---

*Citation for published version:*

Dussaillant, Alejandro, Buytaert, Wouter, Meier, Claudio and Espinoza, Fabián (2012) Hydrological regime of remote catchments with extreme gradients under accelerated change: the Baker basin in Patagonia. Hydrological Sciences Journal, 57 (8). pp. 1530-1542. ISSN 0262-6667 (Print), 2150-3435 (Online) (doi:10.1080/02626667.2012.726993)

*Publisher's version available at:*
http://dx.doi.org/10.1080/02626667.2012.726993

---

*Citation for this version held on GALA:*

Dussaillant, Alejandro, Buytaert, Wouter, Meier, Claudio and Espinoza, Fabián (2012) Hydrological regime of remote catchments with extreme gradients under accelerated change: the Baker basin in Patagonia. London: Greenwich Academic Literature Archive.
Available at: http://gala.gre.ac.uk/9655/

---

# Hydrological regime of remote catchments with extreme gradients under accelerated change: the Baker basin in Patagonia

Alejandro Dussaillant J.[1,4], Wouter Buytaert[2], Claudio Meier[3,4] and Fabián Espinoza[5]
1 Civil Engineering Deparment, University of Greenwich, UK
A.DussaillantJones@greenwich.ac.uk
2 Imperial College London, UK
3 Depto. Ingeniería Civil, Universidad de Concepción, Concepción, Chile
4 Centro de Investigación en Ecosistemas de la Patagonia, Coyhaique, Chile
5 Dirección General de Aguas, región Aysén, Coyhaique, Chile

Received 7 June 2010; accepted 2 April 2012; open for discussion until

**Editor** Z.W. Kundzewicz

**Citation** , 2012. *Hydrological Sciences Journal*, 57 (?), ???–???.

**Abstract** The Baker basin (27 000 km$^2$) is located in one of the most unique and remote areas of the planet. Its hydrological regime is poised to undergo dramatic changes in the near future due to hydropower development and climate change. The basin contains the second largest lake in South America, and part of a major icefield. This study documents the natural baseline of the Baker River basin, discusses the main hydrological modes and analyses the potential for sustainable management. Annual precipitation varies several-fold from the eastern Patagonian steppes to the North Patagonian Icefield. The westernmost sub-basins are strongly governed by glacier-melt with a peak discharge in the austral summer (January–March). The easternmost sub-basins have a much more seasonal response governed by quicker snowmelt in spring (November–December), while they exhibit low flows typical for semi-arid regions during summer and autumn. Topography, vegetation and wetlands may also influence streamflow. The strong spatio-temporal gradients and variability highlight the need for further monitoring, particularly in the headwaters, especially given the severe changes these basins are expected to undergo. The large diversity of hydrological controls and climate change pose significant challenges for hydrological prediction and management.

**Key words** natural flow regime; catchment classification; runoff ratio; climate change; hydropower; Prediction in Ungauged Basins; Baker River

## 1 INTRODUCTION

During the last couple of decades, sustained advances have been achieved in the quantification and prediction of hydrologic fluxes, such as precipitation, streamflow and sediment discharges. However, the development of concepts and the application of prediction tools have hitherto mostly focused on relatively data-rich areas in developed, temperate regions of the world. This is a sensible approach, given the available hydrologic knowledge, as well as the socio-economic importance of these catchments. However, it also risks leaving out a large set of natural catchments that exhibit extreme behaviour and/or are particularly data-sparse, and which are under increased development pressures. In view of the increased societal emphasis on providing hydrological predictions in such environments (Sivapalan, 2003; Beven, 2007), there is a strong scientific need to describe and analyse such catchments and provide adequate prediction techniques.

This study intends to contribute to the worldwide efforts on catchment characterisation and classification by describing and analysing a set of river basins in one of the most hydrologically diverse, and data sparse regions in the world: the Baker River basin in Patagonia.

Chilean Patagonia is a nearly pristine environment, with several endemic but poorly characterised species and unique aquatic ecosystems, including a high diversity of lakes, rivers, and fjords. Gradients in topography and climate are exceptionally high (Fig. 1). The distance between the fjords and the highest peaks (>3000 m altitude) is often less than 50 km. Precipitation may vary from 400 to 6000 mm per year over distances as short as 60 km. Most rivers in the Baker basin are influenced by storage and release from lakes and/or glaciers, while geology is heterogeneous and topographic controls on streamflow vary strongly (HidroAysén 2008). These differences result in a large diversity of flow regimes, ranging from semi-arid to perennially wet, with significant glacier melt contributions. Additionally, natural hazards occur frequently, thus quickly changing the hydro-geomorphological behaviour of rivers. These include large volcanic eruptions (e.g. Hudson 1991, Chaitén 2008), and recently recurring glacial-lake outburst floods (e.g. at least nine jökulhlaups occurred from the Cachet 2 lake since 2008; Dussaillant *et al.*, 2009b, 2010).

Furthermore, Patagonia has been identified as a region particularly vulnerable to climate change (UNEP 2010). There is mounting evidence that the Patagonian Icefields are undergoing accelerated retreat, and suffering the highest rates of mass balance losses from all the large ice areas on Earth in relative terms (Aniya, 2007; Rignot *et al.* 2007; Dyurgerov & Meier, 2005), while meteorological studies have shown significant positive temperature anomalies for the southern (Rasmussen *et al.*, 2007; Schneider & Gies, 2004) and northern Patagonia (Villalba *et al.*, 2003; Masiokas *et al.*, 2008).

From a socio-economic viewpoint, the Baker River basin is the most important basin in Chilean Patagonia. The basin is shared between Chile and Argentina, contains the second largest lake in South America (General Carrera Lake), and includes a Biosphere reserve (San Rafael in the Northern Patagonian Icefield) that hosts several endemic aquatic species (Bledsoe *et al.*, 2009; Zemlak *et al.*, 2010). Population is sparse yet vulnerable in this harsh environment. As recent unrest shows, the region is at a crossroads regarding resource management (particularly water) and alternative future development pathways. Growing activities are eco-tourism and salmon farming, and more recently hydropower development (Dussaillant *et al.* 2009a). Particularly, plans for a series of hydropower dams are in an advanced stage (Vince, 2009; Gardner 2011).

As such, there is an urgent need to describe and analyse the hydrological behaviour of these pristine basins. This will not only provide a baseline to assess the impact of future human activities on the Patagonian hydrology and its dependent ecological and geomorphologic processes; it will also provide insight in the capacity to predict the impact of potential interferences on such processes and priorities for further data collection and scientific studies, which is essential for a sustainable ecosystem management. Therefore, the main goal of this paper is to provide a comprehensive overview of the hydrology of the Baker basin and its hydrological gradients and to identify implications for decision-making.

## 2 STUDY SITE, DATA AVAILABILITY AND METHODS

With an area of circa 27 000 km$^2$, the Baker River basin (Fig. 1) is the largest in southern Chile (approx. 46 to 48S, 71 to 73W). It stretches from the eastern slope of the Andes, largely covered by the North Patagonian Icefield (NPI) eastward into the plains of the Patagonian steppe (TwinLatin 2008).

The Baker River has the highest mean annual discharge rate of all Chilean rivers (circa 1100 m$^3$/s). It flows out of Bertrand Lake, which in turn receives the draining waters from bi-national General Carrera Lake. Both lakes have a combined surface area of circa 1900 km$^2$ (Zambrano *et al.*, 2009), and are located at an elevation of approximately 200 masl. The most important inflow comes from the Ibáñez, Murta, Leones, and Soler rivers on the northern shore, while the main tributary to the southern shore is the smaller Jeinimeni. The Baker River flows broadly south into the Chilean fjord system, connected to the Pacific Ocean. It has an average slope of 0.6% over its last 90 km. The main tributaries to the Baker (all of which have mean flows at least one order of magnitude smaller than the mainstem) are the Nef, Colonia, and Ventisqueros, on the western side, and the Chacabuco, Cochrane, Del Salto, and Ñadis, on the east.

