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Characterization of hydrogeological dynamics through summer runoff analysis and runoff hydrograph separation in two watersheds of Chiloé, Chile

Caracterización de la Dinámica Hidrogeológica Mediante el Análisis de la Escorrentía Estival y la Descomposición del Hidrograma de Escorrentía en dos Cuencas de Chiloé

Daniel Paez[1,3], Jose Luis Arumi* [2,3], Jerónimo Paredes[2]

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*Autor de correspondencia

Resumen

La isla de Chiloé está sufriendo escasez estacional de agua superficial que aumenta la demanda de agua subterránea. Estudiamos la interacción entre la escorrentía superficial y subterránea en dos cuencas que disponen de estaciones de aforo en los ríos Vilcún y San Pedro. Los datos de escorrentía se analizaron mediante análisis de frecuencia; el uso de indicadores para determinar la contribución de la descarga de las aguas subterráneas al río; y tres técnicas de separación de flujo base, para estimar la recarga de aguas subterráneas. Los resultados fueron consistentes en indicar que la cuenca del río Vilcún presenta una mayor dependencia de los aportes de agua subterránea para sostener la escorrentía (54% y 65%) en comparación con la cuenca del río Grande (34% y 46%). En cuanto a la recarga media anual, para la cuenca del río Vilcún se estimó entre 5,9 y 6,4 m3/s, lo que representa un rango de 47 a 51% de la escorrentía total; y para el río Grande entre 6,6 y 9,8 m3/s, lo que representa un rango de 25 a 37% de la escorrentía total. Ambas cuencas cuentan con almacenamiento de agua subterránea que permite una escorrentía continua a pesar de sus esperadas diferencias hidrogeológicas. Se anticipa que el uso intenso de aguas subterráneas u otra alteración de factores que modifican el almacenamiento de aguas subterráneas en las cuencas hidrográficas estudiadas conducirán a cambios significativos en los regímenes hidrológicos de estos dos ríos de la isla de Chiloé.

Palabras clave: Descarga subterránea, flujo base, análisis de frecuencia, escasez hídrica estival

Abstract

Chiloé Island had evidenced seasonal surface water scarcity that increasingly demand groundwater. We study the interaction between surface and groundwater flows using river runoff data available from the two gauging station existents at the island at the Vilcún and San Pedro rivers. The runoff data were analyzed using frequency analysis consisted of the graphic comparison of the flow duration curve;the use of indicators to determine the contribution of streamflow groundwater discharge to the river; and three baseflow separation techniques, through which the baseflow index was calculated for the annual and summer periods, while annual baseflow volume was quantified as a method of approximating groundwater recharge. Results were consistent in indicating that the Vilcún River watershed presents greater dependence on groundwater inputs to sustain runoff (54% and 65%) compared to the Grande River watershed (34% and 46%). Regarding the mean annual recharge, for the Vilcún River watershed was estimated between 5.9 and 6.4 m3/s, which represents a range of 47 to 51% of total runoff; and for the Grande River between 6.6 and 9.8 m3/s, which represents a range of 25 to 37 %, of total runoff. Both watersheds have groundwater storage that permits continuous runoff despite their expected hydrogeological differences. It is anticipated that intense use of groundwater or another alteration of factors that modify groundwater storage in the studied watersheds will lead to significant changes in the hydrological regimes of these two rivers of Chiloé Island.

Keywords: *Groundwater discharge, base- flow, frequency analysis, summer water scarcity*

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[1] Master program of Agricultural Engineering; Water Resources Department, Faculty of Agricultural Engineering, Universidad de Concepción. Chillan, Chile. dpaezz@gmail.com

[2] Water Resources Department, Faculty of Agricultural Engineering, Universidad de Concepción. Chillan, Chile, jarumi@udec.cl, jparedes@udec.cl

[3] CHRIAM Water Center Universidad de Concepción. Chillan, Chile

1. INTRODUCTION

South-central Chile is in the midst of a drought that has lasted 12 years (Garreaud et al., 2017; CR2, 2018) and resulted in a significant transformation of the territory, as agriculture, which is the main economic activity of the area, is progressively adapting to the persistent lack of rain through a transformation of its production patterns, for which it has had to incorporate irrigation using groundwater, since there is no canal infrastructure and it is more economical for producers to construct deep wells.

It is expected that this increase in groundwater extraction will alter the water balance of aquifers and river systems with which they are connected. In decreasing precipitation conditions, (climate change scenario) the decrease in natural recharge along with an increase in extractions will produce a decrease in the discharges that feed rivers and groundwater-dependent ecosystems, resulting in a decrease in dilution flows during summer and conflicts over multiple competing water uses (drinking water, industrial, energy and tourism purposes, among others).

Because this area was always characterized by its abundant precipitation and watercourses with continuous runoff, there is no detailed hydrological or hydrogeological information to define the components of the water balance. Thus, it is necessary to develop methodological approaches that allow information on the characteristics of the hydrogeological dynamics of the study area to be obtained.

Methods of studying water resources based on the determination of water balance components require an extensive infrastructure for capturing meteorological and hydrogeological data, which must be associated with a recording period that is extensive and equivalent among all involved variables. In addition, the methods used in the runoff analysis are based on measurements reflecting all gain and loss processes at the watercourse monitoring point (Lastoria, 2008, Kirchner, 2009), reflecting the interaction of complex surface runoff, subsurface flow and groundwater flow processes (Balek, 1989).

Some of the most common methods that allow the relationship between groundwater storage in a watershed and runoff to be addressed are stream flow frequency analysis and hydrograph separation (Brodie and Hostetler, 2005).

Frequency analysis is carried out by creating a flow distribution curve (FDC), which consists of a graphic relationship between stream flow magnitude and the frequency with which each recorded stream flow is exceeded. It is considered an important tool for describing the behavior and variability of river runoff, as it is an indicator of the hydrogeological characteristics of a watershed (Smathkin, 2001; WMO, 2009). The portion of the FDC that specifically represents low-flow stream flows can be set arbitrarily between exceedance probabilities of 50 to 100 %. Curves with a gentle slope in this section indicate a significant contribution from groundwater storage to watercourse runoff, while pronounced slopes indicate greater daily discharge (Q) variability and typically correspond to watersheds with impermeable lithographic substrate, with low storage and a rapid precipitation response (WMO, 2009).

