Groundwater in the Chilean North: A Brief Synopsis

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ABSTRACT

This paper synthesises information on the groundwater resources in the northern part of Chilean mainland, scattered to date.

The climate in the Chile increases in aridity towards the north and becomes extremely arid in coastal areas. North of 27ºS, precipitation ranges from less than 1 mm/y at the coast and in the Central Depression to 350 mm in the Andes. The lower, extremely arid parts make up the Atacama Desert.

This paper focuses on groundwater resources in the Chilean North, where water is scarce and a growing mining and agro industrial activity puts an increasing pressure on the resources. Ground water resources are found mainly in sedimentary basins. The geological evolution of the basins is always associated to the overarching process of the Andes Range uplift. There is however a great variety of different geological settings that produces different types of groundwater basins, with different dimensions and recharge mechanisms.

In order to give a general view on the hydrogeology of the Chilean North it was necessary to strongly simplify the often complex natural situations and to classify the groundwater basins. The main criterion for the classification was the geological setting as it controls much of the geographic location, hydraulic characteristics, size and geometry of the basins. Three types of groundwater basins are discussed in the paper. These basins host the biggest portion of the groundwater resources in the North. There is a brief description of the geology and groundwater characteristics for each.

Keywords: Hydrogeology, Chile, Groundwater, Resources, Management

INTRODUCTION

Chile's mainland stretches from 18°S to 56°S, approximately 4200 km along the west side of the Andes. The physical geography is characterized by a general subdivision of the country from West to East into a Coastal Area that quickly rises into the Coastal Mountain Range; farther to the East follows the Central Depression that separates the Coastal Mountain Range from the much larger Andes Mountain Range with volcanoes above 6000 m altitude (Fig. 1). This general pattern however varies, as the coastal range submerges into the Pacific Ocean in the northern and southern ends of the country.

The climate towards the North becomes arid to extremely arid. North of 27°S, precipitation ranges from less than 1 mm/y at the coast and in the Central Depression to 350 mm in the Andes. The lower, extremely arid parts make up the Atacama Desert. This paper focuses on groundwater resources in the north of the Chilean mainland, where water is scarce and a growing mining and agro industrial activity puts an

