurtado) and La Paloma (Rio Grande) is clearly enriched in ^2H and ^{18}O in

consequence of the dry climate in both watersheds. Similarly to the Huasco catchment, the isotopic signature of the groundwater at Monte Patria and Ovalle correlates significantly to the lake water of the dams. Therefore, it is assumed that groundwater is a mixture of base flow from the corresponding rivers and of bank filtrate from the reservoirs.

4 Estimation of groundwater contribution in the Huasco and Limarí catchments

To assess the water resources in the agricultural intensively used watersheds of Rio Huasco and Rio Limarí, the contribution of the surface and groundwater components has to be estimated. As shown above, the hydrochemical and isotope signatures of river water and groundwater distinguish in the different tributaries and groundwater abstraction wells of the both river catchments. Based on the knowledge available from the neighbouring Elqui catchment (Strauch et al., 2006), a first estimation of the ratio of subsurface flow (groundwater, base flow) and total flow (river water) in the groundwater exploration areas of Vallenar, Monte Patria, and Ovalle is reported. The water isotopes $^2\text{H}/^{18}\text{O}$ and, unlike the Elqui study, the electrical conductivity (EC) as a summary parameter of the hydrochemistry are used and combined with the hydrological balance equation applied by Kobayashi et al. (1999), Morche (2006) and Lehmann (2004) for hydrograph separation in mountain water catchments. There, the total flow within a catchment is the sum of surface flow or direct flow characterized by precipitation and rain events, and subsurface flow or base flow which corresponds to the groundwater component:

Table 3. Contributions of groundwater to the total river flow in areas of groundwater abstraction.

	$\delta^{18}\text{O}$ (in ‰)	EC (in $\mu\text{S cm}^{-1}$)
	$\delta^{18}\text{O}_{\text{Precipitation}} = -15\text{‰}$ (Tapado glacier, Elqui Valley)	$\text{EC}_{\text{Precipitation}} = 200 \mu\text{S cm}^{-1}$ (mean precipitation La Serena, Elqui Valley)
	$\delta^{18}\text{O}_{\text{River=samples}}$ (No)	$\text{EC}_{\text{River=samples}}$ (No)
	$\delta^{18}\text{O}_{\text{Groundwater=well water}}$ (No)	$\text{EC}_{\text{Groundwater=well water}}$ (No)
	Direct flow= Surface flow	Base flow= Groundwater
	Direct flow= Surface flow	Base flow= Groundwater
Monte Patria	$\delta^{18}\text{O}_{\text{River}}: -11.91 \dots -12.00$ (21, 27) $\delta^{18}\text{O}_{\text{Groundwater}}: -10.63$ (32)	$\text{EC}_{\text{River}} = 287 \dots 318$ (21, 27) $\text{EC}_{\text{Groundwater}} = 631$ (32)
	31% 69%	73-80% 20-27%
Ovalle	$\delta^{18}\text{O}_{\text{River}}: -8.87$ (29) $\delta^{18}\text{O}_{\text{Groundwater}}: -8.50$ (30)	$\text{EC}_{\text{River}} = 464$ (33) $\text{EC}_{\text{Groundwater}} = 641$ (30)
	6% 94%	40% 60%
Vallenar	$\delta^{18}\text{O}_{\text{River}}: -11.91$ (1) $\delta^{18}\text{O}_{\text{Groundwater}}: -11.80$ (15)	$\text{EC}_{\text{River}} = 652$ (1) $\text{EC}_{\text{Groundwater}} = 895$ (15)
	4% 96%	35% 65%

$$Q_{\text{Totalflow}} = Q_{\text{Directflow=Surfaceflow}} + Q_{\text{Baseflow=Groundwater}} \quad (1)$$

For the isotope balance follows

$$\delta_T Q_T = \delta_S Q_S + \delta_G Q_G \quad (2)$$

where the δ values stand for the isotope concentration.

Using the two-component isotope mixing model, the ratio of the subsurface/groundwater flow to the total flow follows after Eq. (2)

$$Q_G/Q_T = (\delta_{\text{River}} - \delta_{\text{Precipitation}}) / (\delta_{\text{Groundwater}} - \delta_{\text{Precipitation}}). \quad (3)$$

Instead of isotopes EC values can also be used.

For the groundwater abstracting areas, measured data from the regions themselves and from the Elqui catchment are appropriated (see Table 3).

For the roughly estimation of the contribution of groundwater to the total river flow in the area of Vallenar, Monte Patria and Ovalle, the percentages are calculated after Eq. (3) as reported in Table 3. The parts of groundwater distinguish according to the parameters used.

In the Monte Patria region before the inflow to the La Paloma reservoir, groundwater contribution to the river water (discharge) is estimated in a range of 70% by ^{18}O . For the regions of Vallenar and Ovalle, the groundwater and river water do not distinguish each other, but are enriched in ^{18}O relative to the mountain input. However, the interaction between groundwater and surface water controls the isotope signature which explains the high groundwater input of >90% in the Vallenar and Ovalle region. The main aquifer in the surroundings of Vallenar is controlled by the Santa Juana reservoir, and the Rio Huasco function as a discharge drain for that

aquifer (Rojas et al., 2008). Thus, the pollution of groundwater by anthropogenic activities could play an important role for the water quality in downstream areas, and for the water use there.

In contrast to the isotope parameter, the EC parameter reflect stronger the different mineralization of river and groundwater caused by geogenic and anthropogenic impacts. The higher mineralized river and groundwater particularly in the Vallenar and Ovalle regions is obviously caused by anthropogenic pollution affecting both compartments. This assumes a higher groundwater input up to 65%. In Monte Patria, the groundwater input does not extend 27%.

5 Conclusions

By means of a multi-parameter approach using hydrochemical and isotope methods, the water components of river catchments in semi-arid environment as surface water, subsurface and groundwater, and precipitations can be characterized due to their origin, interaction each other, and contamination.

For the Huasco and Limarí catchments, the river water corresponds clearly to the high mountain sources region fed by precipitation as shown by the ^2H and ^{18}O relation. The arid conditions within the catchments influence strongly the surface water by evaporation processes.

On the other hand, the groundwater formed by infiltration processes is considered as a mixture of river water, dammed water and partly water from fractured aquifers. However, because of the intensive agriculture in the lower part of the

catchments groundwater is significantly affected by anthropogenic activities as the water quality shows.

Moreover, combining the hydrological water balance and the isotope mixing model, the interaction between groundwater and river water could be estimated. It can be concluded for the lower parts of both catchments that groundwater discharges from the shallow aquifers into the rivers.

Such multi-methodological studies can help to improve the knowledge about the surface and groundwater dynamic which is important for a sustainable water resource management in arid zones.

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