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Notes

Determination of base flow by three filter of separation in a catchment of Coast Mountain range, Biobío región, Chile

Determinación del caudal base a partir de tres filtros de separación en una cuenca de la Cordillera de la Costa, región del Biobío, Chile

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Abstract

Several authors have demonstrated that use of empirical methodologies, such as Graphical Separation and filtering methods, generate a rational estimation of base flow, but many assumptions should be assumed in its calculation process, which difficult its comparison overall between routines programmed inside softwares. To avoid the uncertainty of source of parameters and procedure used, the aim of study was to use three separation filters of base flow (algorithms of Lyne & Hollick, Chapman and Eckhardt) which present several examples of its use around of world, where detailed clearly procedure of calculation.

Example of this is the parameter, that all those filters share it and it was defined through Master Recession Curve, avoiding this way to assume its typical value of = 0.925 used regularly. Results of base flow calculated for basin located inside of field María de las Cruces, in the mountain of the coast of the south central of Chile (37°S), demonstrated that the filter Lyne & Hollick represented the behavior of base flow in function of runoff flow and moment hydrologic reflected by precipitations regime. According to data obtained of gauge station observed that present period 2009-2014, the model presented a flow of runoff compounded mainly for base flow (BFI of 0.67 in average), what is similar got with Graphical Separation method, mainly for the summer flows.

Keywords: Base flow, filters, master recessive curve, BFI index.

Resumen

Varios autores han demostrado que el uso de metodologías empíricas, como el Método Gráfico o el uso de filtros, generan una estimación razonable del caudal base, pero varios supuestos deben ser asumidos en su proceso de cálculo, lo cual dificulta la comparación entre ellos, sobre todo entre rutinas programadas al interior de un *software*. Para evitar la incertidumbre del origen de los parámetros y procedimientos usados, el objetivo del estudio fue usar tres filtros de separación de caudal base (algoritmos de Lyne & Hollick, Chapman y Eckhardt) que presentan algunos ejemplos de su aplicación alrededor del mundo, donde se detallan los procedimientos de cálculo. Tal es el caso del parámetro α, que comparten estos filtros, determinado por medio de la curva de recesión maestra $(\alpha = e^{-k})$, lo cual evita asumir su típico valor de α = 0.925, usado regularmente. Los resultados de caudal base calculados para la cuenca ubicada al interior del predio María de las Cruces, en la cordillera de la costa del centro-sur de Chile (37° S), demostraron que el filtro de Lyne & Hollick representó el comportamiento del caudal base en función de la escorrentía superficial y el momento hidrológico reflejado por el régimen de las precipitaciones. De acuerdo a los datos obtenidos de una estación fluviométrica se observó que para el periodo 2009-2014, el modelo presentó un caudal de escorrentía compuesto principalmente por el caudal base (BFI de 0.67 en promedio), lo que es similar a lo obtenido por medio del Método Gráfico, principalmente para los caudales estivales.

Palabras clave: caudal base, filtros, curva de recesión maestra, índice BFI.

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Introduction

Hydrograph is a graphical representation of the surface run-off that corresponds to water excesses caused by storms. This run-off presents greater values during and after of storm events, and it presents lower values or base flow associated to periods without precipitations (low runoff), where the channel is fed by a groundwater discharge (Eckhardt, 2008; Welderufael & Woyessa, 2010). A correct estimate of the base flow is relevant in fields such as: the water resources planning for droughts, the estimate of transport of nutrients and pollutants, the calibration of hydrological patterns, the hydraulic work installations (dums or electric power plants) and the environmental protection (Huyck *et al*., 2005; Eckhardt, 2008; Stadnyk *et al.,* 2015).

The base flow has been estimated for empirical, chemistry, and analytical methods with filters. The empirical methodologies as graphical method consider that in dry periods between rainfall events, the surface flow consists in base flow. During the events of precipitation are carried out graphic extrapolations of minimum flow, generally in a linear way, in order to estimate base flow (Huyck *et al.,* 2005). The chemistry methods consider the stable tracer or isotope to drag the movement of water (underground and surface) linking to rainfall events (Klaus & McDonnell, 2013; Zhang *et al*., 2012), but these methods present a disvantage to be high in its cost of implementation, however, the results got that present a physical base that support them.