Based on the characteristics of the FDC, various authors have proposed indicators that relate difference exceedance stream flows in order to characterize groundwater contribution to surface runoff, including those that stress the Q90/Q50 relationships mentioned in Smathktin (2001) and the ([Q25/Q75]1/2) relationship of Walton (1965). The latter has been used extensively to characterize watersheds in wet climates of Canada (Singer and Cheng, 2002; MNRF-Ontario CA., 2014).

According to Smathkin (2001), analysis using FDC can be applied to various time periods, for example, for runoff observed only in the summer period or in a specific month. In addition, various specific exceedance indicators are typically used to define regulatory conditions or establish baseline environmental conditions.

Hydrograph separation methods are based on the classical definitions of runoff generation described by Horton (1933) and were refined and spread over the course of the twentieth century in works such as those Linsley et al. (1958; 1982) and Toebes and Ourivev (1970). They have been used both to determine the proportion of groundwater contribution to sustaining watercourse runoff flows through the determination of the base flow index (BFI) (Institute of Hydrology, 1980; Smathkin, 2001, WMO, 2009) and to obtain a first approximation of groundwater storage recharge (Fetter, 1994; Rutledge, 1998; Brodie and Hostetler, 2005; Lee et al., 2006).

Nowadays manual hydrograph separation processes have been replaced by automatic analysis using digital processors, which allow both fast processing of a large amount of data and decreases in inconsistencies caused by subjective valuation of the process (Sloto and Crouse, 1996)

Based on the aforementioned methods and availability of daily runoff data from public stations, this work aims to contribute to the knowledge of hydrological system functioning on Chiloé Island through the application of a streamflow data analysis method to allow the importance of groundwater storage and its relationship with flow maintenance during the low-flow season to be understood and the potential recharge of these hydrogeological systems to be estimated.

2. CASE STUDY

Due to the drought that has persisted since 2007, there have been increasing difficulties supplying the population with water, mainly in rural areas. This situation has resulted in the implementation of palliative measures such as communal emergency plans to supply the population, with reaches and costs that have increased over time (Mallén, 2015), as well as recent decrees that have declared the Quemchi and Quellón provinces to be a water scarcity zone in 2017 (MOP, 2017). In the document “Water resources strategy of the Chiloé Province” (Gobernación Provincial de Chiloé, 2015) the phenomenon was identified as a seasonal water shortage problem that is having social and environmental effects.

From a water availability perspective, one of the most determining factors of the vulnerability of Chiloé is its island status and lack of connection with the Andes Mountains, which has a bearing on the lack of winter snow reserves. Thus, the only means of support for both surface runoff and aquifer recharge is rainfall (DGA, 2016). In addition, the forecast for water demand in Chiloé indicates a significant increase in water consumption for energy production from surface sources and industry from underground sources (DGA, 2007).

Despite the identified effects, there have been no indications of a push for initiatives that involve a comprehensive assessment of water resources knowledge in order to predict behavior and possible effects on the water supply if water from some sources or in specific locations of the territory is overused. The scarcity and low quality of hydrological information is another major barrier to establishing a correct assessment and forecast of water availability on the island (DGA; 2014).

2.1 General characteristics of the territory.

Chiloé Island has an area of approximately 8,400 km2 and is located in the south of Chile, between parallels 41° and 43° South (Figure 1). In administrative terms, it is part of the Los Lagos Region, and, along with the other islands of the archipelago, makes up the Chiloé Province.

The relief of the island comprises two large domains: along the western side of the island, the Coastal Range, a mountain range with a north-south orientation, which reaches a maximum height of 890 m.a.s.l. and is up to 30 km wide along its east-west axis; and a system of plains and hills that are distributed all along the Eastern side of the island, at altitudes that vary between 0 and 250 m.a.s.l., which belongs to the marine or fluviomarine plain domain (Borgel, 1983).

The climate of Chiloé is temperate-rainy without a dry season and characterized by low daily and annual thermal amplitude and precipitation distributed throughout the year (Errazuriz et al., 1998), although with moderate seasonal behavior (Figure 2; Valdez, 2009; Juliá & Carmona, 2011). The driest month is February, in which between 3 and 6% of annual precipitation occurs, while 19% of annual precipitation is concentrated in the December-March quarter. The precipitation rate varies locally due to the orographic forcing exerted by the Coastal Range (Fuenzalida, 1982; in Figueroa, 2014), with values that reach an annual average close to 2000 mm/year in the lowest parts of the island, and over 4000 mm/year in the highest parts of the Coastal Range (DGA, 1988). The geology of the study area is composed of metamorphic rocks of the Paleozoic-Triassic Age and sedimentary deposits of the Pleistocene-Holocene. The metamorphic rocks are distributed along the western side of the island and make up the highest parts of the Coastal Range. Their dominant lithology consists of schists, metasandstones and metacherts that are characterized by low permeability; thus, they do not constitute significant aquifers (Troncoso et al., 2008; Paez et al., 2015). The unconsolidated sedimentary deposits are associated with the last glacial periods (mainly Llanquihue glaciation and Santa María glaciation) that affected this part of the territory during the Pleistocene-Holocene, and are distributed throughout the center and Eastern edge of the island (Duhart et al., 2000). They comprise a variety of interbedded lithological facies, which range from glaciofluvial sand and gravel deposits to fine sands and clays of glaciolacustrine facies. Therefore, they constitute free to confined aquifers with large sizes that are the island's main sources of groundwater. The transmissivity of this unit varies between 50 and 750 m/day, and its static level is highly variable, depending on the local hydrostratigraphic conditions (Troncoso et al., 2008; Páez et al., 2015).