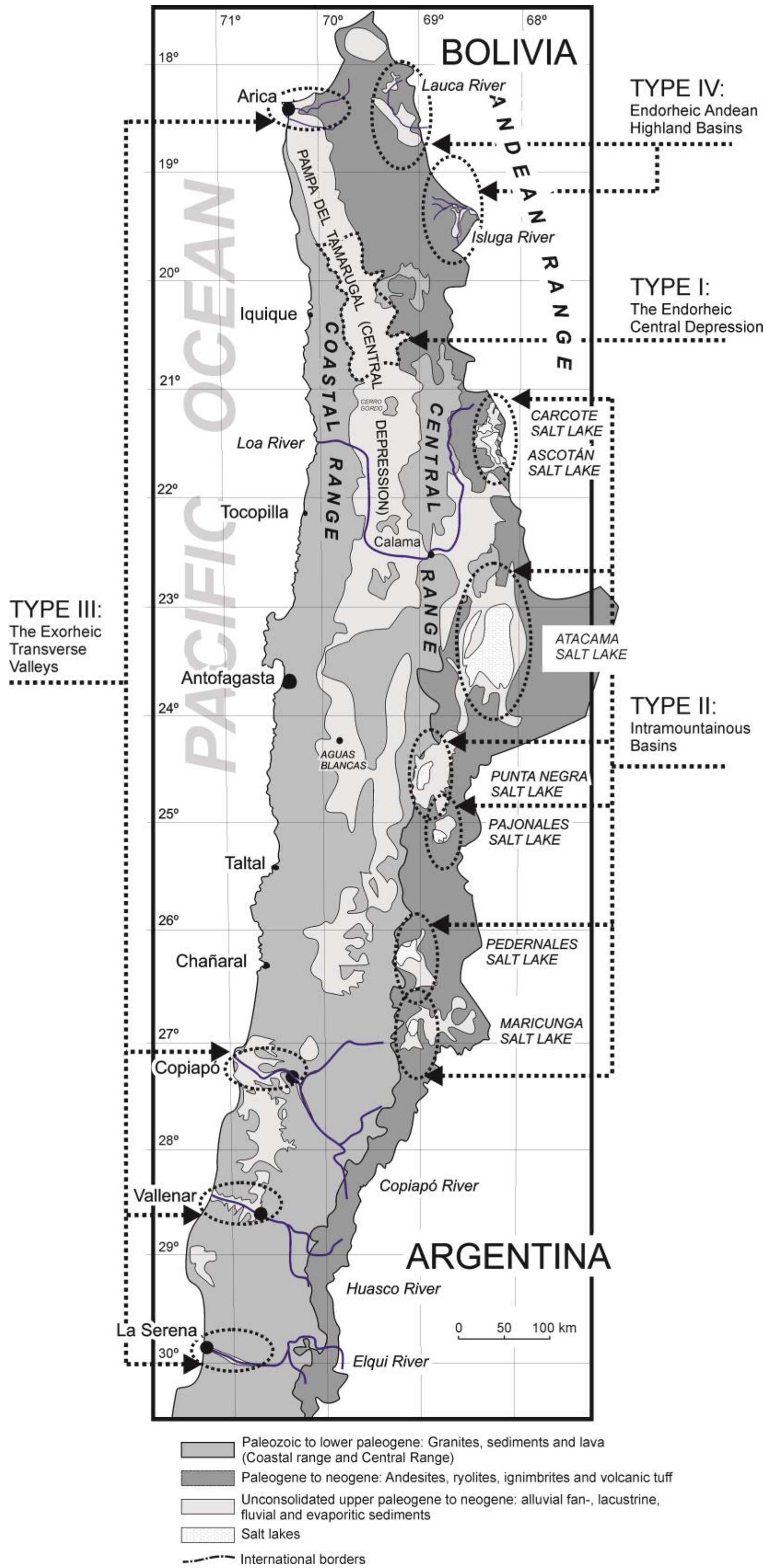

Figure 1 Groundwater basin types in northern Chile I through III as referred to in this paper. Type I is characterized by a clear division between coastal range, central depression and Andes Range. South of Cerro Gordo, the Andes Range splits into several horst and graben structures and develops a series of intramountainous basins (Type II) , where salt lakes can be found, like the *Atacama*, *Punta Negra*, *Ascotán* and *Carcote*. Type III is the E-W pointing river valley aquifer that drains into the Pacific Ocean.

increasing pressure on the resources. For the purpose of this paper, the Chilean North is defined as the part of the country located north of the capital. Groundwater is found mainly in sedimentary basins, the richest of them being located within the central depression. The geological evolution of the basins is always associated to the overarching process of the Andes Range uplift. There is however a great variety of different geological settings that produce different types of groundwater basins with changing geological and tectonic settings, dimensions and recharge mechanisms.

In order to give this brief overview on the hydrogeology of the Chilean North it was necessary to strongly simplify the often complex natural situations, highlight certain general patterns and omit other, less representative ones and to exclude areas that do not host major groundwater resources. It was further necessary to classify the groundwater basins. The main criterion for the classification was the geological setting as it controls much of the geographic location, hydrologic characteristics, size and geometry of the basins.

Three types of groundwater basins are discussed in the paper. They host the largest portion of the groundwater resources in the North (there are, however, other types of minor importance, like the endorheic highland basins in the far north, which are not considered in this paper). There is a brief description of the geology and groundwater characteristics for each.

THE GROUNDWATER BASIN TYPES OF THE CHILEAN NORTH

According to current knowledge, all major groundwater resources in the Chilean north are located in sedimentary basins. Sedimentation is occasionally interbedded with layers of ignimbrite or volcanic tuff. Aquifers of lesser importance are found in valley sediments of little extension and fractured rocks. The classification of groundwater basins in the Chilean North was based on structural and to lesser degree hydrographic criteria: Type I, The Endorheic Central Depression is a large sedimentary basin between the coastal mountain range and the Andes, roughly between 19°30´S and 21°S, known as the Pampa del Tamarugal, Type II, Intramountainous Basins: South of 21°S, the western flank of the Andes Range breaks up in a series of horst and graben structures that give way to the development of sedimentary basins of varying size, and Type III, Exorheic Transverse Valleys: This type includes river valleys with varying sedimentary deposits, which generally drain high Andean areas and flow from East to West. They occur in the extreme North of the territory.

TYPE I, THE ENDORHEIC CENTRAL DEPRESSION (PAMPA DEL TAMARUGAL)

Between 19°30'S and 21°S the Coastal Range rises parallel to the Andean Range and reaches 3000 m altitude, producing an Endorheic Central Depression (ECD) with a groundwater reservoir of unique importance (Fig. 1). North of it the Coastal Range dips below the Andean piedmont sediments and ignimbrites and allows the Andean Rivers to reach the Pacific Ocean. To the South, the ECD ends at the *Cerro Gordo* (Fig. 1), where the impermeable basement crops out.

The ECD in this area is named Pampa del *Tamarugal*, the *Tamarugo* Flatlands, after the prevailing vegetation of the area. It is a neogene and paleogene fluvial and alluvial basin, filled with sediment previously eroded in the Andes. The average altitude of the plane is 1200 m a.s.l.. The surface of the ECD is about 4000 km^2. (Fig. 2). Precipitation and direct groundwater recharge in the Pampa area is almost nil. Potential evaporation lies between 2000 and 2500 mm/a (Rojas & Dassargues, 2007).

Geology

Massive sedimentation into the ECD starts in the early to middle Oligocene (García, 2001) or early Miocene (Vogel et al., 1980). At the bottom lies the Azapa Formation, generally fluviatile in the east and clay rich, of lacustrian origin in the west (Karzulovic, 1979). During the Pliocene, volcanic activity in the Andes of northern Chile increases. Above the Azapa Formation lies the 60 to 200 m thick sequence of the Altos de Pica Formation, in which ignimbrites, rhyolites and volcanic tuff are frequently to be found between the terrestrial layers. Brüggen (1950) refers to it as *formación liparítica*.

