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Recent climatic events controlling the hydrological and the aquifer dynamics at arid areas: The case of Huasco River watershed, northern Chile

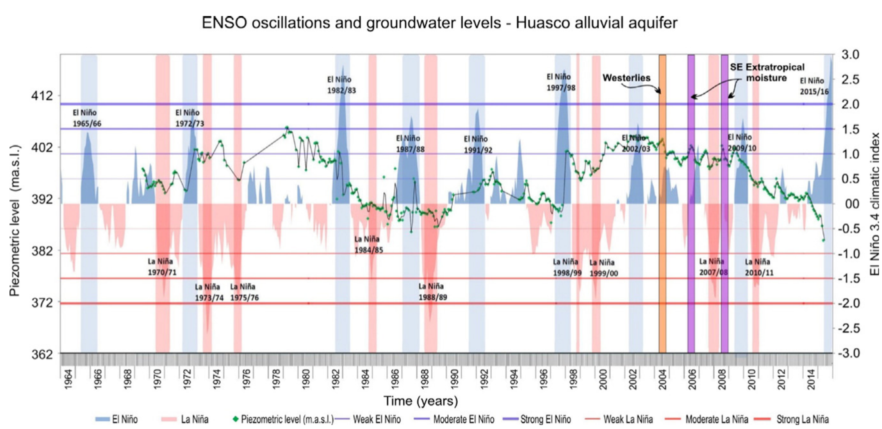
I. Salas [a,b], C. Herrera [b,c,*], J.A. Luque [b,c], J. Delgado [a], J. Urrutia [b,c], T. Jordan [d]

[a] Department of Mining Engineering, Universidad de Antofagasta, Antofagasta, Chile
[b] Departamento de Ciencias Geológicas, Universidad Católica del Norte, Antofagasta, Chile
[c] CEITSAZA - Centro de Investigación Tecnológica del Agua en el Desierto, Universidad Católica del Norte, Antofagasta, Chile
[d] Department of Earth & Atmospheric Sciences and Atkinson Center for a Sustainable Future, Snee Hall, Cornell University, Ithaca, NY 14853-150 4, USA

HIGHLIGHTS

- The aquifers in arid areas are very sensitive to climate change.
- The El Niño and La Niña control streamflow and groundwater recharge.
- The ENSO oscillations could be connected to the Hale solar cycle.

GRAPHICAL ABSTRACT



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ABSTRACT

The investigation assesses the influence of recent climatic events in the water resources and the aquifer dynamics in the Huasco watershed by means of the analysis of precipitation, streamflow and piezometric levels during the last 50 years. These hydrological and hydrogeological parameters were evaluated by an exploratory geostatistical analysis (semivariogram) and a spectral analysis (periodogram). Specifically, the hydrological and hydrogeological data analyses are organized according to three sub-basins, the Del Carmen River (Section I), the El Tránsito River (Section II), and the Huasco River (Section III). Data ranges for rainfall are from 1961 to 2015, for streamflow from 1964 to 2015, and for groundwater levels from 1969 to 2014, available from Water Authority of Chile. The analyses allowed the identification of cycles in the hydrological and hydrogeological records. The study area is located in a transient climatic fringe where the convergence of several climatic systems can be identified in the hydrological and hydrogeological records. Results indicate that the nival areas and the small glaciers are especially important to the recharge processes in the Huasco watershed during the spring-summer snowmelting. Water reservoirs in the main aquifer (Section III) and in the Santa Juana dam are highly sensitive to ENSO oscillation climatic patterns. The main climatic events that control this record are the El Niño and La Niña events. In addition, the climatic influence of the westerlies and the SE extratropical moisture were also identified. Spectral analysis identified the presence of a 22.9-year cycle in piezometric levels of the alluvial aquifer

* Corresponding author.
E-mail address: cherrera@ucn.cl (C. Herrera).

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of the Huasco River. This cycle is consistent with the 22-year Hale solar cycle, suggesting the existence of a solar forcing controlling the ENSO oscillations. Moreover, semivariogram and spectral analysis identified a 10.65-year cycle and a 9.2-year cycle in groundwater, respectively, which were attributed to the strong mode of ENSO oscillations.

1. Introduction

The arid Huasco River basin is located in north-central Chile, between 28°–30° S, south and west of the continental-scale Arid Diagonal, (Garreaud et al., 2007; Juliá et al., 2008; Garreaud, 2011; Aguilar et al., 2013). The Arid Diagonal has been defined as a transition zone between the influences of frontal precipitation systems coming from the south, which are blocked by the activity of the Pacific anticyclone, and those systems of tropical and subtropical circulation providing moisture from the Atlantic through the Amazon Basin (Vuille and Ammann, 1997) (Fig. 1). Each of those precipitation systems has a marked seasonal cycle. Additionally, the precipitation regime is influenced by a humidity source coming from the lowlands of the Argentine region (Vuille and Keimig, 2004; Placzek et al., 2009). A final climate domain is pertinent during the warm phase of ENSO (El Niño Southern Oscillation), when more intense precipitation impacts the coastal parts of northern Chile (Rutllant. and Fuenzalida, 1991) and the lower parts of Huasco River basin (Favier et al., 2009).

This study of the Huasco River basin is motivated by the growing demand for using the superficial and subsurface water resources of the system for irrigation and mining activities in the Atacama region, which have caused a severe groundwater drawdown during the last 30 years (D.G.A., 2007, 2013). Aquifers in arid areas become the main source of water for human activities and are often subjected to intensive exploitation (Custodio et al., 2016). Aquifer recharge is important both for hydrologic understanding and for effective water resource management (Nimmo et al., 2005). Along with the severe water stress predominating in the basin, a continue decrease in precipitation rates and a growing aridification characterizes the climate variability (Squeo et al., 2006). To better understand the water resources and

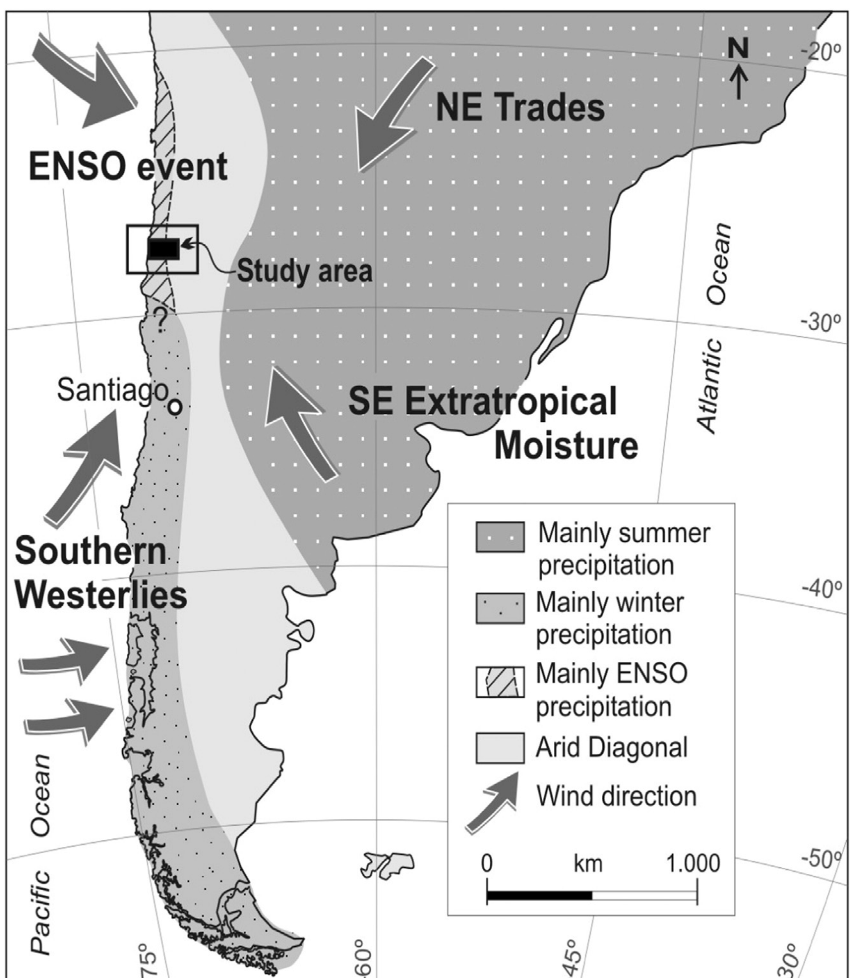

Fig. 1. The main climatic events which control the Huasco River watershed: the ENSO events, the southern westerlies, the Southeast Extratropical Moisture and the Northeast trades. Seasonality of this system is driven by shifts in the position of the Pacific anticyclone, which blocks Southern Westerlies rainfall events. Northwestern water vapor source is closely related to ENSO variability. A different moisture path is strongly correlated to Andean rain when high humidity is centered directly east of the Andes at the latitudinal range of the Huasco basin (SE Extratropical Moisture). Ultimately, a potential northeastern source of water vapor is from the equatorial Atlantic Ocean (NE trades). In this case, seasonal variability is related to the summer season southward displacement of the Intertropical Converge Zone (ITCZ), allowing the Atlantic moisture to cross the Amazon.

predict its future variability, it is particularly attractive to evaluate the spatial and temporal extent to which each of the regional precipitation sources contribute to the recharge of the hydrogeological system and how the system responds to climate variability. Previous studies in the area showed that the runoff comes mainly from high altitudes (Favier et al., 2009), while groundwater is a mixture of river water, dammed water and fractured aquifers, discharging to the rivers (Strauch et al., 2009).

In arid areas, potential evapotranspiration exceeds precipitation for most of the year (Freeze and Cherry, 1979). In these areas, the recharge tends to occur in occasional moments or in short, periods of time, where seasonal rainfall and its effect on surface runoff can produce the best conditions to generate recharge (Nimmo et al., 2005). In these conditions, the records of hydrodynamic changes in the aquifer system are an excellent tool to evaluate the impact of the different moisture sources in aquifer recharge and storage along the basin. This can be assessed by the oscillations of piezometric levels, which depends of the magnitude of each moisture source causing precipitation, and their spatial and temporal variation in the basin (Custodio et al., 1997; Healy, 2010). The study of temporal variation of groundwater levels in arid zones has always been an important sensor for recharge evaluation and, together with the analysis of temporal rainfall records and its relationship with river flows, allows assessment of the aquifer response to changes in climatic conditions in annual and decadal scale. The aquifers located in arid areas are more sensitive to changes in climate conditions and any important event of precipitation or drought can be recorded and quantified through the study of such piezometric oscillations (Allison et al., 1994; Custodio et al., 1997).

The consequences of runoff and groundwater systems of precipitation events are complex phenomena. It is expected that greater water infiltration will occur in the highest parts of the basin due to greater precipitation, mainly as snow, for which the main recharge mechanism would be snowmelt. The flow of the Huasco River has also been altered by human activities, especially by the construction of the Santa Juana dam in 1995. Therefore, the comparison between precipitation, surface runoff and variations of piezometric levels before and after its contruction not only will allow an understanding of the response of the aquifers to climatic fluctuations, but also an assessment of the impact of the dam on the natural system. Due to low precipitation values that occur in the coastal area of the Huasco River basin, it has always been assumed that the aquifer recharge in this area is virtually zero. However, recognition of small springs in the coastal sector and isotopic studies indicate an actual small recharge to aquifers, although the mechanisms of their generation are not well known (Herrera and Custodio, 2014).

