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Unraveling complex hydrogeological processes in Andean basins in south-central Chile: An integrated assessment to understand hydrological dissimilarity

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Key words: Mountain hydrology, Water balance, Hydrological similarity

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Abstract

Groundwater storage, drainage and interbasin water exchange are common hydrological processes, but often difficult to quantify due to a lack of local observations. We present a study of three volcanic mountainous watersheds located in south-central Chile (~36.9° S) in the Chillán volcanic complex (Chillán, Renegado and Diguillín river basins). These are neighboring basins that are similar with respect to the metrics normally available for characterization everywhere (e.g., precipitation, temperature and land cover). In a hydrological sense, similar (proportional) behavior would be expected if these catchments would be characterized with this general information. However, these watersheds show dissimilar behavior when analyzed in detail. The surface water balance does not fit for any of these watersheds individually; however, the water balance of the whole system can be explained by likely interbasin water exchanges. The Renegado River basin has an average annual runoff per unit of area on the order of 60 to 65% less than those of the Diguillín and Chillán rivers, which is contradictory to the hydrological similarity among the basins. To understand the main processes that control streamflow generation, two analyses were performed: i) basin metrics (land cover, geologic, topographic and climatological maps) and hydro-meteorological data analyses and ii) a water balance model approach. The analyses contribute to a plausible explanation for the hydrogeological processes in the system. The soils, topography and geology of the Chillán-Renegado-Diguillín system favor the infiltration and groundwater movements from the Renegado River basin, mainly to the neighboring Diguillín basin. The interbasin water exchanges affect hydrological similarity and explain the differences observed in the hydrological processes of these three apparently similar volcanic basins. The results highlight the complexity of hydrological processes in volcanic mountainous systems and suggest that a simple watershed classification approach

based on widely available data is insufficient. Simple local analyses such as specific flow analysis with a review of the geology and morphology can contribute to a better understanding of the hydrology of volcanic mountainous areas.

1.- Introduction

Mountainous watersheds are complex hydrological systems that contribute runoff to lowland areas, provide a favorable temporal redistribution of winter precipitation to spring and summer runoff, and reduce the variability of flows in the adjacent lowlands (Viviroli et al., 2011). This redistribution function of mountainous watersheds is critical for both the ecosystem and the main economic activities in south-central Chile (e.g., hydropower, agriculture, industrial activities and water supply). These activities are highly dependent on water storage in snow, glaciers or groundwater, and therefore on the related water availability during spring and summer (Meza et al., 2012).

Despite the hydrological importance of mountainous watersheds in providing freshwater resources (40% of the world population depends on mountainous regions for water supply, Beniston, 2003), little is known about key hydrological processes in these systems. Processes such as mountain block recharge (Viviroli et al., 2007), surface and groundwater connections (Hughes, 2004) and interbasin groundwater transfer (Zanon et al., 2014) are still rather poorly understood in most mountainous areas around the globe. The intrinsic complexity of recharge processes and the fact that such processes are extremely difficult to observe further contributes to this problem (Ajami et al., 2011; Hartmann et al., 2014).

Genereux and Jordan (2006) discuss how documenting and quantifying the long-distance (interbasin) subsurface movement of water between different groundwater systems and the influence of groundwater on surface water quantity and quality are of fundamental significance in hydrogeology and hydrology. Such processes have not been sufficiently studied in high-elevation basins (Cortés et al., 2011) and are often poorly understood in places, mainly because they often remain hidden from our current measurement methods (Wagener et al., 2007) and are often costly to quantify (Zanon et al., 2014). In south-central Chile, the Chillán-Renegado-Diguillín system (Figure 1) has been studied very little. A first attempt was recently carried out by Arumí et al. (2014), who used recession flow analysis and stable isotope analysis to estimate groundwater storage trends in the upper part of the Diguillín basin. They concluded that the Diguillín River is supported by two main groups of springs, one at the headwaters, connected to a volcanic aquifer, and one downstream of the junction with its main tributary (the Renegado River). Complementarily, Naranjo et al. (2008) described that the Chillán volcanic complex presents several small thermal and cold springs distributed along the perimeter of the volcanic complex, such as those described by Arumí et al. (2014).

Within this context, this paper goes further in analyzing and integrating different sources of information to i) understand the groundwater connection and storage-runoff process and ii) estimate the interbasin flow exchange between Andean basins in south-central Chile, taking as a case study the system of the Chillán-Renegado-Diguillín river basins. In order to achieve these goals, we used an approach based on i) a basin metrics (land cover, geologic, topographic and climatological maps) and hydro-meteorological data analyses and ii) a water balance model analysis.

2.- Study Area and Data

The study area includes three neighboring volcanic mountainous watersheds located in south-central Chile at the hillslope of the Chillán volcanic complex: the Diguillín River (207 km^2), Renegado River (127 km^2) and Chillán River (210 km^2) basins (Figure 1.b).

To derive the basin metrics, climatological, land cover, morphological and geologic maps and an aerial picture of the study area were constructed. The land cover map (Figure 1.a) was constructed based on the 300 m resolution map presented by Bontemps et al. (2013). The Bontemps et al. (2013) land cover map is derived from global time series acquired by the Envisat MERIS Full and Reduced Resolution dataset (FR and RR, respectively) and from SPOT-Vegetation (SPOT-VGT) sensors. The spatial resolution of the source data varies from 300 to 1000 m and the time periods available lie within the years 1998 to 2012. Complementarily, an aerial picture of the watersheds based on ESRI World Imagery (Figure 1.b), a terrain map based on the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) of 1 arc-second satellite stereo images (Figure 1.c) and a geologic map (Figure 1.d) extracted from Sernageomin (2003) (scale 1:1.000.000) were constructed. The climatological maps constructed use mean annual precipitation (Figure 1.e) and temperature (Figure 1.f). Additionally, several metrics were included in Figure 1 to further characteristics the basins.

