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# Andean Mountain Groundwater, Drinking Water Sources, and Vulnerability: A Case Study in Central Chile

*José Luis Arumí, Enrique Muñoz and Ricardo Oyarzún*

## Abstract

This chapter presents a study of the Diguillín basin in central Chile where geology is dominated by the Nevados del Chillan volcanic complex. The headwater of the basin has two watersheds: Renegado creek and Alto Diguillín. The hydrogeology was studied using field surveys, streamflow gauging, environmental tracers, and a hydrological model. Surface water balance does not fit for both watersheds because there is a deficit/excess of superficial runoff. Renegado soils are predominantly sands over a basement composed of fractured rock; infiltration of rain and snowmelt predominates over surface runoff, resulting in about 5 m<sup>3</sup>/s of depth groundwater that flows to the Diguillín River, discharging in a cluster of springs located 3 km downstream of the surface connection. Therefore, drinking water availability for the communities located at the Renegado watershed is limited to some springs that are located around the valley. There is a significant expansion of second home construction in the area of the Renegado watershed; because of its skiing and hot springs, it is a major tourism center. Due to the extensive use of septic tanks, located above the highly permeable soils that overlie the fractured rock aquifer, there is concern about how water quality may be affected.

**Keywords:** mountain groundwater system, volcanic geology, water balance, vulnerability, drinking water sources

## 1. Introduction

Mountain watersheds are rather complex hydrological systems that provide water resources to downstream communities for irrigation, industrial activities, human consumption, and ecosystem sustainability [1]. Considering that 40% of the world population are dependent on mountainous regions for its water supply [2], a proper understanding of the hydrological processes of mountain systems is critical to ensure the sustainable development of mountain communities.

In mountain watersheds, water can be stored and released by a combination of hydrological components that may include glaciers, snowpack, lakes, and groundwater. Of these storage components, the less understood is groundwater, which in many cases is neglected. However, in some areas, groundwater release can be the only available water source for local communities during the dry season.

Worldwide, there is a consensus that in central Chile, climate change will affect the dynamics of glaciers and snowpack, increasing the amount of melting in spring and early summer and reducing the amount of melting in late summer and early autumn, which is low-flow season in Mediterranean climate areas, like central Chile [3–5]. Thus, groundwater storage and liberation will be more important in terms of the resilience of mountain communities to climate variability, especially in mountainous areas where the presence of fractured porous rock systems produces conditions for the maintenance of minimum flow due to the liberation of groundwater [6–9].

In the Andean watersheds of the Central Valley of Chile (33.5°–41.5°S), there is little information about the role that fractured porous rock groundwater systems play in the generation of streamflow, mainly because most research has been focused on snow hydrology, as snowmelt drives the streamflow generation in central Chile during spring and summer [3–5]. However, in south central Chile (36°–41.5°S), where the Andes Mountains are lower than 3000 [masl], snowmelt ends in mid-January and until the beginning of the rainy season in mid-April; streamflow in the rivers depends on base flow generated by groundwater exfiltration. Therefore, understanding groundwater recharge, storage, and release processes becomes critical to manage mountainous hydrological systems and therefore to protect water resources.

On the other hand, it is important to highlight that Chile, during the last 20 years, has experienced an increase in income levels, which produced a strong demand for second homes, especially in high-demand tourism areas, especially in the central area of the country. One of these tourism areas is the Renegado Valley, which is associated with a world-class ski center that also has hot springs, the “Termas de Chillán” complex. At the end of the last century, the valley was part of a large farm that was exploited for forestry and cattle feeding. In the 1990s, the land was divided, and the tourism-related development process began, resulting in a community that stretches along the 30-km mountain valley without any planning for both drinking and wastewater.

This chapter presents the results of research work that had as an initial objective the study of the hydrology of the Renegado Valley, as water availability was identified as a key limitation for the further development of the area. Therefore, the initial research question was why does the Renegado Creek exhibit a permanent shortage of streamflow during the dry season?