The analytical method consits in the use of filters that have as aim to delete the high signal of peak flow by means of mathematics attenuation and smoothing. Although, The empirical and analytical Methods lack of physical bases in their definitions (Huyck *et al*., 2005; Collischonn &

Fan, 2012; Ladson *et al*., 2013; Bren, 2015), have showed positive results on the estimate of base flow when these are compared with chemistry methods (Larocque *et al*., 2010; Zhang *et al*., 2012). An example of this, are the works of Arnold & Allen (1999) and Lim *et al*., (2005), who in comparing real values of base flow with separation filters, achieved positives curve adjustments (R^2 = 0.86 for monthly flows and 0.91 for daily flows of 50 stations, respectively. The mains filters of separation of base flow correspond to algorithm of Lyne & Hollick (Lyne & Hollick, 1979; Spongberg, 2000), Chapman (Chapman, 1991; Welderufael & Woyessa, 2010) and Eckhardt (Eckhardt, 2005; Collischonn & Fan, 2012; Zhang *et al*., 2012), that conceptually correspond to an attenuation of flows by means of a mathematical filter that reduces the variability of flow and the maximum amounts. The filters consider different types of linearity assumption on the increasing curves just after of increasing of hydrograph or recession, for what it is neccesary to verify its accuracy with indexes as the BFI (Base Flow Index), defined by Lvovich (1972) (Smakhtin, 2001).

In the works developed until now in Chile, have not been used separation filters in determination procedures of base flow, existing an inclination to Graphical Methods (Pizarro-Tapia *et al*., 2013; Balocchi *et al*., 2014), perhaps, the lack of continuous data of basin discharges.

Based on these antecedents, the aim of this study is to determinate the base flow by means of three separation filters and contrast it with the empiric and graphical method.

Materials and methods

Study area

The study area corresponds to a basin of 19.1 ha that has been located in the field María de las Cruces (Figure 1), situated approximately to 45 km to southwest of the Concepción City, Bio Bío Region, Chile. The basin presents a parental metaphoric material, characteristic of western slope of the coast mountain range, with sandy-ground, an average elevation approximately of 319 a m.a.s.l., and an average slope of 43.6%. The basin has an oval-shaped, with a value of Gravelius of 1.35 and a stretching radio of Schumm of 0.71, which indicate a pronounce relief to flat.

The basin was forested with *Pinus radiata* in 1994, which presented a density of 1000 trees ha^{-1} in 2009, when the gauging station was installed. This has a west exhibition and a rainfall system which is characterized by an oceanic climate with rainfall mediterranean influence. Temperatures of the area range from 7.2° to 18° a maximum and the annual rainfall are of 1200 to 1600 mm per year (DGA, 2017) approximately.

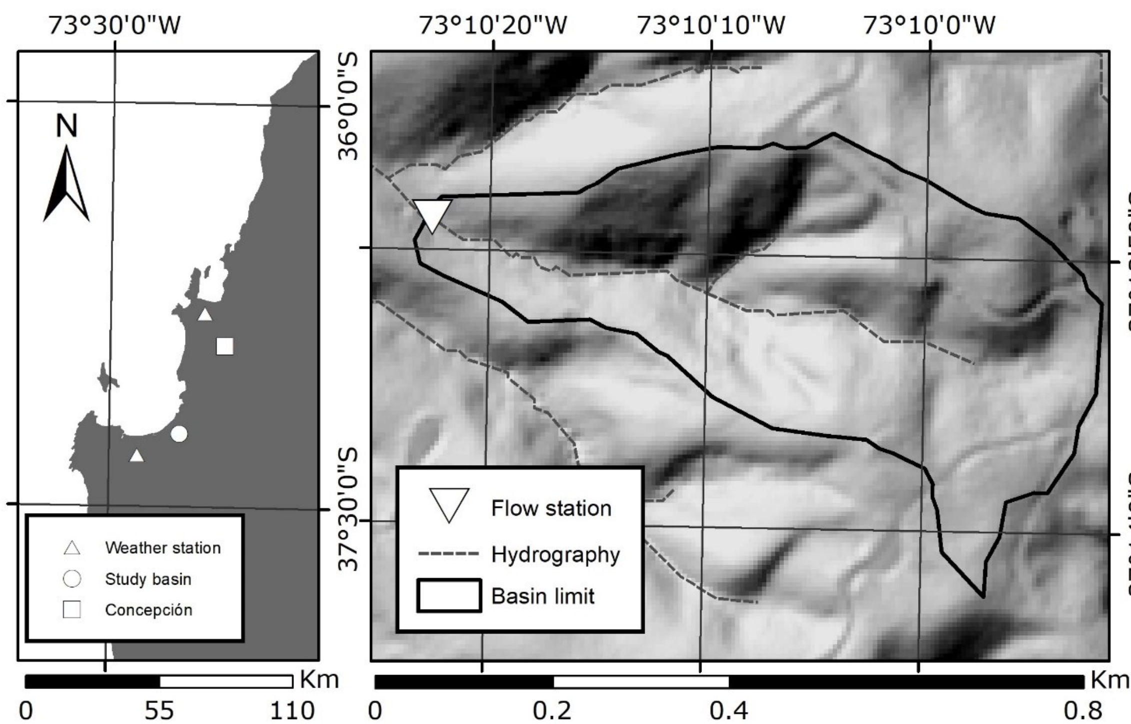

Figure 1. Location of the study area of the Region of Bio Bío (Left) and gauging station of the basin (right).