Meteorological and gauging stations are scarce, with a density for both of around 1/3000 km$^2$. The length of the records ranges from 50 years to less than 10 years, with substantial gaps (Fig. 1). Gauging stations tend to be clustered in lower areas around the Baker River itself, with a general lack of stations in the Western mountain sub-basins (Fig. 1), which have NPI glaciers in their headwaters. In only one glaciated basin flow monitoring started recently (2009), motivated by repeated glacier hazards and hydropower development pressures (Dussaillant *et al.*, 2010).

We present results here based on a recently integrated database of station records, merging historic data and more recent records from several state agencies and private companies, as well as hydro-geomorphological data from the recent 2008 Twin Latin EU FP6 project (Twin Latin, 2008) and from the environmental impact study for the hydropower projects in the Baker basin (HidroAysén 2008). Available weather data (Fig. 1) originates from 12 meteorological stations in the area, which measure precipitation and temperature. Precipitation data, mostly daily totals, were compiled from the Chilean Water Authority (DGA), the Chilean National Meteorological Office (DMC), and the previously state-owned hydropower company (ENDESA). We also used one station from Perito Moreno in Argentina (provided by DGA), located at the eastern limit of the basin. Streamflow records consist mainly of daily flows for 7 gauges installed by ENDESA, which are still operational and currently managed by DGA, plus 5 discontinued ENDESA stations. Stations were checked for consistency using double-mass curves.

Due to substantial data gaps, the analysis of precipitation gradients had to be limited to the 1977-1991 period, when data availability is highest (Fig. 1), and most gauges were managed by ENDESA. Remaining gaps in the precipitation stations were filled with linear regression using the station with the highest correlation. Average precipitation over each catchment was obtained using Thiessen interpolation. The more advanced techniques of ordinary kriging and co-kriging (e.g. with altitude and distance to ocean) were tested but did not improve the interpolation. Runoff ratios were calculated over the period for which discharge data are available.

The glacierized catchments in the Baker basin still have no direct gauge records. Therefore, for the Nef and Colonia rivers, discharge was calculated from the difference in river flow measurements at stations located upstream and downstream of their confluences with the Baker River (Fig. 1). Some of these stations have data since 1963, but the common and complete period was 1977-2008 and 1980-1989 for Nef and Colonia rivers, respectively. For estimating the Nef discharge we used the difference between Baker-Bertrand and Baker-Chacabuco, while for Colonia, from the latter and Baker-Colonia, considering the contributions of both Cochrane and Del Salto rivers (see locations in Fig. 1).

## 3 RESULTS AND DISCUSSION

### 3.1 Meteorology and precipitation gradients

Geology and climate gradients follow mainly an E–W gradient from the continental plains (Patagonian steppes) to the Pacific Ocean. At this latitude, the Andes follows the Pacific coastline closely, such that most of the basin lies on the eastern slopes. In the east of the basin, grasses and low shrubland dominate (e.g. Chile Chico, the lower part of the Ibáñez basin). Western catchments generally drain from ice fields (Fig. 1) and contain more forest cover due mainly to higher precipitation (e.g. Lago Vargas; Fig. 2), such as the upper Ibáñez, most tributaries to the northern shore of the lakes, and most right-side tributaries to the Baker. These contrasts result in a wide range of flow regimes, as will be described in the next subsection.

In general, the Baker River basin has a mono-modal precipitation pattern (Fig. 2), with most of the precipitation occurring in the Austral autumn and winter (April-August). During this time, most of the precipitation falls as snow, delaying the hydrological response until late spring (Nov-Dec) and summer (Jan-Mar).

In terms of total precipitation amount, there are strong differences within the basin, as evidenced by Fig. 2. For example, the driest station (Chile Chico, 220 mm/year) exhibits almost an order of magnitude less rainfall than Lago Vargas (1707 mm/year). As expected, there is a strong West-East gradient, with the driest stations such as Chile Chico and Entrada Baker located in the eastern Patagonian steppes, and Lago Vargas near the west coast. Even along the shoreline of General Carrera Lake, Puerto Guadal in the west receives 3 times more rainfall than Chile Chico in the east (Fig. 2).

### 3.2 Flow regime characterisation

**3.2.1 Water yield and streamflow seasonality** Table 1 shows the spatially averaged mean yearly precipitation and discharge. It is clear that the reported flow and precipitation volumes do not match, resulting in unrealistic runoff ratios. The strong E-W gradient in precipitation, and the lack of rain gauges in the western part of the Baker basin as well as at higher elevations, result in severe underprediction of precipitation in the basins that extend to the west (e.g. Río Ibáñez and Río Murta). Other sources of errors are the precipitation and discharge measurements, and the contribution of glaciers. Glaciers may currently be in non-equilibrium state due to regional warming (see section 3.2.2), but this extra contribution to streamflow is impossible to quantify. The unrealistic values of the runoff ratios in the glacierized basins (Table 1) cannot be attributed to glacier melt. A mass loss of several meters of glacier thickness per year would be needed over the entire monitoring period to create the runoff ratio bias (Table 1). Therefore it is evident that precipitation measurement errors dominate. These may be introduced by the fact that a large proportion of precipitation falls as snow in the western catchments, which given to high winds can suffer from strong snow undercatch (Sevruk & Nespor 1998), and because stations cannot discriminate rainfall from snow since they are not heated. Additionally, even though they are updated with gauging campaigns every 3 months, errors in the streamflow rating curves may potentially be significant because of the variable nature of alluvial channels. This process may be extreme, such as in the case of the Ibáñez, which was recently filled with volcanic ash. However, the strong agreement between the deviations of the runoff ratio and the precipitation gradients (Table 1) suggests that the lack of precipitation data is indeed the major error source (Valery et al. 2009).

Stations are particularly scarce at higher elevation near the NPI, where much larger precipitation, in the order of up to 5 to 10 m per year, must be occurring given previous estimates based on water budgets (Peña & Escobar, 1987; Bravo, 2010) and atmospheric analyses (Schneider & Guies, 2004; Rasmussen *et al.*, 2007). This affects mostly the water budget for those basins located closer to the ocean (e.g. Murta) and the NPI (e.g. Nef and Colonia). This is further corroborated by the fact that the Chacabuco and Cochrane basins, on the east section, give more realistic estimates (Table 1).

The flow regime of the Baker River itself is characterised by very stable discharges as shown in Fig. 3a and 4a, due to the buffering capacity of General Carrera Lake (Fig. 1). Low flows occur during July-September while October-March is the period of high flows (Fig. 4a) driven by first snow melt and then ice ablation.

The attenuated flow pattern of the Baker river contrasts strongly with the behaviour of most tributaries (Fig. 3b). The Ibáñez River, main tributary to General Carrera Lake, exhibits more variability, with flows starting to decrease in January and February (Fig. 4a), a hydrological response driven by spring and early summer snowmelt. Mean monthly flows are lowest from June to September, with occasional flood-producing storms, while the February-May period presents only slightly higher discharges. High flows tend to concentrate between October and January, the snowmelt period, and are circa double low flows. But floods may happen during any month of the year, evidencing that Ibáñez is also rainfall driven. The Murta River behaves in a similar way (Fig. 3b), albeit with higher yields and lower absolute flows (data not shown). Note that in some years both rivers have periods of higher flows during March-April, due to autumn rains, but they receive no significant ice melt contributions contrary to the Baker. The smaller Jeinimeni River is predominantly driven by snowmelt (Fig. 3b), because of the smaller glacier area compared to Murta and Ibáñez (Table 1).

Colonia River is a major Western tributary to the Baker. For the 1980s period that we have available (Fig. 4b), the lowest flows occurred in July-Sep while the highest occurred in Dec/Jan melt season. Compared with Nef in the same period, the other glacierized basin with data, high flows are on average 70% higher in the Colonia.

Apart from the lake-controlled Cochrane River (Fig. 3b), Eastern tributaries share a similar behaviour with a snowmelt-driven regime, although Salto River circa doubles the flow of Chacabuco (Fig. 4c). Comparing Eastern semiarid catchments to Western glacierized ones (Fig. 4), the latter have higher variability, from low winter flows to high summer flows driven by melt.