The main objectives of this research are to determine the contribution by the different moisture sources to the Huasco River groundwater system and to assess the impact of the Santa Juana dam on the hydrological and hydrogeological system. This will allow the evaluations of, first, the changes in the precipitation pattern, and if they happen at random or not, second, the frequency of precipitation events associated with certain moisture sources, and third, identification of which of them is controlling the system variations. For this purpose, the use of geostatistical methods are very effective in the spatial and temporal analysis of hydrological and hydrogeological data (Samper and Carrera, 1990; Mateu and Morell, 2003), as shown by numerous investigations that used geostatistics to estimate the spatial and/or temporarily changes of hydrogeological variables. Some recent examples are Ahmadi and Sedghami (2007); Webster and Oliver (2007) and Ta'any and Tahboub (2009).

2. Study area

The watershed of the Huasco River is located in the Third Region of Atacama, northern Chile (Fig. 2). It has a surface area of 9850 km^2, extending between parallels 28°27′–29°33′S and the meridians 71°11′–69°56′W. The basin is exorreic, i.e. runoff water is continuous until it empties into the Pacific Ocean (Salas, 2014). This river is formed in the area of Junta Del Carmen, 90 km from its mouth at the Pacific Ocean, by the confluence of its two main tributaries, which are the Del Carmen River (Section I, southern) and the El Tránsito River (Section II, northern). The Huasco River has a reservoir above the Santa Juana dam, located in Section III. The reservoir has a volume of 166 million m^3, , and began its operations in September 1997. The main objective of the Santa Juana dam is to regulate the Huasco River flow in order to

Fig. 2. The watershed of the Huasco River is located in the Third Region of Atacama, northern Chile. The hydrological and hydrogeological data analyses are organized according to three sub-basins, the Del Carmen River (Section I), El Tránsito River (Section II), and Huasco River (Section III). Gauging stations (streamflow), meteorological stations (precipitation) and monitoring wells (piezometric levels) are shown. Five glaciers and four glacierets exist in the uppermost area of the Huasco River watershed.

guarantee the water supply to near 10 ha used for agriculture and is administrated by Junta de Vigilancia Río Huasco y sus Afluentes (JVRHA, 2014).

The Huasco River basin is formed, in its lower part, by a WNW-oriented valley of 90 km long and a surface slope of 1.8% to 2.6%, filled by the fluvial-alluvial Atacama Gravels, which are poor to moderately selected gravels with intercalations of massive sands with some parallel lamination interbedded by clay. Underlying this unit are intrusive rocks that covers a great part of the side valleys, along with metamorphic rocks and calcareous successions (Godoy and Lara, 1998; 1999) (Fig. 3a). The Atacama Gravels cover approximately 325 km^2 and present a moderate to lower consolidation degree, with numerous sandy

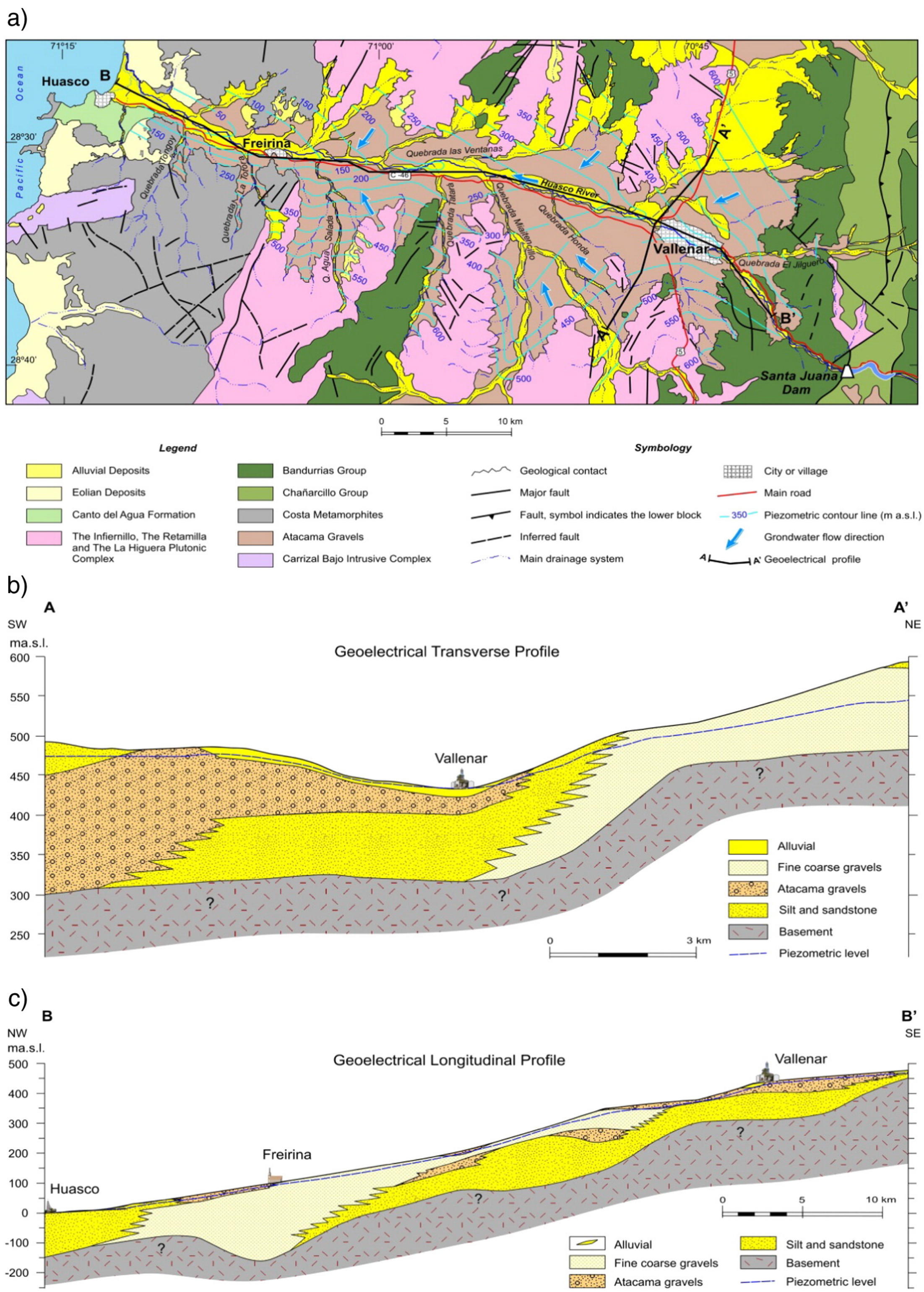

Fig. 3. a) Geological map of the Huasco River basin (for Section III, downstream the Santa Juana dam) and piezometric contour lines are shown. b) Geoelectrical transverse profile near the location of Huasco: silt and sandstones are more abundant at the central part of the valley, while the gravels are dominant in the margins. c) Geoelectrical longitudinal profile of the Huasco River basin: profile shows the lateral variation of the sedimentary facies filling the basin. Piezometric levels indicate the existence of a gaining stream system.

lenses and paleochanels filled with unconsolidated sandy gravels. Multiple episodes of erosion and deposition controlled by the combined effects of tectonic, eustatic and climatic processes during the Quaternary are shown by terraces and different sedimentary structures that are present (Riveros and Riquelme, 2009). Beginning at a distance of 5 km from Pacific Shoreline, there are 5–10 km long side valleys with an approximate orientation N—S which are connected to the main Huasco River. Those side valleys present slopes of 8% filled by poorly sorted massive gravels in a sandy-clay matrix of alluvial environment and well sorted sands from eolian deposits restricted in the upper parts. The geology in Section I and II is characterized by the low presence of Quaternary sedimentary units, limited to the active valleys and the high presence of intrusive rocks of varied composition, like gabbros, monzodiorite, monzogranite and granite. Volcanics formations composed mainly of rhyolitic and dacitic pyroclastic breccias with andesitic and basaltic lavas are present with a much less areal extent. These geological units are affected by two major N—S oriented fault systems and the geomorphological features of this zone have been shaped by the erosive action of glacial and high mountain rivers activity (Riquelme et al., 2010).

The main aquifer in the Huasco River basin is located downstream of the Santa Juana dam (Section III). The piezometric map (Fig. 3a) shows that the main direction of groundwater flow is preferentially toward west, indicating a contribution from the aquifer to the river. In some areas, there is a lateral groundwater supply from canyons with a north-south orientation, like Maitencillo, Tongoy, La Totora and Ojos de Agua. This means that water comes from reserves hosted in clastic sediments on the slopes that probably recharge at the top of the hill, allowing the existence of springs in these canyons. In addition, the recharge is produced from irrigation return, infiltration of runoff at the ends of the canyons and from the high mountains, where the precipitation is higher. One of the most important groundwater discharge mechanisms is the extraction wells, followed by the natural discharge to the sea and the evapotranspiration from vegetation near the riverbed, corresponding to olive trees and phreatophytes.

The aquifer thins progressively from west to east and it is 6–17 km wide including the side valleys. It is thicker between the Pacific Ocean and Quebrada Maintencillo (50–460 m). In the area between Maintencillo and the Santa Juana reservoir, the maximum depth to the base of the aquifer is 120 m, shallowing to near zero near the reservoir. The aquifer sediment distribution is shown in profiles that show the electrical resistivity of the medium obtained by a geophysical survey conducted in 2009 (Fig. 3b and c). In these profiles, it is shown that the Atacama Gravels cover most of the valley fill, with intercalation of alluvial sediments. In the upper part of the basin, the aquifer is mainly a fractured medium with thin layers of unconsolided sedimentary deposits and the one located in the El Tránsito valley has an increased exploitation of water due to agricultural activities (D.G.A., 2013).

Pumping tests indicate medium to high permeability and response characteristic of an unconfined aquifer. The Atacama Gravels, which occupy most of the paleo-valley fill (Welkner et al., 2006), have a permeability that ranges from 0.1 to 5.9 m/day in the Coastal Cordillera area, while in the area surrounding Vallenar, the values vary between 1.9 and 14.9 m/day (Herrera et al., 2010). The difference between these values reflects the high heterogeneity of the medium, corresponding to poorly sorted gravels, sand and silt. The eolian sand deposits are assigned a hydraulic conductivity of 15 m/day, based on similar materials in the Doña Ana region, Spain (Trick and Custodio, 2004). Alluvial deposits of gravel, sand and silt that occupy low slopes and that fill the north-south orientated valleys have a permeability of 25 m/day (D.G.A, 2007).