Precipitations

The precipitations in the study area were registered with an electronic rain gauge T.E HOBO brand, TR-525M model and a datalogger software, which were installed in field María de las Cruces about 3.7 km west of basin, approximately. The trends of the registered data were contrasted with the trends of the gauge states of Concepción DGA (code BNA: 8410001-3) and Carampangue in Arauco (code BNA: 8520000-3), with a distance between 46 and 7.8 km of the study area, respectivately.

Flow

The basin flow was registered with a gauging station that was installed on 02 January 2009, which consisted in a thin plate weir with a hole of 90° where a trueblue serie 555 brand with a datalogger pressure sensor was installed. In the installation considered OMM (OMM, 1994) recommendations, and the sensor was configured to record data each 5 minutes.

Analysis

From the rainfall data registered between on 01 may 2009 and on 30 April 2014, was calculated the master recession curve, and it was evaluated the graphical method and three separation filters of the base flow in a daily level. The curve of recession was estimated with an excel spreadsheet programmed by Posavec *et al*., (2006); the graphic method on base to the methodology described by Pizarro & Novoa (1986); and the filters corresponded to Lyne & Hollick (1979), and Chapman (1991) algorithms according to recommendations made by Ladson *et al*., (2013); the algorithm by Eckhardt (2005) was applied according to methodology of Collischonn & Fan (2013). Once the flows were separated in base and surface flow, it was made the BFI index calculation to monthy and annual level to comparation. In adittion, it was carried out a descriptive analysis of the flows and comparative tests as those of U de Mann-Whitney and Kruskal Wallis to establish statistical differences among methodologies applied. The previous analysis were made on the statistic R for Windows.

Recession curve

The recession curves on the way αe^{-k} was analyzed with a calculation routine developed by Posavec *et al*., (2006) y Posavec *et al*., (2010), in Microsoft Excel and visual basic, implementing a Graphical Method based on the "matching strips" (Toebes *et al*., 1969) procedure. 5 linear and no linear equations were evaluated to adjust segments in the Master Recession Curve. To delete subjective elements of the recession analysis, the routine used an objective and automatic search to the best adjust of the recession curve, by means of the coefficient of determination R^2.

Separation filters of base flow

The separation filters evaluated were the Lyne & Hollick algorithm (equation 1); the Chapman algorithm (equation 2), and the Eckhardt algorithm (equation 3), subject to the conditions of equation 4, indicated below:

$$q_{f(i)} = \alpha q_{f(i-1)} + \left(q_{(i)} - q_{(i-1)}\right)\frac{1+\alpha}{2} \qquad (1)$$

$$q_{f(i)} = \frac{3\alpha-1}{3-\alpha} q_{f(i-1)} + \frac{2}{3-\alpha}\left(q_{(i)} - \alpha q_{(i-1)}\right) \qquad (2)$$

$$q_{b(i)} = \frac{(1-BFI_{max})\alpha q_{b(i-1)} + (1-\alpha)BFI_{max}q_{(i)}}{1-\alpha BFI_{max}} \quad (3)$$

$$q_{b(i)} = \begin{cases} q_{(i)} - q_{f(i)} & \text{if } q_{f(i)} \geq 0 \\ q_{(i)} & \text{if } q_{f(i)} < 0 \end{cases} \quad (4)$$

where: $q_{f(i)}$ is the surface flow at the moment i, $q_{b(i)}$ is the base flow at the moment i, $q_{(i)}$ is the total flow at the moment i, $q_{f(i-1)}$ is the surface flow at the moment i – 1,$q_{b(i-1)}$ is the base flow at the moment i – 1,

$q_{(i-1)}$ is the total flow at the moment i – 1, α is the parameter of the slope of the master recession curve expressed as: e^{-k} y BFI_{max} is maximum value of BFI index that the equation can assume.