**3.2.2 Temporal trends and potential impacts of climate change** The analysed time period may have been affected by increased regional warming and ablation. Mean maximum temperatures for the summer period (JFM) are presented for Cochrane and Chile Chico, which have the longest and most complete records in the Baker basin.Data of Balmaceda and Coyhaique, which are located in other basins further north (Fig. 5) are just included for comparison. There is a very similar temporal pattern for all stations, even for Chile Chico, which has a milder climate. There has been a slightly increasing trend in the moving average (not shown) but it was found not to be significant at a 95% confidence level with a Mann-Kendall test. Also, there is an apparent upwards shift of the moving average by the end of the 1970s, which has been reported before and maybe related to a shift in temperatures in the north Pacific (HidroAysén, 2008; Trenberth *et al.*, 2007). The apparent increase of mean summer temperatures in the area during the 1980s is possibly related to the retreat experienced by the glaciers of the NPI since the 1990s (Aniya 2007) but needs further study. Additionally, since 2008 summer temperatures have been particularly high. These latter two aspects are further elaborated below.

Figure 6 shows mean annual discharge for the entire available time series. Gauge data at the tributaries to Carrera Lake, Murta and Ibáñez rivers, seem to show a slightly different trend in the 20-year period (Fig. 6a). While Murta annual flow has been constant to slightly decreasing, the Ibáñez River shows a slightly more upward trend. Noting that the discharge range is comparatively much reduced in Fig. 6b, it actually shows a similar behaviour in the three Baker gauges: a decreasing trend in discharge until the 1990s followed by either a levelling or a slight upwards trend (except on the Baker gauge at the confluence of Chacabuco). This explains why the clearest trend in annual flows is that shown by the Nef discharge signal (Fig. 6a), since it is estimated by the difference from Baker@Chacabuco and Baker@Bertrand (Fig. 6b).

Scrutinizing the Nef data at a monthly scale shows a notable increase for the Nef summer flows (JFM) in the last 15 years (Fig. 7, smoothed trend included). A non-parametric Mann-Kendall test showed no significant trend for the 1977-2008 period. However, given that in the last couple of decades the Nef basin has experienced significant glacier changes (Aniya 2007) and that there is some regional evidence of climate change (Villalba *et al.* 2003; Masiokas *et al.* 2008), we also restricted the test to the last 15 years. This shows a significant ($p<0.02$) increase, as also evidenced by Fig. 7 using locally weighted polynomial regression. This augmented ice-melt flow behaviour is supported by the behaviour of the Nef Glacier (Aniya 2007; Winchester et al 2001). Aniya (2007) analysed glacier dynamics since 1990, reporting successive states of glacier advance (1991-

1993), snout disintegration (1994 - 1996), retreat (1996 - 2000), stability (2000 - 2002), advance (2002-2004) and further slight retreat (2004-2005). Since 1994 there was significant areal loss, which was most acute during 1994-1999. These glacier and streamflow dynamics seem consistent with the upward summer maximum temperatures tendencies (Fig. 5). Nevertheless, more specific glacier mass balance studies and prolonged monitoring data are deemed necessary to confirm this. Note that similar increases in summer flows have been reported in glacierized valleys in other regions of the world such as in North America (Stahl & Moore 2006), the Himalayas (Rees & Collins 2006), and in the Alps where flows showed peaking in the 1950s (Lambrecht & Mayer 2009).

Centre of mass analysis of the summer (ice-dominated) melt was performed for the Nef River, which is again the only Icefield river discharge signal possible to extract from available data. No apparent trend in the 1977-2002 period was evidenced, and only a slightly earlier melt in the order of a week since 2004. Other long record gauges showed no trends either (e.g. Baker@Bertrand showed no changes in the period, data not shown).

Finally, we also note here that regression analyses in the 1977-1991 data-filled period showed no significant correlation between variables; for example, between discharge and precipitation (Maturana 2009). This is probably due to melt being a major source, or the disconnection between locations of streamflow gauges and meteorological stations, specifically at subcatchment level and particularly for Western, NPI draining valleys. And again highlights the issues with interpolation of the rain gauges and closing the water balance of the subcatchments (Table 1).

## 4 IMPLICATIONS FOR HYDROLOGICAL UNDERSTANDING, PREDICTION AND MANAGEMENT

Flow regimes in the Baker basin are very diverse: they range from extremely well regulated outflows from the lakes General Carrera and Cochrane, to flashy regimes of the smaller tributaries. Clearly, there is an E-W gradient. Western catchments (e.g. Ibáñez, Murta) are probably influenced by snow/ice melt and strong frontal rain regimes originating over the eastern Pacific. As a result, these rivers have a marked seasonal pattern with a maximum discharge occurring in the austral summer (Fig. 3). These processes probably obfuscate snowmelt driven processes, which dominate small and unregulated basins such as Jeinimeni and cause a much earlier seasonal peak (Fig. 3). The difference in altitudinal gradient further influences the timing and dispersion of the snowmelt peak.

We hypothesise that the presence of wetlands, and differences in land cover (Table 1) further contribute to gradients in water yield and flashiness. For example, the Ñadis River has a significant wetland area immediately upstream from its confluence with the Baker, which might be affecting the inflow into the Baker River through storage and release. Since there is no gauging station on Ñadis, this aspect remains to be studied.

Many of these processes are expected to undergo severe changes in the near future. Several studies are showing that Patagonian glaciers are especially vulnerable to global change (Aniya, 2007; Dyurgerov & Meier 2005; UNEP 2010). Increases in temperature and changes in precipitation may affect the ecological characteristics of the wetlands and their related water storage capacity. Additionally, the projected large dams would have considerable downstream effects including those from the planned hydro-peaking operations (HidroAysén 2008; Gardner 2011). Finally, increased human presence, if only as a side effect of hydropower activities, may induce land use and land cover changes.

The question remains as to what extent the impact of such processes can be predicted for applying it to decision support and policy-making. Although a full hydrological model implementation is beyond the scope of this study, it is obvious that such task will be challenging, since currently basic hydrological variables such as water yield and seasonality are highly variable and hard to predict. Indeed, the unrealistic runoff ratios obtained in this study suggest that further modelling is probably of little use before the water balance of the basins can be closed properly (Klemes 1988; Buytaert & Peaver 2010). The rest of this section elaborates on pathways for further research.

New data products originating from remote sensing and are becoming increasingly available (e.g. PERSIANN; Hsu *et al*., 1997) while their usefulness for hydrological applications is currently questionable (Pan *et al*., 2010), and this is expected to be worse in mountain climates with strong gradients (Peaver, 2009; Ward *et al.* 2011). More advanced interpolation techniques for ground based stations may be another route to improve precipitation maps, including co-variables such as catchment land cover, which can be linked to rainfall regime (Winter 2001; Schröder 2006; Bravo 2010).

The Baker basin may also provide a good setting for studies of non-stationarity, tipping behaviour and climate change (Milly *et al*. 2008; Rockstrom *et al*. 2010). The hydrological behaviour of the main stem changed over the previous 40-year from a gentle sinusoidal to a behaviour notoriously affected by more frequent occurrence of extreme floods, driven by glacier lake outburst floods (GLOFs) down the Colonia (Fig. 8). This behaviour may have corresponding tipping points for hydro-geomorphology, sediment transport and water-sediment-vegetation interactions, and biogeochemical fluxes through the river down to fjord ecosystems. As a recent seminar has stressed (RG 2010) further hydro-ecological investigations are therefore urgently needed, integrating glaciology, hydrology and ecological studies, and where comparisons to other deglaciating areas of the world would be useful (e.g. Milner *et al*, 2009; Russell *et al*. 2006).

