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Relative contribution of groundwater and surface water fluxes in response to climate variability over a mountainous catchment in the Chilean Andes

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Abstract In the semi-arid region of Norte Chico (Chile), climate variability, mainly controlled by ENSO and LNSO events, generates a high variability of both surface water and groundwater fluxes. Taking the upper Elqui catchment as an example, this study found that, during LNSO events, the abnormally high values (>200%) of the runoff coefficient may be the consequence of a groundwater contribution to surface water flow. During ENSO events, however, the lower values (<100%) of the runoff coefficient and the dynamics of the water table level highlight the recharge of the subsurface compartment. For the hydrological years characterized by a high Pluviometric Index during the 1977–2008 period, three dynamics of interaction between groundwater and surface water are identified: (i) the water table increases before the river discharge, and its logarithmic increase highlights a rapid recharge related to the concomitance of snowmelt and rainfall events; (ii) the water table increases after the river discharge and its exponential increase shows a progressive intensification of the recharge over time; and (iii) the water table and the river discharge increase are concomitant. Dynamics (i) and (ii) are observed during the ENSO events, when precipitation occurs over a long period; dynamic (iii) is observed during the neutral years, when high intensity precipitations occur over short periods. Accordingly, if the present climate trend marked by an increased frequency of El Niño events in recent decades (IPCC, 2007) persists, this should favour dynamics (i) and (ii), and thus enhances the relative importance of the groundwater resource with respect to surface water resource. However, both the present positive trend in temperature and the difference of trends at the scale of the catchment may favour the less efficient of these two dynamics in terms of groundwater recharge.

Key words hydro-climatic variability; water resource; surface/subsurface interactions; snowmelt; Río Elqui, North-Central Chile

INTRODUCTION

In North-Central Chile, climate variability controlled mainly by the El Niño and La Niña events causes substantial disparity in precipitation intensity and distribution. The water balance is rarely respected at an annual scale in the catchments of the region (Favier *et al.*, 2009), mainly due to lack of understanding of orographic enhancement of precipitation, and of glacier contributions. However, the imbalance of the water budget could also arise from an underestimation of the subsurface compartment's contribution to surface runoff. A better characterization of the surface and subsurface compartments' functions and interactions to each other is therefore of prime importance to better understand Andean hydrological systems. Using the upper Elqui catchment as an example, surface and groundwater fluxes are analysed in this study, according to the spatio-temporal climate variability over 32 years (1977–2008).

BASIN DESCRIPTION AND METHODS

The Elqui catchment (9700 km^2, Fig. 1(a)), is one of the three main hydrographic networks of the Coquimbo region (Chile). It lies between latitudes 29°27′S and 30°34′S and longitudes 71°22′W and 69°52′W, and runs between the Pacific coast and the summit ridge of the Andes, which exceeds 6000 metres in some places. Like most rivers of this region, the Río Elqui exhibits a strong interannual variability in river discharge (mean annual discharge between 2 and 33 m^3/s). This river starts at the confluence of the Río Turbio and Río Claro (altitude 815 m) – its two main tributaries having catchment areas of 4200 and 1550 km^2, respectively. They both have a nival hydrological regime, typical of arid mountainous areas, with the highest river discharges recorded from November to February. From a geological point of view, the catchment consists of four major types of formation: granite, volcanic rock, volcano-sedimentary deposits, and Quaternary sedimentary cover. The latter, mainly alluvial and colluvial, can be as thick as 200 m and forms the main aquifers in the study zone (USDI, 1955). This aquifer can store and release large volumes of water (Miranda & Llanca, 2003). In the Río Turbio and Río Claro catchments as far as 3 km downstream of their confluence (Algarrobal), deposits can be more than 100 m thick, and their permeability have been assessed at 10m/d, which allow rapid groundwater transfers. Regarding the substratum, the plutonic rocks display different hydraulic conductivities as a result of fracturing at various scales (USDI, 1955).