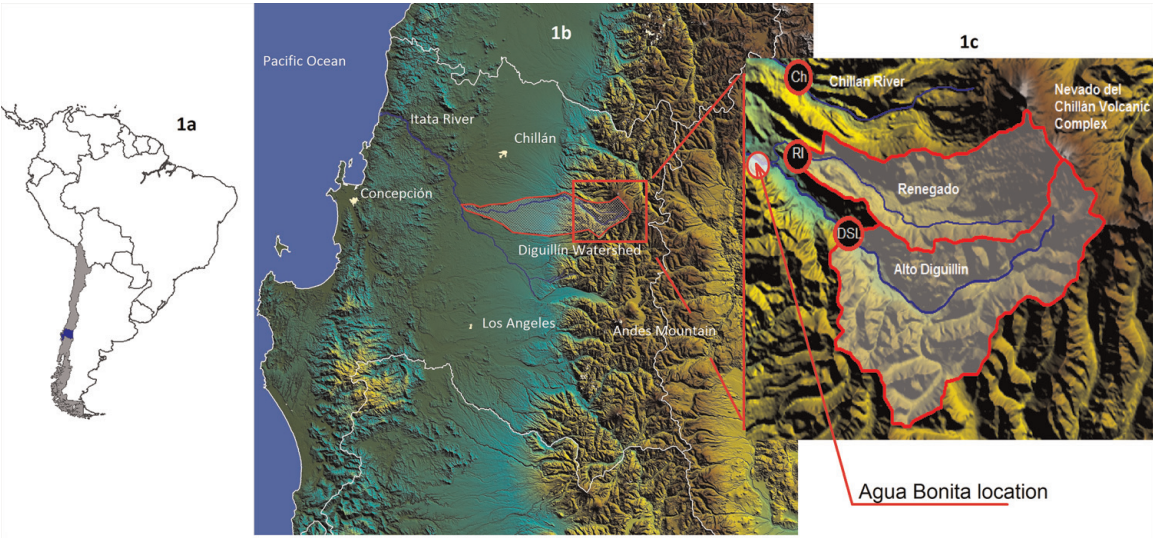
The answer to that question is rooted in the hydrogeological characteristics of the Renegado Valley [10–12]. But that answer, which will be presented in this chapter, raised a second question about the vulnerability of the drinking water sources of the communities that are being developed along the mountain valley.

## **2. Methods and materials**

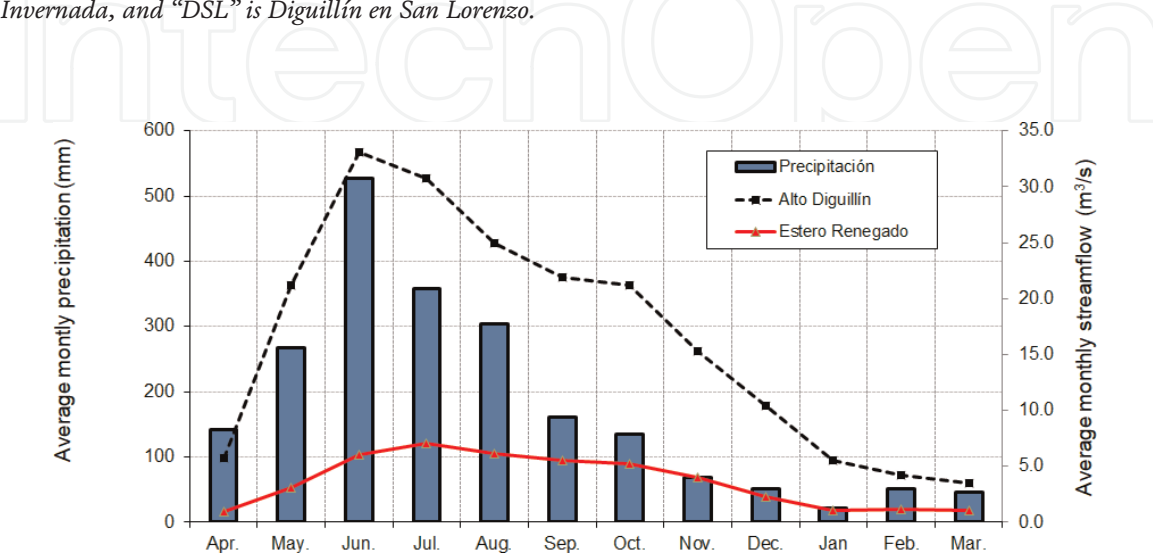
### **2.1 Study area**

The Diguillín River watershed is located in central Chile at latitude 36.9°S and longitude 71.4°W (**Figure 1a**) and drains the southwestern section of the Nevados de Chillán volcanic complex, located in the Andes Mountains (**Figure 1b** and **c**). At the upper part of the watershed, there are two gauging stations that define the two sub-watersheds that are shown in **Figure 1c**: Alto Diguillín (207 km<sup>2</sup>) which is controlled by the Diguillín en San Lorenzo (DSL) gauging station and Renegado Valley (127 km<sup>2</sup>) which is controlled by the Renegado en Invernada (RI) gauging station.