For hydrologic science, a growing concern relates to the limits of prediction in ungauged basins (PUB), particularly where it is most difficult, such as in regions with high gradients and scarce data as Patagonia. This region offers challenges from several perspectives, including: (i) bridging gaps in scientific knowledge, particularly in relation to physical processes and their gradients; (ii) assessing climate change impacts, which are difficult to detect given the sparse and short record yet are critical in view of the accelerated changes that are expected; (iii) and the prediction capacity of environmental models required for management. Even the application of very simple concepts such as closing the water balance has proven difficult if not impossible with the currently available data. This does not forebode well for the predictive capacity of more complex hydrological models, which are arguably necessary to evaluate the impact and appropriateness of management scenarios that aim at minimising the potentially devastating effects that natural and human induced changes may have on the ecosystem.

## 5 CONCLUSIONS

To our knowledge, this paper is the first to characterise the hydrology of the Baker basin in Patagonia in detail. The Baker basin is the largest in the country and in Chilean Patagonia, while the Baker is the Chilean river with highest flows. Precipitation mainly falls in autumn and winter (April-August), of which a significant part is snow. It exhibits a strong W-E gradient, with highest precipitation occurring near the ocean in the western side while the driest conditions exist towards Argentina in the East. It is likely that the local mountain topography further affects precipitation patterns but station density currently does not allow to analyse this in detail..

The general trend is on western catchments being more influenced by the wet conditions favoured by the proximity to the ocean and with a substantial glacier melt influence from the North Patagonia Icefield. These catchments therefore show a strong seasonal pattern with maximum flow in summer. Conversely, eastern catchments are drier and virtually without glacier melt influence in their river regimes, and thus more influenced by spring melt and winter rains. But within both regions, differences are substantial. In the west, the variable occurrence of glacier lake outburst floods is one of the main differentiators. It is notable that after 40 years of absence, a new GLOF cycle has started in 2008, with strong impacts on the hydrological and geomorphological regime of the otherwise very stable Baker river. In the east of the basin, some drier eastern catchments have substantial wetlands in their floodplains (Ñadis) as opposed to others (Salto, Chacabuco). Tributaries to Carrera Lake also have diverse controls, which can be mainly snowmelt (Jeinimeni) or a mixture of melt and rainfall (Murta, Ibáñez). .

These hydrological regimes have implications for decision making, particularly now that heavy pressures for hydropower and other developments are occurring. This study has shown knowledge gaps and especially some previously undocumented variability regarding catchment behaviour. Particularly, very little is known of catchments with significant mountain and glacier area, partly because of the few if any stations that gauge them. This is made even more urgent given the accelerated glacier retreat and the expected even higher impact of climate change in this circumpolar region. Although the effort to monitor these areas has been initiated by the Chilean water authority DGA, much more stations are needed (and with the ability to better measure snow precipitation in windy conditions). Among other things, a priority will be to close the water budget and reduce the uncertainty, for example, as evidenced by unrealistic runoff ratio we obtained. Their deviation seems related with that of precipitation gradients, indicating that the lack of data for the latter is the major error source. Localised short-term campaigns combined with remote sensing and using co-variables such as vegetation cover might aid in this issue. As such, the review and analysis of all the available data, characterising the hydrological regime, will provide essential input to improve management strategies as well as impact studies for future economic activities.

**Acknowledgements** We wish to pay tribute *In Memoriam* to Felipe Herrera and Pedro Nahuelcar, lost in the Steffen Glacier Huemules River while performing their invaluable monitoring duties for Dirección General de Aguas region Aysén. A. Dussaillant appreciates help and data provided by P. Debels, A. Stehr, F. Romero and H. Alcayaga (EULA Twin Latin project), M. Aguayo (UdeC-EULA), and discussions with M. Sepúlveda and B. Reid (CIEP). Special thanks to J. Carrasco from Dirección Meteorológica de Chile, and A. Montecinos, for helping gather additional data. W. Buytaert also thanks project MECESUP UCO0308 at UdeC-DIC for supporting his 2008 stay at Universidad de Concepción, Chile, when part of the analysis was done. The authors appreciate the comments of the anonymous reviewers who helped improve this paper.

## REFERENCES

Andréassian, V.*et al.*, 2009. Crash tests for a standardized evaluation of hydrological models. *Hydrology and Earth System Sciences*, 13, 1757–1764.

Aniya M 2007. Glacier variations of Hielo Patagónico Norte, Chile, for 1944/45-2004/05. Bull. Glaciol. Res. 24, 59-70

Arias, M.A., 2009. Flow duration curve estimation using regionalisation techniques: application to Baker River. Project for Civil Engineering Title, Universidad de Concepción, Chile. 152 pp. In Spanish.

Beven, K., 2007. Towards integrated environmental models of everywhere: uncertainty, data and modelling as a learning process. Hydrol Earth System Sci 11, 460–467.

Bledsoe, B., *et al.*, 2009. Applying the Ecological Limits of Hydrologic Alteration (ELOHA) framework in central and southern Chile: prospects and challenges. 7th Ecohydraulics conference, HEIC January 2009, Concepción, Chile

Brabets, T.P. and Walvoord, M.A., 2007. Trends in streamflow in the Yukon River Basin from 1944 to 2005 and the influence of the Pacific Decadal Oscillation. *Journal of Hydrology*, 371: 108–119

Bravo, J., 2010. Hydrologic Prediction in Ungaiged Basins: Use of Estimation Tools for Precipitation, Evaporation and Streamflow for the Water Budget of Baker Basin, Patagonia, Chile. Project for Civil Engineering Title, Universidad de Concepción, Chile. 114 pp. In Spanish.

Buytaert, W., Dussaillant, A., Maturana, O., Arias, M., 2009. Characterisation of the hydrological regime of Patagonian river systems. Geophysical Research Abstracts, Vol. 11 11, EGU2009–6014.

Buytaert, W. and Peaver, L., 2010. Evaluation of different precipitation products for hydrological prediction in mountainous areas. EGU General Assembly. 2 - 7 May 2010, Vienna.

CONAF, 1997. Catastro y Evaluación de Recursos Vegetacionales Nativos de Chile, Corporación Nacional Forestal (digital Chilean land cover survey database)

DGA, 1987. Water Budget of Chile. Dirección General de Aguas, Ministerio de Obras Públicas, Santiago, Chile (in Spanish).

Dussaillant, A., Bravo, G, and Rojas, X., 2009a. Natural flow regime studies under low information contexts and ungauged catchments: application to Baker River basin, Patagonia, Chile. 7th Ecohydraulics conference, HEIC January 2009, Concepción, Chile.

Dussaillant A, Benito G, Buytaert W, Carling P, Meier C & Espinoza F. 2009b. 2008-2009 Glacial-Lake Outburst Floods in Baker Basin, Patagonia, Chile. Geophysical Research Abstracts 11, 1442.

Dussaillant A, G Benito, W Buytaert, P Carling, C Meier, F Espinoza. 2010. Repeated glacial-lake outburst floods in Patagonia: An increasing hazard? Natural Hazards 54 (2): 469

Dyurgerov MB & MF Meier 2005. Glaciers and the Changing Earth System: a 2004 Snapshot. Institute of Arctic and Alpine Research, University of Colorado, Boulder, USA. Occasional Paper 58. INSTAAR/OP-58 ISSN 0069-6145. 118 pp.

Gardner 2011. Massive Chilean dams approved. Nature 17 May 2011: 297.

Hannah DM, BPG Smith, AM Gurnell & GR McGregor. 2000. An approach to hydrologic classification. Hydrol. Proc. 14: 317-338.

Harris NM, AM Gurnell, DM Hannah & GE Petts. 2000. Classification of river regimes: a context for hydroecology. Hydrol. Proc. 14: 2831-2848.

HidroAysén 2008. Proyecto HidroAysén - Environmental Impact Study, in Spanish, available at www.e-seia.cl

Hodgkins G.A. , R.W. Dudley, T.G. Hunting 2003. Changes in the timing of high river flows in New England over the 20th Century. J. Hydrol. 278: 244–252

Hsu K., X. Gao, S. Sorooshian, H.V. Gupta, 1997. Precipitation estimation from remotely sensed information using artificial neural networks, Journal of Applied Meteorology 36: 1176-1190.