In the upper part of the Huasco River basin, five smalls glaciers (Valle Encierro, Estrecho, Amarillo, Guanaco and Ortigas 1) and four glacierets (Esperanza, Toro 1, Toro 2, Ortigas 2) have been recognized (Rabatel et al., 2011), usually at altitudes between 4780 and 5485 m a.s.l. (Nicholson et al., 2009). These smalls glaciers and glacierets do not show high flow rates and are located at the peaks of Section I and Section II, on slopes preferably oriented to southeast or southwest (Pellicciotti et al., 2014). During the summer months, the glacier dinamics are dominated by ablation process by melting and sublimation, whereas accumulation predominates mainly in the winter months. Measurements made in Pascua Lama showed that the total mass loss of these glaciers by sublimation, in the summer months, ranges from 1.26 to 2.25 mm, being negligible during winter (Favier et al., 2009). Besides, field observations of glaciers in Encierro valley allows the determination of an approximately discharge of 20 L/s. Nicholson et al. (2009) estimate a total surface of 23.17 km^2 bared glacier, while rock glaciers cover a total of 6.3 km^2 in the upper part of the Huasco river basin. These ice bodies have experienced reductions of their volume over time, probably driven primarily by the decreasing trend in precipitation in the basin and secondarily by the temperature changes observed over the last decades (Rabatel et al., 2011). The total areal reduction of the ice bodies over the period from 1955 to 2007 was about 29%, being larger in glacierets with a reduction of approximately 54% and glaciers with 17%. Estimations of water balance in the Elqui basin allows the researchers to hypothesize that the total contribution of the glaciers to discharge would be between 4 and 9%.

In the basin of the El Tránsito River is the Estrecho Glacier, which surface was 1.25 km^2 in 2010. The reduction from 1976 to 2010 is 0.40 km^2 (24% variation). In the basin of the Del Carmen River, the main glacier is Guanaco (Fig. 2), with an area of 1.74 km^2 in 2010. The total reduction from 1976 to 2010 is 0.37 km^2 (18% variation). The Ortigas 1 glacieret and Ortigas 2 glacier are smaller, with surface areas of 0.81 km^2 and 0.71 km^2 respectively, by 2010, with a variation of 30% and 27%. These ones could disappear in the medium term if the reduction that has been observed since 1976 (D.G.A., 2011) continues.

3. Climatic setting

Climatic changes control fluctuations in water supply in environmental systems (Luque and Julià, 2002; Julià and Luque, 2006; Nielsen et al., 2016). The very low magnitude of precipitation in northern Chile is due to three factors: descending air in the southeast Pacific anticyclone; a low sea surface temperature caused by the cold Humboldt Current, which inhibits evaporation from the ocean surface; and the descending path of any air masses that cross the Andes from the east. Seasonality of this system is driven by shifts in the position of the Pacific anticyclone, which blocks westerlies rainfall events. A wintertime translation to the north permits more south Pacific anticyclones to migrate northward and it thus allows frequent storm fronts to reach the coastal arid regions of Chile. To the north of the Huasco basin, summer precipitation dominates from two different sources. A northeastern source of water vapor is ultimately from the equatorial Atlantic Ocean. Seasonal variability is related to the summer season southward displacement of the Intertropical Converge Zone (ITCZ), allowing the Atlantic moisture to cross the Amazon (Salio et al., 2002; Jordan et al., 2015). This northeastern water vapor source is closely related to ENSO variability. Vuille and Keimig (2004) describe an additional interannual control on precipitation, which corresponds to an eastern water vapor source, that is drawn from farther south in mid-latitude South America. This second moisture path was shown by Vuille and Keimig (2004) to correlate most strongly with Andean rain when high humidity is centered over the Sierras Pampeanas, essentially directly east of the Andes at the latitudinal range of the Huasco basin. For simplicity, we refer to this as the SE Extratopical Moisture water vapor path.

In the Huasco River basin, precipitation usually occurs as snow and is concentrated in the period from May to August. Those four winter months account for 85% of the total annual precipitation, although sporadic storms occur in summer. The highest rainfall value is recorded in July, with mean values ranging from 13 to 19 mm below the Santa Juana dam and from 23 to 32 mm above it. The mean annual precipitation below Santa Juana dam presents little variation, with values ranging from 43 mm/year registered in Freirina Station to 53 mm/year in Santa Juana station. In contrast, upstream of the Santa Juana dam, the mean annual precipitation varies strongly with altitude, ranging from 53 mm/year immediately upstream Santa Juana dam to 200 mm/year in areas above 4500 m a.s.l. As pointed earlier, the main contribution to the surface runoff recorded throughout the year comes for these areas above 4500 m a.s.l. (D.G.A., 2007, 2013).

The potential evapotranspiration is high throughout the whole Huasco River basin. In the region upstream from the Santa Juana dam, the potential evapotranspiration is up to 1800 mm/year, which causes evaporation of most of the precipitation that occurs on slopes and areas without vegetation, without creating surface runoff (D.G.A., 2007). Below Santa Juana dam, the evapotranspiration is higher and two regions with different values can be recognized. The first of these is characterized by sparse vegetation and total evapotranspiration is limited by scarce precipitation. The second area is highly cultivated and evapotranspires water from irrigation that has been supplied by the Santa Juana dam, rivers and wells.

The hydrology of the Huasco River shows a bimodal behavior with maximum values in winter and spring. The El Tránsito (4 m^3/s), Del Carmen (0.6 m^3/s) and Potrerillos (2 m^3/s) rivers have peak flows that occur from the months of November to January (D.G.A., 2013).

Favier et al. (2009) showed that snow melting is a significant source of surface water in catchment areas of central Chile (26°-32° S), where snow is present for four months above 3000 m a.s.l. Gascoin et al. (2011) reported a characteristic annual cycle of rain and snow in winter and melting in spring and summer in the Huasco River basin and they remark the significant importance of the five glaciers (Valle Encierro, Estrecho, Amarillo, Guanaco and Ortigas 1) and four glacierets (Esperanza, Toro 1, Toro 2, Ortigas 2). Snow accumulated in cryosphere generates a significant run-off during summer to the Huasco River, which triggers increased streamflow and rise in the level of Santa Juana reservoir.

The hydrological dynamics of the basin are altered during El Niño years, when precipitation is augmented. In the Atacama region, the El Niño event typically brings a high rainfall rate to the middle and lower elevation regions, and heavy snow in the upper part of the basin (Aceituno, 1990; Rutllant. and Fuenzalida, 1991; Garreaud and Battisti, 1999; Rosenthal and Broccoli, 2004; Cane, 2005; Garreaud et al., 2007). The frequency of the El Niño events is variable, generally within a range of 3–6 years (Trenberth and Hoar, 1997; Timmermann et al., 1999; Salinger et al., 2001; Gosai et al., 2002; Cai et al., 2004; Squeo et al., 2006). The La Niña events are associated with less precipitation and snow in the high mountains during the winter season, which adversely affects the volume of river flows in the following spring and summer (Aceituno and Garreaud, 1995; Allan et al., 1996).

4. Methodology

4.1. Geoestatistical analysis from the monitoring stations located at the Huasco catchment basin

Geoestatistical analysis was conducted according to the following steps: preliminary data analysis, exploratory analysis, structural analysis, adjustment of the theoretical model to the experimental semivariogram and cross-validation.

Preliminary analysis consisted of classifying, ordering and integrating all data from precipitation, run-off and piezometric levels from each monitoring station located at the headwaters of the Huasco catchment area for approximately the last 50 years. Hence, a data base was generated and it is constituted by 3 meteorological stations, 3 gauging stations and 3 piezometric stations. This information was obtained from the Dirección General de Aguas (D.G.A.), the public institution that manages water resources in Chile.

For the exploratory analysis, statistical techniques were used in order to characterize the data from all parameters. The purpose of the structural analysis (semivariogram) was to determine the structure of the regionalized variable: range, sill, and nugget effect (Matheron, 1971). The regionalized variable is time. For this purpose, the experimental semivariogram is determined and then, through a process of adjustment, a theoretical model is proposed. Geostatistical analysis of parameters (precipitation, run-off and piezometric levels) was graphically represented, with focus on the experimental semivariogram and the theoretical models (Samper and Carrera, 1990).

In order to determine what is the better adjustment (e.g. quadratic, spherical, exponential, gaussian, linear or hole-effect), comparison between models was conducted and the adjustment was supported by cross-validation (Gambolati and Volpi, 1979) (Table 1). Cross-validation displays the real and the estimated value of the parameter, and leads to the following statistical data: the test data standardized error (with the error variance), the test robust standardized error (with the error variance) and the robustness. When cycles were identified in the hydrological and hydrogeological records, a hole-effect model was proposed. When no cycles were detected, a spherical model was proposed.

4.2. Spectral analysis

Hydrological and hydrogeological data for the Huasco watershed were analysed by means of spectral analysis, which characterizes the frequency content of a signal. The main aim of estimating the spectral density in hydrological and hydrogeological data is to detect periodicities in their historical records, expressed by a periodogram. The periodogram identifies peaks at the frequencies corresponding to specific periodicities and constitutes the technical process of decomposing a complex signal into simpler parts. This mathematical technique is frequently used in palaeoenvironmental studies (Yiou et al., 1997; Lamy et al., 2001; Bahr et al., 2006; Ortiz et al., 2013). For the data associated with the Huasco catchment, spectral analysis was used for the streamflow and the piezometric levels and also for the climatic index El Niño 3.4. Due to the high randomness associated with precipitation in the study area, spectral analysis was not initially conducted for rainfall.

Correlation analysis between ENSO with precipitation and streamflow record was carried out using the El Niño 3.4 index (Bunge and Clarke, 2009), which corresponds to the sea surface temperature (SST) anomaly averaged over the equatorial box bounded by 5°N, 5°S, 170°W, and 120°W. The El Niño 3.4 index used the "uninterpolated" sea surface temperature data from the Second Hadley Centre Sea Surface Temperature dataset (HadSST2). Data for the date range from January 1873 to December 1979 were obtained from http://ocean.fsu.edu/, and data from NOAA (http://climexp.knmi.nl/data/inino5.dat) are used for the period from January 1980 to December 2015.

4.3. Analysis of temporal hydrological parameters

The identified periods of enhanced groundwater storage have been compared to the pluviometric record, to river run-off and to piezometric levels, all from observation points located at the catchment area of the Huasco River (Section I, II and III). Monthly analyses of these records also have been carried out to identify periods of high hydrological recharge. In addition, snow precipitation from the upper watershed was also considered in order to assess the role of the nival system. For the catchment area of the Huasco River no meteorological station was encountered to provide available snowfall record, hence the Quebrada Larga station from the Dirección General de Aguas (D.G.A.) was finally considered, which is located to the south, near the study area (catchment of the Elqui River, Coquimbo Region).

The record of water volume in the Santa Juana reservoir, as well as the climatic, hydrological and hydrogeological parameters in the cathment basin, has also demonstrated the existence of periods with significant water stress. Moreover, these drought episodes also have been identified in detail using a daily resolution. The roles of the

Table 1
Model parameters (Spherical and Hole-Effect) and cross-validation.

