Abstract

Floods are among the most destructive natural hazards on Earth. In paleohydrology, sediments are generally considered as one of the best archives to extend flood records to pre-historical timescales. Doing so requires being able to identify flood deposits from sediment archives and decipher between flood types. The latter is particularly important in glacierized regions, where meteorological floods frequently co-occur with Glacial Lake Outburst Floods (GLOFs). In Patagonia, results from a recent study suggest that GLOFs are recorded in downstream fjord sediments as fine-grained and organic-poor layers, representing the high amount of glacier rock flour transported during lake outbursts, whereas meteorological floods are represented by coarser and more organic deposits. However, not all fine-grained organic-poor deposits could be associated with historical GLOFs. Here, we reconstruct the provenance of these Baker River flood deposits using $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon\text{Nd}$, taking advantage of the clear lithological differences that exist between both sides of the watershed. Our results show that both $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon\text{Nd}$ are suited to reconstruct sediment provenance in the Baker River watershed but that $\varepsilon\text{Nd}$ is the most effective and the least affected by grain-size variations. Our provenance results confirm that the 21st century fine-grained and organic-poor deposits represent GLOFs and that the largest winter meteorological flood on record has a distinct coarse and
organic-rich signature. However, our results show that rain-on-snow events that occur in summer, and therefore primarily affect the western glacierized part of the watershed, have the same fine-grained organic-poor signature as GLOFs. Therefore, this study shows that the sedimentary signature of rain-on-snow floods in partially glacierized watersheds depends on the season during which they occur. We anticipate that our findings will contribute to a better interpretation of flood records from partially glacierized watersheds.

Keywords: Glacial Lake Outburst Floods, rain-on-snow floods, Patagonia, paleohydrology, grain size, Nd isotopes, Sr isotopes

1. Introduction

Floods are arguably one of the most catastrophic hydrological hazards on Earth. These ubiquitous events can cause enormous economic loss and casualties (e.g., Hirabayashi et al., 2013) and the ongoing intensification of the hydrological cycle is expected to result in an increase in both their frequency and magnitude at various locations globally (Kundzewicz et al., 2014; Breugem et al., 2020). In glacierized regions, meteorological floods frequently co-occur with Glacial Lake Outburst Floods (GLOFs), i.e., floods caused by the sudden emptying of ice- or moraine-dammed lakes (e.g., Carrivick & Tweed, 2016). As the number and size of glacial lakes are currently increasing worldwide (Shugar et al., 2020), it is urgent to
understand how GLOFs respond to climate change to assess how their frequency and magnitude will evolve in a future warmer world.

The lower Baker River watershed (47–48°S) in Chilean Patagonia is particularly vulnerable to both meteorological floods and GLOFs (Dussaillant et al., 2010, 2012; Iribarren Anacona et al., 2014; Jacquet et al., 2017; Vandekerkhove et al., 2020b; Benito et al., 2021). This results from the hyperhumid climate that is typical of Chilean Patagonia (Garreaud et al., 2013), and from the abundance of glacial lakes formed by the recession of outlet glaciers, primarily from the Northern Patagonian Icefield (NPI) (Davies & Glasser, 2012; Wilson et al., 2018). Until recently, most of the historical GLOFs that occurred in the lower Baker River watershed were thought to have originated from the Colonia River, due to the abrupt draining of either Cachet II or Arco lakes (e.g., Harrison & Winchester, 2000; Dussaillant et al., 2010; Jacquet et al., 2017). However, recent studies indicate that at least one historical GLOF within the Baker River watershed originated from a smaller moraine-dammed lake not related to the NPI (Iribarren Anacona et al., 2014; Vandekerkhove et al., 2021).

One of the best archives of Baker River floods are the sediments deposited in the fjord immediately downstream of the Baker River (Martínez Channel). Based on a comparison of sedimentological data with historical chronicles, Vandekerkhove et al. (2021) showed that the 21st century GLOFs originating from Lake Cachet II were recorded in the fjord’s sediments as fine-grained and organic-poor deposits. This is in contrast with the common idea that floods are consistently recorded in sediments as
turbidites (e.g., Schillereff et al., 2014; Wilhelm et al., 2015) but it accurately reflects the release of large amounts of glacier rock flour in Baker River during GLOFs. Older Martínez Channel sediments also contain fine-grained organic-poor deposits and turbidites relatively rich in organic matter, which were tentatively attributed to GLOFs and meteorological floods, respectively, by Vandekerkhove et al. (2021). However, based on sedimentological and chronological criteria only, several of these flood layers could not be attributed to historical flood events, rendering the conclusions about the exact signature of GLOFs and meteorological floods relatively uncertain.