Finally, the observations described by Ladson *et al*., (2013) were used, which defined a standard approximation to the use of this filters, due to its evaluation of different softwares that included this type of calculations, it was found that each result was different to one same series of data. These observations were the fololwing: Reflect the first 30 and last 30 data of the series like a mirror, in order to adjust the filter pass in the data. At the end of the calculation, this reflected series is not included in the final calculations; specify the initial values of each pass of the filter; specify a minimum number of filter passes; in this case it was three, assuming a first pass in a descending way, then ascending and descending again; and consider the literature available in the definition of the parameters of the equations.

BFI Index

This index was developed during the base flow studies in the United Kingdom by *Institute of Hidrology* in 1980 (Collischonn & Fan, 2012), which was defined the proportion between the base flow divided by the total flow. The ecuation 5 expressed its form:

$$BFI = \frac{\sum_{t1}^{t2} Q_{base\ flow}}{\sum_{t1}^{t2} Q_{flow}} \quad (4)$$

Where: t_1 and t_2 corresponded to intervals defined monthly and per periods.

Results

Precipitations

The rainfall record in the study area was in average of order of 1158 mm per year, and the gauging stations of Concepción (DGA) and Carampangue in Arauco did not show a trend in their rainfall for the last 20 years (Figure 2). This fact was corroborated by the Mann Kendall statistic test (Kendall, 1975), with a null hypothesis (H_0) indicates that there is not a trend in rainfall annually (p-value of 0.26291 and statistical value of Kendall's tau of -0.193).

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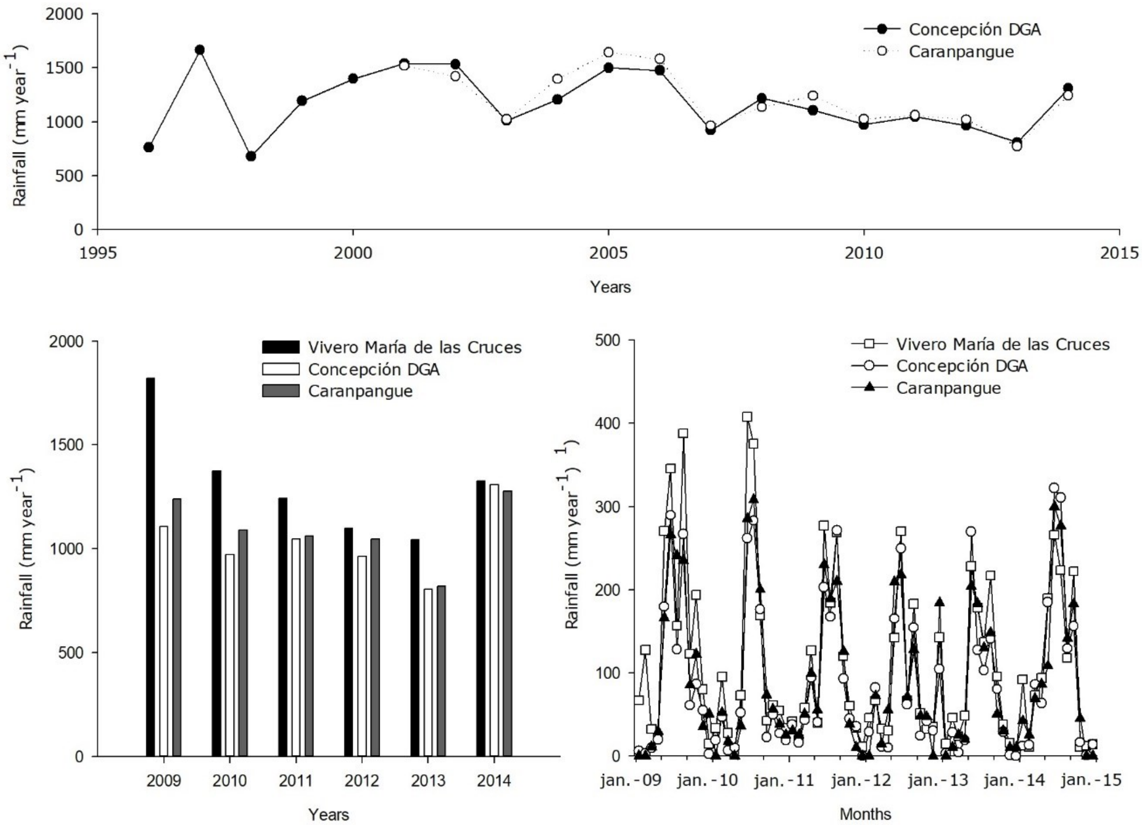

Figure 2. Historical Record (up), annual (below left), monthly (below right) of the Rainfall of the study area.