Variable	Sections	Model parameters				Cross-validation results (standardized error -1.5 and 1.5)							
		Model	Nugget	Sill	Range	Correlation index	Test data	Test data standardized error mean	Test data standardized error variance	Robust data	Robust data standardized error mean	Robust data standardized error variance	Porcentage robustness
Precipitation (mm)	I	Spherical	1.5 $(mm)^2$	1.8 $(mm)^2$	3776 days	0.256	15108	−0.00077	3.53148	14666	0.03338	0.03018	97.1%
	II	Spherical	3.2 $(mm)^2$	3.5 $(mm)^2$	900 days	0.177	7888	−0.00010	0.96076	7772	0.03132	0.03035	98.5%
	III	Spherical	1.4 $(mm)^2$	1.6 $(mm)^2$	1041 days	0.092	2703	−0.00015	1.02962	2638	0.04035	0.04054	97.6%
Streamflow (m^3/s)	I	Spherical	6.5 $(m^3/s)^2$	22.1 $(m^3/s)^2$	423 days (structure #1) y 1200 days (structure #2)	0.994	8483	0.00000	0.03036	8455	-0.00063	0.01029	99.7%
	II	Spherical	5 $(m^3/s)^2$	13.9 $(m^3/s)^2$	570 days (structure #1) y 5430 days (structure #2)	0.978	18209	0.00008	0.09111	18129	0.00034	0.04104	99.6%
	III	Spherical	25 $(m^3/s)^2$	119 $(m^3/s)^2$	386 days (structure #1) y 3765 days (structure #2)	0.966	14412	0.00001	0.22029	14276	0.00163	0.02149	99.1%
Piezometric level (ma.s.l.)	I	Spherical	0.9 $(ma.s.l)^2$	1.1 $(ma.s.l)^2$	1950 days	0.679	243	0.00649	0.91629	219	−0.00901	0.53173	90.1%
	II	Spherical	1.7 $(ma.s.l)^2$	4.3 $(ma.s.l)^2$	2941 days	0.878	323	0.01398	0.84757	284	-0.01200	0.44826	87.9%
	III	Hole-effect	2.3 $(ma.s.l)^2$	28.3 $(ma.s.l)^2$	9500 days	0.930	390	−0.00361	1.14978	349	0.03238	0.39573	89.5%

multiple potential precipitation sources (e.g., westerlies, Amazon basin) as controls on the Huasco River basin hydrological and hydrogeological parameters have been determined by comparing the precipitation, the river run-off and the groundwater level time series from characteristic climatic time series.

The El Niño and La Niña events are identified by means of the El Niño 3.4 index from NOAA database. The El Niño events are related to high positive values of the index and the intensities of the events are determined by their values. According to Trenberth, K. and National Center for Atmospheric Research Staff (2016), strong mode occurres when the index is above +1.5, and moderate mode when the index ranges from +1.0 to +1.5. When the index ranges from +0.5 to +1.0, the El Niño event is considered weak. When the index ranges from 0.0 to +0.5 no El Niño event exists. On the other hand, the La Niña events correspond to high negative values of the index where strong modes occurred when the index is below −1.5, and moderate mode when the index ranges from −1.0 to −1.5. When the index ranges from −0.5 to −1.0, the La Niña event is considered weak. As in the case of the El Niño events, when the index ranges from 0.0 to −0.5, no La Niña event exists.

5. Results and discussion

5.1. Geoestatistical results

Geostatistics of daily precipitation data indicate a significant random behavior, leading to a weak correlation and an important nugget effect. For all three sections of the catchment area, this trend can be identified in the adjusted semivariograms by means of a spherical model with high nugget effect. In Section I, the nugget effect is 1.54 mm^2, i.e. the nugget effect provides the 82% of the randomness (Fig. 4a). In Section II, the nugget effect is 3.2 mm^2, providing the 90% of the randomness (Fig. 4b) and Section III exhibits a nugget effect of 1.4 mm^2, which represents the 88% of randomness (Fig. 4c).

The experimental semivariogram of streamflow data is adjusted to a spherical model. The nugget effect for Section I is low (6.5 $(m^3/s)^2$), whereas the nugget effect for Section III is significantly higher (25 $(m^3/s)^2$). This is due to the random error associated with each Section: for Section I, the random error is 29% (Fig. 4d); for Section II, random error accounts for 36% (Fig. 4e); for Section III, randomness accounts for 21% (Fig. 4f).

The semivariograms of the piezometric data for Sections I and II are also suitably described by a spherical model with low nugget effect, with random errors of 46% (Section I) (Fig. 4g) and 28% (Section II) (Fig. 4h). In contrast, piezometric levels in Section III, which is the alluvial aquifer, are adjusted to a hole-effect (t) model and they show a randomness of 8% (Fig. 4i). Here, the signal displays a 10.65-year cycle.

Finally, the cross-validation was conducted in the geoestatistical analysis (Table 1). For the entire catchment basin, correlation indices for precipitation are very low because there is no relation between the model and the experimental data. In contrast, the correlation index is significant for streamflow and piezometric levels. Robustness from hydrological and hydrogeological data are high (>88%), hence the spherical model and the hole-effect (t) model adequately explain the empirical data in each specific case.

Results indicate the existence of a significant randomness in precipitation (ranging from 82 to 90%), attributable to the arid climate of the study area (Fig. 5). The streamflow record shows randomness between 21 and 36%, indicating that hydrological processes in the drainage system organize the random precipitation into a more structured seasonal fluctation. Those hydrological processes are likely related to the melting of winter snow and to glacial melting in the headwater areas of the catchment (Estrecho, Amarillo, Valle Encierro, Toro 1, Toro 2, Esperanza, Guanaco, Ortigas 1 and Ortigas 2; Fig. 2).

The minimum randomness of groundwater in Section III (8%) is due to the granular porosity of the alluvial aquifer of the Huasco River valley

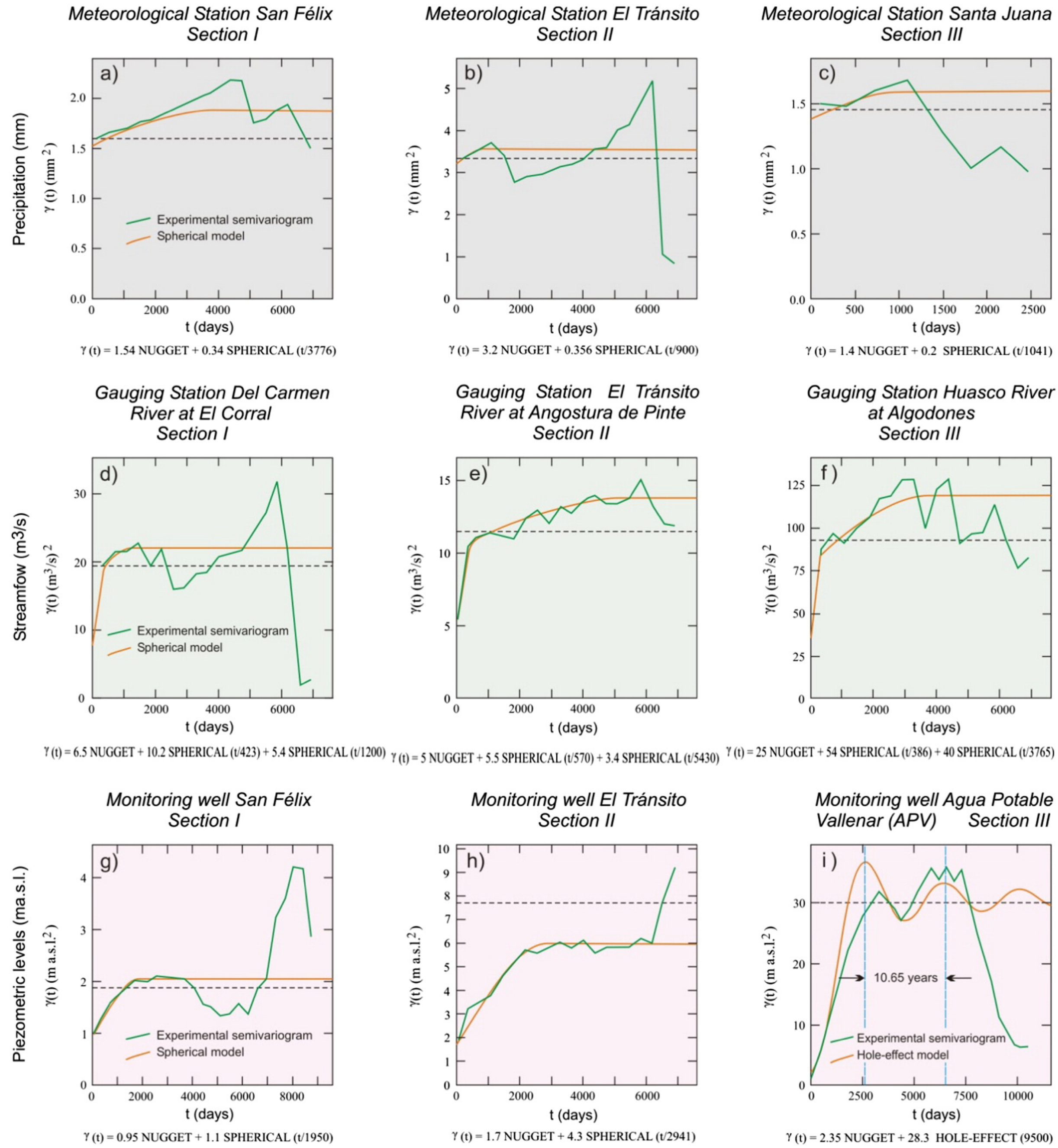

Fig. 4. Geostatistics for the precipitation data (a, b and c), the streamflow data (d, e and f), and the piezometric levels (g, h and i) from Huasco River watershed. The adjusted semivariograms for precipitation shown a significant random behavior, leading to a weak correlation of the data and an important nugget effect. The semivariograms for streamflow data are most appropriately adjusted to a spherical model. The semivariograms for piezometric levels in Sections I and II are also suitably described by a spherical model with low nugget effect. In contrast, piezometric levels in Section III (the alluvial aquifer) are adjusted to a hole-effect (t) model, which displays a 10.65-year cycle.

and its isotropic character. On the other hand, higher randomness detected in groundwater in the headwater areas (Sections I and II), from 28 to 46%, suggests the existence of an anisotropic aquifer. In the absence of alluvial or glacial deposits in the upper part of the catchment, the anisotropy is likely attributable to fractured aquifers.

In Section III, the groundwater record shows the existence of a 10.65-year cycle associated with the hole-effect model in the semivariogram analysis. A detailed discussion is given in Section 5.8 (Climatic cycles).

5.2. Oscillations in the Santa Juana dam

Oscillations in the Santa Juana dam are associated with several environmental factors that trigger water recharge events in the catchment basin of the Huasco River. Two environmental factors are considered to be of primary importance. The first is wet weather fronts coming from the Pacific Ocean during winter, which reach northern Chile and the catchment basin of the Huasco basin. The second is meltwater related to the spring and summer period, which provides an abrupt increase in streamflow in the headwaters region of the catchment basin.

Recharge episodes of these two types are assumed to have existed in the catchment area during historical times. For this reason, the Santa Juana dam serves as a hydrological sensor for the catchment basin of the Huasco River, and correspondences between recharge events, precipitation, run-off, and piezometric levels can be sought.