In the Alto Diguillín sub-watershed, there is a national protected area called Reserva Ñuble and some farms dedicated to forestry and cattle production; in contrast the Renegado Valley, as described before, has been intensively populated for second homes, due to the tourism value associated with the Volcan Chillán Ski Area and the existence of hot springs. Additionally, there is a marked difference between both sub-watersheds when the streamflows are compared. The Renegado Creek exhibits much lower values than the Alto Diguillín (**Figure 2**), more than can be easily explained based on watershed extent. In fact, the Renegado Creek exhibits lower specific flows (flow rate per unit of area), in comparison with those of the neighboring watersheds Alto Diguillín and Chillán (used for comparison in **Figure 3**), even when those rivers exhibit the same East to West orientation and a similar rainfall distribution. That lower specific flow is consistent with the water availability limitation for the development of the community along the valley, which is one of the research questions of this work.

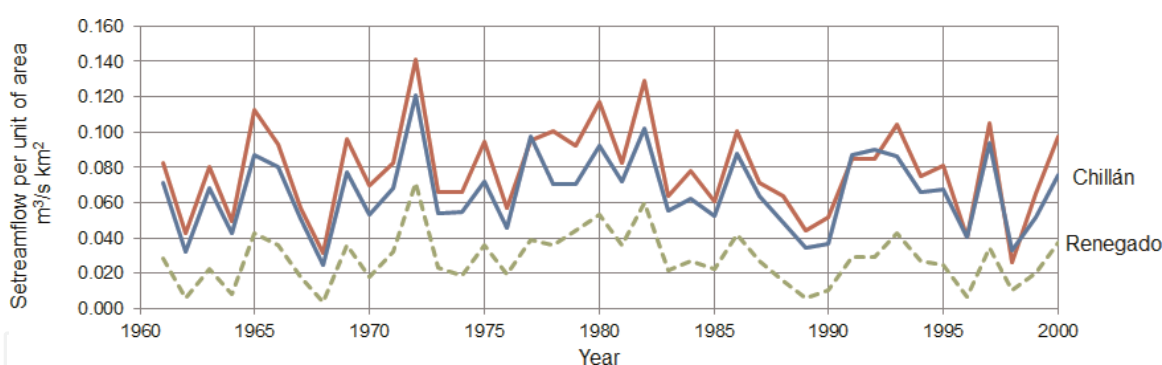


**Figure 1.**  
(a) Diguillín watershed location in South America; (b) the Biobío Region, showing the main cities of Concepción, Chillán, and Los Angeles; (c) location of the Renegado Creek and Alto Diguillín sub-watersheds at the upper section of the Diguillín watershed, the Agua Bonita location where a large cluster of springs flows to the Diguillín River, and also the location of gauging station: “Ch” is Chillán River, “RI” is Renegado en Invernada, and “DSL” is Diguillín en San Lorenzo.



**Figure 2.**  
Average rainfall and streamflow measured at the Diguillín River at San Lorenzo and Renegado Creek in Invernada.





**Figure 3.** Comparison of measured monthly specific streamflow for Alto Diguillín and Chillán Rivers with Renegado Creek.