Recession curve

The best estimate achieved for the master recession curve which was obtained by dividing the data in three series (series I from 0 to 2%, series II from 2 to 24% and series III from 24 to 100%, extracted from the duration curve), what allowed to adjust an exponential curve with R^2 = 89.9% and α parameter = 0.9514 from the slope (Figure 3). This parameter is used as a one of the input factors in the separation filters (Lyne & Hollick, Chapman and Eckhardt).

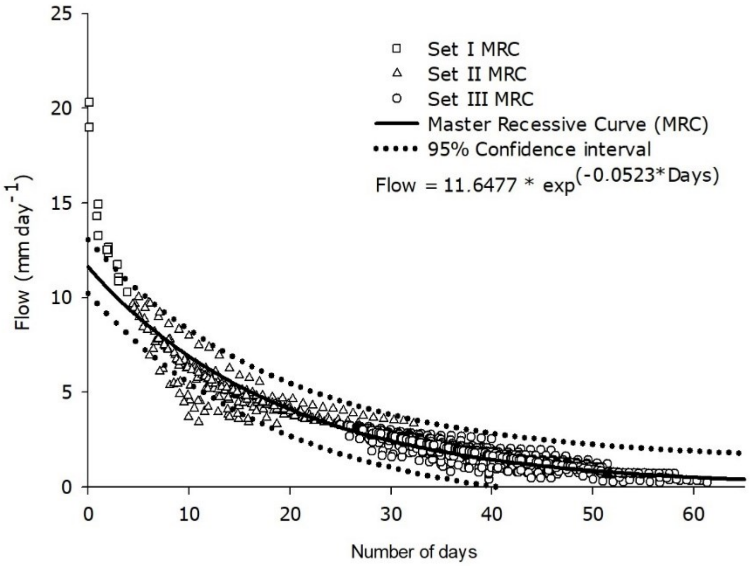

Figure 3. Master recession curve generate from a excel spreadsheet programmed by Posavec *et al*., (2006).

Separation filters of base flow

The separation methods of Chapman and Eckhardt presented linearity when the flows were separated, unlike the Lyne & Hollick technique which was much more variable on its estimation according to the hidrograph form, where the base flow was greater if the maximum flow was grater (Figure 4). For the summer time that was defined (Figure 5), The Lyne & Hollick method represented a base flow much more near to the superficial in summer, what demonstrated that this estimate asumes all the surface flow, which is not affected by rainfall, corresponding to base flow.