From the inauguration of the dam in 1997 to the present, the water reservoir has fluctuated between periods of more and less volume

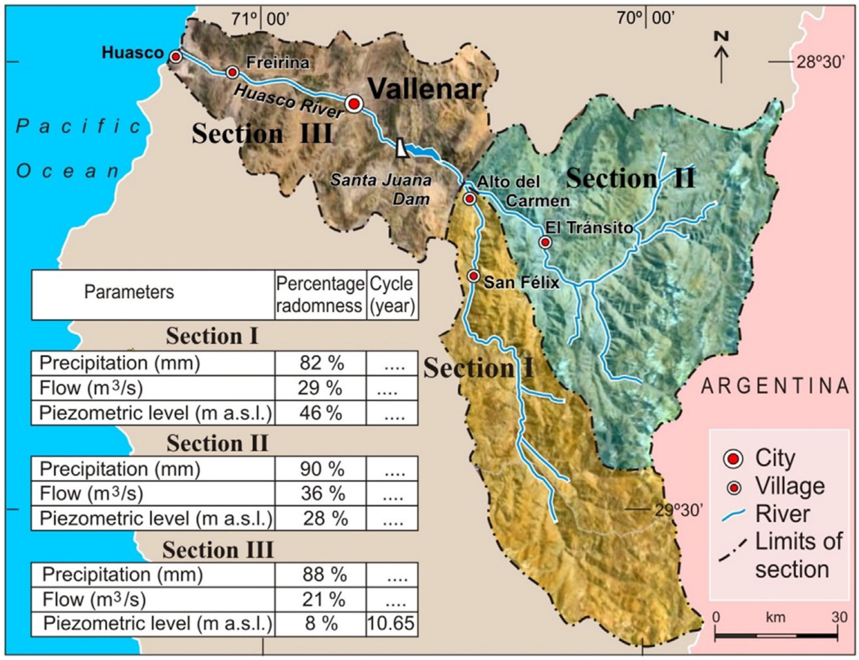

Fig. 5. Spatial distribution of the randomness and cycles associated with the precipitation, streamflow, and piezometric level, at Huasco River watershed.

(Fig. 6). Periods above the exceedance limit of the dam (166 million m^3) can be identified as well as periods when the water reservoir is below the normality limit (100 million m^3) and even below the partial failure limit of the system (13 million^3). The criteria on which 'exceedence' and 'failure' limits are based were defined in D.G.A. (2013). We focus on six intervals when the reservoir surpassed the exceedance limit (Fig. 6, intervals 1–6) and on the months preceding those exceedance conditions during which the water stored in the aquifer increased from a previous minimum. Continued recharge is anticipated to have occurred during part of each exceedance interval. However, the reservoir record is relatively insensitive to recharge once exceedance is surpassed. Hence, we define the time periods of interest to be from the initiation of rise in the reservoir till the end of each exceedance period (Table 2).

The six intervals are preceded by water recharge conditions related to intense rainfall and snowfall (Periods 1a to 6a) and subsequent summer snowmelting, around 3–4 months later (Periods 1b to 6b). Fluctuations of reservoir height due to human intervention were also considered from water releases reported in Asociation of Huasco River and are shown in Fig. 6. Data suggest that the main observed fluctuations in water reservoir were not triggered by anthropic factors. The water reservoir of Santa Juana dam has been below the normality limit (100 million m^3) from 29th December 2010 to the present (February 2016). Specifically, from 23th December 2014 to 1st April 2015, the reservoir exhibited historical minimum values which are below the partial failure limit of the system (13 million m^3). Between 1st April 2015 and the present (February 2016), the water reservoir recovered to above the failure limit, but remained below the normality limit of the dam.

5.3. Periods of water recharge

Assuming that the Santa Juana dam records natural recharge episodes, similarities to precipitation and streamflow records are indicative of the controls on recharge in the catchment basin. Fig. 7 shows the historical record related to precipitation and streamflow in Sections I, II and III, respectively. The six periods of enhanced recharge are identified in Fig. 6 and are transferred to Fig. 7, for which relationships are examined.

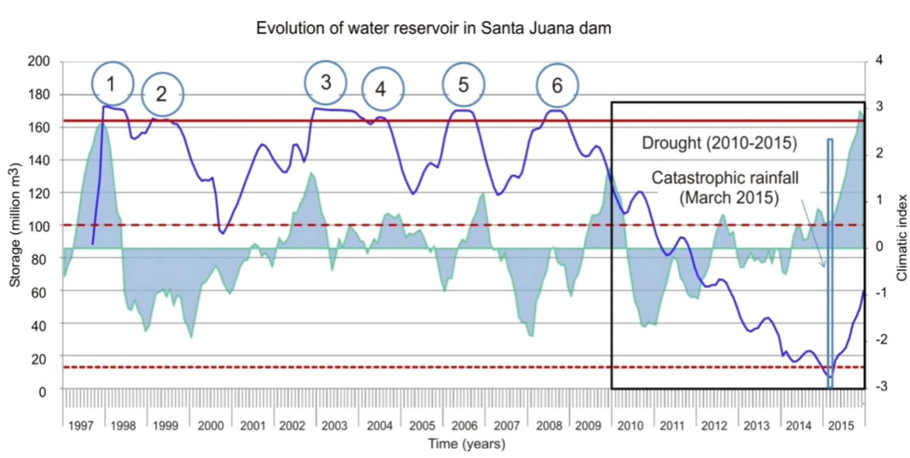

Fig. 6. Water reservoir of Santa Juana dam from 1997 to 2015 compared to the El Niño 3.4 climatic index. From inauguration of the dam in 1997 to present, the water reservoir has fluctuated between periods of more and less volume. Six intervals when the reservoir surpassed the exceedance limit.

Table 2
Periods when the water reservoir of Santa Juana dam surpassed the exceedance limit (Periods 1 to 6) are shown. The six intervals are preceded by conditions of water recharge due to intense rainfall and snowfall (Periods 1a to 6a) and subsequent summer snowmelting around 3–4 months later (Periods 1b to 6b). The melting process during summer triggered an abrupt increase in streamflow, which rapidly originated the beginning of water exceedance conditions. The exception of this is Period 4, when no snowmelting was detected and rainfall constituted the only factor which triggered the beginning of exceedance conditions. Precipitation and streamflow records were obtained from observation points shown in Fig. 2. Snow precipitation records were obtained from the 'Quebrada Larga' station, located close to the studied area (catchment of Elqui River, Coquimbo Region). (-*) indicates that no record is available, (-**) indicates that lack of peak in the signal.

Water reservoir in Santa Juana dam			Winter precipitation			Summer snowmelting		Climatic event
Period of exceedence	Date when exceedence began	Date when exceedence ended	Period of precipitation	Date when intense rainfall occurred	Date when intense snowfall occurred	Period of water recharge	Date when a peak in streamflow occurred	
1	1 December 1997	11 July 1998	1a	June and August 1997	-*	1b	From November 1997 to January 1998	1997/98 El Niño
2	18 February 1999	4 March 1999	2a	June and July 1998	From February to March 1999	2b	From January to April 1999	1997/98 El Niño
3	20 November 2002	13 January 2004	3a	From May to August 2002	From July to September 2002	3b	From November 2002 to January 2003	2002/03 El Niño
4	22 July 2004	10 August 2004	4a	July 2004	-**	4b	-**	Westerlies
5	3 March 2006	2 October 2006	5a	From April to August 2005	From June to September 2005	5b	From November 2005 to February 2006	SE Extratopical Moisture
6	3 June 2008	3 December 2008	6a	From May to July 2008	-**	6b	From November 2007 to January 2008	SE Extratopical Moisture

In addition to the six periods, one period of persistent groundwater decline was also identified.

5.4. Period 1. Between 1st December 1997 and 11th July 1998

The start date for this first recharge interval is ambiguous because the reservoir was inaugurated during a season of unusual rainfall. In headwater areas of the catchment basin (Sections I and II), elevated precipitation was recorded in July and August 1997 (Fig. 7a and b). These winter precipitations are associated with the 1997/98 El Niño climatic event (see Fig. 6). Moreover, during spring and summer, a high streamflow (around 40 m^3/s) was detected and it is inferred to have been driven by melting snowpack. Both precipitation and snowmelt provided high rates of groundwater and water recharge in the catchment basin of the Huasco River.

5.5. Period 2. Between 18th February and 4th March 1999

No important precipitation was recorded at the headwater area of the catchment during this period and only a low rainfall rate was detected in June and July 1998 (Fig. 7a and b). Streamflow did not increase until summer (January–February 1998), when it ranged from 3.5 to 4.5 m^3/s. Nevertheless, during spring and summer, the reservoir volume increased by a modest amount. We interpret that melting of the snowpack from the previous year (Period 1) was responsible for this long-lived yet modest recharge event with a delayed effect.

5.6. Period 3. Between 20th November 2002 and 13th January 2004

Heavy rainfall was recorded between April and August 2002 in the headwaters areas (Fig. 7a and b). This precipitation was related to the 2002/03 El Niño event. However, it was not until the spring and summer snowmelt that streamflow increased abruptly (to around 12 and 16 m^3/s) and that the aquifer recharged rapidly.

5.7. Period 4. Between 22th July and 10th August 2004

A small magnitude of groundwater recharge event is defined by the exceedance criteria at the Santa Juana reservoir. Rainfall was widespread in July 2004 (Sections I, II and III) in comparatively large amounts (47–65 mm) (Figs. 8 and 9). Nevertheless, streamflow remained low (ranging only from 1.8 to 2.1 m^3/s). Hence, these data suggest that rainfall led to modest direct recharge, with no subsequent snowmelt. Rainfall associated with Period 4 is attributed to the westerlies.

5.8. Period 5. Between 3rd March and 2nd October 2006

In the headwaters areas, rainfall around 28–34 mm was recorded between April and August 2005 (Fig. 7a and b), which was likely accompanied by snow in the high Andes (Table 2). Nevertheless, precipitation was relatively weak and was not related to any the El Niño event. The streamflows of the Del Carmen and El Tránsito rivers peaked (4.2–6.1 m^3/s) during the snowmelt (spring-summer). These data suggest that extratropical moisture from southeast triggered the hydrological supply during this period.

5.9. Period 6. Between 3rd June and 3rd December 2008

In the headwaters areas, rainfall of 5.7–7.0 mm was recorded between June and July 2007 and 48–50 mm in June and July 2008 (Fig. 7a and b). The modest liquid rain recorded in 2007 is insufficient to explain the rise in streamflow during spring 2007 and summer 2008, which suggests that heavy snow accompanied the liquid rain in the El Tránsito sub-basin (Table 2). The precipitation was not associated with any El Niño event (Fig. 6). Regarding streamflows, values showed a peak ranging from 7.5 to 8.3 m^3/s during snowmelting in spring-summer for the El Tránsito River (Section II). On the other hand, streamflow related to the Del Carmen River (Section I) only reached a peak between 2.6 and 3.0 m^3/s, suggesting that Section II constitutes the main water recharge of the Huasco River watershed. Overall, these data indicate that extratropical moisture from southeast constituted the main hydrological supply during this period.

Section III in the catchment area of the Huasco River (Fig. 7c) shows a similar behavior regarding the meteorological and hydrological data compared to those observed for the headwaters areas.

