Geochemical and isotopic characterization of surface river-alluvial groundwater relationships in a high altitude semi-arid basin, Elqui (Chile)

POURRIER J.[1,2] *, BATIOT-GUILHE C.[1], TAUPIN J.D.[1], PATRIS N.[1], JOURDE H. [1]

1 UMR 5569 Laboratoire HydroSciences, HSM -Université de Montpellier - CNRS –IRD, 163 rue Auguste Broussonnet, 34090 MONTPELLIER, France

2 CEAZA (Centro de Estudios Avancados en Zonas Aridas), Raúl Bitrán 1305, La Serena, Región de Coquimbo, Chile

*now at ITK, CAP ALPHA Avenue de l'Europe, 34830 Clapiers, France

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Semi-arid, mountainous watersheds are characterized by a strong stress on their superficial and underground water resources, in the context of environmental change. The main concern is to improve knowledge about interaction processes between cryospheric, hydrologic and hydrogeologic compartments, with the aim to define a hydrological conceptual model.

Study area

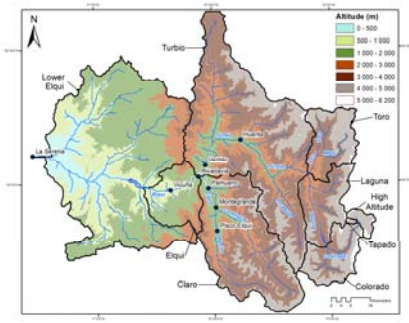


Fig. 1: Elqui valley and limits of the basins and of its tributaries

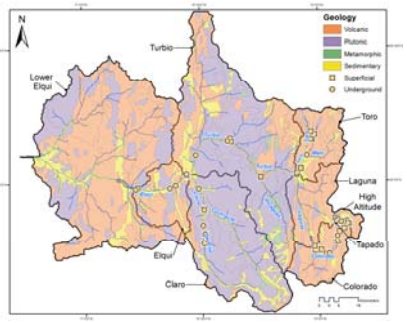


Fig. 2: Geological map of the study area and sampling sites location

The study area is located in Chilean Andes (800 - 5500 m.a.s.l):

- **Basin:** 9600 km², with a strong altitudinal gradient between the Pacific Ocean and summits of the Andes overpassing 6000 m.a.s.l.
- **Climate:** semi-arid climate influenced by ENSO/LNSO climatic oscillations (decrease of the amount of precipitations during La Niña phases and no particular trend during Neutral and El Niño phases), also characterized by an altitudinal gradient from the Pacific coast (80 mm/year) to the mountainous areas (300 mm/year)
- **Geology:** The upper zone (> 3000 m) comprises various volcanic rocks including locally mineral-rich areas (El Indio Gold Belt) and is supplied by several glaciers including the Tapado and rock glaciers. Several zones include mining activities (El Indio mining) or mineral-rich terrains. The lower part of the basin is composed of plutonic rocks and detrital terrains in which alluvial aquifers are developed.

Methods

- 5 field campaigns in the upper part of the Elqui watershed (>2000 m.a.s.l.) from 2011 to 2013, under high and low waters,
- Important field work and instrumentation was necessary to equip a number of sites were no piezometric or discharge measurement data from the DGA (Direccion General del Agua) were available, especially in the upper part of the basin,
- Springs and surface waters (Fig.2): physico-chemical parameters (pH, T° , EC) were measured in-situ and samplings conducted for chemical (major and trace elements) and isotopic analyses.

Results

In the upper part, 3 geochemical facies exist:

•HCO_3-Ca: meltwater with rapid transit,

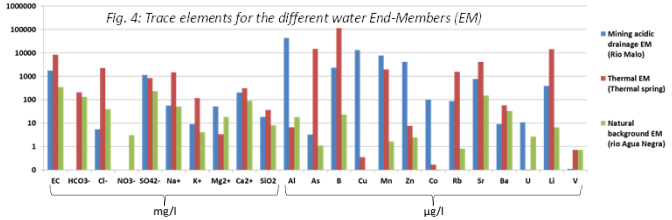
•SO_4-Ca : meltwater with slower transit through volcanic rocks or rocky glaciers rich in sulphide minerals like pyrite or water circulation through hydrothermal alteration zones (old mines, pH=4 and high EC: *Toro* sector),

•Cl-Ca : only one thermal spring (> 40° C) linked to a mixing between fresh water from melting and a high temperature deep fluid circulating upward to surface through faults.

In the lower part, conservation of HCO_3-Ca and SO_4-Ca types depending on the origin of water from upper part:

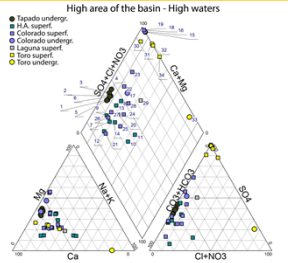
HCO_3-Ca : main circulation on or into plutonic formations (low or medium EC: *Claro* sector). SO_4-Ca : circulation on or into volcanic terrains or hydrothermal alteration zone with AMD (Acid Mine Drainage) (Higher EC: *Turbio* sector).