Above the Altos de Pica Formation lies the Diablo-Formation, composed of up to 110 m of gravel, conglomerate, silt and clay. This formation, between parallels 19°45´S and the South end of the *Pampa del Tamarugal*, is in part overlaid by the Huaylas Formation series of ryolites and terrestrial sediments (Tobar et al. 1968, Vogel, 1972, Salas et al., 1966). In the ECD, the neogene sediments can be up to 450 m thick; together with the paleogene layers, the total thickness of the basin filling can reach 900 m.

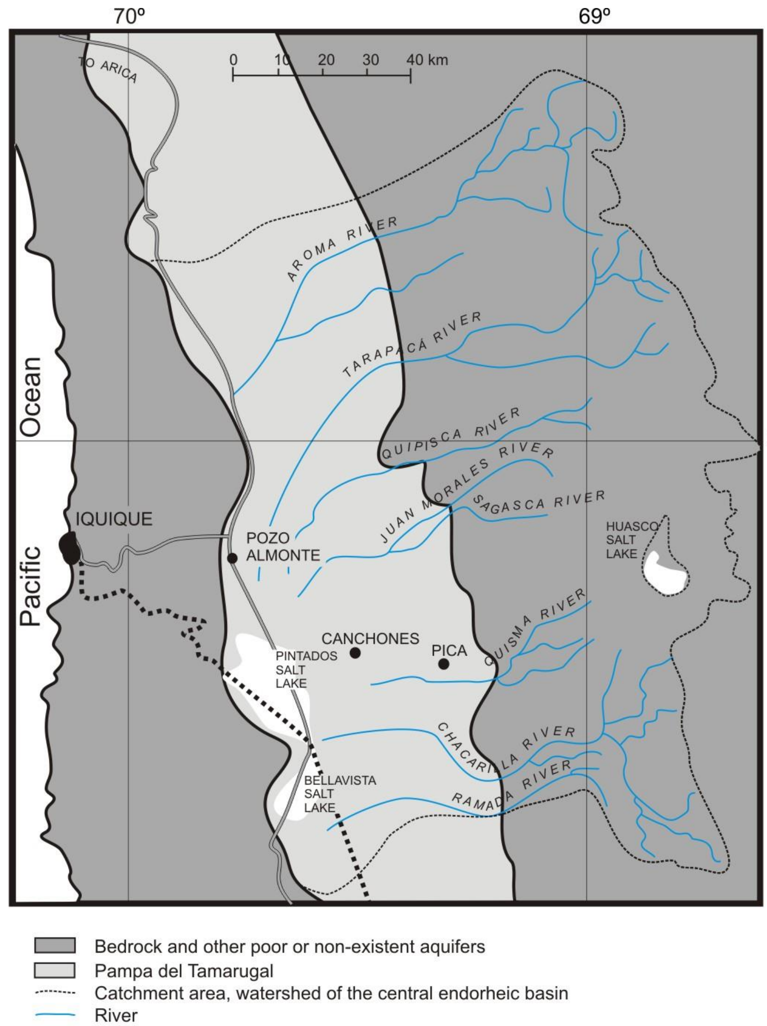

Figure 2 Catchment area and orography of the Basin Type I, the *Endorheic Central Depression – ECD – located in the Pampa del Tamarugal*.

Hydraulics, recharge and discharge

The pre-paleogene sedimentary, volcanic and metamorphic formations build the impermeable basement of the basin. The conglomerates and sandy layers of the upper 120 m of the Altos de Pica Formation provide the most important aquifers (Karzulovic, 1979). This formation is a series of layers that starts at the bottom with a generally thick layer of low permeability conglomerates, followed by volcanic tuff. They are covered by permeable sands and conglomerates, a layer of rhyolite and finally thick deposits of gravel and sand. As the volcanic layers thin out towards the West, sedimentary formations thicken. Their fluvial origin accounts for lateral and vertical hydraulic heterogeneities.

In the ECD, several rivers that come down from the Andes die in the alluvial fans of the Pampa. The most important are from North to South: *Aroma*, *Tarapacá*, *Quipisca*, *Sagasca / Juan de Morales*, *Quisma* and *Chacarilla* (Fig. 2). Their flow direction is generally North-East – South-West. Only the *Aroma* and *Tarapacá* are perennial. The rest is intermittent and infiltrates in the upper part of their hydrographic basin. Flow rates show a strong increase due to summer precipitation in the highlands.

Natural groundwater flows from North-East to South-West and into the *Bellavista Salt Lake* (Fig. 2), its natural point of discharge by evaporation. Groundwater depth decreases towards the point of discharge.

The upper aquifers (down to 20 m below surface) are generally unconfined or leaky. Lower aquifers are mostly confined. Billinghurst (1893) describes an artesian well near Pica in an aquifer 124 m below surface. Water levels however will most likely have dropped in the meantime due to intense water extraction from numerous wells in the basin.

Wells registered at the *Dirección General de Aguas* (DGA, 1988) show transmissivities between $6 \cdot 10^{-4}$ m^2/s and $1.5 \cdot 10^{-2}$ m^2/s with an almost normal distribution and a median of approximately $5 \cdot 10^{-3}$ m^2/s. This matches the average transmissivity of $5 \cdot 10^{-3}$ m^2/s, provided by Fritz et al. (1981).