Within and close to the study area there are only three rain gauges (Figure 1.b), all of them located at low altitudes. Therefore, to estimate precipitation and temperature values for each basin and better represent its spatial distribution within the study area, AgMERRA datasets of 0.25° resolution (~25 km) for the 1980-2010 period were obtained (Ruane et al., 2015). AgMERRA datasets provide daily, high-resolution and continuous meteorological series over the 1980-2010 period. These datasets combine daily resolution data from retrospective analyses (the Modern-Era Retrospective Analysis for Research and Applications) from NASA (Rienecker et al., 2011) with in situ and remotely-sensed observational datasets for temperature, precipitation, and solar radiation (Ruane et al., 2015). The AgMERRA datasets exhibited negative bias in precipitation (~30 to 50% less) for the study area (Ruane et al., 2015). To address this issue, they were amplified to achieve the mean annual total estimated for the study area using the isohyets method and annual precipitation isohyets published by DGA (1987).Finally, in order to analyze the runoff generation processes in the basins, monthly streamflow data were obtained from the Renegado at Invernada (RI), Diguillín at San Lorenzo (DSL) and Chillán at Esperanza stations (Figure 1.b). Although RI and DSL have more recent records, CE does not have data beyond 1994, since the gauging station was destroyed by a flood in 1995. Therefore, the common period of 1980-1994 was used in order to use a comparative period for the analyses.

Figure 1.a shows that the land cover of the three basins is very similar (cover distribution percentages are included in the map). The three basins are mostly covered by evergreen and semi-deciduous forests (Figueroa et al., 2007) (~78% in Chillán and ~65% in Diguillín and Renegado) and to a lesser extent by forest-shrubland-grassland (~17% in Chillán and ~30% in Diguillín and Renegado). In addition, a small portion of the Chillán River basin (~1.5 km^2) is covered by permanent snow and ice associated with the glacier documented by Zenteno (2009) and Rivera and Bown (2013).

The elevation map (Figure 1.c) shows that the three basins have the same maximum elevation, but that their elevation distributions differ. The elevations of the Renegado River basin (median elevation of ~1550 masl) are concentrated slightly above those of the Diguillín (median elevation of ~1450 masl), while both are above those of the Chillán River basin (median elevation of ~1291 masl). The elevation ranges of the Diguillín (min/max 700/3171 masl) and Renegado (min/max 825/3180 masl) river basins are similar, while that of the Chillán River basin, which has a lower minimum elevation, is slightly wider (min/max 423/3188 masl). In addition, all of them present the highest elevations at their eastern limits (Chillán Volcano) and slopes in a W-E direction.

Most of the area of the watersheds is composed of units of volcanic origin with the common characteristic of having been formed by lavas cooled outside of the volcano, resulting in highly fractured soil layers deposited among the basins. The geologic map (Figure 1.d) shows six main deposits. Four of them are volcanic deposits related to the Chillán volcanic complex, which cover 84% of the total area of the system. The remaining surface is covered by granodiorites and diorites. The Renegado River basin has the lowest proportion of volcanic deposits coverage (75% of its total area) and the Diguillín River basin has the highest (90% of its total area). In the upper third of the Renegado River basin, at its southern edge, a granodiorite-diorite deposit (commonly an impermeable layer) is found. Such deposits are also found at the headwaters of the Diguillín River.

Frontal systems produce most of the precipitation from deep stratiform clouds that develop along warm and cold fronts, covering large areas (usually larger than the study area) (Garreaud et al., 2009). Additionally, winds and frontal systems move in a W-E direction. Therefore, the spatial variability of precipitation within the study area (Figure 1.e) is highly longitudinal (in terms of amounts) due to the increase in precipitation caused by orography

(Garreaud et al., 2009), while latitudinal variations are mostly noticed at larger (e.g., regional) scales.

According to the corrected AgMERRA datasets, the mean annual precipitation of the system is around 2283 mm while the mean annual air temperature is 10.5 °C, ranging from 4.4 °C in the coldest month of winter (June) to 18.0 °C in the hottest month of summer (January). The Chillán River basin shows the lowest annual precipitation (2207 mm against 2371 and 2308 mm for Renegado and Diguillín river basins, respectively) although precipitation is practically the same across the system. Regarding the temperature distribution, the Chillán, Renegado and Diguillín river basins present mean annual temperatures of 10.2, 9.4 and 9.2 °C, respectively.

After an initial review of basin maps and metrics (Figure 1), the basins of the Chillán-Renegado-Diguillín system would typically be classified as similar and, therefore, in a hydrological sense, it is reasonable to expect that they would "behave similarly" (Winter, 2001) and that main hydrological processes would be equivalent or proportional.

Complementarily, to further investigate the behavior of the basins, the monthly runoff per unit of area for each basin (q), so-called specific flow were calculated and compared among basins. Results related are shown in section 4.1.

3.- Model and Methods

3.1 Water Balance Model

To complement the previous analyses, an approach based on a water balance was used. Each basin independently and the whole system of three basins were analyzed in order to estimate how much water is “gained” or “lost” by each basin. Considering that the modeling approach seeks to identify potential interbasin groundwater flows and that the study area, like most of the Andes, is a data-sparse area (Viviroli et al., 2011), the lumped water balance model presented in Muñoz (2010) and Muñoz et al. (2014) was used (Figure 2).

The model includes a rainfall-runoff component that considers the watershed as a double storage system: unsaturated (US) and saturated (SS). US represents the water stored in the unsaturated soil layer as soil moisture and SS represents the water that covers the saturated soil layer. The model needs two inputs: precipitation (PM) and potential evapotranspiration (PET). The model output is the total runoff (ETOT) at the watershed outlet, and includes both the groundwater contribution (ES) and surface runoff (EI), the amounts of which are calculated through six calibration parameters, plus one for the precipitation modification. Additionally, the model includes a snowmelt-runoff component that calculates the snowfall (Psnow) based on precipitation above the 0 degree (base temperature at which liquid precipitation starts) isotherm falling as snow. Psnow is stored in the snow storage system (SN), from which the melting calculations are performed based on the concept of the degree-day method (Rango and Martinec, 1995). Thus, the potential melting (PSP) is estimated, and then based on the snow stored, the actual melting (PS) is calculated. Then PS is distributed into the rainfall-runoff model through the factor of snowmelt transference F. Additionally, to consider the sub-monthly variability of the air temperature in the basin, a factor of minimum snowmelt (DM), which is defined as a fraction of the snow stored in the basin, is incorporated into the model. Table 1 presents a brief description of the model parameters, their influence on the model and the regular range considered for parameter estimation. A further description of model design and equations can be found in Muñoz (2010) and Muñoz et al. (2014).