6. Last climatic events

6.1. The 2010–2015 drought episode

As opposed to the hydrological recharge episodes detected between 1997 and 2010 (periods 1 to 6 of the Santa Juana reservoir), the 2010–2015 period is associated with a dry climatic interval that triggered a significant decrease in the water stored by the dam, as well as in the

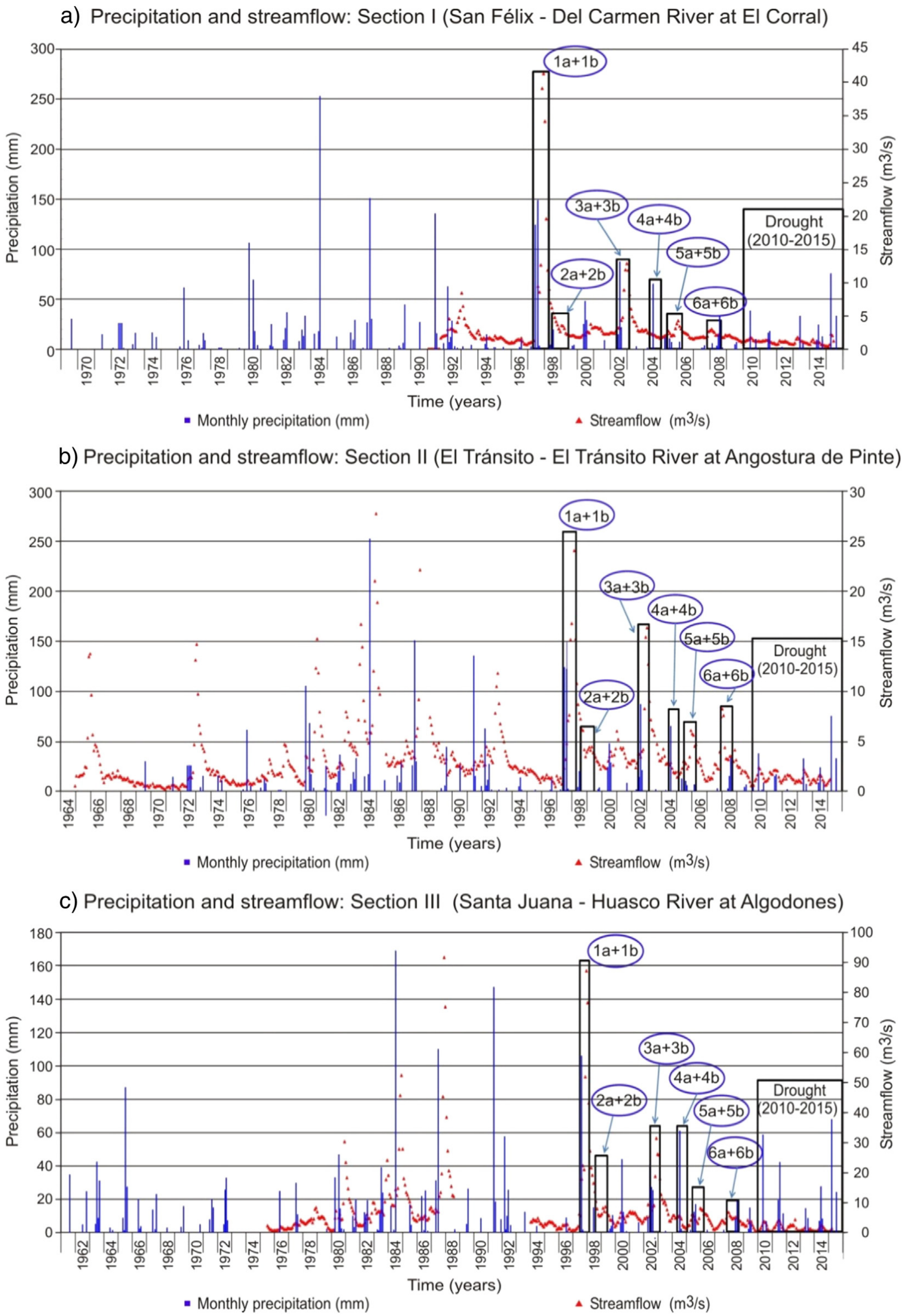

Fig. 7. Historical record of precipitation and streamflow in: a) Section I (San Félix meteorological station), b) Section II (El Tránsito meteorological station), c) Section III (Santa Juana meteorological station). The six periods of higher recharge are shown together with the hydrological record. These six intervals are preceded by water recharge due to intense rainfall and snowfall (Periods 1a to 6a) with its subsequent summer snow melting (Periods 1b to 6b).

groundwater of the alluvial aquifer and in the headwater areas (Fig. 5). Previous climatic investigations describe this period in Chile as a significant drought period (Boisier et al., 2016). Climate records for the last six years have demonstrated the existence of deficit in the rainfall regime between 20% and 60% over a large area of Chile, between the IV Region of Coquimbo and the IX Region of La Araucanía, which was especially intense during the last three years (Garreaud, 2015).

The drought related to the 2010–2015 period is evident in the hydrological and hydrogeological parameters in the catchment area of the Huasco River, mainly in the streamflow record (Fig. 7)

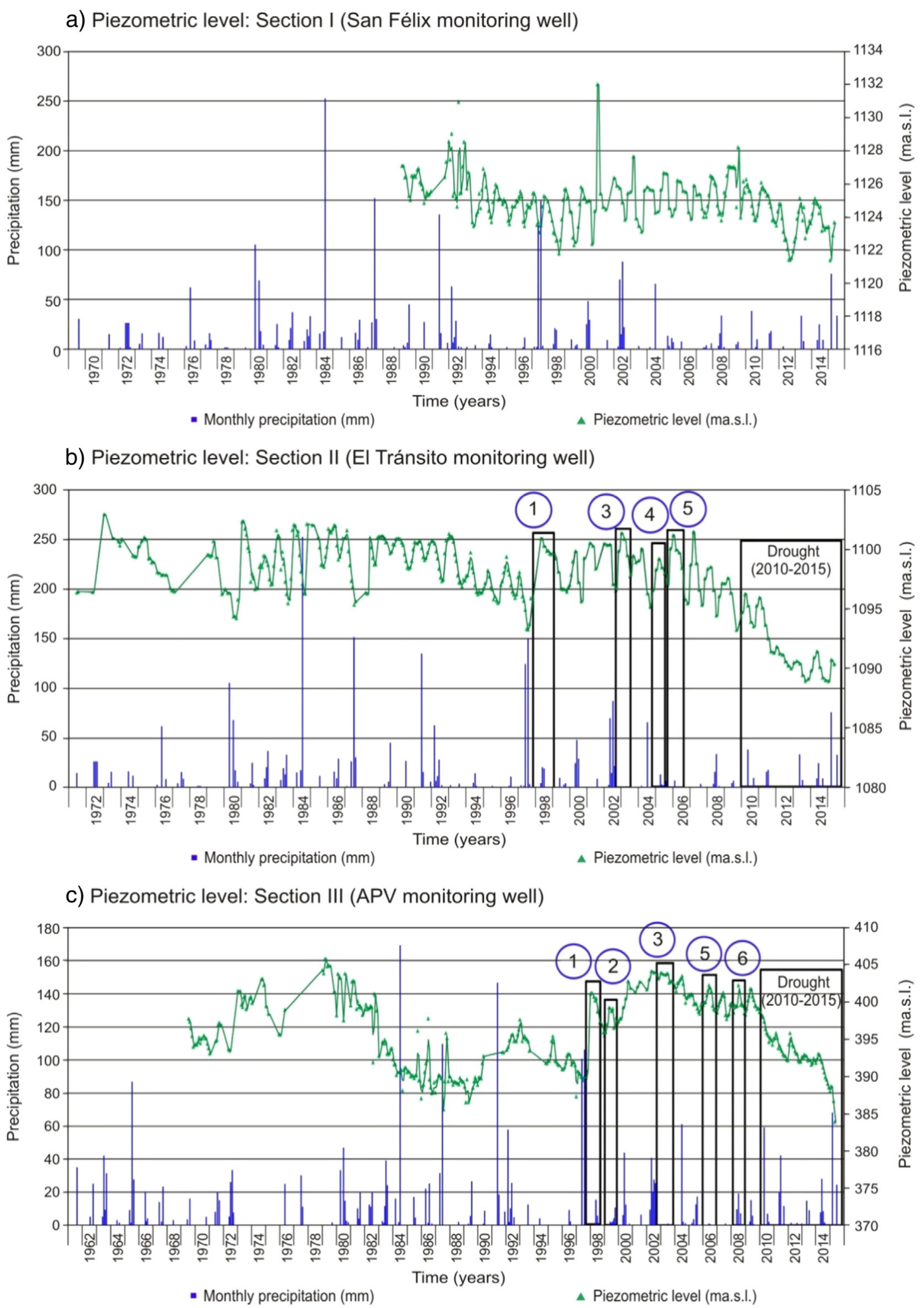

Fig. 8. Historical records of precipitation and piezometric levels from the headwaters area of the catchment in: a) Sector I (San Félix monitoring well), b) Sector II (El Tránsito monitoring well) and c) Sector III (APV monitoring well). The piezometric levels are shown together with higher recharge events defined in Fig. 6 (Intervals 1–6).

and the groundwater record (Fig. 8). In addition, the drought was clearly detected in the Santa Juana reservoir (Fig. 6). Boisier et al. (2016) demonstrate that, whereas anthropogenic forcing and the Pacific Dipole Oscillation both contributed to diminished recharge since 1980, there is a major contribution to the 2010–2015 droughts by natural forcings, as the La Niña conditions were persistent.

6.2. The catastrophic event of 24–26th March 2015

Intense rainfall occurred between 24th and 26th March 2015 in northern Chile, in the provinces of Antofagasta, Atacama and Coquimbo, and caused catastrophic flash floods. In the watershed of the Huasco River, precipitations related to the catastrophic event ranged from 61 to 76 mm (Fig. 6) and snowfall was heavy (D.G.A, 2015). The Santa

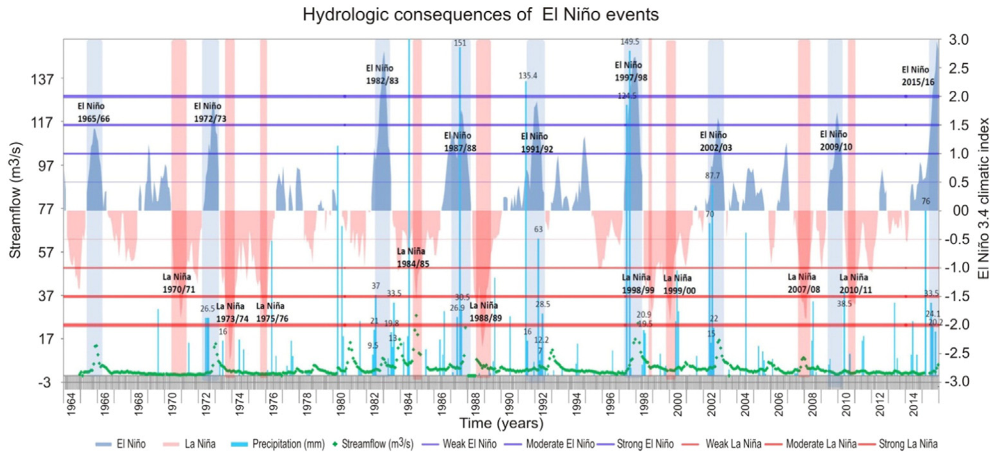

Fig. 9. The hydrological record displays the climatic oscillations associated with some El Niño events, characterized by a significant precipitation during winter in the months of June–July-August. Later, during spring and summer (November–December-January), melting in the headwaters of the watershed triggers an abrupt increase of streamflow. Some La Niña events also correlate to the anomalies in the hydrological records, causing a lack of precipitation and a significant decrease of streamflow in the catchment.

Juana reservoir level rose significantly in the months after this intense rainfall (Fig. 6).