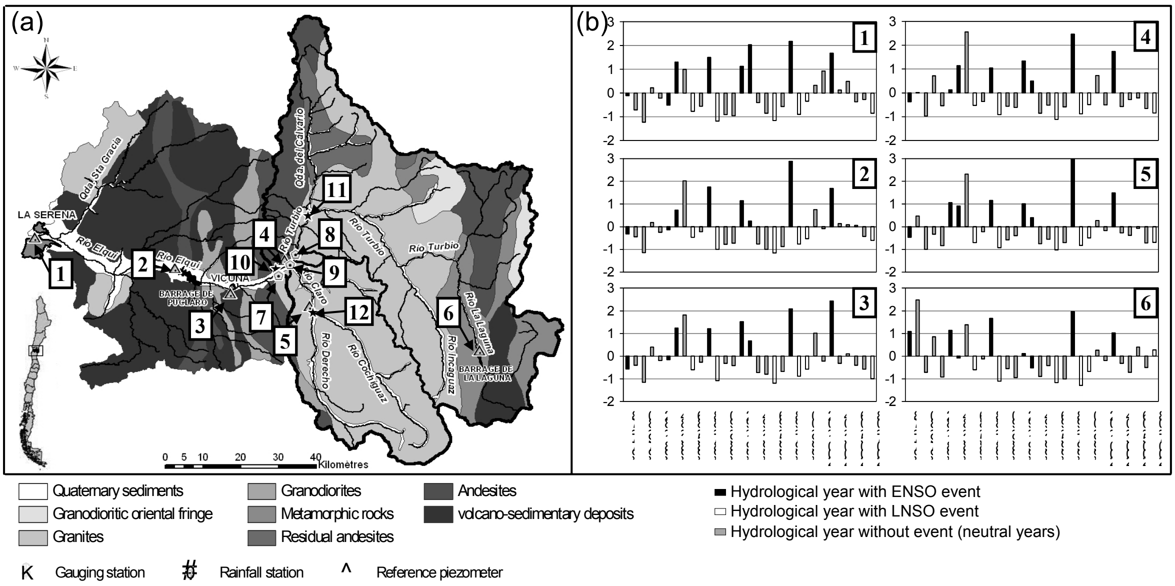

Fig. 1 (a) General context of the Río Elqui catchment (Cabezas *et al.*, 2007) and monitoring network: meteorological stations (La Serena (1), Almendral (2), Vicuña (3), Rivadavia (4), Monte Grande (5) and La Laguna (6)), gauging stations (Río Elqui at Algarrobal (7), Río Turbio at Varillar (8) and Río Claro at Rivadavia (9)), and reference piezometers (Algarrobal (10), Bocalume (11) and Monte Grande (12)); (b) Pluviometric indices (PI) calculated for the period 1977–2008 at the meteorological stations.

Climate is semi-arid in this region. Precipitation is less than 100 mm along the coast and more than 400 mm in mountain areas, where snow depths can reach several metres in exceptional years. The uneven precipitation over the catchment is analysed with pluviometric indices (PI), defined as centred reduced values for each hydrological year (April to March):

$$PI = \frac{xi - \bar{x}}{\sigma} \tag{1}$$

where xi is precipitation of year i, $\bar{x}$ is mean annual precipitation over the reference period, and σ is standard deviation of annual precipitation over the reference period.

PI, identifying excess or shortage of precipitation relative to the reference period, is compared over the last 30 years with ONI (Oceanic Niño Index) data based on Pacific Ocean surface temperature anomalies in the NIÑO 3.4 region.

For each catchment, we considered a reference piezometer representative of the natural dynamics of the subsurface compartment (no pumping and strong inter annual variability) and a hydrometric station (Table 1). Hydrological years with a high PI were selected for analysis of the existing relations between surface and subsurface compartments. Four of these years are marked by El Niño events: 1987–88, 1992–93, 1997–98 and 2002–03. Two others are neutral years (no events): 1978–79 and 1984–85. As for precipitation characterization, hydrological indexes *HI* (centred reduced discharge values) and piezometric indices *PZI* (centred reduced piezometric values) are calculated to assess variation of discharge and groundwater flow in relation to the reference period, respectively.

Table 1 Altitude of the reference piezometers and hydrometric stations for the three catchments.

	Reference piezometers	Hydrometric station
Río Turbio catchment	Bocalume (altitude 1025 m)	Varillar (altitude 860 m)
Río Claro catchment	Monte Grande (altitude 1111 m)	Rivadavia (altitude 820 m)
Upper Elqui catchment	Algarrobal (altitude 767 m)	Algarrobal (altitude 760 m)

To complete the analysis, runoff coefficient (*RC*) is also calculated :

$$RC = \frac{R}{P} \tag{2}$$

where *R* is the cumulated runoff flow volume at the outlet of the catchment, and *P* the volume of precipitation over the catchment during the hydrological year. For each catchment (Table 2), the cumulated runoff flow accounts for irrigation and canal intake (available data until 1998–99), and *P* is calculated with precipitation data interpolated at 200 × 200 m resolution using the inverse distance weighting (IDW) method. Runoff coefficient *RC* is influenced by geology, topography, soil type, land use and plant cover. It gives an idea of soil infiltration capacity and evapotranspiration, but also allows identifying the contribution of subsurface flow to surface flow when abnormal *RC* values (> 60–70%), are obtained (Jourde *et al*., 2007). Then, comparing these values with the expected *RC* values according to the characteristics of the watershed, allows quantification of the subsurface flow contribution.