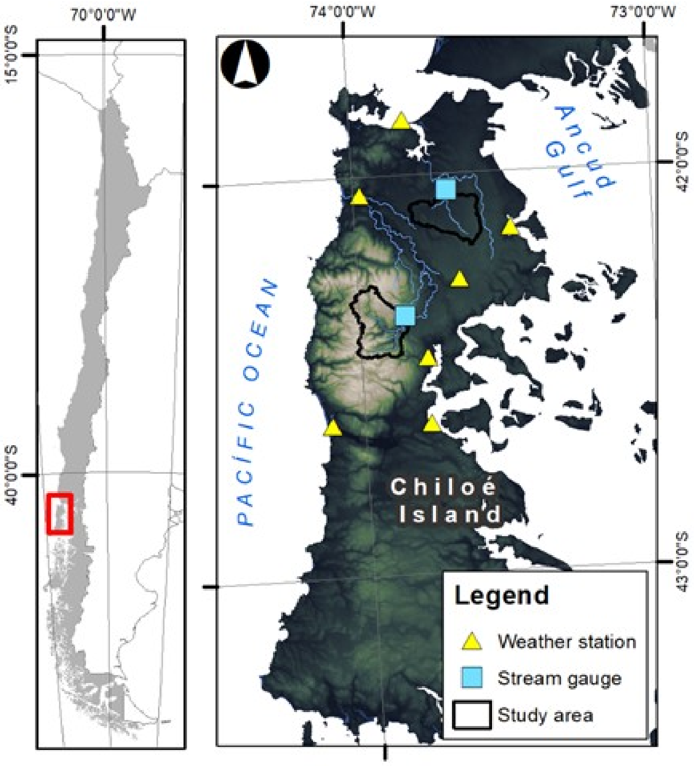

Figure 1. Study area location

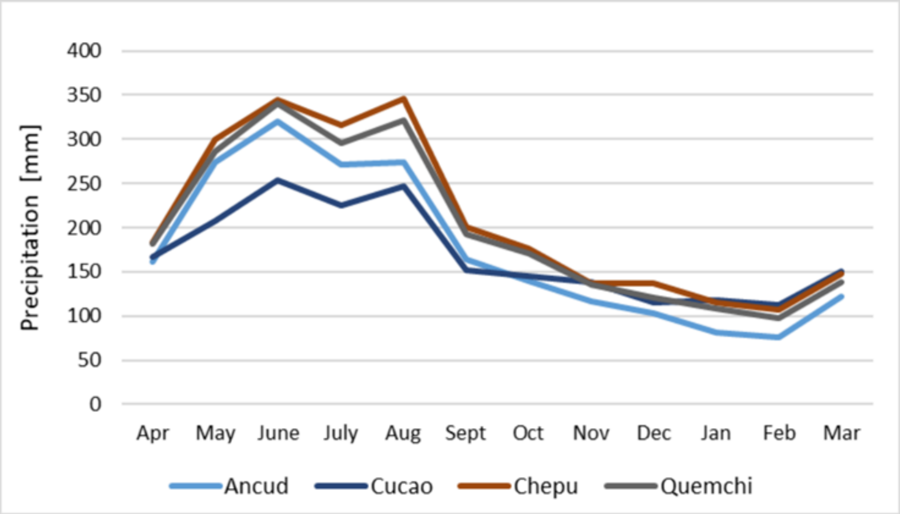

Figure 2. Monthly precipitation hydrographs for the selected stations in the study area

2.2 Analyzed watersheds

On Chiloé Island there are only two watersheds with stream flow records maintained by the General Water Directorate (DGA): the Vilcún River watershed, with the Vilcún River at Bel Ben stream flow monitoring station, and the Grande River watershed, with the Grande River at San Pedro station. Both stations define sub-watersheds, the main morphometric characteristics of which are shown in Table 1.

The reliefs of the two watersheds are very different, which is highlighted by the contrast presented by the hypsometric curves in Figure 3, which shows the greater altimetric difference in the watershed of the Grande River, the headwaters of which are located at an elevation considerably higher than the Vilcún River watershed. The geological characteristics of the two watersheds also contrast. While in the Vilcún River watershed the geology is completely composed of permeable semi-consolidated sedimentary deposits, mainly of glacio-fluvial and morainic origin (Pleistocene-Holocene), more than 90% of the Grande River watershed is made up of metamorphic rocks (Carboniferous-Permian), which have been described as hydrogeological units with low to no groundwater potential due to their low permeability (Troncoso et al, 2008; Páez et al., 2008). A small fraction of this latter watershed is composed of sedimentary material similar to those described above and current Grande River fluvial deposits. Using the precipitation isohyets from the DGA (1987), which were complemented by the records of Juliá and Carmona (2011), the average annual precipitation in each watershed was calculated, with values of 4131 mm/year in the Grande River watershed 2294 mm/year in the Vilcún River watershed.

Table 1. Main morphometric characteristics of the studied watersheds

Variable	Vilcún River watershed	Grande River watershed
Area [km^2]	176.7	203.8
Average height [m]	108	473
Maximum height [m]	207	857
Minimum height [m]	21	80
Average slope [°]	4	15
Maximum slope [°]	33	61

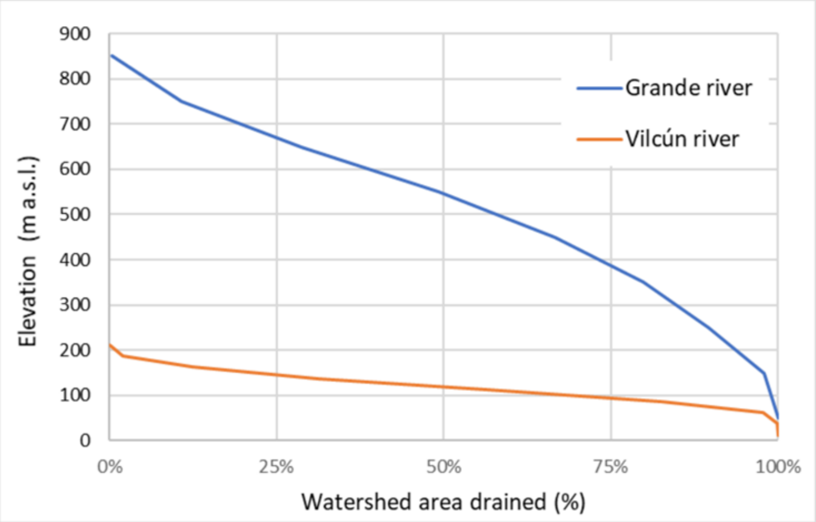

Figure 3. Hypsometric curve of the watersheds defined by the Vilcún River at Bel Ben and Grande River at San Pedro streamflow monitoring stations.