Properly interpreting flood deposits in terms of specific flood type is crucial to generate independent records of meteorological floods and GLOFs, and therefore use these records to acquire a mechanistic understanding of the factors affecting flood occurrence. Such an objective calls for a detailed investigation of sediment provenance. Being able to track sediment provenance is also of prime importance to understand the lake or icefield at the origin of each GLOF. This is particularly relevant in Patagonia, where glaciers may respond differently to climate according to their longitudinal position (precipitation-driven vs ablation-driven; e.g., Bertrand et al., 2012a).

With this in mind, this study aims to reconstruct the provenance of Baker River flood deposits preserved in the sediments of Martínez Channel using Sr and Nd isotopes. These two geochemical tracers reflect the type and age of the source rocks (Faure and Mensing 2004) and they are particularly suited for fine-grained siliciclastic sediments (Jonell et al., 2018). They are also known to accurately reflect
the differences in the bedrock lithologies that occur in western Patagonia (Liu et al., 2020). To achieve this goal, we first compare the isotopic signature of suspended sediments from the largest tributaries to the lithology of the bedrock in their respective watersheds, and we use these results to define the sediment end-members. We then investigate the influence of grain size on Sr and Nd isotopes using measurements obtained on eight grain-size fractions separated from a bulk river sediment sample from the Baker River mouth. Finally, we use Sr and Nd isotopes to reconstruct the provenance of historical (1975–2017) flood deposits of known and unknown origin identified in a sediment core from the head of Martínez Channel. The provenance results are then compared with historical data to refine the sedimentological interpretation of the deposits. We anticipate that our results will constitute a strong basis for future paleohydrological research in glacierized regions, including the generation of independent meteorological flood and GLOF proxy records.

2. Setting

2.1 Study area

Baker River is the largest river in Chile in terms of mean annual discharge (Dussaillant et al., 2012). It originates at Lake Bertrand and it discharges in Martínez Channel near the town of Tortel (Figure 1), where it forms a large subaquatic delta incised by submarine channels (Vandekerkhove et al., 2020a). The Baker River watershed is relatively large (29,202 km²) and it comprises numerous icefields and
glaciers, including several outlet glaciers of the Northern Patagonian Icefield (NPI) in the west, the San Lorenzo icefield in the southeast, and smaller mountain glaciers, including those of the Cordon de los Ñadis (Figure 1). Due to the input of large amounts of glacial meltwater in summer, Baker River shows sizeable variations in discharge with seasons, ranging from 600 m³/s in winter to 1200 m³/s in summer (Dussaillant et al., 2012). Baker River is fed by several large proglacial rivers originating from NPI outlet glaciers on the western side of the watershed, such as Colonia River, and by smaller rivers from the east, some of which are proglacial in nature (e.g., the del Salto and los Ñadis rivers).

In addition to Baker River, three other large rivers discharge at the head of the Baker-Martínez fjord system: Huemules River, which originates from Steffen Glacier at the southern end of the NPI; Bravo River, which drains a relatively small watershed to the east of the fjord complex, and Pascua River, which is the outflow of Lake O’Higgins and is fed by meltwater from the Southern Patagonian Icefield (SPI) (Figure 1).

The Baker River watershed presents a wide range of environments that mostly reflect the strong west-to-east gradients in precipitation and, to a lesser extent, elevation and therefore surface temperature. The western part of the watershed is characterized by a cold and hyperhumid climate, with annual precipitation reaching 3000–4000 mm/yr, whereas its eastern part across the border with Argentina is warmer and semi-arid, with precipitation dropping below 500 mm/yr (Garreaud et al., 2013; Fick & Hijmans, 2017).
The sediment budget of Baker River is dominated by particles originating from its lower watershed, i.e., downstream of Bertrand and Cochrane lakes (Figure 1). This sub-division in upper and lower watersheds (Figure 1) mostly reflects the ability of lakes General Carrera and Cochrane to trap most of the sediment produced in the upper watershed. The main sources of sediment to Baker River are therefore located in the lower watershed, which is composed of two main lithological units (Figure 1) (SEGEMAR, 1998; SERNAGEOMIN, 2003; Gómez et al., 2019): the Patagonian Batholith (PB), which is located to the west and is composed of Cretaceous to Miocene granitoids, and the Eastern Andean Metamorphic Complex (EAMC) to the east. Although the PB and EAMC are each composed of lithologies of distinct ages, the exact distribution of the sub-units is not reported in the literature (e.g., Pankhurst et al., 1999; Augustsson & Bahlburg, 2003). Volcanic rock formations crop out in the eastern part of the watershed and thick fluvioglacial deposits marking the maximum Quaternary extent of the Patagonian Ice Sheet occur in the easternmost part of the watershed in Argentina (Boex et al., 2013; Kaplan et al., 2005). It is worth noting that the location of Baker River roughly corresponds to the limit between the PB and EAMC lithologies (Figure 1). Therefore, all proglacial rivers originating from NPI outlet glaciers (e.g., Huemules and Colonia rivers) predominantly drain the PB, whereas those to the east, including Chacabuco, del Salto, and los Ñadis, mostly drain the EAMC (Figure 1; Table 1). To the south, the Bravo River watershed and the lower Pascua River watershed, i.e., downstream of the large Lake O’Higgins, are almost entirely composed of EAMC (Figure 1; Table 1).
2.2 Flood history