Table 2 Runoff coefficients (*RC*) in the Río Turbio, Río Claro, and upper Elqui catchments for each hydrological year. Grey and light grey shading indicate years corresponding to El Niño and La Niña events, respectively. Greyed runoff coefficients were calculated with data series slightly incomplete.

		1977~78	1978~79	1979~80	1980~81	1981~82	1982~83	1983~84	1984~85	1985~86	1986~87	1987~88
Río Turbio catchment	**P (mm)**	160	253	37	201	54	210	206	350	69	108	296
	RC	26%	46%	119%	29%	69%	29%	30%	41%	79%	45%	47%
Río Claro catchment	**P (mm)**	129	193	21	191	47	200	222	359	60	99	299
	RC	88%	111%	544%	89%	236%	77%	91%	96%	258%	137%	131%
Upper Elqui catchment	**P (mm)**	150	235	33	198	52	206	210	352	66	105	296
	RC	15%	29%	132%	30%	80%	34%	41%	55%	104%	44%	39%

		1988~89	1989~90	1990~91	1991~92	1992~93	1993~94	1994~95	1995~96	1996~97	1997~98	1998~99
Río Turbio catchment	**P (mm)**	22	77	54	222	122	40	75	14	46	387	35
	RC	293%	48%	56%	16%	58%	119%	47%	204%	48%	38%	200%
Río Claro catchment	**P (mm)**	14	74	66	232	157	42	65	8	59	423	34
	RC	1027%	137%	122%	57%	127%	277%	167%	1041%	70%	93%	434%
Upper Elqui catchment	**P (mm)**	20	76	57	225	132	40	72	12	49	396	35
	RC	332%	49%	47%	21%	70%	119%	50%	208%	36%	56%	205%

RESULTS AND DISCUSSION

In the Río Turbio catchment, analysis performed at annual time scale shows that *HI* is always greater than *PZI* (Fig. 2) in the wet years (high *PI*). This results from a faster hydrological response of surface water compartment than subsurface groundwater compartment. However, *PZI* remains high in the year following a wet year, and is in most cases higher than that of the preceding year while *HI* decreases strongly. This is related to the greater inertia of the subsurface compartment, highlighted by a long recession period (1 to 2 years). Finally, shortage of rainfall results in both small *HI* and *PZI* values in years following the dry years. This yearly dynamics is less obvious in the Río Claro catchment where irrigation water feeds canals and reservoirs; this can