Klemes V, 1988. A hydrological perspective. J. Hydrol 100: 3-28.

Lambrecht A & C Mayer. 2009. Temporal variability of the non-steady contribution from glaciers to water discharge in western Austria. J. Hydrol. 376: 353-361.

Masiokas MH, R Villalba, BH Luckman, ME Lascano, S Delgado& P Stepanek. 2008. 20th-century glacier recession and regional hydroclimatic changes in northwestern Patagonia. Global Plan Change 60: 85-100.

Maturana 2009. Flow series prediction using regionalisation techniques: application to Baker basin. Project for Civil Engineering Title, Universidad de Concepción, Chile. 111 pp. In Spanish.

Merz R & Bloschl G. 2004. Regionalisation of catchment model parameters. J. Hydrol. 287: 95-123.

Milly, P.C.D, J. Betancourt, *et al.* 2008. Stationarity is Dead. Whither Water Management? Science 319. 573-574.

Milner AM, LE Brown & DM Hannah. 2009. Hydroecological response of river systems to shrinking glaciers. Hydrol. Proc. 23: 62-77.

Novotny EV, H G. Stefan. 2007. Stream flow in Minnesota: Indicator of climate change. J. Hydrol. 334: 319– 333

Olden JD & NL Poff 2003. Redundancy and choice of hydrologic indices for characterizing river streamflow regimes. River Res. Appl. 19: 101-121.

Pan M, H Li & E Wood, 2010. Assessing the skill of satellite-based precipitation estimates in hydrologic applic ations. Water Res. Res. 46, W09535. doi:10.1029/2009WR008290

Peaver, L., 2009. The use of remotely-sensed precipitation estimation for hydrological prediction in Patagonia. MSc thesis, Imperial College London, London.

Peña H & F Escobar 1987. Aspects of glacial hydrology in Patagonia. Bull. Glac. Res. 4: 141-150.

Poff, NL, JD Allan, MB Bain, JR Karr, KL Prestegaard, BD Richter, RE Sparks, & JC Stromberg 1997. The natural flow regime. Bioscience 47 (11): 769-784.

Post DA & JA Jones. 2001. Hydrologic regimes of forested, mountainous, headwater basins in New Hampshire, North Carolina, Oregon and Puerto Rico. Adv. Water Res. 24: 1195-1210.

Rao AR & VV Srinivas. 2006. Regionalization of watersheds by hybrid-cluster analysis. J. Hydrol, 318: 37-56.

Rasmussen L., H. Conway & C. Raymond 2007. Influence of upper air conditions on Patagonia Icefields, *Global Planet. Change*, doi: 10.1016/j.gloplacha.2006.11.025

Rees HG & DN Collins. 2006. Regional differences in response of flow in glaciarized Himalayan rivers to climatic warming. Hydrol. Proc. 20: 2157-2169.

RG 2010. Glacier Risks Symposium, Chile Sep 2010, www.riesgosglaciales.net/eng.

Rignot, E., Rivera A. and Casassa G. 2003. Contribution of the Patagonia Icefields of South America to Global Sea Level Rise. Science, 302, 434-437

Rockstrom, J. *et al*. 2009, A safe operating space for humanity, Nature, 461(7263), 472-475.

Russell AJ, MJ Roberts, H Fay, PM Marren, NJ Cassidy, FS Tweed & T Harris. 2006. Icelandic jökulhlaup impacts: Implication for ice-sheet hydrology, sediment transfer and geomorphology. Geom 75, 33 – 64.

Sanborn SC & BP Bledsoe. 2006. Predicting streamflow regime metrics for ungauged streams in Colorado. Washington and Oregon. J. Hydrol. 325: 241-261.

Schneider C & D Gies. 2004. Effects of El Niño-Southern Oscillation on southernmost South America precipitation at 53°S revealed from NCEP-NCAR re-analyses and weather station data. Int. J. Climatol. 24: 1057-1076.

Schröder B. 2006. Pattern, process, and function in landscape ecology and catchment hydrology – how can quantitative landscape ecology support predictions in ungauged basins (PUB)? Hydrol. Earth Syst. Sci. 3: 1185–1214

Seibert J. 1999. Regionalisation of parameters for a conceptual rainfall-runoff model. Agr For Meteor. 98-99: 279-293.

Sevruk, B. & Nespor, V. 1998. Empirical and theoretical assessment of the wind induced error of rain measurement. Water Sci. Technol. 37(11), 171–178.

Sivapalan M. 2003. Prediction in ungauged basins: a grand challenge for theoretical hydrology. Hydrol. Process. 17, 3163–3170

Stahl K & RD Moore. 2006. Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. Water Res. Res. 42, W06201, doi:10.1029/2006WR005022

Trenberth KE *et al*. 2007: Observations: Surface and Atmospheric Climate Change. In: Climate Change 2007: The Physical Science Basis. Working Group 1, IPCC Assessment Report 4. Cambridge Univ Press, UK, and USA.

Twin Latin 2008. [Debels P, A Stehr, ed.]. Hydrology of Baker basin. Unpublished report for www.twinlatin.org EU FP6 project.

UNEP 2010. Kaltenborn, B. P., Nellemann, C., Vistnes, I. I. (Eds). 2010. High mountain glaciers and climate change – Challenges to human livelihoods and adaptation. United Nations Environment Programme, GRID-Arendal, www.grida.no, 52 pp.

Valéry, A., Andréassian, V. & Perrin, C. 2009. Inverting the hydrological cycle: when streamflow measurements help assess altitudinal precipitation gradients in mountain areas. In: New Approaches to Hydrological Prediction in Data–sparse Regions, 281–286, IAHS Publ. 333.

Villalba R., A Lara, JA Boninsegna, M Masiokas, S Delgado, JC Aravena, FA Roig, A Schmelter, A Wolodarsky & A Ripalts. 2003. Large-scale temperature changes in the southern Andes: 20th-century variations in the context of the past 400 years. Climatic Change 59: 177-232

Vince G. 2009. Dams for Patagonia. Science 23 July 2010: 329 (5990), 382-385. DOI:10.1126/science.329.5990.382.

Wagener T & H Wheater. 2006. Parameter estimation and regionalization for continuous rainfall-runoff models including uncertainty. J. Hydrol. 320: 132-154.

Wagener T, M Sivapalan, P Troch & R Woods. 2007. Classification in hydrology. Geography Compass 1: 10.1111/j.1749-8198.2007.00039.x

Ward, E., Buytaert, W., Peaver, L., Wheater, H., 2011. Evaluation of precipitation products over complex mountainous terrain: a water resources perspective. Adv Water Res doi:10.1016/j.advwatres.2011.05.007

Winchester, V., Harrison, S., & Warren C.R. 2001. Recent retreat Glacier Nef, Chilean Patagonia, dated by lichenometry and dendrochronology. Arc. Antarct. Alpine Res. 33(3): 266-273.

Winter TC. 2001. The concept of hydrologic landscapes. J. Am. Water Res. Assoc. 37: 335-349.

Young AR. 2006. Stream flow simulation within UK ungauged catchments using a daily rainfall-runoff model. J Hydrol 320, 155-172.