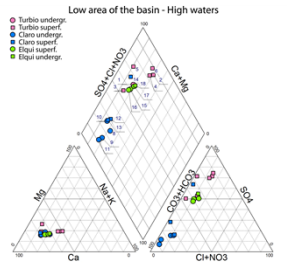
In the lower part, in spite of an important dilution process reducing EC, chemical profiles are preserved. The geochemical facies SO4-Ca and Cl-Ca are also marked by specific trace elements showing high concentrations (> 1000 µg/l for Al, As, B, Cu, Mn, Zn, Rb, Sr, Li). These two facies differentiate from one another by specific trace elements: high content in Al, Cu, Mn, Zn, Co linked to AMD ; high content in As, B, Rb, Sr, Li characterizing deep circulation fluids.



N°	Name	Date
1	APR Rivadavia	2011
2	Rio Turbio conf. Incaguaz	2011
3	Rio Incaguaz conf. Turbio	2011
4	Rio Turbio amont Huanta	2011
5	Rio Llanos de Huanta	2011
6	Rio Turbio (Rivadavia)	2011
8	APR Horcon	2011
9	APR Pisco Elqui	2011
10	APR Montegrande	2011
11	APR Paihuano	2011
12	Rio Derecho (Alcohuaz)	2011
13	Rio Derecho (Montegrande)	2011
14	Rio Cochiguaz conf. Derecho	2011
15	APR Andesclito	2011
16	APR Diaguitas	2011
17	APR Tambo	2011
18	Rio Elqui (El Tambo)	2011

APR : Agua Potable Rural (Groundwater)





N°	Name	Date
1	GFO (Glacial Foreland Outlet)	2013
2	GFO²	2013
3	Double spring	2011
4	Rio Kinnard	2013
5	Tapado Kinnard (A.N.)	2011
6	Small Rio	2013
7	Rio Agua Negra	2013
8	TKAG	2013
9	Rio 3.2	2013
10	3.1 (Spring)	2013
11	5.2 (Spring)	2013
12	Rio 5	2011
13	Rio 4	2013
14	Rio 3	2013
15	Rio 2	2013
16	Rio 1	2013
17	Rio Colorado	2013
18	Rio Laguna	2013
19	Rio Toro (El Indio)	2011
20	Rio Malo conf. Toro	2011
21	Rio Toro + Malo (El Indio)	2011
22	Thermal spring (El Indio)	2011
23	Rio Toro (douane)	2011

Fig. 3: Piper diagram for the different surface waters and groundwaters across the basin under high water conditions

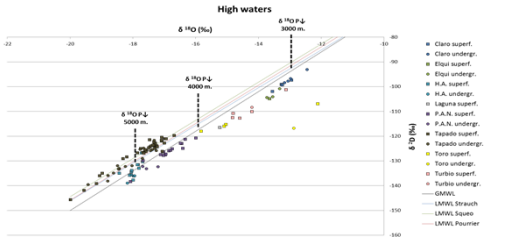
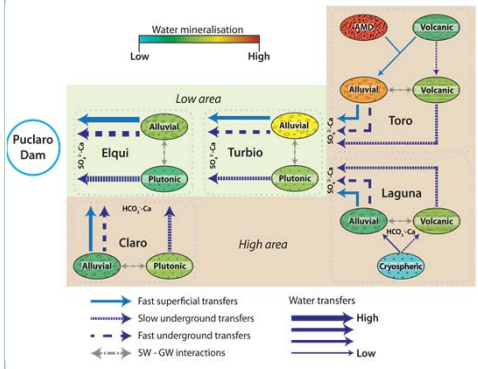


Fig. 5: Water isotopes content in various hydrological compartments (132 samples)

Precipitation and snow cover show a deuterium excess > +12‰, which is typical of high altitude rainfall in arid context and/or a continental recycling of water vapor (Atlantic origin). In contrast the surface and groundwaters are marked by a clear evaporation process consistent with the arid context. For each altitude level, surface water and ground water show identical values indicating that the main recharge process is infiltration through the river bed, explaining the presence of evaporation effect on both reservoirs. Water linked to hydrothermal processes in Toro site can show high enrichment in ^{18}O, linked to a geothermal effect (long term rock-water contact at high temperature).

Conclusion



In the high part of the Elqui watershed, water quality is affected by interactions with hydrothermally altered areas or AMD. The dilution of highly mineralized waters (*Toro*) with cryospheric meltwaters (*Laguna*) preserves downstream water geochemical facies. In the lower part, *Turbio* sector still shows high mineralization. Mineralization decreases further downstream (under 800 m.a.s.l., *Elqui* sector) indicating flow contributions from other plutonic and alluvial compartments. Thus, the water chemistry in this watershed is more related to the geological composition of hydrogeologic compartments than the precipitations chemistry or the AMDs. Finally, analyses of alluvial superficial waters and ground waters showed that the river-aquifer system is very connected. The consideration of the strong relationship between surface waters and groundwater in this type of mountainous, semi-arid watershed appears as a good way to improve water governance plans.