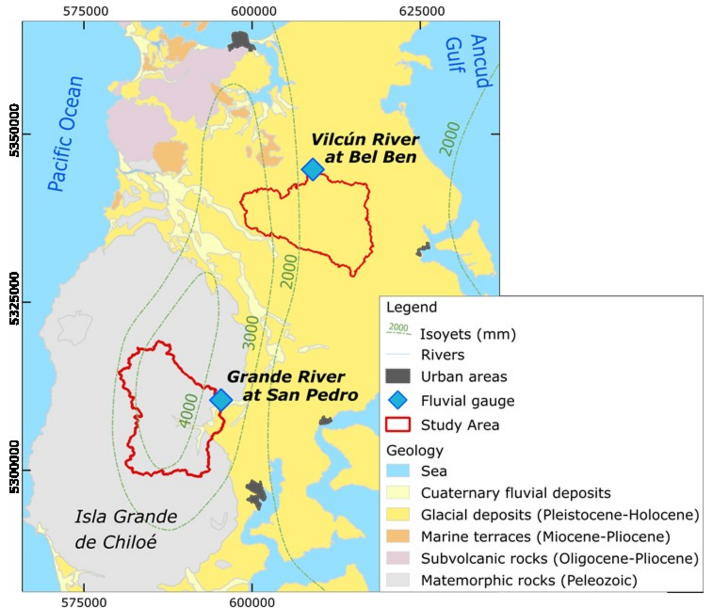

Figure 4. Geological map of the study area. Also shown are the isohyets created by the DGA (1987)

3. METHODS

3.1 Runoff characterization

The runoff of both watersheds was characterized through the calculation of various flow indicators such as mean annual runoff (MAR), absolute minimum daily stream flow (MDS) and the flow duration curve (FDC). For all of the calculations, the precipitation and runoff series were ordered by hydrological year, from April to March, in accord with the seasonality of south-central Chile. MAR is equal to the mean value of total annual runoff, within the available data series. Along with the absolute minimum daily stream flow records, the 95th percentile of daily runoff over the analysis period was determined as an indicator of the minimum stream flow regime of each watershed. In the case of the FDC the stream flow data were graphed on the Y axis, on a logarithmic scale, and exceedance frequency on the X axis, on a linear scale. Finally, the relationship between exceedance percentiles Q25 and Q75 defined by Watson (1965, in Singer & Cheng, 2002) was analyzed to identify the relative importance of base flow contribution for sustaining stream flows in summer. This indicator is calculated using the following expression:

$$(Q_{25}/Q_{75})^{1/2} \qquad (1)$$

A lower value of this relationship indicates a greater groundwater contribution. The FDC analysis was carried out for all years less than 15 days without daily records, from December to March, for a total of 21 years.

3.2 Hydrograph separation and base flow quantification

In the runoff hydrograph, base flow consists of water with a delayed release from underground storage (soil and aquifer), in contrast with the immediate runoff generated as a short-term response following a precipitation event (quick flow). In this work hydrograph separation was used to calculate the base flow index (BFI, Institute of Hydrology, 1980; Smathkin, 2001, WMO, 2009) as a means of assessing the relative importance of underground discharge for sustaining stream flows and to estimate the total annual base flow volume, which allows an approximation of the recharge for each studied watershed to be established (Fetter, 1994; Rutledge, 1998; Brodie & Hostetler, 2005). The base flow index (BFI) is described as an indicator of the hydrogeological properties of a watershed (WMO, 2009). It is defined as the ratio of the volume consisting exclusively of base flow and total runoff volume. In watersheds with high groundwater contribution to river runoff, the BFI nears 1.

$$BFI = V_{base}/V_{total} \tag{2}$$

The BFI is sensitive to periods without data, such that a day without records can result in the omission of various days of data for the calculation of base flow; therefore, the missing data must be reviewed and filled in before carrying out the calculation (WMO, 2009). The separation of base flow from runoff hydrographs with daily-level data was achieved through the application of three automated methods (PART, HYSep local minimum and two-parameter digital filtering) implemented in the USGS Groundwater Toolbox (Barlow et al., 2014). The PART method (Rutdlege, 1998) works by scanning the daily runoff series to identify the days that meet a requirement of 'antecedent recession' and designates as groundwater discharge the total runoff on those days. For the remaining days, groundwater discharge is calculated using linear interpolation between the prior days. The 'antecedent recession" requirement is based on the difference in daily runoff records in the interval between the examined day and N previous days, where N is given by the expression:

$$N = A^{0,2} \tag{3}$$

Where A is the watershed area in square miles. This empirical relationship was originally proposed by Linsley et al. (1982) and represents the number of days elapsed between a precipitation event and the end of direct runoff. The HYSep local minimum method (Sloto & Crouse, 1996) verifies that the runoff record is a local minimum in an interval I defined by:

$$I = [0.5(2N * -1)] \tag{4}$$

Where N is the same value calculated by the Linsley et al. (1982) expression. Each minimum value corresponds to a base flow value for the given day, while for the intermediate days the base flow value is determined by linear interpolation. Digital filter techniques come from signal analysis and consist of the separation of hydrograph components that behave as high-frequency signals (direct runoff or quick flow) from those that behave as low-frequency signals, where base flow is found (Sponberg, 2000; Schwartz et al., 2012). Two-parameter digital filtering (Eckhardt, 2005; 2008) calculates the base flow on a given day (bt) using the following expression:

$$b_t = \frac{(1 - BFI_{max})\, a\, b_{t-1} + (1 - a)\, BFI_{max}\, y_k}{1 - a\, BFI_{max}} \tag{5}$$