Zambrano, G., Abarca, R., Cretaux, J-F., Reid, B. 2009. First insights on Lake General Carrera / Buenos Aires / Chelenko water balance. Adv. Geosci. 22: 173-179

Zemlak TS, EM Habit, SJ Walde, C Correa & DE Ruzzante. 2010. Surviving historical Patagonian landscapes and climate: molecular insights from *Galaxias maculatus. BMC Evolutionary Biology*, 10:67 doi:10.1186/1471-2148-10-67

Table 1: Catchment characteristics, including average precipitation (Avg. P), average discharge (Avg. Q), and runoff ratio (RR) of the studied basins for the period 1977-1991

| Gauge station | Gauge altitude [masl] | Area [$km^2$] | Glacier/ice area [%]* | Forest area [%]* | Wetland area [%]* | River length [km] | Avg P [mm/y] | Avg Q [mm/y] | RR |
|---|---|---|---|---|---|---|---|---|---|
| Río Ibáñez | 220 | 2407 | 29.4 | 34.9 | 0.9 | 88 | 817 | 1911 | 2.34 |
| Río Murta | 219 | 896 | 37.6 | 45.9 | 3.4 | 56 | 1175 | 3347 | 2.85 |
| Río Jeinimeni | 219 | 1395 | 8.9 | 6.2 | 0.6 | 50 | 407 | 589 | 1.45 |
| Baker @ Bertrand Lake | 200 | 15997 | - | - | - | 0 | 647 | 1117 | 1.73 |
| Río Nef | - | 700 | 44.1 | 12.7 | 0.1 | 35 | - | 4054 | - |
| Baker @ Chacabuco | 160 | 16788 | - | - | - | 19 | 678 | 1197 | 1.77 |
| Río Chacabuco | 145 | 1444 | 8.7 | 16.7 | 0.3 | 76 | 557 | 412 | 0.74 |
| Río Cochrane | 140 | 4415 | - | - | - | 24 | 394 | 95 | 0.24 |
| Río del Salto | 123 | 1240 | 9.4 | 38.1 | 0.2 | 65 | 851 | 1001 | 1.18 |
| Río de la Colonia | - | 1292 | 47.3 | 10.2 | 0.1 | 25 | - | 3371 | - |
| Baker @ Colonia | 105 | 26199 | - | - | - | 91 | 636 | 1124 | 1.77 |
| Río de los Ñadis | - | 993 | 17.1 | 32.5 | 1.8 | 50 | - | - | - |
| Baker @ Ñadis | 40 | 27378 | 14.5 | 18.4 | 0.6 | 119 | 689 | 1077 | 1.56 |
| Río Ventisquero | - | 1030 | - | - | - | 17 | - | - | - |

* data extracted by Maturana (2009) and Arias (2009) from a CONAF (1997) Chilean land cover survey

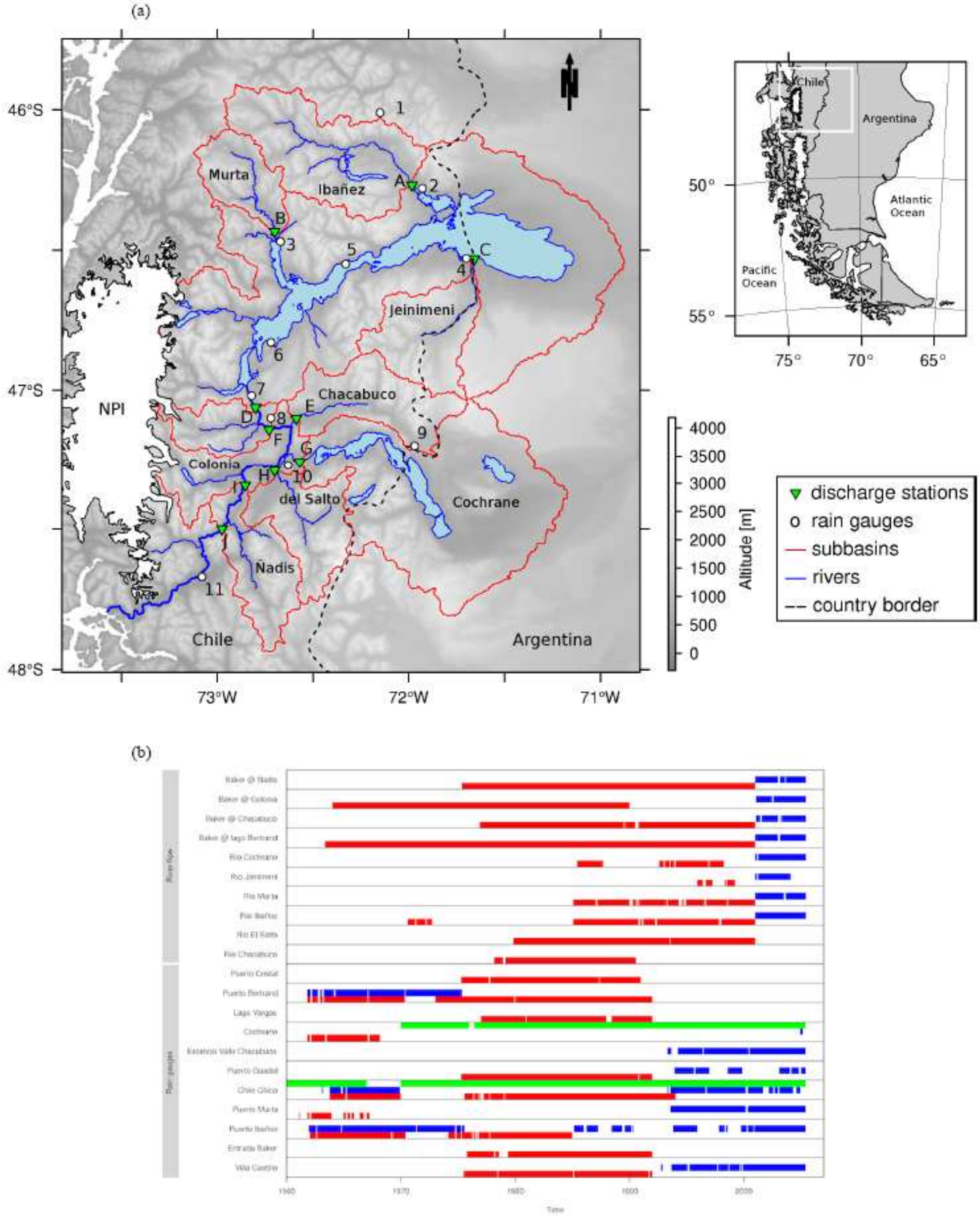

**Fig. 1** (a) Baker basin, with names of rivers of monitored first-order sub-basins indicated on the map, as well as available precipitation (numeral) and streamflow (letter) gauging stations in the Baker basin. ([1 = Villa Cerro Castillo; 2 = Puerto Ibáñez; 3 = Puerto Murta; 4 = Chile Chico; 5 = Puerto Cristal; 6 = Puerto Guadal; 7 = Puerto Bertrand; 8 = EV Chacabuco; 9 = Entrada Baker; 10 = Cochrane; 11 = Lago Vargas; A = Río Ibáñez; B = Rio Murta; C = Río Jeinimeni; D= Río Baker at Lago Bertrand; E = Río Chacabuco; F = Río Baker upstream of Chacabuco; G = Río Cochrane; H = Río del Salto, I = Río Baker downstream of Colonia, J = Río Baker downstream of Ñadis). (b) Availability of data precipitation and streamflow data in stations at Baker basin. (Sources: DMC (top-green); DGA (middle-blue); ENDESA (bottom-red)).