As forcing, the model requires precipitation and potential evapotranspiration. The corrected AgMERRA datasets were used to estimate basin precipitation and the Thornthwaite method (Thornthwaite, 1948) and AgMERRA temperature series were used to estimate basin potential evapotranspiration. The Inverse Distance Weighting method was used to estimate representative values for each basin.

3.2 Monte Carlo Framework

To ensure the closure of the water balance, the model includes a scale factor (A) that permits the inputs of water (precipitation) in the Muñoz (2010) model to be increased or decreased. In order to estimate potential interbasin water exchanges, factor A was estimated for each basin and for the system. Considering that around 0.75% of the area of the Chillán basin is covered by permanent snow (Figure 1.c) and, moreover, the lack of measurements and knowledge of the characteristics of the glacier located at the headwaters of the Chillán River basin, the water balance approach did not include the glacier melting contributions for the modeling stage of either the system or the Chillán River basin model.

An approach based on Monte Carlo simulations and regional sensitivity analysis (Wagener et al., 2001) was first used to estimate values of A. A was defined as the median of the best 10% models according to a predefined objective function (the Runoff Coefficient Error – ROCE). Based on prior experiences (Muñoz et al., 2014, Pinto, 2014, Toledo et al., 2015), 10,000 simulations were performed using randomly selected parameter values (sampled according to a uniform distribution) within the initial range defined in Table 1.

Aimed at first ensuring the closure of the water balance, ROCE was used as objective function (Eq.1). ROCE captures the overall accuracy of the water balance i) by combining the flows into one characteristic hydrological descriptor, the mean annual runoff coefficient (defined as Q/P), and ii) by minimizing the absolute difference between total measured and simulated runoff. The absolute error in the runoff coefficient is then calculated as follows, where the mean annual flow $\overline{Q}$ and the mean annual precipitation $\overline{P}$ are used for the simulated (s) or observed (o) flows (van Werkhoven et al., 2009),

$$\mathrm{ROCE} = \mathrm{abs}\left(\frac{\overline{Q_s}}{\overline{P}} - \frac{\overline{Q_o}}{\overline{P}}\right) \qquad \text{[Eq.1]}$$

After defining A (using ROCE), 10,000 new simulations were performed and parameter values were estimated as the median of the best 10% behavioral models. To define the behavioral models, the Nash-Sutcliffe Efficiency (NSE) was used, where models with NSE values greater than 0.75 were considered as behavioral (Van Liew et al. (2005) classified models with NSE over 0.75 as “good”).

In order to demonstrate the representativeness of the models and results, two periods with available common data among basins were considered to carry out the analyses. Period 1, from 1980 to 1987 (P1), and Period 2, from 1988 to 1994 (P2), were defined. In addition, a cross validation was performed, i.e., P1 was used for calibration and P2 for validation, and then P2 was used for calibration and P1 for validation.

4.- Results

4.1 Specific Flow Analysis

To analyze the behavior of the basins, the annual precipitation distribution over the study area and the monthly runoff per unit of area for each basin (q), so-called specific flow, were plotted (Figure 3). Figure 3 shows that the Renegado River basin, which is located between the Chillán and Diguillín rivers, yields much less specific flow (about 2 to 4 times less) than its neighboring basins, even though they are in close proximity, appear to be similar and, moreover, are driven by similar climatic patterns (Garreaud et al., 2009, Pinto, 2014). Additionally, the Diguillín River shows larger q values than the Chillán River for most of the year (about 1 to 1.4 times more between April and November), although this relationship is inverted in summer, when the Chillán River basin shows larger q values (1.1 to 1.4 times) than the Diguillín River basin (Figure 3.b).

We expect basins with similar metrics to have similar runoff generation processes (Reed et al., 2006, Wagener et al., 2007); and therefore, similar specific discharge curves should be expected. However, significant differences among basins can be noticed here. The specific discharge curves provide insights into the main characteristics and the dominating hydrological processes of the basins (and the system) that allow us to obtain and analyze complementary information in order to redefine our conceptual model of the system.

A first line of evidence that may explain the observed behavior is related to aspects of geology and morphology. The geology of the upper section of the Diguillín watershed is described in detail by Dixon et al. (1999), Sernageomin (2003) and Naranjo et al. (2008). They explain the strong influence of the volcanic processes associated with the Chillán volcanic complex, which is composed of several types of structures created by different processes that have occurred over approximately 650 million years. They found mostly lavas of high permeability caused by fast cooling processes with consequent fracturing in rocks.

Naranjo et al., (2008) described most of the lavas that filled the Renegado basin valley, highlighting three formations: i) Los Pincheira lavas: deposited in Middle Pleistocene, these lavas covered the Renegado valley by crossing a glacier and thereby forming large walls (very steep hills over 100 m tall), which give the valley a U-shape. At the lower border of the glacier, the lava flow opened and the walls disappeared; ii) Diguillín Lavas: deposited in Middle Pleistocene after the Los Pincheira lavas, these lavas descended through the Renegado valley but were blocked by the former and forced to deviate to the Diguillín River, forming the surface connection with that river and defining the western edge of the Renegado River basin; and iii) Atacalco lavas: these lavas were deposited in the Middle-Upper Pleistocene and filled the Renegado valley. They accumulated in the Atacalco area (upper north Diguillín basin) and laterally covered both the Los Pincheira and Diguillín lavas. All these lavas are characterized by a dense jointing, favoring the fast movement of groundwater.