Where α is the (dimensionless) recession constant, bt and bt-1 are the base flow of time interval t and t-1, BFImax is the long-term maximum value that the relationship between base flow and total runoff can have and yk is the runoff record of the calculated day. To select a recession constant for each watershed an analysis of recession segments was carried out using the RECESS application of the same program. Recession segments over 12 days were selected by eliminating the first days that departed from linear or quasilinear behavior. Thus, a value of 0.950 was obtained for the Vilcún River watershed and 0.977 for the Grande River watershed. According to Eckhardt (2005) the value of BFImax depends on the hydrogeological characteristics of each watershed, and can be preliminarily set at 0.8 for perennial watercourses that drain porous or detrital aquifers and at 0.25 for watercourses that flow over a fractured rock substrate. In this work this parameter was estimated using the method proposed by Collischonn and Fan (2013), which is implemented in the GW Toolbox application and likewise uses watershed runoff data and the previously defined recession constant.

3.3 Record availability and analysis period

Daily records were collected from the Vilcún River at Bel Ben and Grande River at San Pedro DGA stream flow monitoring stations. The data were compiled from the DGA institutional web portal. The records of the Vilcún and Grande River stations cover the period between 1990 and 1991 to 2017, respectively. However, after 2004 there are significant interruptions in the data, which made it necessary to select an equivalent record period to allow the results to be compared. The analysis of summer runoff indicators was carried out only in years with complete records, in the December to March period. The record period selected for the summer runoff analysis ultimately covered the period of hydrological years between 1991 and 2012, with the exclusion of 2005 and 2007, which is equivalent to 20 years of analysis. For the annual base flow analysis a similar period was chosen, but with the additional exclusion of 1996, 2004, 2008 and 2010, resulting in a total analysis period of 14 years.

Table 2. Stream flow monitoring stations of the study

Gaugin Station	**Coordinates WGS-84, 18S**	**Watershed area**	**Record period**
Vilcún River at Bel-Ben	N:5344739; E: 609034	176 km^2	1990 to 2017
Grande River at San Pedro	N: 5310444; E: 595392	203 km^2	1991 to 2017

In Figure 5 it is observed that the runoff regimes of both watersheds are in harmony with precipitation distribution, which highlights their pluvial character. The difference in absolute stream flow volume between the two watersheds (Figure 5a) also appears in the runoff hydrograph normalized by watershed area (Figure 5b), which indicates that this difference is not a result of the watershed dimensions. According to what can be observed in Figure 5 it is estimated that the factor that most influences this behavior is the greater precipitation over the Grande River watershed due to the orographic effect on precipitation distribution caused by the Coastal Range.

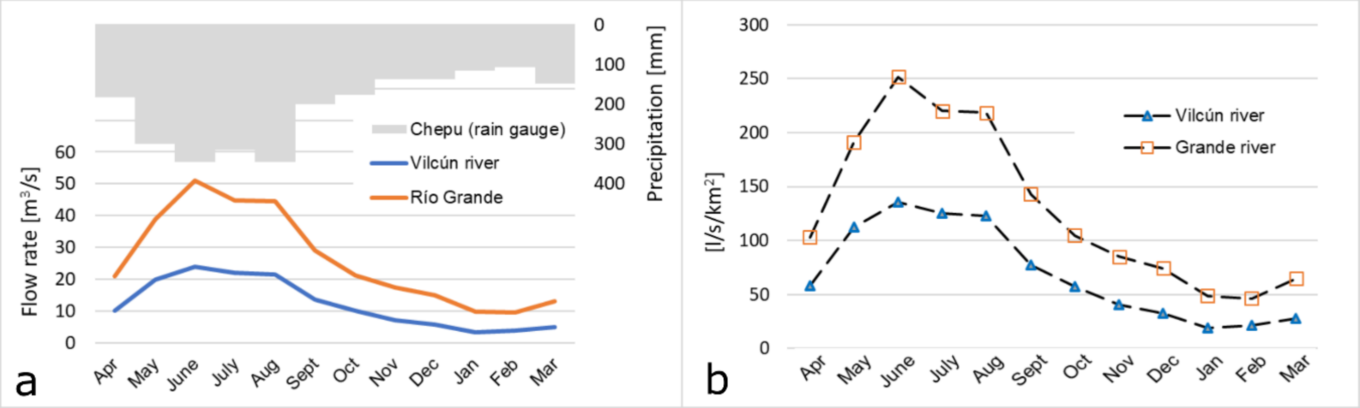

Figure 5. a) Monthly runoff hydrograph for the Grande and Vilcún River stations. Upper half of the graph shows precipitation at the Quemchi station. b) Monthly specific stream flow hydrograph for the Vilcún River at Bel Ben and Grande River at San Pedro stream flow monitoring stations.

4. RESULTS

4.1 Runoff indicators: MAR, 95th percentile and minimum daily stream flow.

The value of the absolute minimum stream flow for the Grande River station reached its extreme in hydrological year 2007, with 1.02 m^3/s. Meanwhile, at the Vilcún River station that same year, there is a significant interval of days without records in the months of February and March, after a recording of 0.2 l/s, which could correspond to an unrecorded zero flow events. The minimum recorded value in the Vilcún River watershed was reached in hydrological year 2003, with 0.16 m^3/s. The minimum stream flow distribution extends from December to April, with greater frequency during the months of February and March. In addition, the value of the 95th percentile, which corresponds approximately to the stream flow that is not exceeded during the 18 lowest-flow days in the watercourse, is shown in Table 3.