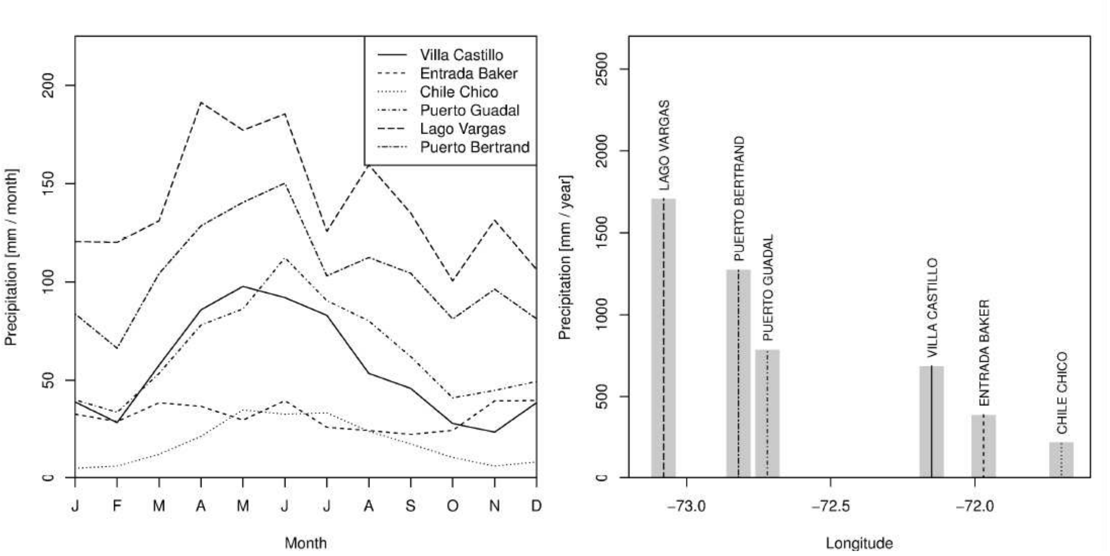

**Fig. 2** Monthly precipitation measured at selected stations within the Baker River basin (mean for 1977–1991).

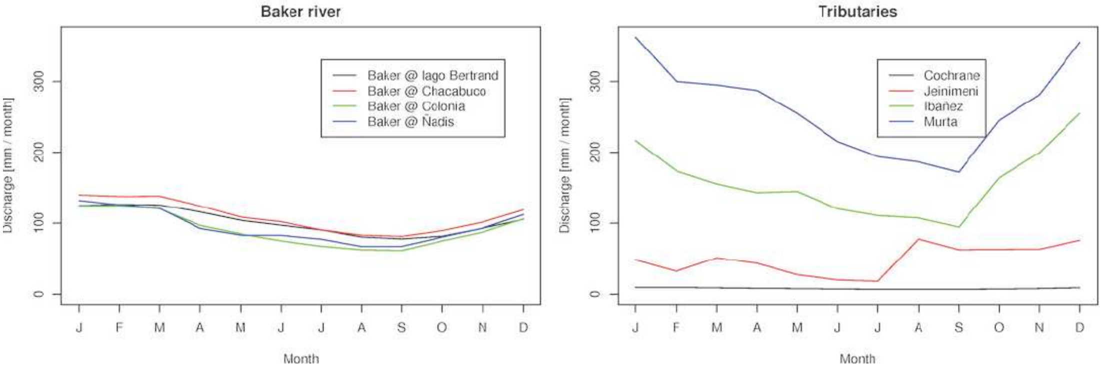

**Fig. 3** Seasonality of streamflow: (a) [LEFT] Mainstem Baker River stations; (b) [RIGHT] Other rivers in the basin.

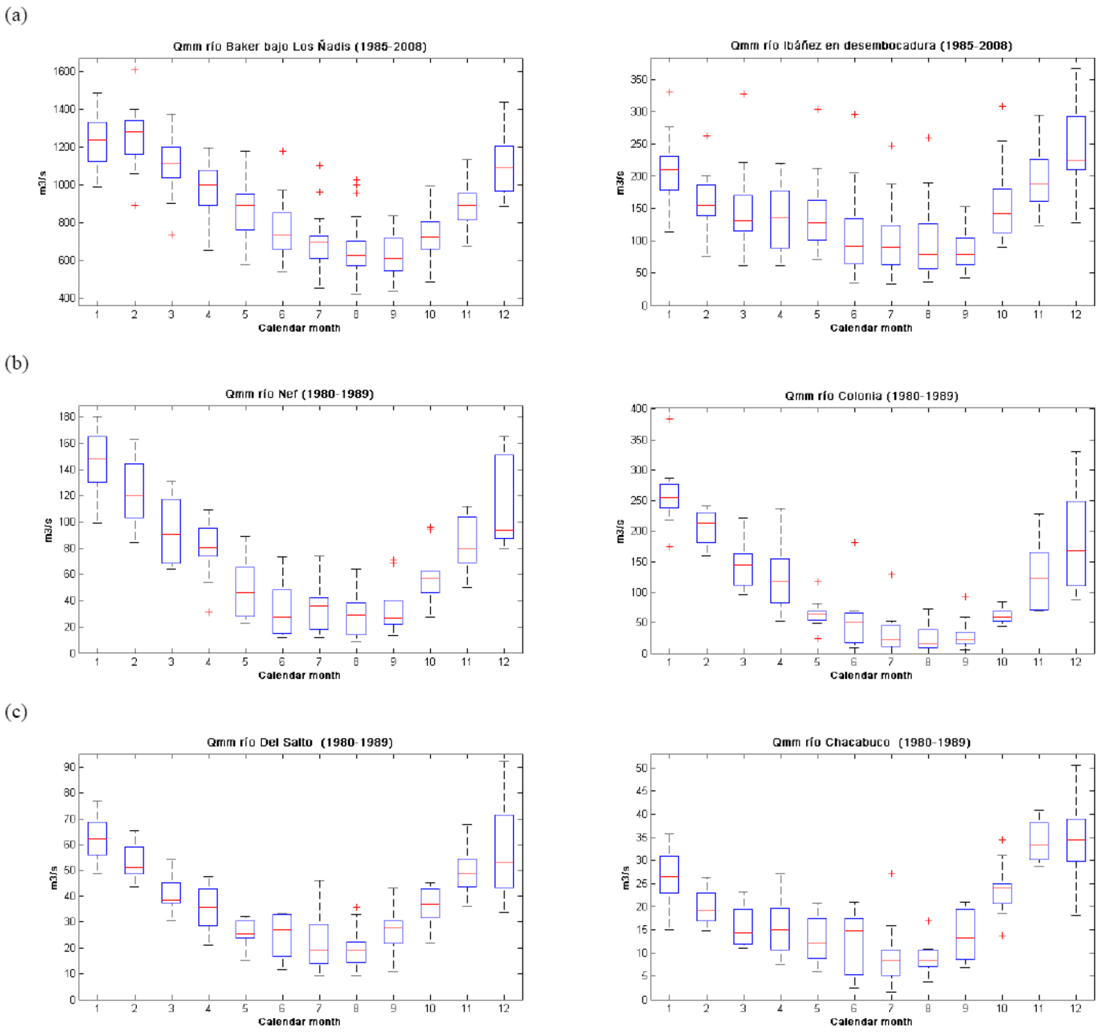

**Fig. 4** Mean monthly discharge boxplots: (a) [TOP] Baker River downstream of Los Ñadis, and Ibáñez River at its entrance into General Carrera lake; (b) [CENTRE] Nef and Colonia western river catchments (discharge signal); (c) [BOTTOM] Del Salto and Chacabuco eastern river catchments.

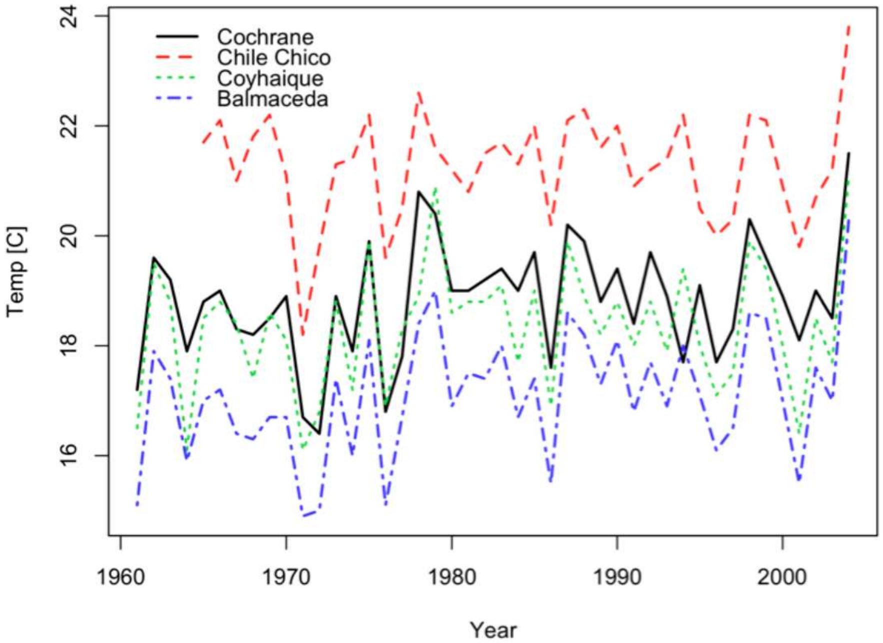

**Fig. 5** Mean maximum temperatures for the January-March period at the stations in Cochrane and Chile Chico (Coyhaique and Balmaceda stations, north of the Baker basin, shown as a reference).