## 2.2 Field research

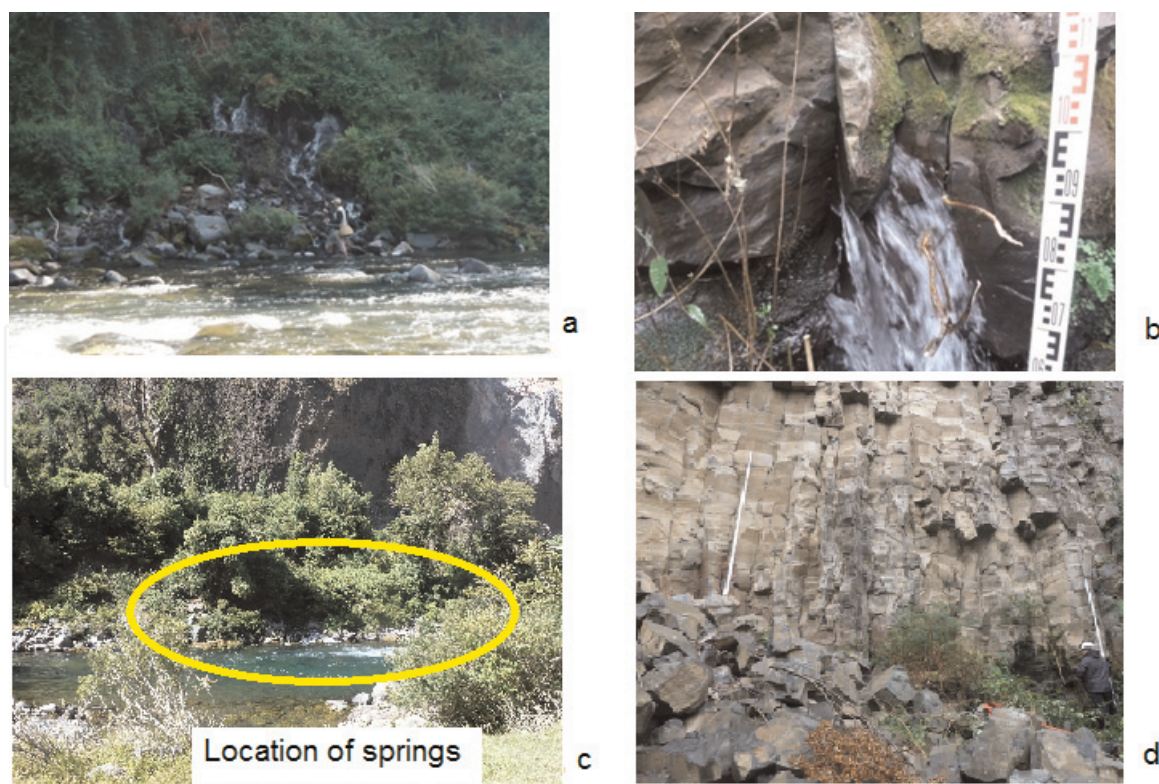
Due to the existence of several infrastructure projects that have been proposed for the Diguillín River watershed, previous studies were considered as the base for the initial characterization of the watershed. The study for irrigation planning conducted by the National Commission of Irrigation (CNR) in the Itata River basin, which concludes that the Diguillín River receives flow from groundwater discharge in the middle part of the watershed, which becomes relevant during the low-flow season between January and April [13], was particularly important. Hydrological data for the watershed (streamflow and rainfall) were collected from the database of the Chilean Water Authority (Dirección General de Aguas, DGA).

In addition, to incorporate local knowledge about the Diguillín River, a series of interviews of various stakeholders such as the river authority (Junta de Vigilancia), villagers of every sector, mountaineers, and sport fishermen was carried out in order to determine if the existence of springs that feed the Diguillín River was true.

The available geological information came from two principal publications that describe the geology of the upper part of the Diguillín River watershed [14, 15]. Both references explain the marked influence of the volcanic processes associated with the Nevados de Chillán Complex on the development of this watershed. The geological information [15] includes a geological map at 1:50.000 scale which was digitalized in a raster format and virtually mounted on Google Earth, using Global Mapper software.

As a complementary analysis for the identification of hydrological processes, a hydrogeochemical data analysis was performed. Samples of rain, snow, surface water, and springs collected from the Renegado, Diguillín, and Chillán Rivers during 2012 and 2013 were considered. Samples were chemically analyzed for mayor cations and anions (i.e.,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{HCO}_3^-$ ,  $\text{SO}_4^{2-}$ ) in the Laboratory of Soil and Plants Analysis of the University of Concepción. Additionally, concurrent samples were derived to the Chilean Commission of Nuclear Energy for the environmentally stable isotopes analysis ( $^{18}\text{O}$  y  $^2\text{H}$ ). Further description about the technics used can be found in Arumí et al. [10]. Also, samples were analyzed for  $^{222}\text{Rn}$  by the Environmental Laboratory of University of La Serena using a DurrIDGE RadH<sub>2</sub>O equipment [16].

The analysis of secondary information suggested the existence of a cluster of springs discharging into the Diguillín River, in a gorge located downstream of the confluence of the Renegado Creek and the Diguillín River. This sector was studied in detail by walking surveys, which allowed the identification of a 2-km section of the river with clusters of fractured rock-related springs that discharge to the



**Figure 4.**  
(a) Large spring draining to the Diguillín River in Agua Bonita; (b) water is channeled through multiple small fractured rock springs (b); (c) springs are located at the base of cliffs of a gorge that can be reached only in summer conditions when the river flows are minimal; (d) typical fractured rock profiles observed along the Renegado sub-watershed at the location of the spring cluster.