6.3. Evolution of piezometric levels

The piezometric levels recorded in the headwaters area of the catchment (Section I and II) are associated with those episodes of high hydrological recharge shown in Fig. 6. Time comparisons show that the aquifer is very sensitive to melting events that occur during spring and summer months, as long as a precipitation event triggers snowfall in the headwaters area.

6.4. Headwaters of the catchment at Section I

In Section I, at San Félix monitoring well, the piezometric levels shows values ranging from 1122 to 1128 m a.s.l. during 1991–2015, hence water level fluctuated only 6 m (Fig. 8a). The record of piezometric levels suggests that Section I does not constitute a significant factor that determines the episodes of groundwater recharge of the reservoir nor of the alluvial aquifer of the Huasco River (Section III).

6.5. Headwaters of the catchment at Section II

In Section II, at the El Tránsito monitoring well, piezometric levels during 1993–2009 ranged from 1095 to 1100 m a.s.l. (Fig. 8b). However, between 2010 and 2015 the piezometric levels reached minimum historical values, reaching as low as 1088 m a.s.l. From 2008 to 2015, the water levels trended downward and, at the beginning of 2009, the annual cycles were of a smaller magnitude than before. These values are consistent to a dry climatic episode described in Boisier et al. (2016) that provoked serious drought conditions. Some of the high values of piezometric levels correspond to episodes detected in the dammed reservoir (especially Periods 1, 3, 5) (Fig. 6) and the trend is similar to that of the piezometric levels of the Alluvial Aquifer of the lower Huasco River basin (Section III). These similarities suggest that the hydrogeology of Section II (upstream) and Section III (downstream) are strongly connected.

6.6. Alluvial Aquifer of the Huasco River (Section III)

In Section III, at Vallenar monitoring well (APV), piezometric levels show values ranging from 390 to 405 m a.s.l., during 1991–2015 (Fig. 8c). Piezometric levels follow a similar temporal pattern as in Section II, and times of high piezometric level in this Alluvial Aquifer well correspond to times that the reservoir was full (Fig. 6). The water level rise (>10 m) related to Period 1 (December 1997–July 1998) deserves special mention. This large magnitude aquifer recharge was triggered by heavy precipitation during winter 1997 (Fig. 8) brought by the 1997/98 El Niño event, and the subsequent spring and summer snowmelt. From January 1998 to September 2009, piezometric levels were high and relatively stable, suggesting the existence of river training related to Santa Juana dam. On the other hand, between September 2009 and May 2015, water levels decreased markedly, to a minimum historical value of 384 m a.s.l. (Fig. 8c). During the same period, a sharp decline was also detected in Section II (Fig. 8b). This episode was triggered by drought conditions. The water volume in the reservoir at the Santa Juana dam was also low (Fig. 6), ranging from 149 million m^3 in September 2009 to only 5 million m^3 in March 2015.

6.7. Climatic pattern of La Niña and the SE extratropical moisture

Some La Niña events also correlate to anomalies in the hydrological records (Fig. 9). The La Niña events of 1970/71, 1971/72, 1973/74 and 1975/76 are all characterized by both a lack of precipitation and a significant decrease of streamflow in the catchment. The four La Niña events (1970–1976) caused a drought in the Huasco River watershed. The La Niña years of 1988/89, 1998/99 and 1999/2000 triggered similar decline of precipitation but with less impact on streamflow because the drought was attenuated by the groundwater and snow stored from the immediately preceding the El Niño events.

The index El Niño 3.4 also indicates the existence of a La Niña event in 2007/08, which was associated with scarcity in winter rainfall on the western flank of the Andes and with an abrupt increase in streamflow of the Huasco River in summer. This behavior differs from that of the previously the La Niña events and suggests the existence of another climate factor in addition to the ENSO oscillations. Precipitation data indicates that the SE Extratropical moisture caused the water recharge associated with 2007/08, which provided snow on the eastern slope of the Andes (see Table 2). The weak La Niña event in 2005/06 is also related to a significant increase in streamflow in the drainage system and to a lack of precipitation at the monitored stations, suggesting the intervention of the SE Extratropical moisture events. Although rainfall was detected in summer 2006 in the headwaters of the catchment (Section II), precipitation was not registered downstream (Section III). These observations suggest the existence of a SE Extratropical event.

6.8. The westerlies climatic influence

Inside the climatic pattern of the ENSO oscillations, the watershed of the Huasco River also records some westerlies events coming from the southwest, as suggested by the humid front of July 1984 and the subsequent melting event in December 1984. In addition, similar wet events also occurred in April and July 1980 (with melting in summer 1981) and winter 1983 (with melting in summer 1984). The coupled system 'rainfall in winter' and 'melting in summer' is also observed for the periods with the westerlies influence. The exception is the event related to July 2004 (see Table 2), when snowmelting was not recorded. Overall, these westerlies events did not affect in an important manner the piezometric levels of groundwater and it is only possible to detect an oscillation of second order in the groundwater records (Fig. 10).

In the catchment of the Huasco River, no evidence was recognized of climatic influence from the northeast trade winds, since rainfall episodes in the study area mainly occurred in winter.

6.9. ENSO oscillations and groundwater

For the available hydrological data (from 1964 to 2015), the watershed of the Huasco River displays climatic oscillations associated with some El Niño events (Fig. 9). Groundwater levels were obtained from D.G.A. (2013) and El Niño 3.4 climatic index was obtained from http://ocean.fsu.edu/(data for the date range from January 1873 to December 1979) and NOAA data from http://climexp.knmi.nl/data/inino5.dat (from January 1980 to December 2015). These El Niño events are characterized by a significant winter precipitation, mainly during June–July–August (JJA). Later, during spring and summer (November–December–January), melting in the headwaters of the watershed triggers an abrupt increase of streamflow. The El Niño events related to 1972/73, 1982/83, 1987/88, 1997/98 and 2002/03 display the coupled system of winter precipitation and spring-summer melting.

The piezometric levels of groundwater in the alluvial aquifer of the Huasco River (Section III, Vallenar area, monitoring well APV) show the control of the El Niño – La Niña climate pattern (Fig. 10). The El Niño events associated with 1972/73 and 1997/98 triggered significant recovery episodes in the piezometric levels of the aquifer, while the La Niña events triggered hydrological stress in the water reservoir, such as during the period 1970/71, which initiated a significant decreasing trend in piezometric levels. The La Niña event associated with 1973/74 did not trigger hydrological deficit in the aquifer since this event immediately occurred after the El Niño event just one year before (1972/73). The La Niña years associated with 1984/85 and 1988/89 constitute the lower and upper limits, respectively, when low piezometric levels were recorded in groundwater of the Huasco aquifer. During this interval, no groundwater recharge processes were identified even during the El Niño event of 1987/88.

At the beginning of 1990, the water table began an 8-year cycle of rise and decline, with shorter fluctuations superimposed. The times of most rapid groundwater recharge were triggered by the El Niño events of 1991/92 and of 1994/95. Piezometric levels abruptly increased again with the El Niño events of 1997/98, which constituted the beginning of a relatively wet period between 1998 and 2010. Within this episode, maximum groundwater levels were recorded during the El Niño of 2002/03. Finally, the La Niña 2010/11 constituted the beginning of persistent drought.

6.10. Climatic cycles from spectral analysis

Periodograms indicate that groundwater of the Huasco aquifer (Section III) is sensitive to the low-frequency climatic fluctuations (9.2-year cycle) related to the strong mode of the ENSO oscillations (10.96 years) as well as the Hale solar cycle (22-year cycle) (Fig. 11). This is consistent with the 10.65-year cycle obtained from the semivariogram (Fig. 4i). The rest of indicators reveal that the Huasco hydrology is sensitive to high-frequency climatic fluctuations (from 2.5-year to 4.6-year cycles) (Fig. 11a–e). Spectral analysis also reveals the existence of the anthropogenic regulation of the Santa Juana dam, since the annual hydrological cyclicity disappears downstream the dam (Fig. 11f and g).

The periodogram from the climatic index 3.4 (NOAA database) shows the existence of cycles with higher frequencies. The main cycle is detected at 3.65 years, which is attributed to oscillations of the El Niño and La Niña events corresponding to the combination of strong and weak modes of the ENSO oscillations, which occur every 3–5 years on average (NOAA, 2005). A detailed definition of the 'strong' and 'weak' ENSO modes is described in Wolter and Timlin (2011). Periodogram also shows the existence of a 10.96-year cycle, which we attribute to the 11-year Schwabe solar cycle related to sunspots (Usoskin and Mursula, 2003).

Spectral analysis indicates the existence of a 22.9-year cycle in the piezometric levels of the alluvial aquifer (Section III), which we attribute to the 22-year Hale solar cycle (Usoskin and Mursula, 2003) (Fig. h). In addition, the same piezometric record semivariogram analysis and spectral analysis indicate the existence of a 10.65-year cycle and a 9.2-year cycle, respectively. We attribute these cycles to the strong mode of the ENSO oscillations, which occur at intervals ranging from 7 to 13.9 years (Jevrejeva et al., 2004; NOAA, 2008). Periodograms reveal that oscillations in water amount in the Huasco alluvial aquifer constitute a sensor of the climate system, which is driven by forcings that have decadal and multidecadal frequencies. The aquifer does not exhibit sensitivity to the weak modes of ENSO oscillations (3–5 years), which are related to higher frequencies.

The streamflow record for Section III shows the existence of the following cycles: 4.6 years, 3.5 years and 2.5 years. Therefore, run-off water

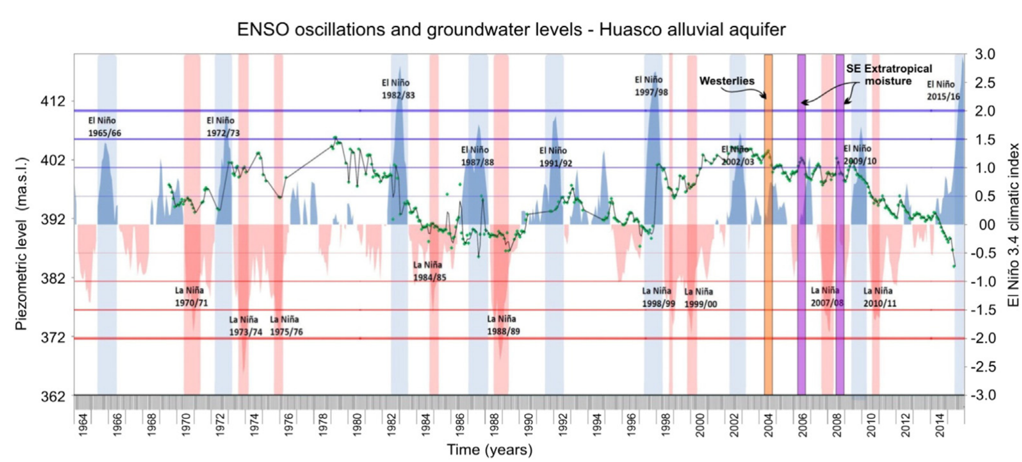

Fig. 10. The records of the piezometric levels of groundwater in the alluvial aquifer of the Huasco River (Section III, monitoring well station APV) show the control of the El Niño – La Niña climate pattern. Also, the influence of westerlies and the SE Extratropical moisture in the piezometric levels are shown.