Table 3. Absolute minimum annual stream flows and 95th percentile

Station	**MAR (mm)**	**MAR (m^3/s)**	**Q_{95}**	**Absolute min Q (m^3/s)**
Vilcún River at Bel Ben	2171	12.15	0.70	0.16
Grande River at San Pedro	4055	26.08	1.90	1.02

4.2 Flow duration curves (flow duration analysis).

In Figure 6 the absolute summer flow duration curves for the entire selected period are shown. It is observed that the two curves mostly follow semi-parallel paths, with differences at the lowest-flow extreme, above 80% exceedance probability. At the extreme right of the graph, the greater descent observed in the Vilcún River curve reflects a greater sensitivity of the watercourse to the low-flow period, exhibiting a greater streamflow decrease in months with less precipitation.

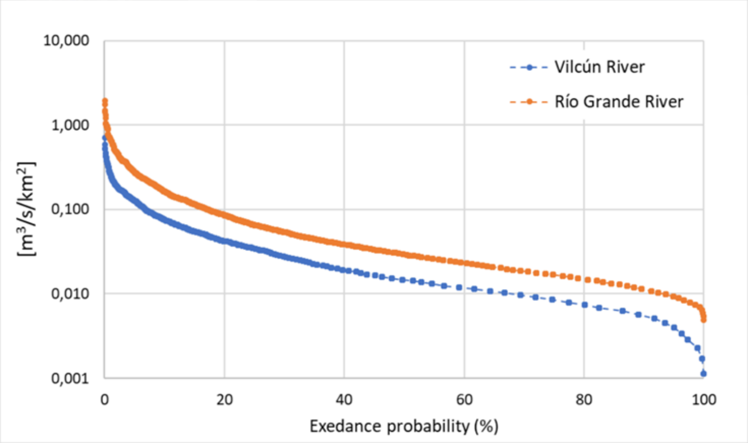

Figure 6. Flow duration curve for common periods from December to April at the two studied stream flow monitoring stations

The monthly data FDC (December to April) for an exceedance probability over 50% are shown in Figure 7. The Vilcún River watershed exhibits greater differentiation in monthly stream flow behavior than the Grande River watershed, the records of which from the summer months are more even. In both watersheds it is observed that the months with the lowest productivity are January and February; in the following months a recovery or increase in stream flow, which is most pronounced in April, can be noted. As observed in Figure 6, the greater sensitivity of the Vilcún River watershed to the decrease in stream flows during the months of December to March compared to the Grande River watershed is evidenced.

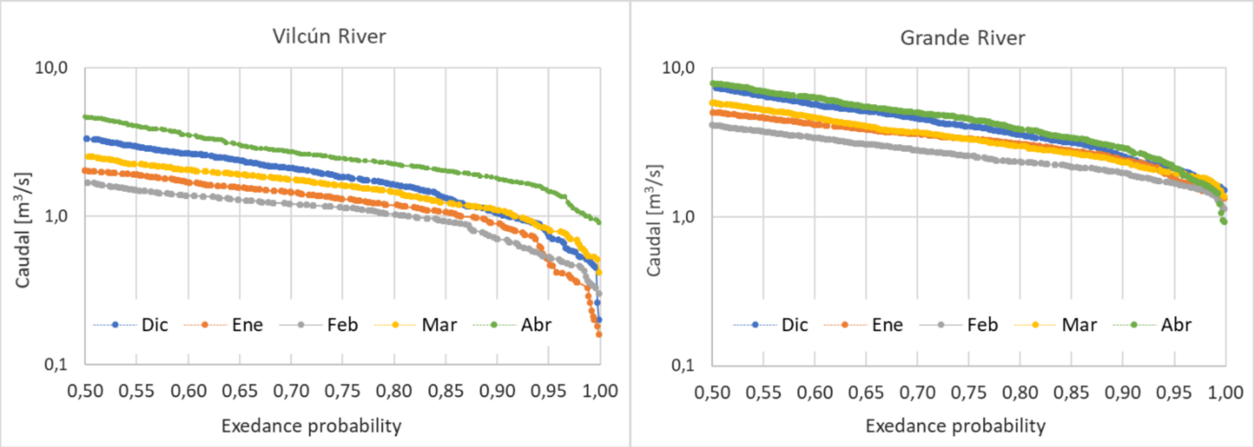

Figure 7. Monthly flow duration curves for the months of December, January, February, March and April at the Grande River and Vilcún River streamflow monitoring stations.

Table 4 and Table 5 show the results of the Walton (1965) index for the estimation of the importance of groundwater contributions to sustaining runoff. A lower value of this index represents a greater proportion of the groundwater component in the runoff of the watercourse. In Table 4 it is observed that the Walton relationship applied to both annual and summer period's exhibits similar values for both watersheds. However, at a monthly level (Table 5), it is observed that the Vilcún River watershed continually obtains lower index values in comparison to the Grande River station, indicating that, in the former, discharge from groundwater storage is more important for sustaining surface flow in the analyzed months.

4.3 Base flow index (BFI)

The BFI results obtained by the three calculation methods, using 0.629 as the BFImax value for Vilcún River watershed and 0.308 for Grande River, for the case of the Digital Filter method (DF 2), are shown Table 6. The results are presented for the December-March period and for the entire hydrological year.

Table 4. Walton (1965) indicator based on exceedance relationships for the annual and summer (December to March) periods

Watershed	Unit	Annual (Q25/Q75)$^{0.5}$	Summer (Q25/Q75)$^{0.5}$
Vilcún River at Bel Ben	m^3/s l/s/km^2	2.29	1.89
Grande River at San Pedro	m^3/s l/s/km^2	2.28	1.90

Table 5. Walton (1965) indicator for exceedance probability in the months of December to April

	(Q25/Q75)$^{0.5}$				
	December	January	February	March	April
Vilcún River	1.91	1.65	1.76	1.90	2.15
Grande River	1.99	1.71	1.81	1.99	2.22

Table 6. Base flow index for the Vilcún River and Grande River watersheds, for the summer and year