Diguillín River (**Figure 4**) in a location locally known as “Agua Bonita” (**Figure 1c**). All the springs were located at the bottom of a hundred-meter-high cliff, in a very difficult-to-access area located along a gorge that can be reached only in summer when river flows are minimal.

Because locations were of difficult access, measurements taken in Agua Bonita were only possible at the end of the dry season (March 2012 and 2013). These measurements were carried out using the FlowTracker Acoustic Doppler Velocimeter, from SonTek. Streamflow was measured at the Diguillín River, above and below this 2-km section. It was found that the river flow increases from 2.5 to 7.4 m<sup>3</sup>/s; therefore, spring discharge was estimated as 4.9 m<sup>3</sup>/s.

### 2.3 Water balance analysis

The water balance was analyzed through a conceptual model approach to better understand the hydrologic behavior of the Renegado and Alto Diguillín watersheds [12]. The model simulates the rainfall-runoff and snowmelt-runoff processes. The rainfall-runoff component was modeled through a lumped model that considered the watershed as a double storage system: subsurface and groundwater. The snowmelt-runoff model calculates the snowfall based on precipitation above the zero-degree (base temperature at which melting starts) isotherm falling as snow. The melting calculations are performed based on the concept of the degree-day method [17]. Thus, the potential melting is estimated, and then based on the stored snow, the real melting is calculated. The model needs the rainfall and the potential evapotranspiration as inputs, and the output is the total runoff at the watershed outlet, including both subterranean and direct runoff, the amounts of which are calculated through six calibration parameters, plus two for the input

modification (useful in the case of non-representative PM and PET data). Further description about the model, its implementation, and calibration can be found in [12].

The major findings in the water balance of the Renegado-Diguillín system were that the low specific flow condition at the Renegado Valley and the existence of the cluster of springs that flow into the lower Diguillín River suggest that a significant part of the base flow that is produced at the Renegado Valley is transferred through a subterranean connection to the spring cluster [12]. To reproduce such conditions, the Renegado-Diguillín model was modified by adding a groundwater connection, where a percentage of the Renegado base flow was transferred to the Diguillín watershed. This finding is consistent with an indirect estimation of groundwater storage evolution [11] based on recession flow analysis. In that work it was shown that whereas for the Upper Diguillín basin and the period 1961–2010, no increase or decrease trend in groundwater storage was detected; for the Renegado sub-basin, it was possible to observe a statistically significant decreasing trend in subsurface water storage.

This water balance analysis allowed the understanding of the observed condition, i.e., that the Renegado Creek presents lower specific flows than the Alto Diguillín River. By adding a groundwater connection between watersheds, it was possible to better simulate the monthly flows of these two basins. Thus, a main conclusion from these studies was that a groundwater contribution provided from the Renegado watershed to the Diguillín watershed was necessary to adequately reproduce the hydrogeological behavior of the Renegado-Diguillín hydrological system. After the calibration processes, it was possible to estimate that about 77% of the base flow is lost through groundwater seepage from the Renegado watershed. That flow was estimated to be around  $4.6 \text{ m}^3/\text{s}$ , very close and on the same order of magnitude to the  $4.9 \text{ m}^3/\text{s}$  measured at the springs cluster located in the Diguillín River.

### 3. Results and discussion

#### 3.1 A plausible explanation for the groundwater connection

As hydrological processes should be highly connected with the geological features in fractured rock settings, it is important to give a look into local geological and lithological conditions in order to have a wider insight into the system under study.

The geology of the upper section of the Diguillín watershed is strongly influenced by the volcanic processes associated with the Nevados del Chillán volcanic complex [15, 16]. This volcanic complex is composed of several types of structures created by different processes that have occurred for approximately 650,000 years [15].

The Nevados del Chillán volcanic complex possesses cold and hot springs distributed along its edge [15], from which it may be inferred that the volcanic complex behaves in a form similar to the systems described by [6, 7]. The existence of cold and hot springs indicates the existence of at least two aquifers: a superficial one that receives its recharge by infiltration of rainwater and snowmelt discharging in cold springs and a deeper system, which is recharged from the superficial system and is in contact with the magma chamber, heating the water and producing vapor that feeds the thermal springs (**Figure 5a**).