Historical Baker River floods consist of GLOFs and meteorological floods. According to historical and instrumental information, most recent GLOFs originated from the Colonia River and were due to the drainage of either Lake Arco (until the 1960s) (e.g., Harrison & Winchester, 2000; Dussaillant et al., 2010), or Lake Cachet II (from 2008 onwards) (e.g., Jacquet et al., 2017; Vandekerkhove et al., 2021). Between 2008–2017, a sequence of 21 GLOFs caused by the sudden emptying of Lake Cachet II occurred (Dussaillant et al., 2010, 2012; Jacquet et al., 2017). During these events, the Baker River tripled in discharge (Dussaillant et al., 2010), and its suspended sediment concentration increased 8-fold, transporting considerable amounts of sediments (1.0–1.5 x 10^5 tons per GLOF event) to the head of Martínez Channel (Quiroga et al., 2012). Local testimonies and satellite images also indicate the existence of a GLOF from proglacial lake Las Lengas, in the los Ñadis valley (Figure 1), in March 1988 (Iribarren Anacona et al., 2014; Vandekerkhove et al., 2021). This event resulted in a significant increase in the discharge of los Ñadis River (Iribarren Anacona et al., 2014), but its signature in the Baker River hydrographs is unclear, possibly due to their low temporal resolution (one measurement daily; Vandekerkhove et al., 2021).

Due to relatively high year-round precipitation and the presence of large icefields and mountain glaciers, this region is also prone to meteorological floods driven by extreme precipitation, high seasonal meltwater discharge, and rain-on-snow events (Dussaillant et al., 2012; Vandekerkhove et al., 2021). Two particularly
large rain-on-snow events occurred in December 1976 and December 1989 (Dussaillant et al., 2012). Another large meteorological flood, possibly also corresponding to a rain-on-snow event, was identified in August 1992 (Vandekerkhove et al., 2020b). During those events, the discharge of Baker River (2000–3000 m³/s) reaches values similar to peak discharge during GLOFs (2000–4000 m³/s; Dussaillant et al., 2012; Vandekerkhove et al., 2021).

3. Material and Methods

3.1. Material

3.1.1 River suspended sediments

Water samples were collected at the mouths of (a) the two largest NPI proglacial rivers (i.e., Huemules and Colonia rivers), (b) four rivers mainly draining the EAMC (i.e., del Salto, los Ñadis, Bravo and Pascua rivers), and (c) Baker River, in Jan–Feb 2019 (Figure 1). To obtain a sufficient amount of suspended sediment (>100 mg) for analysis, around 100 L of water was collected at the center of each river ~20 cm below the surface, either using a telescopic rod with a 2L beaker from a riverbank (Colonia River), or using a bucket from a bridge (del Salto and los Ñadis rivers) or from a boat (Huemules, Baker, Bravo, and Pascua rivers).

All water samples were filtered through a 0.22 µm PES membrane using a pre-rinsed pressurized filtration system. The suspended sediments were kept frozen until processing in the laboratory. They were then separated from the filters by repeated washing with Milli-Q water and ultrasonic bathing. Subsequently, the
suspended sediments were freeze-dried and stored in glass vials. The volume of filtered water and the weight of dry suspended sediment were used to calculate suspended sediment concentrations (SSC).