A clear spatial zoning of hydraulic characteristics is not possible with the information at hand. Vertical permeability is generally low due to the numerous interbedded clay layers and the productivity of the aquifers usually decreases with depth. The deeper lying Paleogene aquifers have generally unfavorable hydraulic characteristics and are not used. Parts of these layered aquifers appear to have no present recharge but host water from humid periods in the Holocene (Fritz, 1981; Aravena, 1995). There is however a present recharge that has its origin in the higher Andes where precipitation is more abundant.

The infiltration of rivers flowing down from the Andes is by far the most important recharge mechanism in the ECD. Infiltration occurs mainly in the upper areas of the alluvial fans and ignimbrite outcrops on the West flank of the Andes (Karzulovic, 1979), which especially between 2500 and 3500 m a.s.l. are fractured by insolation weathering (at Canchones, temperature variations of up to 40°C within 10 hours have been recorded).

References for average groundwater recharge in the ECD vary between 500 l/s (Karzulovic, 1979) and 1000 l/s (DGA, 1988). Rojas & Dassargues (2007) calibrate their numerical flow model with the DGA (1995) calculations for the recharge rate of 975 l/s. The importance of storm runoff for ground water recharge has been a discussed subject. Houston (2001) claims strong influence of infiltrating flash floods after summer precipitations in the highlands and calculates its contribution in Quebrada de Chacarilla alone at over 200 l/s as an average over the year, which would considerably increase the estimates provided by DGA and Karzulovic. Peña et al. (1989) however, gave storm runoff much less importance based on isotope hydrochemistry in the Salar de Llamara, south of the Salar de Bellavista.

The ECD has its natural point of discharge in the *Bellavista* and *Pintados* salt lakes (Grilli et al. 1989, Falcón, 1966, Fig. 2), at the southern end of the basin, where the evaporation in 1980 was calculated at around 286 l/s (DGA, 1988). Since then, the increasing drawdown of the water levels must have diminished evaporation significantly. This assumption is confirmed by Rojas (2005), who calculates evaporation in the salt lake area at around 275 l/s in 1993 with a decreasing tendency.

To this, discharge through evapotranspiration of the *Tamarugo* trees must be added. Merino (1995) calculates this at around 1100 l/s for the whole basin. This value matches approximately the Rojas & Dassargues calculation (2007), which, based on the JICA (1993) and DGA (1988) studies, assume an increase of the evapotranspiration from 210 to 904 l/s between the years 1960 and 1993 due to forestation campaigns. Rojas & Dassargues (2007) suggest an additional discharge of 164 to 365 l/s of out-flowing groundwater at the southern edge of the basin, thus assuming this basin not to be completely endorheic.

In any event, groundwater pumping accounts for the highest withdrawal rates in the ECD. The utilization of the groundwater resources at an industrial scale started with the production of nitrate during the second half of the 19th century. The present pumping rate in the ECD is around 1,500 l/s, 700 of which are for drinking water and taken from the *Canchones* (Fig. 2) and El Carmelo deep wells. The use of groundwater for drinking purposes began in the 60´s. Today the total drinking water supply of Iquique (aprox. 250,000 inh.), *Pica*, *Pozo Almonte* and *Huara* is provided by the *Pampa del Tamarugal* groundwater.

The present groundwater extraction from the ECD aquifers plus the natural discharge of the system, according to all reports clearly exceeds recharge rates, even if there is an additional recharge from higher Andes regions via fractured base rock into the basin as suggested by Margaritz et al. (1990). Since the 60´s, the groundwater levels have fallen in almost all the DGA observation wells between 2 and 4 m (Rojas, 2005). According to Rojas & Dassargues (2007), by 2050, assuming an increasing pumping rate of 20%, water levels will have dropped another 2 m in average.

TYPE II, INTRAMOUNTAINOUS BASINS

South of the Cerro Gordo, the Central Depression continues (Fig. 1, Fig. 3), but not as an endorheic basin. Its ground water resources are generally poor and restricted to small areas, as described by Henríquez (1972) for the Pampa Unión area and Falcón & Henríquez (1968) for the *Baquedano* area, with high concentrations of TDS (Henríquez, 1977). The general lack of groundwater in the *Pampa del Tamarugal* south of the Loa River is due to a change in the geological setting: From the 21°S southwards. The Andes break up into numerous North – South oriented horst-and-graben structures, forming a chain of depressions: the *intramountainous basins* (Fig. 3). They trap water coming down from the Andes. Between the *Pampa del Tamarugal* and these basins rises a large horst structure called *Central Range* (*Cordón Intermedio / Cordillera Media*, Fig. 1), that hosts some of the worldwide most important copper deposits: *Chuquicamata*, *El Abra*, and further South *Escondida*.

The Atacama Salt Lake represents the biggest of these intramountainous basins. Combined with the Calama basin, it hosts around 90% of the groundwater resources of the Tarapacá region (Harza, 1978) with its capital Antofagasta (Fig. 3). The Calama tectonic basin as described by May (2005) is subdivided into the hydrographic units of the Middle and Upper Loa Basins plus the San Pedro and Salado basins, both tributaries to the Middle Loa basin (Fig. 3). The intramountainous basins further comprise the *Ascotán* and *Carcote* Salt Lake Basins in the North (21°30´S), the Punta Negra Salt Lake and Agua Verde Salt Lake Basins in the South, roughly at 25°S. This tectonic pattern continues to the South with the salt lakes of *Pajonales*, *Aguilar*, *Pedernales* and *Maricunga* at 27°S as described by Aguirre (2003), Iriarte et al. (1998) and Iriarte (1999). All but the Loa Basins and its tributaries are endorheic (Fig. 3).