As well as the thermal springs around the volcanic complex, there is a large cluster of hot and cold springs in the “Valle de Aguas Calientes” (Hot spring valley)



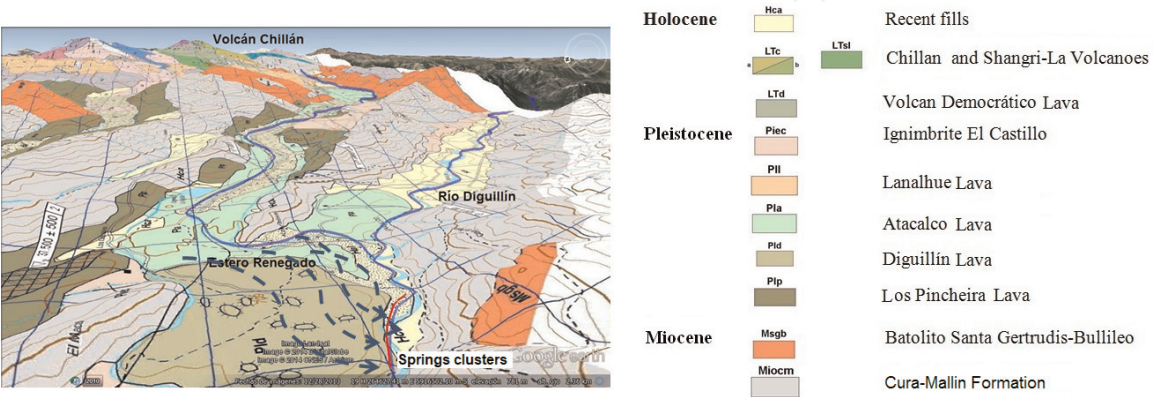
where the headwater of the Diguillín River is located (**Figure 5b** and **c**). This cluster is due to local tectonic features related to the formation of valley, like the fault line shown at **Figure 5a**. This geological trait enhances recharge from snowmelt, rainfall, and runoff from adjacent watersheds to the Alto Diguillín sub-basin, explaining why it has more water than surrounding rivers as can be deduced from **Figure 3**.

In relation to the lower specific flow in the Renegado Creek sub-watershed, particular importance is to be given to the formation of the lava units that filled the valley of the Renegado Creek (**Figure 6**). In effect, this valley was formed from a sequence of lava flows. An earlier lava flow called the Pincheira lavas, of the middle Pleistocene, cut along a large glacier forming walls that give the valley its characteristic U shape; at the end of the glacier, the lava flow opened in what is today the locality of Los Lleuques. Later lava flows (Diguillín of the middle Pleistocene) went down the valley until being blocked by the Pincheira lavas, which forced them to turn toward the south, closing the Renegado valley and forcing a connection with the Diguillín River (**Figures 6** and **7**).

Two additional lava flows that fill the valley covering the Pincheira lavas are the Atacalco lavas (of the Middle-Upper Pleistocene, which correspond to one or more andesitic lava flows, with a layer thickness of 125 m) and the Democrático Volcano