Year	**Vilcún River**						**Grande River**					
	BFI aestival			**BFI Anual**			**BFI aestival**			**BFI Anual**		
	PART	**HYSep**	**DF 2**	**PART**	**HYSep**	**DF 2**	**PART**	**HYSep**	**DF 2**	**PART**	**HYSep**	**DF 2**
1991	0.59	0.53	0.58	0.47	0.42	0.47	0.50	0.46	0.40	0.33	0.32	0.24
1992	0.70	0.69	0.61	0.54	0.50	0.50	0.50	0.49	0.36	0.33	0.34	0.23
1993	0.73	0.65	0.57	0.55	0.50	0.52	0.55	0.47	0.38	0.33	0.29	0.22
1994	0.69	0.69	0.57	0.45	0.46	0.47	0.46	0.42	0.33	0.44	0.49	0.29
1995	0.64	0.57	0.50	0.43	0.42	0.46	0.58	0.49	0.43	0.33	0.33	0.24
1996	0.66	0.61	0.60	0.35	0.37	0.45	0.38	0.44	0.31	-	-	-
1997	0.75	0.67	0.64	0.47	0.42	0.48	0.50	0.47	0.42	0.48	0.46	0.28
1998	0.68	0.59	0.57	0.55	0.48	0.51	0.43	0.39	0.32	0.25	0.25	0.19
1999	0.56	0.49	0.50	0.51	0.48	0.51	0.38	0.35	0.30	0.28	0.26	0.21
2000	0.60	0.54	0.55	0.54	0.54	0.52	0.34	0.39	0.25	0.37	0.38	0.24
2001	0.67	0.59	0.55	0.57	0.54	0.51	0.45	0.41	0.32	0.31	0.39	0.23
2002	0.79	0.44	0.58	0.51	0.47	0.50	0.40	0.36	0.32	0.41	0.43	0.29
2003	0.79	0.40	0.59	0.63	0.54	0.56	0.56	0.54	0.45	0.34	0.32	0.23
2004	0.76	0.65	0.63	-	-	-	0.56	0.55	0.42	0.34	0.35	0.23
2006	0.60	0.50	0.58	0.52	0.44	0.49	0.45	0.45	0.34	0.36	0.37	0.23
2008	0.49	0.47	0.53	-	-	-	0.39	0.33	0.32	0.30	0.30	0.20
2009	0.59	0.53	0.58	0.47	0.46	0.47	0.44	0.42	0.30	0.34	0.34	0.23
2010	0.56	0.54	0.54	-	-	-	0.41	0.40	0.29	0.31	0.33	0.21
2011	0.60	0.58	0.58	0.45	0.48	0.50	0.52	0.48	0.35	0.32	0.33	0.22
2012	0.59	0.54	0.54	0.51	0.45	0.48	0.43	0.41	0.33	0.32	0.31	0.22
2016	0.54	0.49	0.00	0.51	0.44	0.65	0.39	0.41	0.12	-	-	-
Mean	**0.65**	**0.56**	**0.54**	**0.50**	**0.47**	**0.50**	**0.46**	**0.44**	**0.34**	**0.34**	**0.35**	**0.23**

The average summer and annual BFI values are shown graphically in Figure 8, in which it is observed that in the summer, annual and monthly maximum BFI analysis periods, the values obtained for the Vilcún River are always higher than those obtained for the Grande River watershed. In addition, in each watershed, a clear shift toward greater BFI values in the summer season is observed in comparison to the values obtained for the annual period.

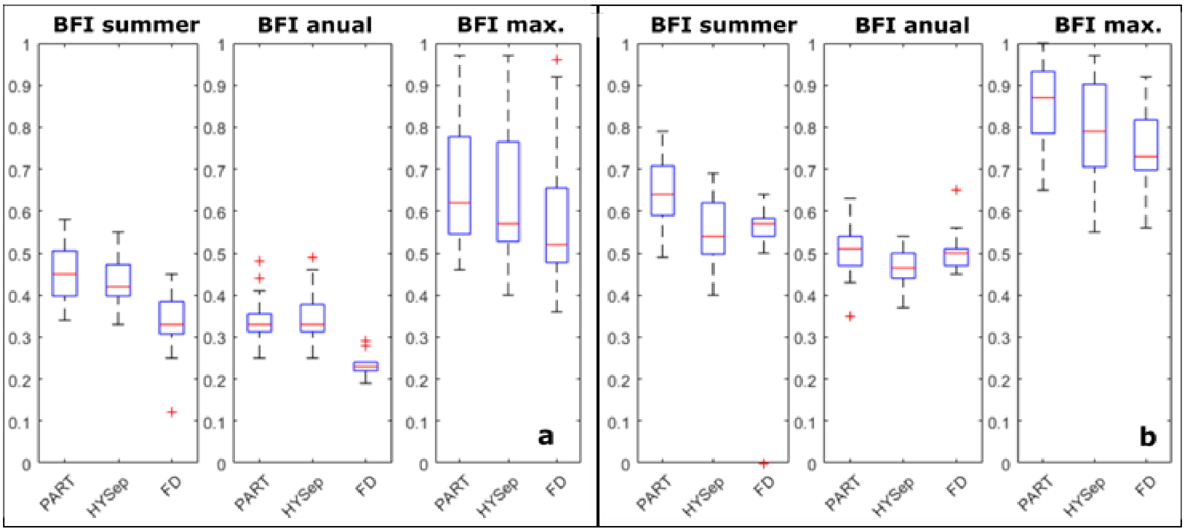

Figure 8. Comparison of obtained BFI results for the three methods used, for both watersheds
(a) Grande River; (b) Vilcún River

The BFI comparison between the studied watersheds (Table 6; Figure 8) shows that in the Vilcún River watershed groundwater discharge plays a greater role in sustaining total stream flow in both the summer and annual periods. According to the results obtained with the three calculation methods, base flow participation in the December-March season accounts for between 54% and 65% of runoff in the Vilcún River watershed, while in the Grande River watershed, this component accounts for between 34% and 46%.

4.4 Annual groundwater discharge

Table 7 shows the annual base flow (BF) calculation in m^3/s. Annual base flow values between 5.9 and 6.4 m3/s were obtained for the Vilcún River watershed, which represent a range of 47 to 51% of the total runoff recorded at the gauging station, and between 6.6 and 9.8 m^3/s for the Grande River watershed, which represent a range of 25 to 37 %, using the three selected methods.