Geology

The horst structure of the *Central Range* is called *Sierra de Domeyko* in the South and *Sierra Limón Verde* in the North (Fig. 3). The range is basically composed of low permeability Jurassic and Cretaceous folded granites and sediments (Zeil, 1964).

The neogene sedimentation processes in the intramountainous basins are equivalent to those described for the *endorheic Basin* of the Pampa del Tamarugal. Sedimentation occurs mainly from the Volcanic Andean range in the East and produces a generally several hundred meter thick sequence of paleogene and neogene alluvial fan deposits, fluvial, and in their western part often lacustrine or evaporitic sediments, interstratified occasionally with less permeable layers of ignimbrites and volcanic ash (Bravo, 1975). The main patterns of the intramountainous basins are therefore similar, consisting of large alluvial fans on one side (mostly in the east) and a gentle slope in the bottom area that ends in a salt pan.

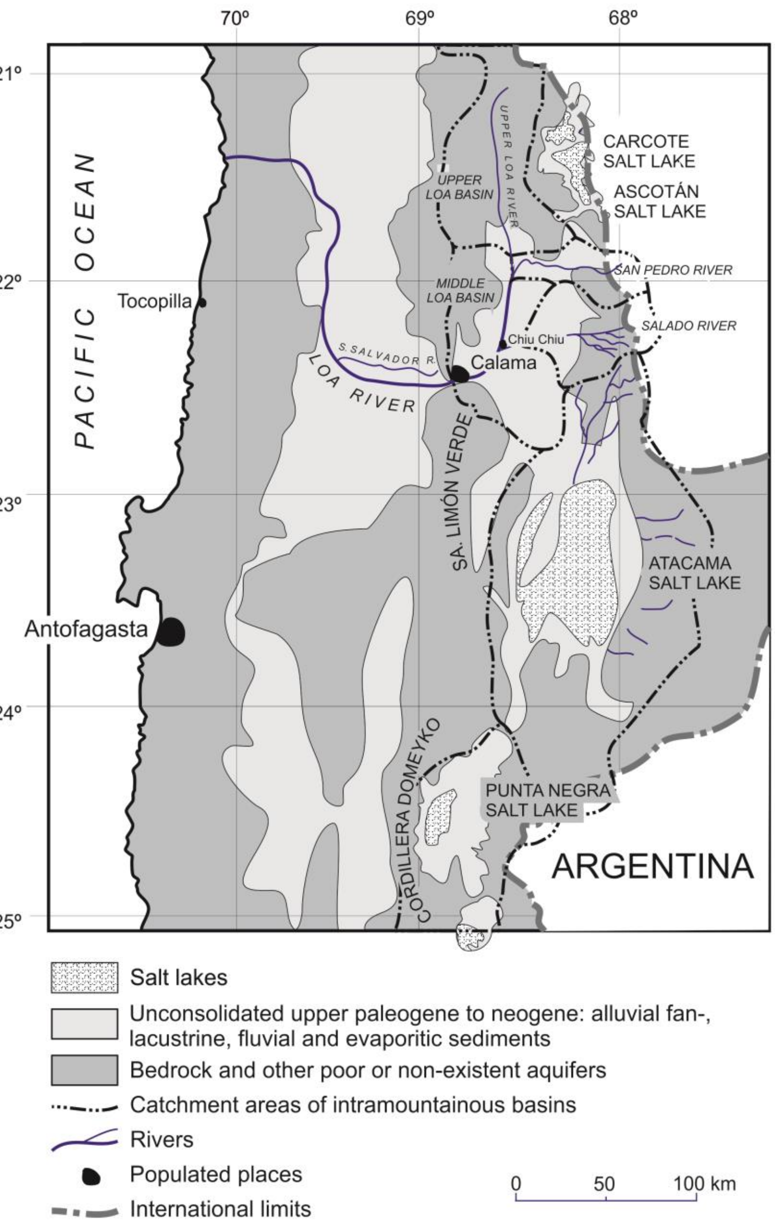

Figure 3 The intramountainous basins and their catchment areas. These depressions form a chain east of the Pampa del Tamarugal and trap the water coming down from the Andes.

Only the middle Loa Basin (Fig. 3) differs from this pattern and comprises aquifers in the 120 m thick Calama Formation and overlying Loa Formation, composed at the bottom of conglomerates and breccia and farther up of an unusual, 50 to 100 m thick series of lacustrine limestones. Naranjo & Paskoff, 1981, place the beginning of the Calama Formation in the Lower Miocene, while Marinovic & Lahsen (1984) place it in the Middle Miocene. This is contradicted by May et al. (2005), assuming the beginning of the Calama Formation during the lower Eocene. Both formations are overlain by the Pliocene Chiu-Chiu Formation. East of *Chiu Chiu*, the limestone shows evidence of karstification with a lake in a typical, large scale doline: The *Laguna Chiu Chiu* or *Inca Colla* (Hauser, 1999).