3.1.2 Bulk river sediments

Bulk river sediment sample RS11-05 was collected from a recently abandoned meander near the mouth of Baker River in November 2011 (Figure 1) and separated into eight grain-size fractions. The fractions coarser than 32 µm (i.e., 32–45, 45–63, 63–90, and 90–125 µm) were separated by dry sieving, whereas the finer fractions (0–4, 4–8, 8–16 and 16–32 µm) were obtained after sedimentation in Atterberg columns following Stokes' law. Sediments coarser than 125 µm were not investigated since they are not representative of the fraction that reaches the fjord (Bertrand et al., 2012b; Vandekerkhove et al., 2020a).

3.1.3 Fjord sediments

A 106.8 cm-long sediment core (FC17-08) collected at the head of Martínez Channel approximately 5 km off the Baker River mouth (Figure 1) was subsampled for this study. This sediment core was obtained on the delta slope at a depth of 207 m using a gravity corer operated from the RV Sur Austral in February 2017. It is the most representative of a set of ten sediments cores collected at the fjord head (Vandekerkhove et al., 2021). An age-depth model was constructed based on $^{210}\text{Pb}$ measurements made at a 10 cm interval on the turbidite-free sediments (i.e., after removing the turbidite at 66–70 cm). A Constant Flux-Constant Sedimentation
(CFCS) model was used to generate the core chronology (Vandekerkhove et al., 2021). According to the age-depth model, FC17-08 covers the period 1982–2017, with sedimentation rates ranging between 2.88 and 3.03 cm/yr (Figure 2). Prior to this study, the sediment core was described, scanned on a Geotek multisensor core logger and on an XRF core scanner, and analyzed for grain size and total organic carbon (TOC) content (Vandekerkhove et al., 2021).

Sediment core FC17-08 is mostly composed of homogeneous silt-sized particles, with intercalations of fine mud layers between 0–27.5 cm and at 82–83 cm, and of a fine-grained turbidite at 66–70 cm (Figure 2). The fine mud layers are typically finer (mean grain size: 5.98 ± 0.82 μm) and less organic (TOC: 0.31 ± 0.06 %) than the background sediment (mean grain size: 7.32 ± 0.65 μm, TOC: 0.36 ± 0.04 %). The turbidite, however, is relatively rich in organic matter (0.57 ± 0.10 %). The mud deposits that occur between 0–27.5 cm have a modeled age of 2008–2017 and were interpreted as the signature of the 21st century Cachet II GLOFs (Vandekerkhove et al., 2021). The turbidite between 66–70 cm (modeled age 1990–2000) was tentatively interpreted as the signature of the 1992 rain-on-snow event, mostly based on its age, but it could also correspond to the 1988 Las Lengas GLOF (Vandekerkhove et al., 2021). The fine mud deposit at 82–83 cm (modeled age 1984–1997) was however associated with more certainty with the 1988 Las Lengas GLOF by Vandekerkhove et al. (2021).

To investigate the provenance of these deposits, a total of seven subsamples were taken from sediment core FC17-08 (Figure 2): two representing background
sediments at 51.0–51.5 and 75.0–75.5 cm; three corresponding to the fine-grained 2008–2017 Cachet II GLOF deposits at 17.0–17.5, 24.0–24.5 and 26.0–26.5 cm; and two in unknown event deposits: one near the base of the turbidite at 69.0–69.5 cm; and one in the fine mud layer at 82.0–82.5 cm.

3.2 Methods

3.2.1 Sr and Nd isotopes

The seven river suspended sediment samples, the eight grain-size fractions of Baker River sediment sample RS11-05, and the seven subsamples from sediment core FC17-08 were analyzed for Sr and Nd isotope ratios at the University of Missouri Research Reactor (MURR), Columbia MO, USA. About 100 mg of sample was digested in 1 mL 14 N HNO₃ + 4 mL 24 N HF, and 6 mL 5–6 N HCl, successively, using several cycles of heating and evaporation. Subsequently, 2 mL 14 N HNO₃ was added to the residues for dissolution and evaporation, followed by 1.5 mL 2 M HNO₃ for final dissolution. The Sr and Nd fractions were then extracted following a protocol slightly modified from Míková & Denková (2007), using chromatographic columns that were homemade out of Pasteur pipets with a 4 mm internal diameter.

The Sr and Nd isotope analyses were conducted on a Nu Plasma II MC-ICP-MS. Analytical conditions are reported in Supporting Information (Text S1). The Sr isotopic results obtained on reference material SRM987 (0.710256 ± 24 [2 sd]) were in agreement with recommended values (Thirlwall, 1991; De Muynck et al., 2009).
The average value obtained for the Nd isotopic standard JNd-1 was 0.512087 ± 0.000011 (2 sd).