The volcanic structures that cover most of the system area were found to be highly permeable. Navarro (2015) measured an infiltration capacity of the soil of 200 mm/hr at the headwaters of the Renegado River basin. In addition, the described deposition sequence caused the Renegado valley to be developed at higher altitudes than the Diguillín, and at elevations similar to those of the Chillán River basin (Figure 4). This situation, combined with permeable and fractured soil layers composed of lava deposits, favors the rapid infiltration process but also gravitational movements of groundwater. Therefore, groundwater likely moves from the Renegado to the Diguillín River basin gravitationally.

These fast infiltration and interbasin groundwater movement processes would explain both why the Renegado River basin does not have significant surface runoff and the results observed from the specific flow analysis.

Complementarily, Masiokas et al. (2009) described that the glacier located at the headwaters of the Chillán River basin has been reduced over the last ~150 years from 30 to 6 km^2. This reduction might explain the higher specific flows (in comparison with the Diguillín and Renegado) observed during summer (Figure 3).

4.2 Watershed Model Analysis

Table 2 shows the results of the modeling approach (model parameters) for each basin modeled independently and for the system as a whole. Table 2 shows that factor A, which ensures the closure of the water balance, is markedly different among the basins. Analyzing each basin as an independent system, it is observed that for the Chillán and Diguillín river basins, precipitation must be amplified by ~24–32% in order to close the water balance. On the other hand, for the Renegado River basin, the results are the opposite, as precipitation must be reduced by ~35–40% to achieve closure of the water balance. Additionally, if the Chillán-Renegado-Diguillín system is assumed as a closed unit, precipitation must be increased by ~14–20% (Table 2).

To estimate interbasin groundwater flows, the mean annual precipitation of each basin and of the system was multiplied by the mean value of A (considering the two calibration periods). As result, a total of 2661 mm is received by the system while totals of 2802, 1487 and 3015 mm are received by the Chillán, Renegado and Diguillín basins, respectively. Based on the differences with the system, and considering the proportions of volume to basin area, the Diguillín and Chillán basins receive 355 and 141 mm, respectively, from the

311 Renegado River basin. Meanwhile, the Renegado River basin loses this amount of water plus 363 mm that goes to neither the Chillán nor the Diguillín River (upstream of the gauge station). This water probably goes downstream to the junction of the Renegado and Diguillín rivers to the springs documented by Arumí et al. (2014).

It is important to point out that the modeling stage did not include glacier melt contributions; therefore, the interbasin groundwater flows should actually be slightly smaller for the Chillán River basin and higher for the Diguillín River downstream of the junction with the Renegado River.

Table 2 shows that the highest C_k values were obtained for the Renegado River basin, suggesting that its groundwater system empties faster and thus varies more throughout the year than those of the Diguillín and Chillán basins. On the other hand, the lowest C_k values were obtained for the Chillán basin, indicating that it is the most stable groundwater system among the basins studied. C_k values of the Renegado River basin indicate that its groundwater system empties nearly twice as fast as the whole system. In addition, the C_k values for the Diguillín basin suggest that it empties slightly faster (1.2 to 1.3 times) than the whole system, but that it also has more variability, which may be influenced by an interbasin groundwater flow from the Renegado to the Diguillín basin.

Regarding the maximum surface runoff coefficient (C_{max}), the Diguillín basin shows the highest values and the Renegado basin the lowest. These results suggest that the Diguillín River basin tends to be more saturated and therefore higher runoff rates can be achieved. Moreover, they suggest that the Renegado River basin tends to infiltrate more water; as a consequence, the surface runoff is reduced. For the Chillán basin, C_{max} values slightly lower than those of the total system are observed. This result may be influenced by the morphology of the basin, where the lower third of the Chillán basin is flatter (in comparison to the rest of the study area), favoring infiltration over surface runoff. In addition, the Diguillín and Renegado basins show higher and lower C_{max} values than the total system respectively, suggesting that i) the Diguillín/Renegado basin generates more/less surface runoff than the average of the study area (the system), and ii) in the Renegado River basin, the infiltration process predominates in streamflow generation.

5.- Discussion

An initial (broad) review of the metrics of the three basins suggests that they are likely to be similar. They are neighboring basins with similar climatic patterns and land cover and the aerial view showed similar qualitative characteristics. In addition, the geology, from a broad view can also be considered to be similar for the three basins, because it is dominated by permeable volcanic material. Moreover, the effect of the glacier flows in summer can be assumed to be negligible due to the small size observed in the land cover map (~1.5 km^2, which is around 0.75% of the area of the Chillán basin). Therefore, the three basins should behave similarly and their hydrological processes are expected to be equivalent.

However, the review of the hydrological data showed that the basins behaved dissimilarly. The Renegado River basin exhibited less specific flow than its neighboring basins, suggesting interbasin water exchanges (Renegado→Chillán and Renegado→Diguillín). In addition, a glacier melting process might be considered for the Chillán River basin after observing the specific flows in summer plus the glacier reductions documented by Zenteno (2009). Such reductions would explain the high specific flows observed in summer for the Chillán River basin, while larger contributions from the Renegado to the Diguillín would explain the higher q values observed for the Diguillín River basin during the course of the year.

The foregoing is in agreement with the modeling approach results. Since the orography produces an increase in precipitation with altitude in the Andes (Garreaud et al., 2009), and considering that the AgMERRA datasets include data from rain gauges (which are only located at low altitudes), values of A higher than one might be expected. However, for the Renegado River basin, contradictory results were obtained.

Although these results may initially be opposite to expectations, they suggest that the Renegado River basin exchanges water with both the Diguillín and Chillán basins. As the Renegado River basin "loses" water, the Diguillín and Chillán basins "gain" it, which explains the higher and lower values for each basin than those estimated for the combined system. These results are consistent with the springs described by Arumí et al. (2014) in the upper third of the Diguillín River basin and downstream of the junction with the Renegado River. The geologic map indicates that soil layers in the Renegado River basin are highly permeable, and the morphologic map shows differences in elevations among rivers (Figure 4). Therefore, gravitational movement of groundwater from the Renegado River to both the Chillán and Diguillín river basins is plausible.