Hydraulics, recharge and discharge

Precipitation in the intramountainous basins depends largely on their geographical elevation and is generally higher than in the *Pampa del Tamarugal*. It reaches 25 mm/a at the *Salar the Atacama* (2300 m a.s.l.), 50 mm/y at the *Vega del Turi* (*Salado Basin* at 3000 to 3300 m a.s.l.), 40 mm/y at the *Ojos de*

San Pedro (3800 m) and 120 mm at the *Ascotán Salt Lake* (3700 m a.s.l.). Potential evaporation for all areas ranges between 1750 and 3500 mm/a (Harza, 1978).

Only in a few areas, such as *Aguas Blancas* (Fig. 1), South-East of Antofagasta, fresh water can be found (Henríquez, 1970). This is recharged by precipitation in the highest areas of the Central Mountain Range, at almost 5000 m, west of the *Punta Negra Salt Lake* (Fig. 3).

The general groundwater flow direction in the intramountainous basins is East-West, controlled by groundwater recharge from the Andes. Exceptions are found in the *Salar de Ascotán*, where a significant recharge occurs from the eastern flank of the *Aucanquilcha Volcano* (aprox. 6200 m a.s.l.), and in the *Atacama Salt Lake Basin*, where 80% of the recharge is provided by rivers that flow into the basin at its north-eastern end. Flow direction here is therefore predominantly NE-SW (Harza, 1978).

All basins host productive aquifers within the unconsolidated layers of neogene sand and gravel. Groundwater is found generally within an unconfined upper aquifer and a lower confined one, separated by one or several layers of ignimbrite or volcanic ash. Artesian fresh water springs were observed in the *Atacama Salt Lake*, in *Tebenquiche*, close to *San Pedro de Atacama* and *Tilopozo*, at the southern end of the salt lake by Galli (1955). Due to the tectonic setting and volcano activity thermal springs are frequent.

Groundwater depth generally decreases towards the salt pan. Transmissivity has been determined by Harza (1978) in all basins shown in Fig. 3 and ranges between $5 \cdot 10^{-2}$ and $7 \cdot 10^{-3}$ m^2/s. Specific yield ranges between 0.15 and 0.2.Depth of the unconsolidated, mostly saturated sediments reach 120 m in the Salado Basin, 350 m in the San Pedro Basin, 250 m in the Loa Basin, 160 m in the Ascotán / Carcote area and more than 400 m in the Salar de Punta Negra Basin (Harza, 1978).

The intramountainous basins are generally endorheic. Only the Loa basins and sub-basins differ, feeding the Loa River, the most important surface water of the Chilean North with a catchment area of around 34,000 km^2 (Fig. 3, Brinck, 1975). At the western edge of the Middle Loa Basin, where the impermeable bedrock crops out, ground water rises to the surface and forms the *Calama wetlands* (*bofedales*).

As a consequence of its geological features, the Middle Loa basin hosts two aquifers, the upper in the carbonate Loa formation and the lower in the granular Calama formation. The Loa Aquifer is fractured and unconfined. The lower aquifer is partly confined by a 30 to 120 m thick layer of clay (Hauser, 1999).

Groundwater recharge of the intramountainous basins is provided mostly by precipitation in the higher altitudes of the volcanic range of the Andes, where it reaches 300 mm/a. Water is led into the basins by mostly intermittent mountain rivers and creeks (during the rainy season between January and April) and subsequent base flow. Recharge rates are estimated by Harza (1978) in the various basins and yield at *Ascotán Salt Lake* (480 l/s), *San Pedro Basin* (700 l/s), *Rio Salado Basin* (1000 l/s), *Atacama Salt Lake Basin* (1600 l/s), *Punta Negra Salt Lake Basin* (800 l/s).

Groundwater recharge in the middle *Loa Basin* occurs through the inflowing rivers *Salado*, *San Pedro* and, first of all, *Loa* (Fig. 3), which gathers precipitation water from the *Miño Volcano* (5600 m a.s.l.). Precipitation in the basin itself is approximately 4 mm/a.

Groundwater discharge in the intramountainous basins occurs through evaporation at open water tables of wetlands and salt lakes, generally found at the western side of the basins (Fig. 3). Only the middle and upper Loa Basin have an important surface water discharge that drains the basin together with the evapotranspiration at the wetlands in *Chiu Chiu* and *Calama*.

The *Salado Basin* discharges through springs (*Baños del Turi* – 145 l/s) that flow into the Salado river (450 l/s) and evapotranspiration at the adjacent wetlands and salt lake (*Vega del Turi*). Harza´s (1978) estimation for the latter is of 400 l/s.