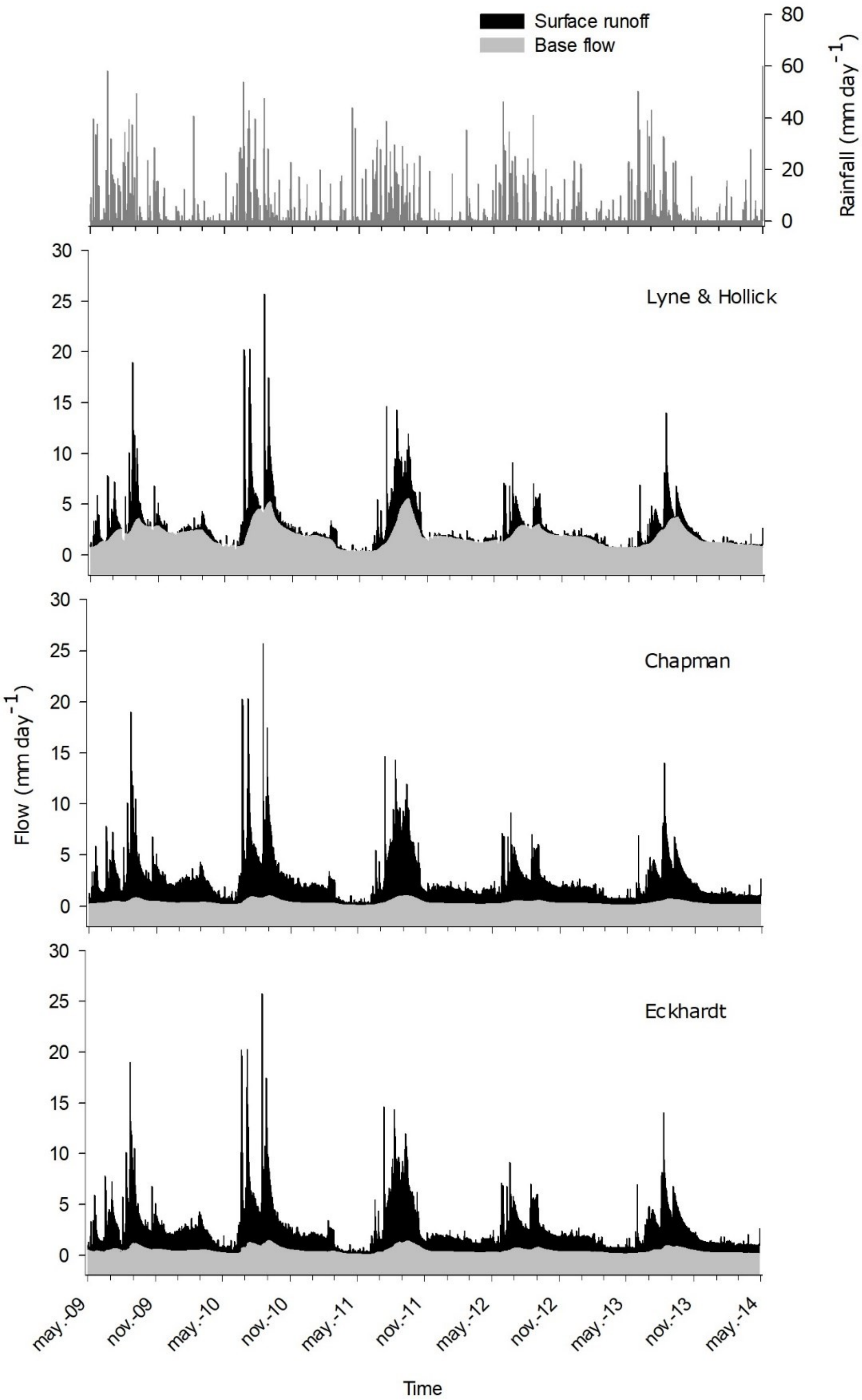
Surface runoff
Base flow
Rainfall (mm day-1)
80
60
40
20
0
Lyne & Hollick
Chapman
Eckhardt
Flow (mm day-1)
30
25
20
15
10
5
0
may.-09
nov.-09
may.-10
nov.-10
may.-11
nov.-11
may.-12
nov.-12
may.-13
nov.-13
may.-14
Time

Figure 4. Separation of surface and base flows by means of Lyne & Hollick, Chapman and Eckhardt filters.