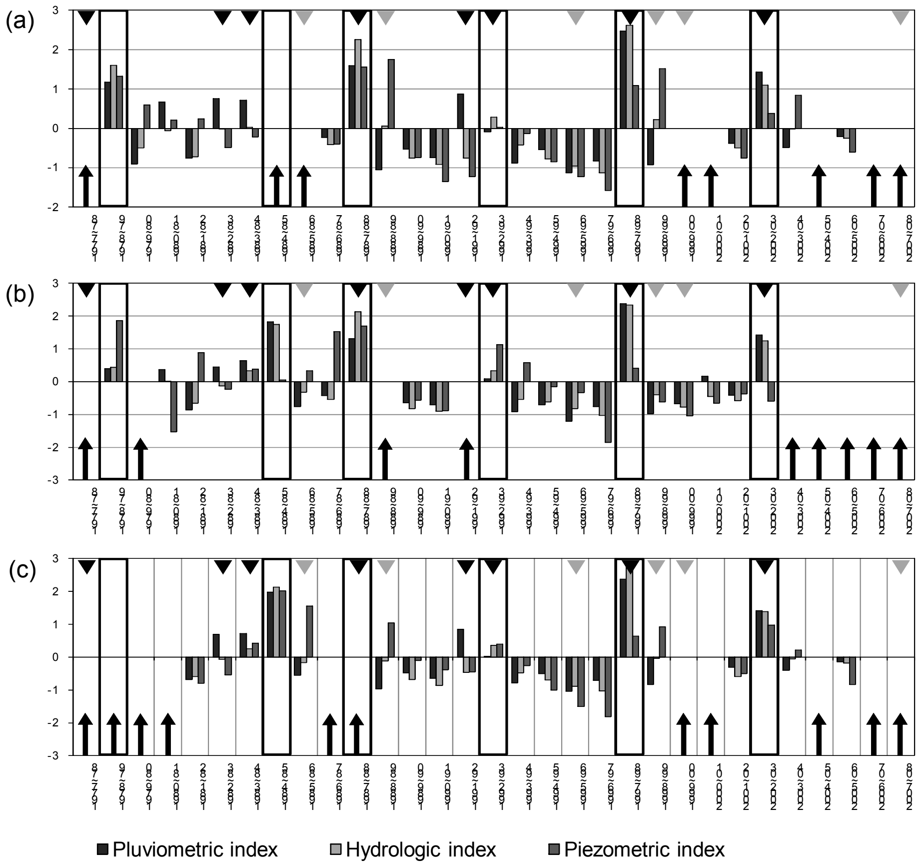

Fig. 2 Pluviometric Index, Hydrological Index, and Piezometric Index for: (a) the Río Turbio catchment; (b) the Río Claro catchment, and (c) the upper Elqui catchment. Top black and grey symbols indicate hydrological years associated to *El Niño* and *La Niña* events, respectively. Bottom black arrows indicate years with missing data.

contribute to recharge and generate both a relative *PZI* increase and an *HI* decrease (as the irrigation water comes from the Río Claro). *PZI* values higher than *HI* values are determined (Fig. 2) in dry years (low *PI*) like 1986–87, 1994–95 and 1995–96, but also in particularly wet years (high *PI*), such as 1978–79 and 1992–93. In both cases, this indicates a preponderant recharge of the subsurface compartment with respect to surface runoff; in dry years (low *PI*), this behaviour could be explained by the geology, with recharge of the subsurface compartment coming from the underlying fractured granite bedrock that, for this catchment, constitutes more than 80% of its area. Another possibility might be the contribution of water from permafrost or snow melt coming from former precipitations. However, this behaviour should occur in a more noticeable manner in the Rio Turbio catchment than in the Rio Claro catchment where elevation is lower, and thus water storage as snowpack or permafrost are less evident; this is not the case. Besides, these dry years (1986–87, 1994–95 and 1995–96) also immediately follow other dry years without noticeable precipitation, which tends to exclude this hypothesis.

In the upper Elqui catchment, indices display the same trends as those of the Río Turbio, which highlights the dominance of this major tributary on the overall dynamics of interactions between surface and subsurface compartments.

During the wet years (high *PI*), the small runoff coefficients (<100%) observed in the Río Turbio and upper Elqui catchments show that the relative contribution of the subsurface compartments to surface flows is lower than in dry years (low *PI*). This also indicates a large recharge of the subsurface compartment, as illustrated by considerable piezometric variations of nearly 50 m at the Bocalume piezometer (see Fig 4(a)). Concerning this recharge, it can take place in various places: (i) recharge in the major bed of the river when a discharge threshold is reached and river overflows; (ii) direct inflow from the subsurface compartments (aquifers) of the river tributaries; (iii) delayed recharge from the fractured bedrock, as seen above.

During the dry years (low *PI*), runoff coefficients are greater than 100% (>200% during *La Niña* events), which can be explained by the strong contribution of groundwater to surface flow. Another possibility may be the contribution of water from permafrost melt or from snow accumulation of former precipitations, as stated previously. However, as explained above, this behaviour should occur in a more noticeable manner in the Rio Turbio catchment than in the Rio Claro catchment; this is not the case. Accordingly, groundwater contribution to surface flow is the most likely hypothesis to explain these high runoff coefficients values during dry years.

Analysis of runoff coefficients in a succession of several dry years shows that the contribution of the subsurface compartment to surface flow considerably increases during the year immediately following an event at the origin of high *PI*, and then decreases gradually. Accordingly, the overall relation between surface and subsurface compartments will be a fingerprint of climate variability.

The relationship between runoff coefficients *RC* and mean annual precipitation (Fig. 3) shows that when precipitation exceeds approximately 60–70 mm, *RC* values remain between 45 and 50%; this indicates a relative equilibrium between runoff and recharge processes. Below this threshold, *RC* values increase exponentially when precipitation decreases. Figure 3 also allows us to identify two categories of hydrological years: (i) hydrological years 1980–81, 1982–83, 1983–84 and 1991–92 (light grey circles) with *PZI* > *HI*, which indicates an aquifer recharge preponderant with respect to surface runoff; (ii) hydrological years 1990–91, 1995–96 and 1996–97 (arrows) with a noticeable contribution of the subsurface compartment to surface flow (high *RC*) as a result of several dry years. Hence, the above mentioned threshold may be used as a warning for drought; indeed, when precipitation remains below this threshold, recharge to the subsurface compartments is zero and the subsurface compartment feeds the river; the consequences are high hydric deficits, highlighted by a severe piezometric decrease in the aquifers.