The connections described are in agreement with the geomorphological information and are consistent with the water balance approach. Regarding the geology, permeable and fractured soil layers favor rapid infiltration and gravitational water movements from the Renegado River basin. Moreover, the deposition sequence caused the Renegado valley to be formed at higher altitudes than the Diguillín and at elevations similar to the Chillán

River basin (see Figure 4). Therefore, it would be expected that more water is transferred to the Diguillín River in comparison to the Chillán River basin.

Tóth (1963; 1999) and Sophocleous (2002) have described the importance of topographic relief for local groundwater flows, highlighting that the higher the topographic relief, the greater the importance of local groundwater systems. Interbasin flow can occur even without geological heterogeneity in such circumstances. Therefore, in the Chillán-Renegado-Diguillín system, topographic relief could play an important role in water redistribution, as has been suggested by the specific flow analysis.

Besides the Renegado to Diguillín interbasin water exchanges identified upstream of the Diguillín at San Lorenzo stream gauge station, another exchange of similar magnitude downstream of the station was identified during the modeling stage, reinforcing the observations by Naranjo et al. (2008) and Arumí et al. (2014). A modified conceptual representation of the complete system after including such connections and the main basin processes is shown in Figure 5.

The finding of interbasin groundwater transfer has important implications for hydrology, ecology and land-water management. For the Chillán-Renegado-Diguillín system, for example, volcanic processes conditioned the geology and morphology, forming fractured and permeable soil layers, but also forming valleys at different elevations within a few kilometers. These conditions favor interbasin exchange and help to explain the differences observed in the hydrology in three apparently similar basins. Interbasin groundwater flow diminishes surface water discharge from basins in which interbasin groundwater flow originates and increases discharge from those receiving this water (Genereux and Jordan, 2006). This phenomenon coincides with the observed behavior in the Chillán-Renegado-

Diguillín system. Along the same lines, Zanon et al. (2014), Montgomery et al. (2003) and Langman and Ellis (2013) have found similar patterns in different sites around the globe, all of which were located in volcanic mountainous areas.

Zanon et al. (2014) showed that two nearly identical or at least very similar neighboring basins (similar in precipitation, temperature, vegetation, soils, geology and topography) in the Central Cordillera of Costa Rica proved to have markedly different behavior. They found interbasin groundwater flow in which one basin (Arboleda River basin) was receiving a large input of groundwater from a neighboring basin (Toscanazo River basin). In addition, the authors describe that these basins are located in a volcanic area with a combination of high-permeability lava beds and lower-permeability ignimbrites and pyroclastics. Montgomery et al. (2003) studied the interbasin groundwater movement in basins of the Chilean Altiplano (in northern Chile), attributing the interbasin water movements to the geological formations and fractured volcanic rock aquifers. In the same way, Langman and Ellis (2013) found in the southern Rio Grande Valley in the southwestern USA that in a volcanic area with permeable layers and geological faults, deep groundwater interbasin connections would be allowed. Larned et al. (2015) stated that streams in tectonically active volcanic landscapes are characterized by complex groundwater-surface water interactions that include interbasin transfers of groundwater. Similar to our study, the investigations described above attributed the interbasin water exchanges and basin dissimilarities in runoff to the volcanic deposits and geological (and relief-related) formations. Therefore, for volcanic mountainous watersheds, complex groundwater interactions across neighboring basins need to be expected.

Hydrological similarity is a concept widely used by hydrological practitioners for estimating available water resources or the probability for hydrological extremes. In particular, it is the basis for runoff predictions in ungauged basins, to assist in the understanding of hydrological processes or to make hydrological predictions (Blöschl et al., 2013; Wagener et al., 2007). In volcanic mountainous watersheds, geology and relief have been shown to be key aspects to consider before assuming hydrological similarity. A good understanding of groundwater movement in adjacent small basins makes possible an accurate representation of the motion of groundwater within the large basin that they form (Tóth, 1963). Therefore, identifying such movements could lead to better water management and planning at basin scale. However, most volcanic mountainous watersheds are difficult to access; therefore, hydrological, climatic and geological information is usually non-existent or not as detailed as desired. Mountain watersheds are essential for supplying and supporting the water needs of adjacent lowlands (Viviroli et al., 2007); additional efforts are therefore needed to adequately estimate complex hydrological processes in such watersheds. Based on the research presented here, a comparison of the specific discharge of neighboring basins would provide key insights into potential interbasin exchanges, contributing to a better understanding of complex mountainous hydrological systems.

6.- Conclusions

This study addressed the issue of hydrological dissimilarity in neighboring volcanic mountainous basins located in the Andean region of south-central Chile. Although the basins had apparently similar characteristics, their hydrological behavior proved to be markedly different. This is explained by the special geological and topography-related characteristics of the volcanic complex where the basins are located, which determine the transfer of water from the Renegado River basin to Chillán and Diguillín river basins. These results highlight the complexity of hydrological processes in volcanic basins of mountainous areas, making it necessary to consider additional efforts to understand the main processes in such systems. Further analyses, such as specific flow analysis, would help us better understand and, moreover, identify potential interactions. It also suggests that practical approaches for hydrologic predictions based on similarity principles as currently applied in the region are insufficient, and that deeper hydrological understanding than currently utilized needs to be embedded to achieve robust estimates of likely hydrological behavior.