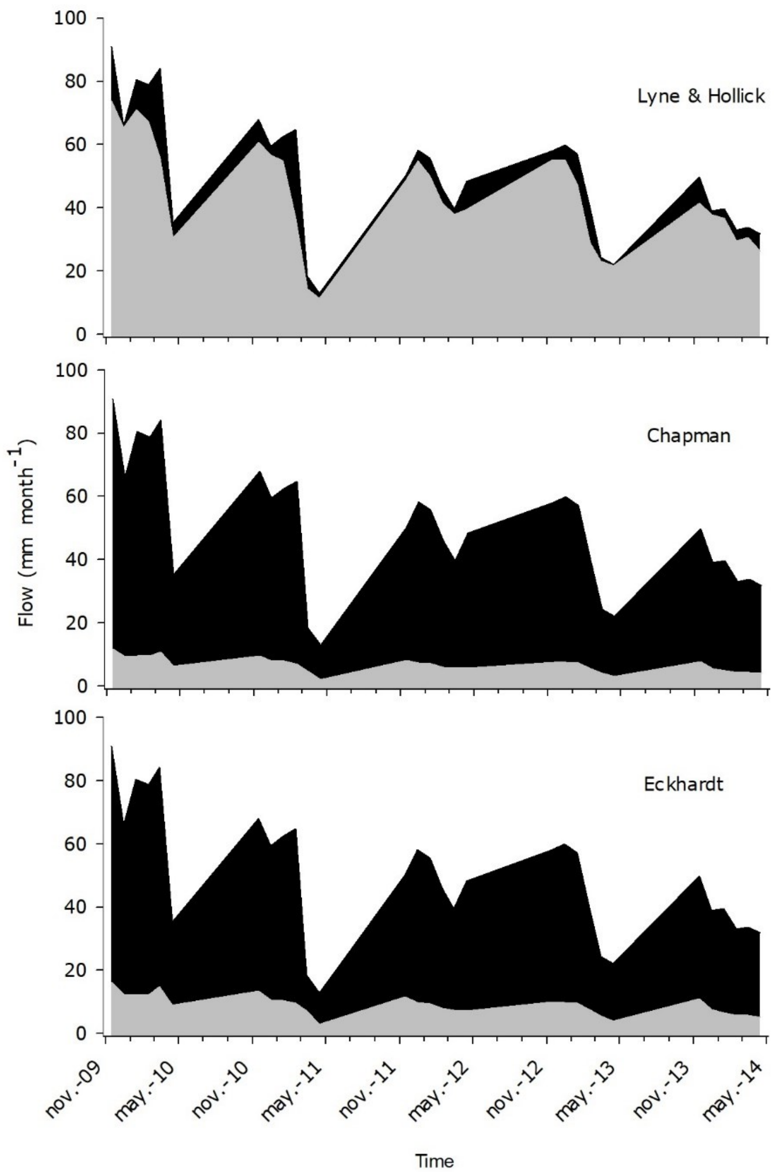

Figure 5. Separation of flows on surface and base flows of means of Lyne & Hollick, Chapman and Eckhardt filter for a summer period between November and April each year.

BFI Index

This index showed results to annual and monthly levels with an evolution to higher base flows as the time passed for the Lyne & Hollick filter, showing a sensitive to any change in the water quantity flow during the year. This was different for the Chapman y Eckhardt filters that did not present variations on the time, letting see that the estimated base flow by means of this methods, only corresponded to a minimum proportion of the flow constantly (Figure 6).

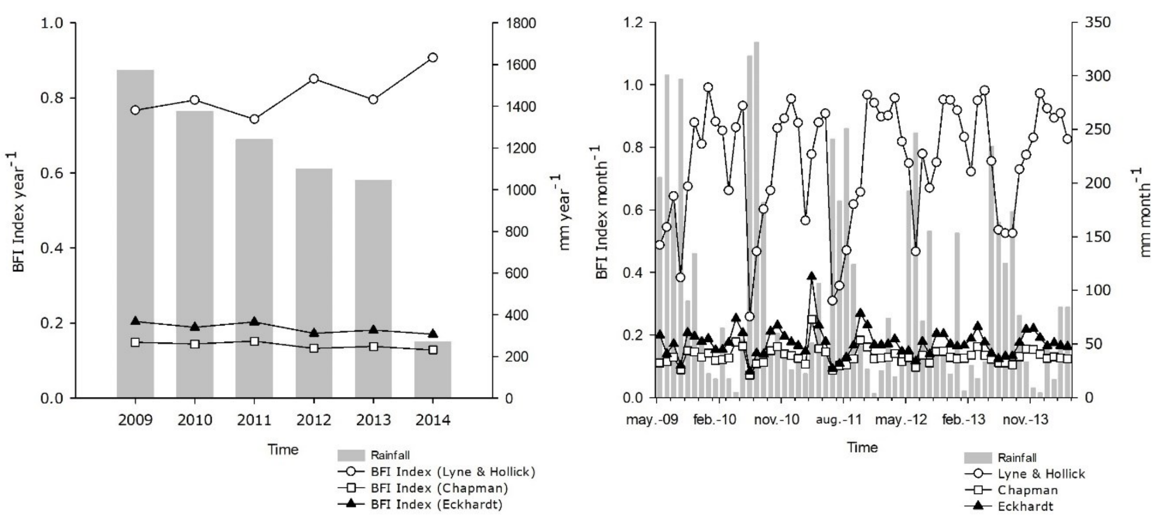

Figure 6. Annual (left) and monthly (right) evolution of the BFI index for the study basin.

It was calculated the separation of flows through of Graphical Method for 16 storms during all period (table 1), with the aim of comparing these filters with a methodology of wide acceptance in Chile, to be reflected a substantial difference that exists between the Chapman and Eckhardt filters, which were estimated in a lower BFI Index on a range between 84 and 87% less than the value obtained with the Graphical Method. (BFI = 0.76). In the case of the Lyne & Hollick, the difference with respect to the Graphical Method only amounted to 30% less than estimated base flow.

Table 1. Comparison of BFI index of different filters with Graphical Method for 16 storms were selected.