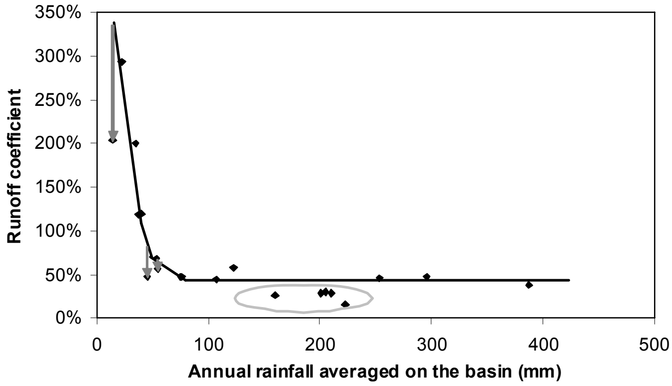

Fig. 3 Variation of the Río Turbio runoff coefficients *versus* mean annual precipitations over the Río Turbio catchment.

Regarding the spatial variability of runoff coefficients, *RC* values are much higher in the Río Claro catchment than in the Río Turbio and upper Elqui catchment; this highlights a greater contribution of the subsurface compartment in the Río Claro catchment, as confirmed by hydrological modelling (Ruelland *et al.*, 2011). This could be explained by the smaller proportion of alluvium in the Río Claro than in the Río Turbio catchment (12.6% cf. 23.5% of catchment area). As a result, the volume of water stored in the subsurface compartment (alluvium) would be potentially smaller in the Río Claro catchment and generate higher cumulated runoff flow volumes (and thus *RC* values). However, as seen above, the most likely hypothesis may be related to the geology, with the recharge of the subsurface compartment coming from the underlying fractured granite bedrock that covers 80% of the catchment area. For hydrological years characterized by