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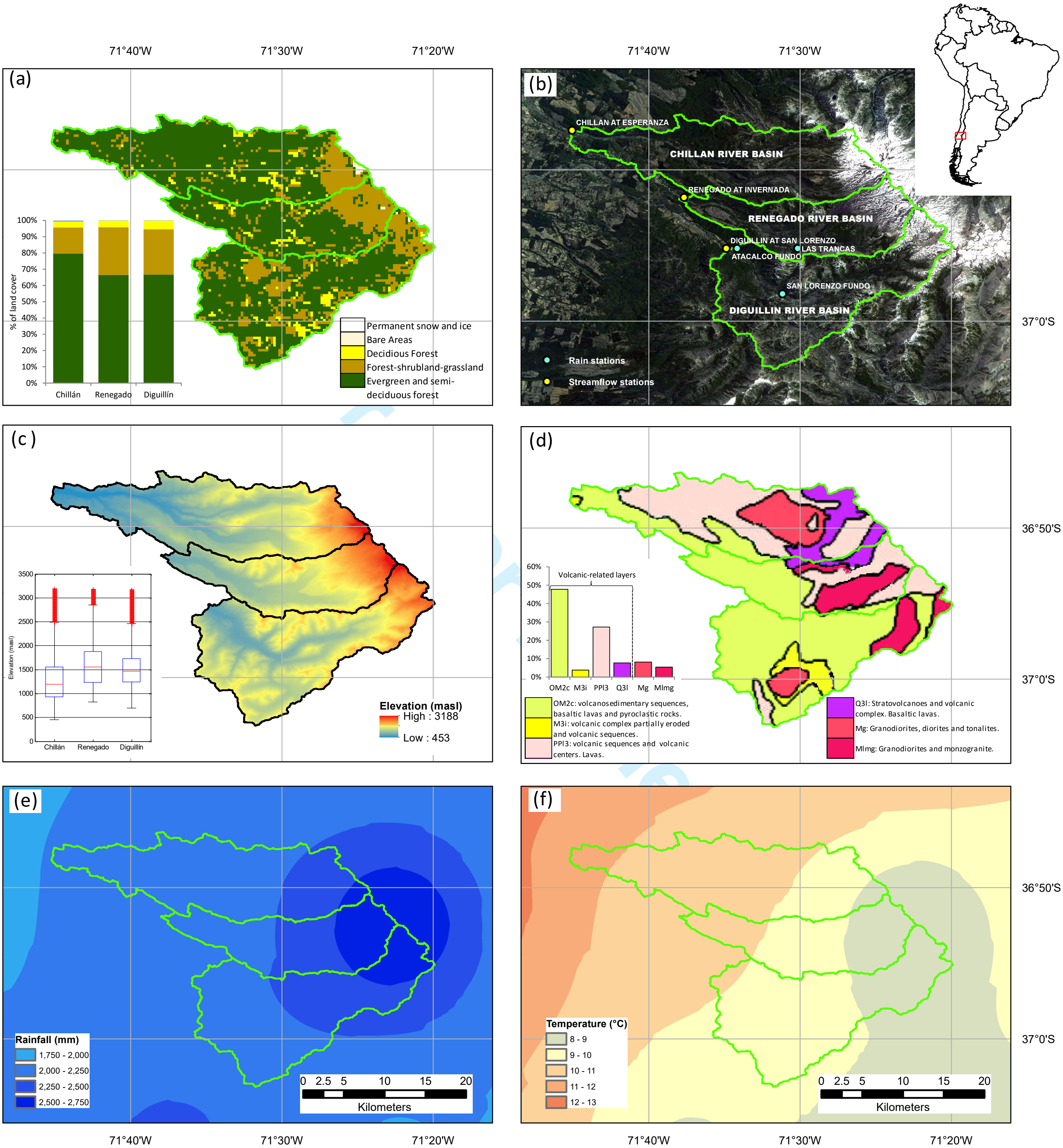


Figure 1. Study area and hydrological similarity maps, including land cover map (a), aerial view (b), terrain map (c), geologic map (d), and mean annual rainfall (e) and temperature (f) climatological maps.

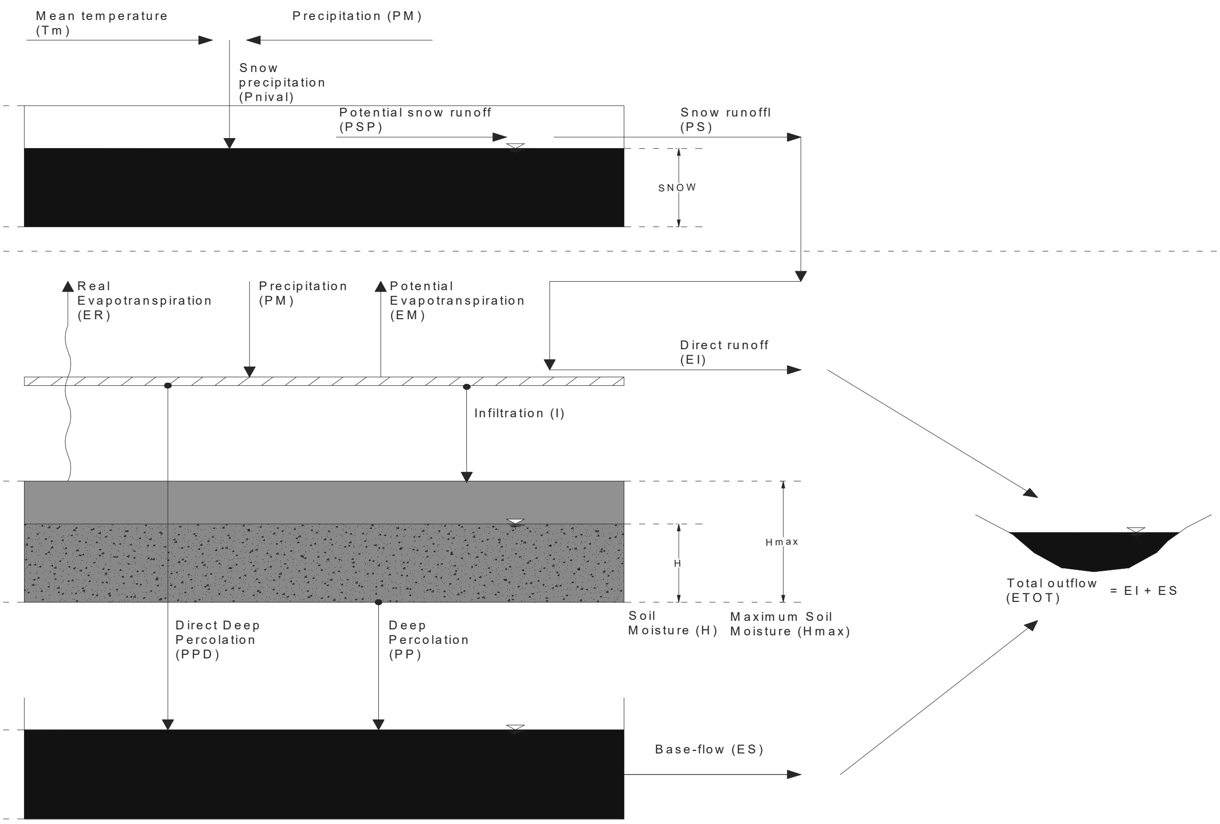


Figure 2. Diagram of the Muñoz (2010) lumped water balance model.