Storms	Start date	End date	BFI Lyne & Hollick	BFI Chapman	BFI Eckhardt	BFI Graphical method
1	15/06/2009	21/06/2009	0.47	0.10	0.12	0.57
2	21/08/2009	28/08/2009	0.32	0.08	0.09	0.76
3	30/10/2009	05/11/2009	0.75	0.11	0.15	0.91
4	04/02/2010	10/02/2010	0.86	0.12	0.16	0.87
5	20/06/2010	28/06/2010	0.23	0.07	0.10	0.52
6	15/08/2010	20/08/2010	0.60	0.11	0.13	0.80
7	10/02/2011	16/02/2011	0.57	0.10	0.13	0.91
8	16/06/2011	22/06/2011	0.23	0.07	0.08	0.56
9	12/07/2011	17/07/2011	0.30	0.09	0.09	0.62
10	08/08/2011	16/08/2011	0.38	0.09	0.11	0.75
11	28/01/2012	01/02/2012	0.86	0.12	0.16	0.95
12	30/05/2012	04/06/2012	0.56	0.11	0.13	0.67
13	13/08/2012	18/08/2012	0.69	0.11	0.13	0.91
14	30/05/2013	04/06/2013	0.43	0.09	0.11	0.67
15	09/08/2013	15/08/2013	0.36	0.08	0.10	0.76
16	27/03/2014	31/03/2014	0.86	0.12	0.16	0.86

Statistic Analysis

There were significant differences in the way to estimate the base flow for each of the methodologies, with a value $P < 2.2 * 10^{-16}$ for the Kruskal Wallis test. The estimates of base flow, compared each other by means of the U de Mann-Whitney test, obtained the same result that the

Kruskal Wallis (Lyne & Hollick vs Chapman test, value $P < 0.001$; Lyne & Hollick vs Eckhardt, value $P < 0.001$; Chapman vs Eckhardt, value $P < 0.019$).

Discusion

The results calculated from the filters generate dissimilar estimates between the techniques, specifically for the methodology proposed by Lyne & Hollick that assumes that the base flow is an important component of the hydrograph, unlike the Chapman and Eckhard base flow with only increases in the winter months and in higher floods The possible explanation of why these last filters only showed variations in the winter months could have been due to the concentration of the precipitations in the winter period (figure 2).

Having as antecedent that the base flow is a predominant component of the hydrograph in various summaries of studies that used disotonic methods in the separation of flows for forested basins (Buttle, 1994; Klaus & McDonnell, 2013); The Lyne & Hollick filter would generate a better estimate of the base flow for the situation analyzed, since this filter estimated a higher base flow.

The filter methods in evaluation showed different responses to a reduction in rainfall (approximately with a deficit of 20% on average in recent years) given that independent of the amount of water entered into the basin, Chapman and Eckhardt filters generate a linear estimate of surface flow especially in the summer period, which shows that both methodologies do not respond to changes that the system may have (whether, this in the rain amounts or in the loss for evaporatranspiration depending on the type of soil).

A different situation was proposed by the Lyne & Hollick filter, which expresses greater sensitivity of entry of water in the winter months, especially for the summer period, where there is an absence of rainfall or surface runoff.

The water quantity flow corresponds entirely to the base flow. The results of the calculated filters used α parameter from the estimated master recession curve to avoiding this way the use of values from the bibliographic, as is recommended by other studies in the use of this type of methodologies in the separation of flow (Eckhardt, 2005; Aksoy *et al*., 2009; Berhail *et al*., 2012). The BFI Index that was calculated to annual and monthly level, presented a semi- declining linear trend in its values for the Chapman and Eckhardt filters; however, in the case of the Lyne & Hollick filter, this trend is opposite, showing that the contribution of the base flow became greater as time passed, which proved that the base flow is predominant and the rainoff surface was minor due to lower rainfall registered in the study period (2009-2014).

As a point of comparison, this type of methodologies of flow separation, which are not commonly used in Chile, used the Graphical Method of separation for some storms, proving only that the Lyne & Hollick filter may present a similarity in the way of estimating the underground contribution, above all in the summer periods (with a difference of less than 7% in average). However, to despite of the differences that were presented by the graphical method with the filters of flow separation, it cannot be determined in advance these last methodologies are wrong in its estimate. This form of flow separation also corresponds to a mathematical approximation that must be validated, but it is widely accepted said Huyck *et al*., (2005).

Conclusions

The calculation of the base flow from the methodology raised by Lyne & Hollick for climatic conditions presented by the basin, has demonstrated a greater adaptability to the changes in the water entry which is reflected in the behaviour curves of the annual and summer months in conjunction with the values of the BFI index.

Although, it has been not known the true values of base flow, with exception of its relative similarity with the Graphical Method, The Lyne & Hollick filter would make it possible to identify changes in the basin behaviour and its form of storing and releasing water having in consideration that the isotopics techniques have demonstrated that the system has not behaved in a linear form, which is not evident in the Chapman and Eckhardt methodologies.

Given this antecedents, it is concluded that the Lyne & Hollick filter is an alternative aproximation to the estimate of the base flow commonly used in Chile, above all in summer periods.

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