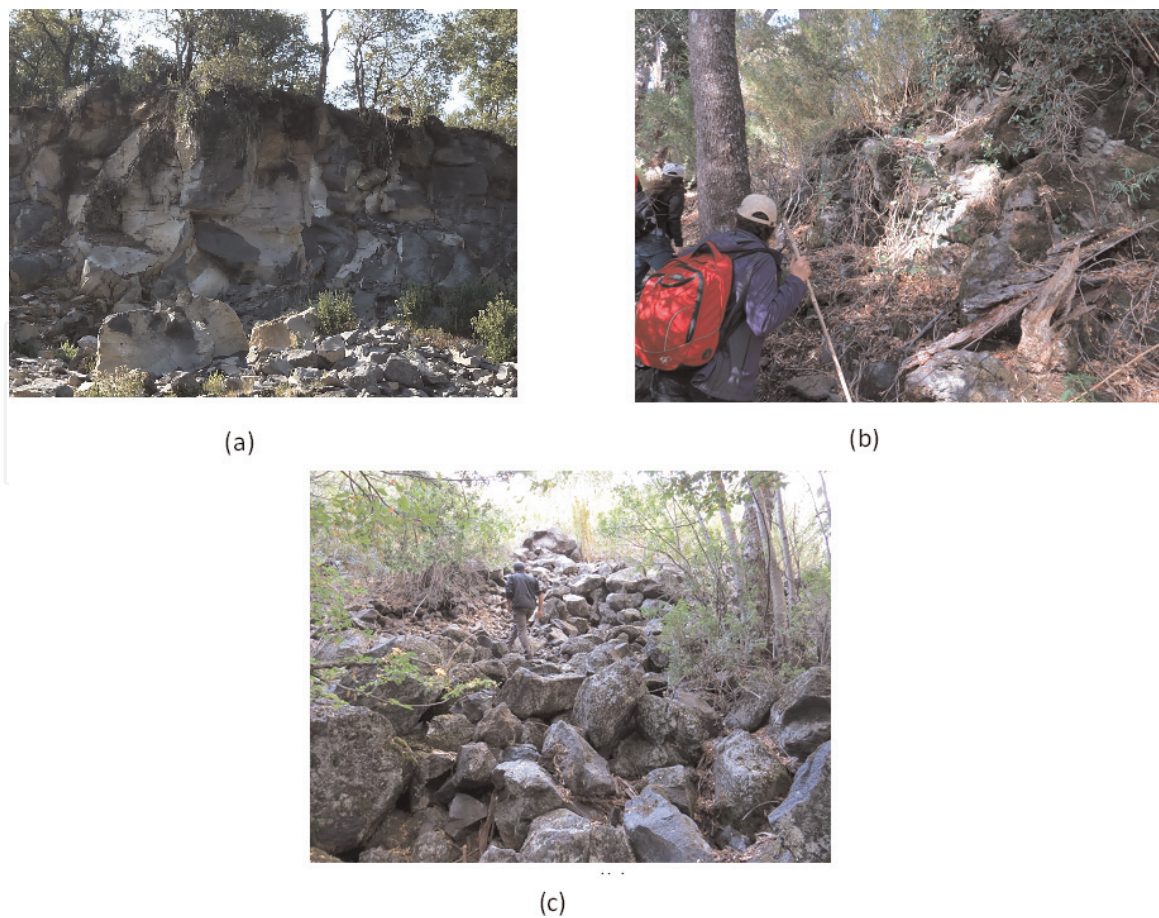


**Figure 5.**  
(a) Scheme of the plausible groundwater system at one volcanic complex; (b) headwaters of the Diguillín River at a thermal spring; (c) Diguillín River; (d) hot water spring; (e) cold water spring.



**Figure 6.**  
Geology of the upper section of the Diguillín River adapted from [15] and pasted on Google Earth. The red line at the right corner indicates a river section where fractured rock springs are located; the dashed blue line represents probable groundwater paths.





**Figure 7.**

(a) *Pincheira lavas*, (b) *Atacalco lavas*, and (c) *Democrático Volcano lavas*, *Las Trancas*.

lavas (LTd) of the Holocene, which are a fundamentally effusive structure of silicious, andesitic to dacitic block lavas (**Figure 7**).

The existence of the Agua Bonita springs is related to the formation of Diguillín lava. It is possible to assume that these lavas entered a postglacial lake which, through the cooling process [15], produced the fracture system which can be observed along the Renegado sub-watershed (**Figure 4d**). The presence of this fractured system causes the groundwater watershed boundary to differ from the surface watershed. In fact, groundwater is moving along paths that were created when the Diguillín lavas filled the valley, and surface water is moving across the watershed created by recent lava flows.

Also, the predominant soils in the upper part of the Renegado valley are sandy soils with high infiltration rates (larger than 200 mm/hr). The existence of these soils on a basement formed by fractured rocks favors groundwater recharge and explains why the Renegado Creek does not have significant superficial runoff. A large amount of rainwater and snowmelt infiltrate into the sandy permeable soil and percolate to the fractured rock system where the water moves through the fractured rock system and discharges in the Diguillín River at the springs described in the previous paragraph.

### 3.2 Discussion

This case study illustrated how groundwater storage and release can be significant hydrological processes in a mountain watershed where the presence of fractured volcanic rock geology produces the conditions for complex groundwater systems.

In recent years it has been understood that volcanic complexes—such as the Nevados del Chillán complex—produce the conditions necessary for significant mountain groundwater systems. At Mount Fuji in Japan, water can flow vertically through fractures, with water from different aquifer formations mixing, as established using isotopes, major ion chemistry, and multivariate statistical methods [7]. In Mexico, the hydrothermal system of El Chichón volcano was also studied using isotopes [6] and water chemistry, allowing the identification of two aquifers that make up the volcanic structure in a system that is controlled by infiltration from rainfall, water percolation, and heating and production of hydrothermal vapor. In Italy, environmental isotope techniques, hydrogeochemical analysis, and hydraulic data were used to identify recharge areas and trace groundwater flows at Mount Vulture [18].