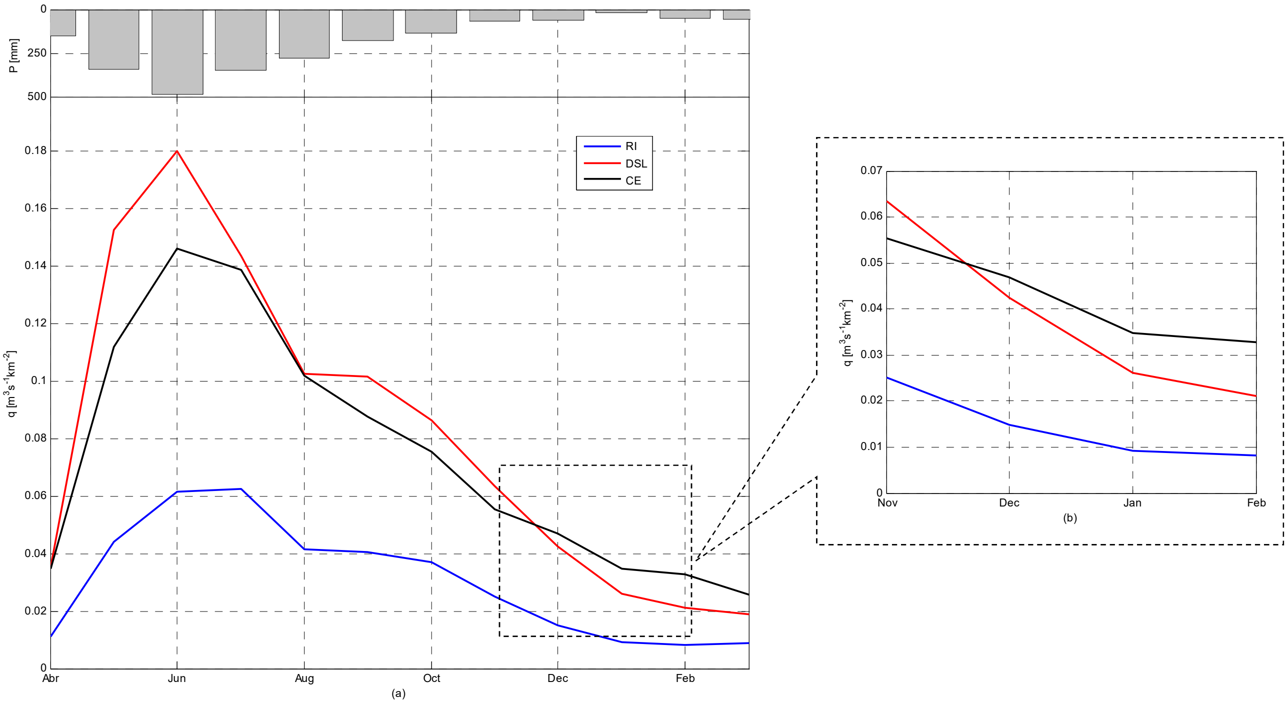


Figure 3. Seasonal precipitation and seasonal variation curves of flow per unit of area (q) for the Renegado at Invernada (RI, blue line), Diguillín at San Lorenzo (DSL, red line) and Chillán at Esperanza (CE, black line) River basins (panel a). Panel b shows a detailed view for the summer season between December and March.