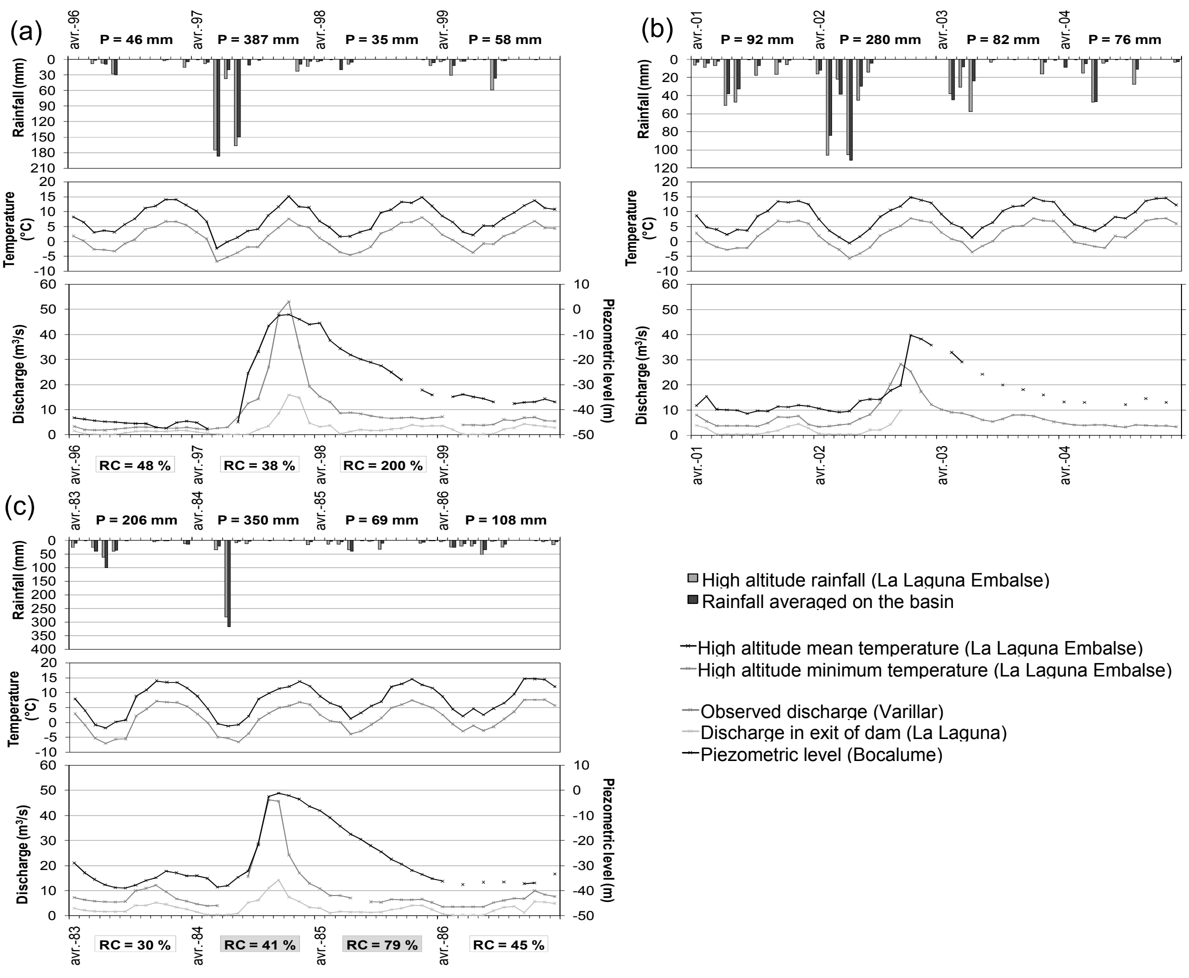

Fig. 4 Hydroclimatic monthly variations for hydrological years: (a) 1996–1999 associated with dynamics 1, (b) 2001–2004 associated to dynamics 2, and (c) 1983–1986 associated to dynamics 3.

high *PI*, it is seen from monthly data (Fig. 4) that three dynamics of interactions between the surface and subsurface compartments can be identified: (i) *dynamic 1* corresponds to a rise in piezometric level that precedes the river discharge increase. It is observed for two *El Niño* events (1987–88 and 1997–98) with high precipitation for two to three months; (ii) *dynamic 2* corresponds to a rise in piezometric level that takes place after river discharge increase. This dynamic is observed for two *El Niño* events (1992–93 and 2002–03), with high precipitation for a longer period (4–6 months); (iii) *dynamic 3* corresponds to a simultaneous increase of piezometric level and river discharge, showing the same transfer dynamics between surface and subsurface compartments. Dynamic 3 is observed in neutral years (1978–79 and 1984–85), with large precipitation during a very short time (one week). If the climate trend marked by an increased frequency of *El Niño* events in recent decades (IPCC, 2007) persists, this should favour dynamics 1 and 2, and enhance the relative importance of groundwater resources with respect to surface water resources. Indeed, these dynamics are associated with large piezometric level rises: + 45 m and + 35 m, for dynamics 1 and 3, respectively, although it is “only” + 30 m for dynamic 2.

The intervals of minimum and mean temperature corresponding to the onset of discharge increase and piezometric levels rise are shown in Fig. 5. These intervals are defined by the monthly temperatures before and after the onset of discharge increase and piezometric level rise, respectively. The intervals of temperature corresponding to the onset of discharge are relatively stable (Fig. 5(a)). In contrast, the temperature intervals corresponding to the onset of piezometric level rise exhibit a high variability (Fig. 5(b)), with dynamic 2 associated with noticeably

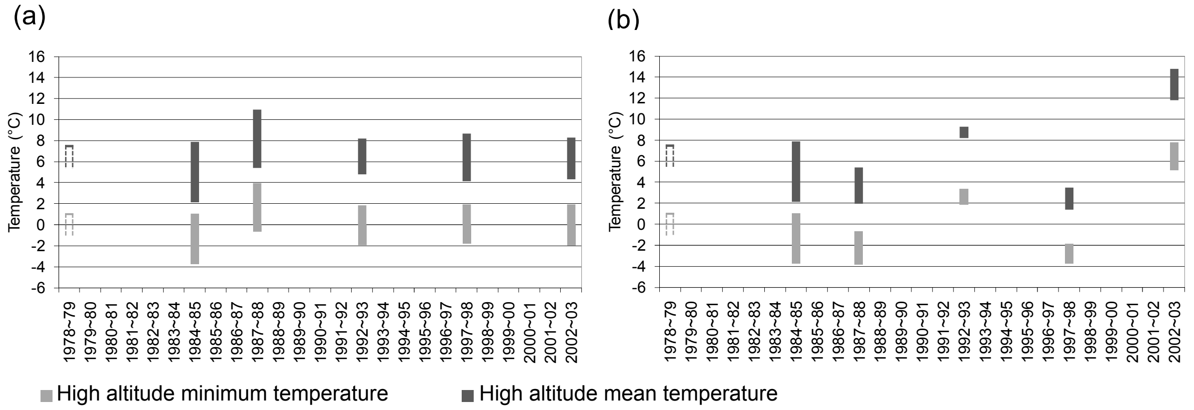

Fig. 5 Temperature intervals corresponding to the onset of (a) discharge increase, and (b) piezometric level rise. Intervals are given for minimum and mean temperatures at La Laguna station (3160 m).

higher temperature. Aquifer recharge therefore involves processes depending on factors other than temperature.