In a tropical mountain cloud forest catchment located in a volcanic area in Mexico, it was found that rainfall-runoff responses are controlled by rapid vertical rainfall percolation through the high permeable volcanic soils, which recharges the groundwater system, while groundwater storage and discharge modulate the streamflow regime of the catchment [9].

In a mountain watershed without glaciers where volcanic processes are the dominant geological feature, spring discharge plays a major role in streamflow generation [19, 20]. Due to the expansion of second home construction in some mountain valleys, especially those associated with a tourist attraction like ski or hot spring resorts, spring water has become more common as a source of drinking water. However, as the recharge areas are also impacted by housing development, the risk of groundwater pollution increases [21], exacerbating the vulnerability of water quality in mountain groundwater systems [21].

As previously stated, land cover changes in Chile have been driven by an increase in income levels, which has led to significant growth in second home construction in the Renegado watershed area, as it is a major tourism center based on skiing and hot springs. There are now more than 1000 vacation houses and several resorts that have been constructed on more than 5000 small parcels that are available in the area. This explosive increase in construction has taken place without any planning or control, as the area is considered rural land.

The lack of a formal drinking water system has led to a trade in building clandestine catchments that are connected to the slopes by rough plastic pipes. Homeowners pay local people to build illegal water connections, which are unfit to provide drinking water. These connections are not only unhealthy; they also affect the few springs that are located around the valley (**Figure 8a**).

While the situation related to drinking water distribution was referred to in **Figure 8a** as “chaotic,” the situation related to wastewater is unknown, but there are reasons to dubiosity. According to Chilean law, disposal of wastewater from small houses located in rural areas should be carried out through the use of septic tanks. With the extensive use of septic tanks, located above the highly permeable soils that overlie the fractured rock aquifer, there is a concern that water quality in the Diguillín River could be impacted by housing and tourism development. Pollutants from the wastewater disposal systems will move through the fractured rock network and discharge into the springs that are used as drinking water sources for the houses and communities that are located down gradient (**Figure 8b**).

In recent years it has been shown that pharmaceuticals and personal care products (PPCP) can be used as indicators of groundwater pollution [22, 23]. A review summarized the use of frequently detected PPCPs, including antibiotics, anti-inflammatories, lipid regulators, carbamazepine, caffeine, and N,N-diethyl-m-toluidide, in groundwater to identify groundwater pollution, analyzing how adsorption to soils and degradation may affect the use of these elements as





**Figure 8.** (a) Chaotic drinking water distribution system at the Renegado Valley; (b) scheme of the plausible pollutants' recharge and discharge processes along the Renegado Valley.

groundwater tracers [24]. In groundwater systems such as the Renegado Valley where transit time is expected to be short, adsorption and degradation effects will be less relevant and therefore PPCP would be a good indicator for consideration.

#### 4. Conclusions

In volcanic mountain watersheds, the groundwater system can play an active role in hydrological processes. The groundwater system at the headwater of the



Diguillín River is very active and, at least, has two main subsystems: the existent aquifers located at the volcanic complex itself and the fractured system of the Renegado watershed. Those groundwater systems produce almost all the streamflow of the river at the end of the Chilean summer and early fall.

Each volcano that exists in Chile is a complex aquifer system by itself. There is a lack of knowledge about the groundwater system at the volcanic complexes. The structure of the aquifer systems and the recharge and discharge processes are unknown. Advances in understanding of those processes will allow advantage to be taken from the geothermal potential of the volcanic complexes.

This analysis makes evident the reasons why the Diguillín River has stable minimum flows during the dry season and why the Renegado Creek has a lower specific streamflow. However, those differences were not so obvious 3 years ago, at the start of this research. It is important to emphasize that in practical engineering, the supposition of constant specific streamflow between neighboring watersheds is widely used. Thus, it is important to carefully check this hydrological similarity through an analysis of the climatic and geomorphologic characteristics, soil type, and use. But in watersheds influenced by volcanic systems, it will be necessary to carefully analyze the geological conditions, especially in relation to fractured rock systems.

The highly permeable soil and the fractured rock system in the Renegado sub-watershed, where there is significant tourism development and construction of weekend houses, raise questions about the fate of pollutants introduced to the systems by wastewater infiltration from septic tanks. The pathways between pollutant recharge areas and spring discharge are unknown and must be identified and ideally measured in order to improve the sustainable development of the watershed.

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