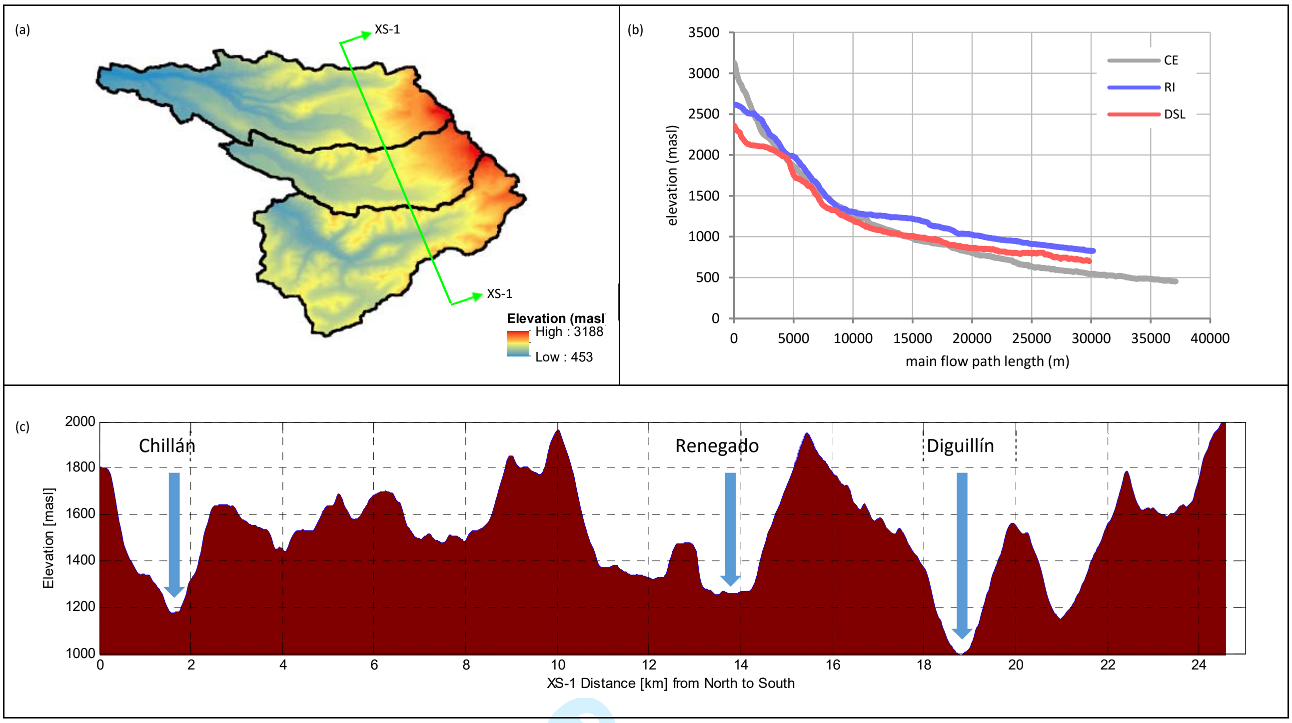
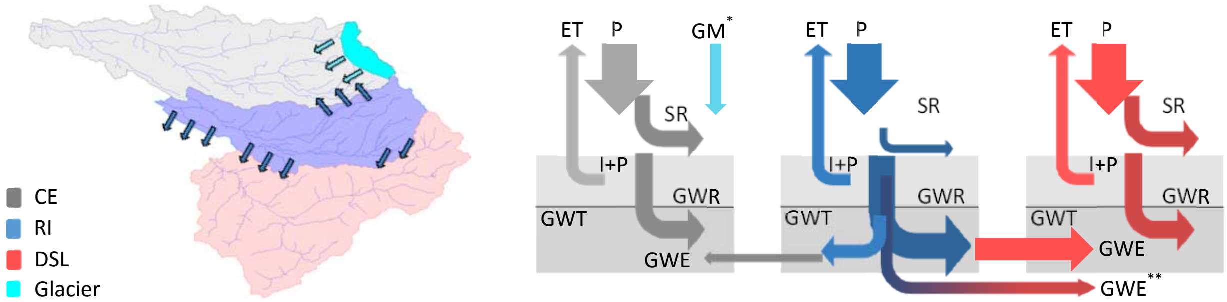


Figure 4. Cross section of the Chillán-Renegado-Diguillín hydrological system at the piedmont of the Chillán volcano.



CE: Chillán at Esperanza River basin (gray shaded area); RI: Renegado at Invernada River basin (blue shaded area); DSL: Diguillín at San Lorenzo River basin (light red shaded area).
ET: Evapotranspiration; P: Precipitation; SR: Surface Runoff; I+P: Infiltration and Percolation; GWR: Groundwater Runoff; GWT: Groundwater Table; GWE: Groundwater Exchange; GM: Glacier-melting.
* Indicates that the GM process is only occurring in summer.
** Indicates that the GWE process is also occurring downstream of the Diguillín at San Lorenzo streamflow station.

Figure 5. Conceptual interpretation of the hydrological processes and connections on the system after a review of the basins' metrics (maps), hydro-meteorological data and a water balance approach.

Table 1. Description of the model parameters, adjustment factors and range for the rainfall- and snowmelt-runoff model.

	Parameter	Description	Influence on	Range
Rainfall module parameters	C_{max}	- Maximum runoff coefficient when the sub-surface layer is saturated.	- EI	0.05 – 0.85
	P_{Lim} (mm)	- Limit of rainfall over which PPD exists.	- PPD	0- 500
	D	- Percentage of rainfall over P_{Lim} transformed into PPD.	- PPD	0 – 100
	H_{max} (mm)	- Maximum capacity of the soil layer to retain water.	- C_{max} and ER	180 - 500
	PORC	- Fraction of H_{max} that defines the soil water content restricting the evaporation processes.	- H_{crit} and ER	0 - 100
	C_k	- Subterranean runoff coefficient.	- ES	0.05 – 0.85
	A	- Adjustment factor of the precipitation data.	- PM	0.80^{*} – 2.50
Snow module parameters	M (mm °C^{-1})	- Parameter of the Degree-day method that defines the fraction of the snow storage which is melted. The method also considers a base temperature (Tb=0 °C) at which melting starts.	- PSP, PS	1 – 12
	DM	- Minimum rate of melting when Tm < Tb.	- PSP, PS	0.00 – 0.50
	F	- Fraction of the real snowmelt that goes to EI.	- EI	0.00 – 1.00

EI: Direct runoff; PPD: Direct deep percolation; ER; Real Evapotranspiration; ES: Groundwater runoff; PM: Precipitation; PET: Potential evapotranspiration; PSP: Potential snowmelt; PS: Actual snowmelt.

* For the Renegado River basin the initial range of factor A was changed to 0.50 – 2.50 because it was found to be identifiable for values close to 0.60.

Table 2. Calibration values of the input modification factor (A) and parameter, and NSE-related values for the median of the 10% best behavioral models after fixing A.

		ROCE	NSE						NSE calibration	NSE validation
		A	Cmax	Hmax	D	Plim	PORC	Ck		
Chillán	P.1	1.240	0.364	393	34.2	113.5	42.5	0.284	0.87	0.86
	P.2	1.299	0.362	388	33.9	94.5	43.1	0.280	0.87	0.87
Renegado	P.1	0.655	0.290	417	41.0	117.4	31.9	0.534	0.85	0.81
	P.2	0.599	0.360	390	24.4	128.2	33.5	0.635	0.82	0.84
Diguillín	P.1	1.298	0.417	398	21.0	97.3	54.6	0.402	0.90	0.88
	P.2	1.315	0.479	402	14.9	91.3	42.9	0.333	0.89	0.90
System	P.1	1.135	0.408	368	28.5	110.1	43.7	0.317	0.89	0.90
	P.2	1.196	0.415	388	22.5	80.8	45.6	0.287	0.91	0.91

P.1: Period between 1964 and 1979.

P.2: Period between 1980 and 1994.