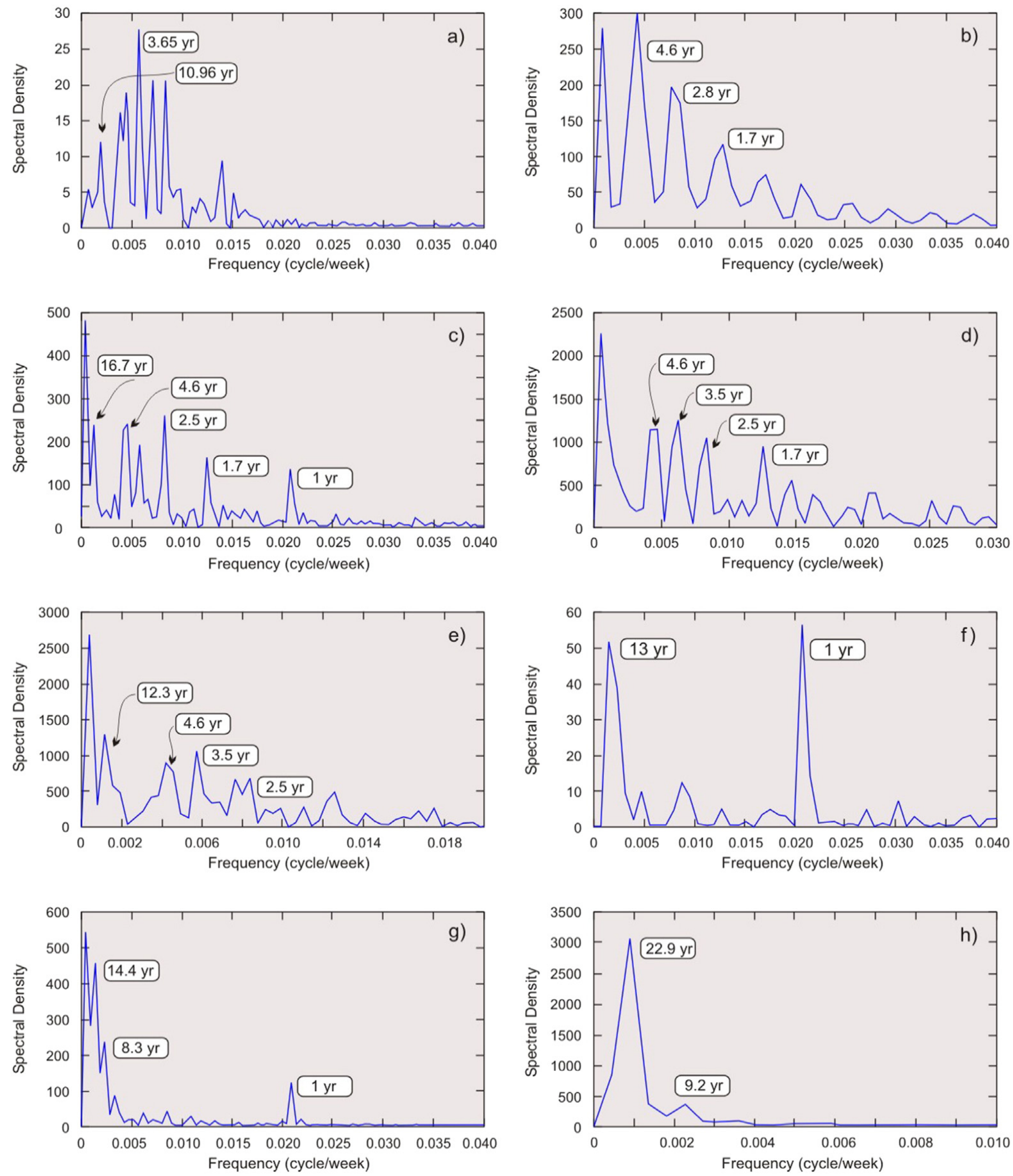

Fig. 11. Spectral analysis of the hydrological and piezometric levels for the Huasco River watershed (Sections I, II and III). The periodograms correspond to: a) the El Niño 3.4 climatic index (NOAA database), b) the streamflow in Section I, c) the streamflow in Section II, d) the streamflow in Section III upstream the Santa Juana dam, e) the streamflow in Section III downstream the Santa Juana dam, f) the piezometric levels in Section I, g) the piezometric levels in Section II and h) the piezometric levels in Section III.

is mainly controlled by high-frequency climatic fluctuations attributed to climate-driven shifts of the strong and weak mode of the ENSO oscillations. The identified El Niño 3.4 cycle (3.65-year) is consistent with those cycles identified in the streamflow record, suggesting the existence of significant control of ENSO oscillations on the melting processes of the Huasco watershed.

In the headwaters of the catchment, the streamflow record in Section II shows sensitivity to 3.5-year variability, but this cycle does not appear in Section I. Therefore, spectral analysis suggests the importance of the melting processes in Section II, which are corroborated by the presence of the main snowfields and glaciers (Estrecho, Amarillo and Valle Encierro). Only in Section II, the streamflow periodograms show a significant cycle beyond the 4.6-year cycle, at 16.7 years. This cycle is attributed to the melting pattern of low frequency related to the combination of the ENSO oscillations, the westerlies and SE Extratropical moisture. In addition, high-frequency annual cycles were identified in the streamflow record within the headwaters of the catchment, located at 1.7 year and 1.0 year. This annual cyclicity was not detected downstream (alluvial aquifer, Section III).

The cyclicity in streamflow was modified by the presence of the Santa Juana dam. Thus, the detected high-frequency cycles upstream of the dam (1.7-year and 1.0-year cycles) disappear downstream, suggesting the effect of the dam regulation. Downstream the dam, the hydrological signal continues to be controlled by the cycles of 4.6 year, 3.5 year and 2.5 year, which are related to the high-frequency ENSO oscillations.

The piezometric levels in Sections I and II show a marked cycle of 1.0 year. The periodogram indicates the importance of the annual cyclicity in the headwaters area of the Huasco watershed, and denotes that groundwater is highly sensitive to local subsoil conditions. Here, the aquifers exhibit poor spatial extent and show a significant anisotropic behavior due to the presence of a low permeability subsoil and/or fractured rock. Hence, the piezometric signal shows a rapid response associated with the hydrological signature of the rivers (El Tránsito and Del Carmen), showing both streamflow records a cycle of 1.0 year. The proximity of the monitoring wells to the rivers contributes to a tight coupling between the streamflow oscillations and the groundwater.

For the headwaters of the catchment (Sections I and II), spectral analysis showed the existence of a cyclicity in the groundwater record ranging from 8.3 year to 14.4 year, which we interpret to be, collectively, the cause of the 9.2-year cycle detected for the alluvial aquifer of the Huasco River (Section III). Therefore, aquifers are not sensitive to the high-frequency oscillations of streamflow (e.g., 4.6-year, 3.5-year and 2.5-year cycles). The cycles related to 8.3 year and 14.4 year are controlled by the strong mode of the ENSO oscillations.

7. Conclusions

Hydrological and hydrogeological records at the watershed and aquifer of the Huasco River indicate that the responses of water resources are highly sensitive to the climatic pattern of the El Niño and La Niña events. Overall, high values in the El Niño climate index 3.4 triggered significant increases in streamflow, and low values initiated dry episodes.

The El Niño years related to 1965/66, 1972/73, 1987/88, 1997/98 and 2002/03 were associated with intense winter rainfall (June–July–August) in the catchment of the Huasco River. Although not well constrained by meteorological data, it is interpreted that heavy snow accompanied those heavy rains. The immediately following spring-summer period (November–December–January) experienced snowmelt and strong streamflow. These observations inidicate the importance to the Huasco hydrological system of coupled processes of winter precipitation in the headwaters areas of the watershed followed by summer melting. As indicated by several previous investigations, the snowfield areas and glaciers constitute a major source of water recharge within the catchment, and explain the streamflow record of the Huasco River.

Some years of La Niña triggered significant episodes of water deficit, such as the events occurred in 1970/71, 1973/74 and 1975/76, which initiated trends toward minimum values in the streamflow record and groundwater level. The La Niña events that occurred immediately after an El Niño event did not show extreme water stress, such as the La Niña events in 1988/89, 1998/99 and 1999/00. Some La Niña events are associated with increased values in streamflow such as the event in 2007/08 and the weak La Niña events in 1978 and 2005/06. The La Niña events of 1978 and 2007/08 were not related to any recorded rainfall, whereas the weak La Niña event of 2005/06 shows slight winter rainfall and also slight summer rainfall. The lack of snow data within the Huasco catchment and the lack of precipitation data for the eastern slope of the Andes at the latitude of the Huasco basin both make it difficult to investigate these discrepancies. Tentatively, the existing data imply the possible existence of an extratropical humid source coming from the southeast, which constitutes a summer source of hydrological recharge mainly located at the headwaters of the watershed. If so, the melting process occurred almost immediately after the precipitation of snow from the eastern source, triggering an increase in the streamflow with no participation of an El Niño event.

In July 1984, the intense rainfall and the increase in streamflow were not related to an El Niño event but to a westerlies-driven winter storm that affected central and southern Chile. The precipitation events associated with 1980 and 1983 were also attributed to westerlies weather fronts, which caused increased values in streamflow by the snowmelt, but did not affect the main piezometric levels of groundwater.

Due to the existence of these westerlies events between 1980 and 1984, the hydrological recharge in the Huasco catchment significantly increased, as is revealed by the high values in streamflow of the river during this period. Previous to this high water recharge in the Huasco catchment, a dry climate episode operated between 1970 and 1976, associated with three consecutive the La Niña events (1970/71, 1973/74 and 1975/76).

In the Huasco watershed, an extreme dry episode persisted from 2010 to 2015, which is widely considered as a significant drought for previously investigations in Chile (Boisier et al., 2016). This episode is clearly detected by minimum values in the streamflow record and by the water level in the Santa Juana reservoir. Currently, the reservoir is recovering after the occurrence of the catastrophic precipitation event of March 2015, although the water levels that preceded the drought period (2010–2015) have not yet been reached.

Hydrological and hydrogeological results indicate the importance of the alluvial aquifer of the Huasco River, since the groundwater of the aquifer is sensitive to the low-frequency climatic fluctuations (from 9.2 to 10.65-year cycle) related to the strong mode of the ENSO oscillations (10.96 years) as well as the Hale solar cycle (22-year cycle). The rest of the indicators reveal that the Huasco hydrology is sensitive to high-frequency climatic fluctuations (ranging from 2.5-year to 4.6-year cycles) associated with the combined action of strong and weak modes of the ENSO oscillations. In addition, spectral analysis reveals the existence of the anthropogenic regulation of the Santa Juana dam, since the annual hydrological cyclicity (1.7-year and 1.0-year cycles) disappears downstream the dam. The presence of the Hale solar cycle in the hydrogeological record of Huasco catchment suggests a potential teleconnection between the solar forcing and the ENSO oscillations. These results can be extrapolated to multiple basins located below the arid diagonal in central Chile, like the Elqui or the Limari River, with historical droughts at present, just like the Huasco basin.

Results regarding the water reservoir fluctuations in the Huasco watershed (streamflow and groundwater) should be considered in order to determine the water management strategy in Chile, specifically in the northern arid area where the water stress is becoming a social issue. The development of water management strategies provides policies and recommendations for the need to shift from sole reliance on the aquifer to renewable supplies. These strategies constitute a key component which guarantees a safe and sustainable water supply for the population in arid areas of the world.

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