Table 7. Average annual runoff and base flow values calculated for the years with complete data in both watersheds

Año	Vilcún River [m³/s]				Grande River [m3/s]			
	Q Anual	PART	HYSep	DF 2	Q Anual	PART	HYSep	DF 2
1991	12.9	6.0	5.4	6.1	27.9	9.1	8.9	6.6
1992	12.0	6.5	5.9	6.0	25.4	9.3	9.5	6.4
1993	11.1	6.0	5.5	5.7	23.6	9.2	8.2	6.2
1994	16.0	7.2	7.3	7.5	36.0	12.3	13.6	8.1
1995	12.9	5.5	5.3	5.9	25.5	9.2	9.1	6.7
1997	13.3	6.3	5.6	6.4	29.5	13.4	13.0	7.8
1998	9.4	5.1	4.5	4.8	20.8	7.0	7.0	5.2
1999	10.9	5.6	5.3	5.6	24.2	7.8	7.3	5.7
2000	15.4	8.2	8.1	7.8	26.9	10.3	10.7	6.8
2001	12.5	7.1	6.7	6.3	24.4	8.8	10.9	6.3
2002	16.8	8.6	7.9	8.4	31.3	11.4	12.1	8.1
2003	12.3	7.7	6.7	6.9	25.1	9.5	9.0	6.5
2006	12.3	6.3	5.4	6.1	25.8	10.1	10.2	6.4
2009	11.3	5.3	5.1	5.3	26.4	9.6	9.7	6.3
2011	11.5	5.2	5.5	5.7	23.7	8.9	9.1	6.3
2012	9.8	5.0	4.4	4.7	25.6	9.0	8.5	6.1
□	**12.5**	**6.4**	**5.9**	**6.2**	**26.4**	**9.7**	**9.8**	**6.6**
%	**100%**	**51%**	**47%**	**50%**	**100%**	**37%**	**37%**	**25%**

5. COMMENTS AND CONCLUSIONS

The studied watersheds have significant topographic and geologic differences that to a large extent determine runoff behavior. The orographic effect strongly impacts the precipitation distribution, resulting in the Grande River watershed receiving more than twice the water that the Vilcún River watershed receives (4131 vs. 2294 mm/year, respectively). The mean runoff (MAR) and minimum stream flow (Q95 and absolute minimum) indicators reflect their differences in stream flow productivity well. Both rivers are perennial, although they exhibit a significant difference in minimum annual stream flow values, which present a range of 0.16-1.58 m^3/s for the Vilcún River and 1.02-2.11 m^3/s for the Grande River.

The results obtained from both FDC analysis and BFI determination are consistent in indicating that the

Vilcún River watershed exhibits greater dependence on groundwater storage contributions to sustain annual and summer runoff compared to Grande River watershed.

The monthly flow duration curve (FDC) analysis showed that both watersheds exhibit their lowest stream flows during the month of February, following the precipitation regime, although the Vilcún River watershed exhibits a greater decrease in stream flows during the summer months, which is interpreted as greater sensitivity to the summer effect. Thus, it bears asking why the watershed with a permeable geological substrate and recognized groundwater storage potential generates this effect on the watercourse of the Vilcún River. It is suggested that the pronounced effect of the decreased stream flow of the watercourse is due to a decrease in the phreatic aquifer level, which could be near the level of the riverbed, decreasing its flows.

The Walton index showed sustained differences between watersheds only in the values calculated at a monthly level for the summer period, indicating that the groundwater component is more important in the Vilcún River watershed in all of the months in the sample. The same indicator applied to the FDC of the entire record period gave very similar values for the two watersheds, which may mean that it is unsuitable for annual records from wet watersheds such as those analyzed in this study.

The base flow separation method using the PART, HYSEP and digital filter (DF) techniques reached values that were consistent with each other. The greatest difference among the selected techniques was obtained with the DF method in the Grande River watershed, which resulted in a BF value around 12% less than that obtained using the PART and HYSEP methods. The observed differences are a result of the sensitivity of this method to the and Bmax parameters, which retrieve information from recession behavior during the longest periods after the end of rainfall. The PART and HYSEP methods depend only on the empirical parameter N of Linsley et al. (1982), making their results insensitive to information provided by recession.

The BFImax parameter determined by applying the GW Toolbox, according to the recession behavior of each watercourse, resulted in values of 0.629 for the Vilcún River and 0.308 for the Grande River, which are consistent with the contrasting lithology on which each watershed lies. In previous works that have used the digital filter method, such as those of Collinshonn and Fan (2013) and Eckhardt (2005), values between 0.25 and 0.51 have been described for watersheds with hydrogeological substrates composed of fractured rocks and between 0.52 and 0.95 for watersheds on detrital aquifers.

Various authors mention that the quantification of base flow allows a first approximation of annual recharge of the groundwater environment of the watershed. In this study recharge ranges of around 50% of precipitation for the Vilcún River watershed, which are equivalent to 6.2 m3/s, and between 25 and 30% of precipitation for the Grande River watershed, equivalent to a range between 6.6 and 9.7 m3/s, were obtained.

The quantification of base flow in the Vilcún and Grande River allowed it to be recognized that the runoff in both watersheds is strongly influenced by discharge from the groundwater environment even though each has a very different geological composition. In the case of the Grande River watershed, it is probable that groundwater storage is shaped by the powerful thickness of the organic soils that sustain rainforest formations. Other natural formations such as the peat bogs that exist in the upper part of the watershed also contribute to maintaining significant water storage, which is subsequently released by gravity with a lag after precipitation peaks.

One of the implications of this assessment is that the exploitation of water from the groundwater environment or significant alteration of land use can result in major changes in summer runoff. In addition, the estimated recharge values must be subject to valuation in conjunction with other variables that depend on water resources in order to define a sustainable use rate to avoid altering river, wetland and forest environments, which make up part of the hydrological equilibrium of Chiloé Island.

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