The logarithmic increase of piezometric levels *versus* time (dynamics 1, Fig. 4(a)) indicates a rapid recharge of the subsurface compartment, which subsequently decreases. This dynamics could be the consequence of a gradual temperature rise (Fig. 4(a)) that causes a slower melt of the snow cover and thus enhances infiltration with respect to runoff in a first stage. In contrast, the exponential increase of piezometric levels *versus* time (dynamics 2 and 3, Fig 4) indicates a delayed recharge of the subsurface compartment. For dynamic 2, this delayed rise in piezometric level than in discharge could be related to aquifer recharge resulting from the overflowing of the Río into its major bed. Besides, precipitation over 4–6 months (1992–93 and 2002–03) affects the structure of the snow cover (hardening and freezing), which can stabilize the cover and delay the snowmelt processes. For dynamic 2, the intervals of temperature corresponding to the onset of discharge, but especially to the onset of recharge, are higher than that for other dynamics (Fig. 5). Figure 6 shows that this dynamic is dominated by surface runoff processes related to a rapid snowmelt, which prevents a large infiltration towards the subsurface compartment.

An analysis of temperature changes in this region (Souvignet *et al*., 2010) shows that both maximum and minimum monthly temperatures have positive trends. Besides, different trends in temperature between the higher and middle elevations indicate a possible variation of the lapse rate—an important feature in the snow accumulation and melt processes. If the present trend in temperature persists, the frequency of dynamic 2, less efficient than other dynamics with respect to groundwater recharge, may thus increase in the future.

At the daily timescale, a strong correlation between temperature and river discharge can be observed for the three dynamics (Fig. 6).

As for the monthly time scale, river discharge increases in two stages: the first stage can be attributed to snowmelt, and the second stage is the main increase of flow, resulting from substantial snowmelt when the *high altitude minimum temperature* exceeds the threshold of 0°C. In dynamic 1 (Fig 6(a)), the main increase in the piezometric level preceding that of river discharge takes place when *high altitude minimum temperatures* remain above –3°C and below 0°C, previously mentioned threshold for a sufficiently long period (estimated to be about a month). Within this temperature range, snow melts and tends to infiltrate the soil layers rather than forming surface runoff. River discharge therefore remains stable while the piezometric level rises. In dynamics 2 (Fig 6(b)), the main river discharge increase, which precedes the rise in piezometric level, takes place when *high altitude minimum temperatures* exceed the –3°C threshold, and do not remain lower than the 0°C threshold for long enough. The snow thus melts more quickly, with melt rates greater than filtration rate, resulting in a strong river discharge increase.

The much later rise in piezometric level might be related to aquifer recharge resulting from the overflow of the Río Turbio from its minor to its major bed, when a 30 m^3/s river discharge