TYPE III, EXORHEIC TRANSVERSE VALLEYS

It was mentioned before, that the predominant geomorphological feature of the Chilean territory is the subdivision from West to East into a Coastal Mountain Range, the Central Depression and the Andes Mountain Range. This set of features, however, is discontinued in some areas and replaced by transverse valleys. In these areas, rivers run east-west in narrow valleys through the Andes and open up when approaching the pacific coast. Transverse Valleys can be found between 27°S and 33°S (from North to South: *Copiapó*, *Huasco*, *Los Choros*, *Elqui*, *Limarí*, *Choapa*, *Quilimarí*, *Petorca*, *La Ligua*, *Aconcagua*). It is only North of Santiago that the Coastal Range and the Central Depression reappears. Here it hosts the most fertile soils of the Chilean mainland. Another set of transverse Valleys are to be found in the northernmost part of the country, between 18°15´S and 18°40´S. It comprises the two major rivers *Lluta* and *San José* (called *Azapa* in its lower course) and their tributaries.

In what follows, the *Copiapó River* is picked out and described as a representative example for the Transverse Valleys between 27°S and 33°S. It appears to be representative not only in hydrogeological terms, but also with regard to its development as an important agricultural area, the mining industry that competes with it for water and the ever higher constraints of available water resources.

<u>The Copiapó Valley</u>

The *Copiapó River* begins with the confluence of its main tributaries, the *Río Jorquera* and the *Río Pulido*, with respective catchment areas of aprox. 4200 and 2000 km². From this point to the ocean, the river has a length of aproximately 162 km and drains a catchment area that extends over 18.400 km². Farther downstream, close to the village of La Junta, the *Copiapó River* is joined by the *Manflas River*. These are virtually the only superficial water courses. Approximately two thirds of the total catchment area does not feature superficial drainage (Fig. 4), except for occasional storm runoff.

Geology

The *Copiapó River* runs through a set of basement formations that contain folded sediment rocks, volcanic and volcanoclastic rocks, with a generally N-S oriented axial plane and varying slopes towards E and W. They constitue the base and the flanks of the river bed and are described in literature as *formación La Ternera*, *formación Lautaro*, *formación Punta del Cobre*, *formación Abundancia* and *Nantoco*, *formación Pabellón* and *Totoralillo*, *lavas and breccias of the Sierra La Indiana*, *formación Bandurrias*, *formación Cerrillos*, *Quebrada La Higuera*, *Lavas of the Sierra La Dichosa*, *Upper Cretacous Subvolcanic intrusives*, *Cretacous Granitoides* and *Paleocene intrusives*. These units are generally impermeable. Although some of them appear to be fractured, their hydraulic permeability and storage capacities are nil (Aguirre, 1999, y Troncoso, 2012).

River sediments are scarce above the confluence with the Manflas river (close to the Lautaro dam), at aprox. 1200m a.s.l. Downstream the confluence, quarternary fluvial and fluvioalluvial sands and gravel make up for thick and continuous confined and unconfined multilayered porous aquifers. Zones of lesser hydraulic permeability are found in old fluvial or fluvioalluvial mudflow sediments (Aguirre, 1999).

Hydraulics, recharge and discharge

In the findings and maps of Aguirre (1999) and Troncoso (2012) on the hydrogeology between the *Lautaro Dam* and *Piedra Colgada,* aprox. 10 km downstream of the city of Copiapó, hydrogeological units are grouped into four categories according to their relevance as a groundwater resource: high yielding, medium and low yield and those of nil relevance.

Aquifers that are relevant for groundwater storage and flow tend to be unconfined, but show local signs of confinement, especially between *Cerrillos* and *Valle Fértil*, as well as downstream the *Lautaro Dam*, between *San Antonio* and *Los Loros*. Between *Los Loros* and *Paipote*, wells yield between 1 and 150 l/s and groundwater levels vary between artesian and 135 m depth (Fig. 4) (Aguirre, 1999, Troncoso, 2012).

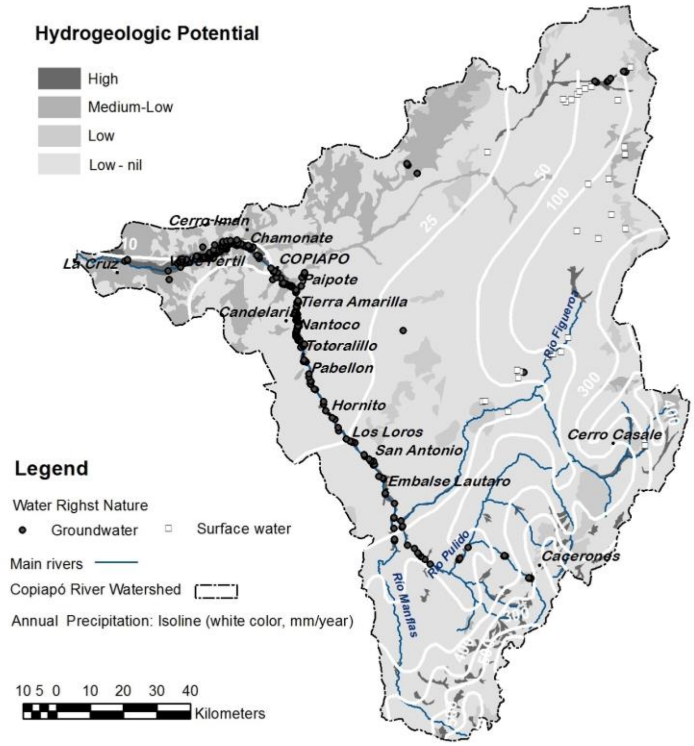

Figure 4 Hydrography of the Copiapó Valley (after Aguirre, 1999, SERNAGEOMIN, 2012, Hidromas, 2013)