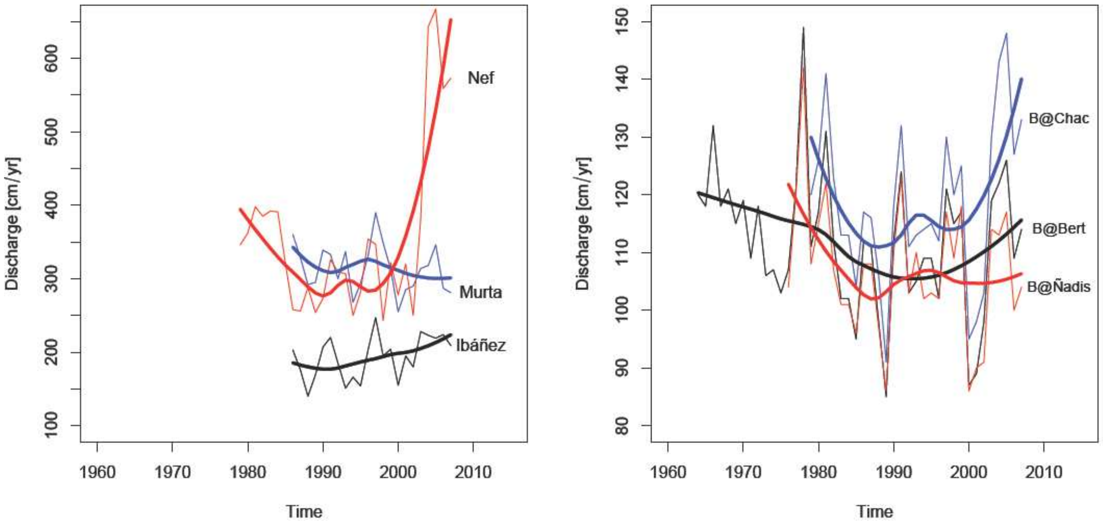

**Fig. 6** Mean annual discharge temporal series for river gauges in the Baker basin, with smoothed trends (thicker lines): (a) [LEFT] Ibáñez and Murta gauges (Carrera Lake tributaries) and Nef streamflow signal; (b) [RIGHT] Baker River mainstem stations at origin (Baker@Bertrand), downstream of Nef and upstream of Chacabuco River (Baker@Chacabuco), and downstream of Ñadis River (Baker@Ñadis)

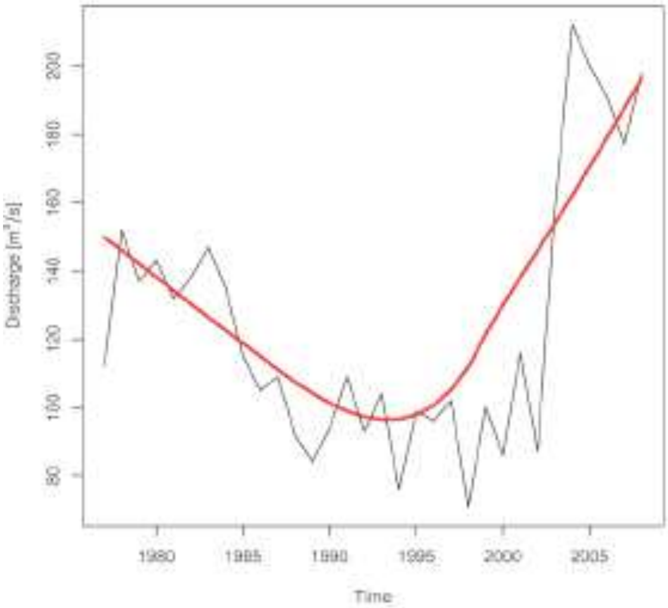

**Fig. 7** Mean monthly discharge signal for the Nef River, summer period (JFM) and smoothed trend.

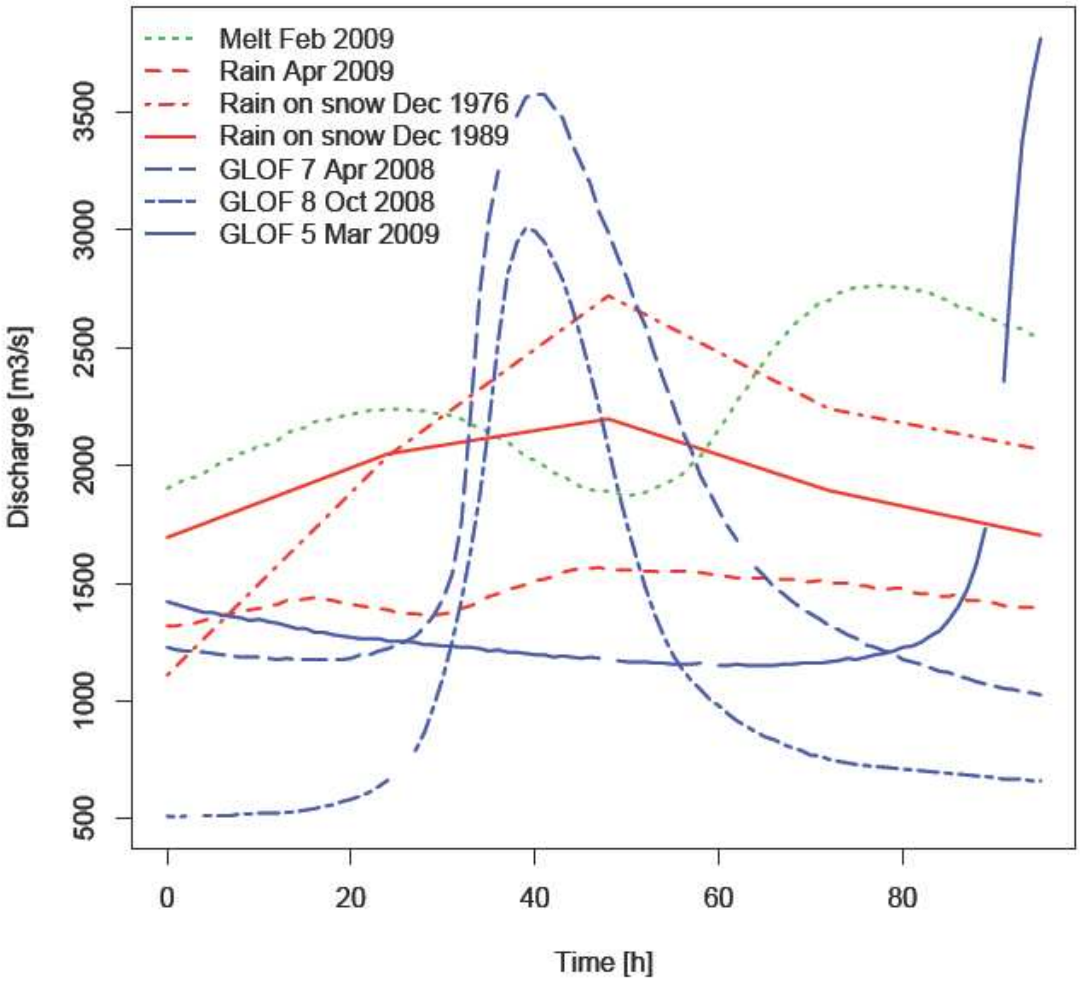

**Fig. 8** Typical floods in the Baker River (Baker gauge immediately downstream from Colonia confluence) due to normal hydrometeorological events in comparison to those caused by glacial-lake outburst flood (GLOF) contributions from Colonia River.