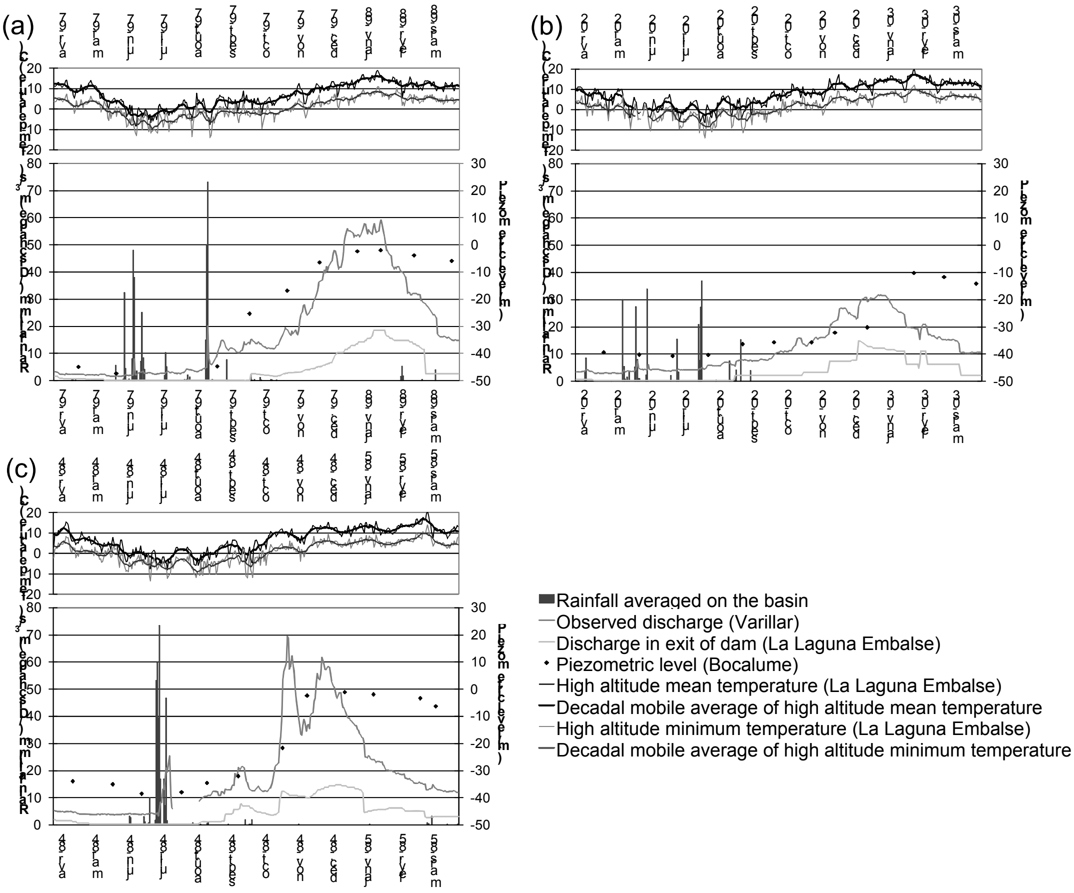

Fig. 6 Daily records of climatic and hydrologic variables for selected hydrological years: (a) 1997–1998 characteristics of dynamics 1, (b) 2001–2004 characteristics of dynamics 2, and (c) 1983–1986 characteristics of dynamics 3.

threshold is reached (Fig 6(b)). Another reason, as proposed in the monthly analysis, would be the change in the structure of the snow cover, more resistant to melt and thus delaying the contribution of melt water to surface flows.

In dynamic 3 (Fig 6(c)), the increase in both the piezometric level and river discharge occurs when high altitude minimum temperatures exceed –3°C and remain within the range previously identified (–3°C and 0°C) but for a shorter period than in dynamic 1. After exceeding the –3°C threshold for several days, a fall in high altitude minimum temperatures to below –3°C causes the refreezing of melt water. When high altitude minimum temperatures overpass the 0°C threshold again, this triggers an increase in river discharge and then a rise in piezometric level, when the 30 m^3/s discharge threshold corresponding to flooding into the major bed is attained.

These temperature thresholds and ranges may thus be used as warning pointers for flood risks downstream in the watershed, especially when dynamic 3, associated with large flood peaks, is likely to occur.

CONCLUSION

Analysis of runoff coefficients over the last decades shows that when annual precipitation is lower than approximately 60–70 mm, the relative equilibrium between runoff and recharge processes is broken, which may generate a large groundwater deficit that will result in a high hydric deficit at the watershed scale. Accordingly, this threshold may be used as a warning for drought. The spatial variability of the runoff coefficients shows higher contributions of the subsurface compartment in zones where granites are the most represented, thus highlighting the recharge of the aquifer from the underlying fractured granite bedrock. Accordingly, such zones would be suitable for sustainable groundwater resource exploitation.

Analyses at the monthly time scale performed for the Río Turbio catchment over the 1977–2008 period allowed us to identify three distinct dynamics of interaction between surface and subsurface compartments. Each of these dynamics is associated with a large groundwater recharge followed by a relatively long recession of the piezometric levels (1–2 years) and a shorter recession of the river (4–6 months). As climate trend is marked by an increased frequency of *El Niño* events in recent decades (IPCC, 2007), this should favour dynamics 1 and 2, associated with such events, and thus enhance the relative importance of the groundwater resource with respect to surface water resource. However, the trend in temperature at the catchment scale may favour the less efficient dynamics (dynamic 2) in terms of groundwater recharge.

Finally, a daily analysis allowed identification of temperature thresholds and ranges that may explain both the onset of surface runoff and groundwater recharge; they could be used as warning pointers for flood risks downstream the watershed, especially when dynamic 3 is likely to occur.

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