High yielding aquifers include those in fluvial deposits, especially fluvial deposits of present time river beds and some fluvial deposits that show interstratification with fluviolacustrine deposits (Fig. 4). These strata types are often interconnected and produce aquifer systems with relatively high storage coefficients and transmissivity values. Medium and low yield aquifers in the *Copiapó River Valley* are typically layers that contain a large interstitial fine sediment fraction, low porosity, low permeability and a certain degree of cementation. These layers generally receive their recharge through vertical infiltration during the meager rainfall events. They represent a relatively small share of the valley formations and can be found in some fluvioalluvial sediment bodies, mud flow deposits, ancient river terraces. There are, however, also high permeability layers like dunes and dejection cones, located at the flanks of the river bed, that produce low yields due to meager to nil vertical recharge.

The *Copiapó Valley* sediments are bedded in a basement of predominantly impermeable rocks with no relevant groundwater ocurrence. Exceptions can be found in fractured rock formations with locally interconnected flow paths but with a generally very limited recharge. A considerable number of intrusive rocks in the valley area form downright geological barriers, as for instance in La Puerta and Piedra Colgada (Fig. 4).

Hydrogeological properties (such as permeability, transmissivity, storage and specific yield) have been described extensively by DGA (1987), Aguirre (1999), SERNAGEOMIN-BGR (1999), SERNAGEOMIN (2012), DGA-DICTUC (2010) and HIDROMAS (2013).

Transmissivity of the valley sediments vary between $1·10^{-3}$ and $2·10^{-1}$ m^2/s. Highest values ($2·10^{-1}$ m^2/s) can be found upriver, close to the *Lautaro Dam* and midway to Copiapó at *El Yeso* and *Totoralillo*. Lowest transmissivity values were measured in *Villa María*, *Hornitos*, *La Puerta* and *Los Loros* (Fig. 4). (DGA 1987a). Intermediate values of $5·10^{-3}$ m^2/s are typically found where *Pulido River* joins the *Ramadillas River*. High variations are found close to *Iglesia Colorada* with values that range between $5·10^{-3}$ and $4·10^{-2}$ m^2/s.

Hydraulic permeabilities of the Copiapó River Valley aquifers typically range between $2·10^{-4}$ and $2·10^{-3}$ m/s, the lower end of this scale is often found perched aquifers. However, clay and silt-layers, located on the borders of the river bed and deposited mainly during occasional flooding, have permeability values as low as $1·10^{-5}$ and $1·10^{-6}$ m/s (SERNAGEOMIN-BGR, 1999).

There is only little information on storage coefficients. Data are provided by DGA (1987) indicate values between 0.016 and 0.11. Other studies (DGA, 1995) calculate averages of 0.05, 0.10 and 0.15 depending on the area. For resource estimation purposes, SERNAGEOMIN-BGR (1999) and DGA (1995 and 2003) assumed a storage coefficient of 0.1. Transmissivity values range between $1·10^{-2}$ and $2·10^{-1}$ m^2/s (DGA, 1987b, 1995).

Aquifer thickness varies strongly along the valley. Drillings proved maximum thickness of at least 180 m. However, geophysical campaigns (Aguirre, 1999 and SERNAGEOMIN, 2012) show fluctuating thicknesses between 100 and 200 m with local peaks of 250 and 300 m. These are supposed to be related to tectonic depressions produced by faults (Fig. 4) within the basement.

Recharge of the *Copiapó River* valley aquifers is produced by vertical infiltration of rainwater (especially in the higher catchment areas in years of high precipitation) and irrigation. In urban areas, losses of the potable water supply system as well as sewage play a major role. Discharge is dominated by groundwater pumping (in wells). A few points of natural spring discharge are left (such as *Los Loros-La Puerta*).

In general terms, there has been a continuous and marked overexploitation of groundwater resources in the aquifers of the Copiapó valley due to extraction rates that exceed recharge rates by far. The success of Chilean table grapes on the international market as of the 80's, led to a remarkable extension of Agricultural surfaces in the valley. Today, the valley is characterized my monoculture and irrigated surfaces are no longer restricted to the floodplain of the river but climb up the flanks.

In addition to this, mining industry and potable water supply of urban areas added another large portion to the demand. According to DGA-DICTUC (2010), natural and artificial recharge adds up to 3.6 m^3/s while estimated consumption is put at 5 m^3/s and therefore produces a deficit of aprox. 40%. These numbers are confirmed by the numerical modeling carried out by HIDROMAS (2013) that considers the time span between 1993 and 2012. The main conclusions are that the upper catchment system (down to *La Puerta* – Fig. 4) features a water surplus. Evidence is given by a large number of natural springs (e.d. in the vicinity of *Los Loros*). By way of contrast, the aquifers downstream of *La Puerta* suffer from a marked and continuous deficit of approximately 1.3 m^3/s, equivalent to 50% of the average recharge volume. This mismatch produces sustained and accelerating groundwater level drawdown since the 90's in several areas of the lower valley, especially between *Mal Paso* and the city of *Copiapó*.

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