The Nd isotopic compositions were expressed as εNd, which is defined as:

\[ \varepsilon_{\text{Nd}} = \left( \frac{^{143}\text{Nd}/^{144}\text{Nd}}{} \right)_{\text{sample}} / \left( \frac{^{143}\text{Nd}/^{144}\text{Nd}}{} \right)_{\text{CHUR}} - 1 \right) \times 10^4 \]

where \((^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}}\) is the value of the Chondritic Uniform Reservoir (0.512638; Jacobsen & Wasserburg, 1980).

The isotopic composition of the sediment samples was compared to the composition of the main bedrock lithologies occurring in their watersheds. These values were collated from the literature, i.e., Pankhurst et al. (1999) for the PB and Weaver et al. (1990) for the EAMC.

### 3.2.2 Grain-size analysis

Grain size was measured on the river suspended sediment samples and on the eight grain-size fractions of RS11-05 using a Malvern Mastersizer 3000 at Ghent University. The grain size of the suspended sediment sample from Bravo River was not measured due to limited sample amount. Organic matter, carbonate, and biogenic silica were removed by sequentially boiling the sample suspended in 10 mL DI water with 2 mL 30% H₂O₂, 1 mL 10% HCl and 1 mL 2 N NaOH, respectively. Each sample was then boiled with 1 mL 2% sodium hexametaphosphate for complete disaggregation before analysis. Sample amount was adjusted to reach a laser beam obscuration between 5 and 15%. The geometric mean of the grain size distributions was calculated with GRADISTAT v.8 (Blott & Pye, 2001). The same
procedure was used by Vandekerkhove et al. (2021) to measure the grain size of the FC17-08 subsamples.

3.2.3 Statistical analysis

To investigate the possible influence of sediment grain-size on the Sr and Nd isotopic composition of the river and fjord sediment samples, the relations between grain size, Sr and Nd isotopes, and bulk mineralogy (measured by XRD and semi-quantified using RockJock v.11; Liu et al., 2019) of the eight grain-size fractions of river sediment sample RS11-05 were examined by PCA using XLSTAT 2019. To overcome the close-sum effect and the non-negative nature of compositional data (Aitchison, 1986, 1990), grain-size mean was expressed in phi units, and mineralogical data were transformed to centered log-ratios.

4. Results

4.1 River suspended sediments

The seven river suspended sediment samples display $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon\text{Nd}$ values that are distinctive from each other (Figure 3a). The suspended sediment samples obtained from the proglacial rivers mainly draining the PB lithology (i.e., Huemules and Colonia rivers) show relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ and high $\varepsilon\text{Nd}$ values (Figure 3a). By comparison, the river suspended sediments from watersheds dominated by the EAMC (i.e., del Salto, los Ñadis, Bravo, and Pascua rivers) are more radiogenic in Sr, but their $\varepsilon\text{Nd}$ values are generally lower (Figure 3a). The Baker River suspended sediment sample displays $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon\text{Nd}$ values in-
between those of the Colonia and Huemules samples. The $^{87}\text{Sr}/^{86}\text{Sr}$ values are negatively correlated to the areal proportion of PB in the river’s watersheds ($r = -0.67$, $p<0.1$), whereas the $\varepsilon\text{Nd}$ values show a stronger and positive correlation with PB proportions ($r = 0.80$, $p<0.05$; Figure 3b).

In terms of grain size, all river suspended sediment samples are composed of clay and silt, with a mean grain size varying between 3.27 µm for the Colonia River and 7.58 µm for del Salto (Figure 4a). Overall, samples from NPI proglacial rivers (Colonia and Huemules) are finer (mean: 3.27 and 3.67 µm) than those from the eastern part of the lower Baker River watershed (del Salto and los Ñadis; mean: 7.58 and 5.54 µm). The Baker River suspended sediment sample is intermediate (mean: 4.53 µm), and its grain-size distribution is similar to that of Pascua River (mean: 4.41 µm).

4.2 Baker River sediment grain-size fractions

The eight grain-size fractions of Baker River sediment sample RS11-05 show an overall decrease in $^{87}\text{Sr}/^{86}\text{Sr}$ as grain size increases (Figures 4b, 5a). The relation between $\varepsilon\text{Nd}$ and grain size is not as consistent. A decrease in $\varepsilon\text{Nd}$ values is observed from clay to fine silt, followed by an increase from fine silt to sand. $\varepsilon\text{Nd}$ values are the highest in the coarsest grain-size fractions.

To further investigate the grain-size control on $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon\text{Nd}$ of sediment, the mean grain size of each of these fractions and their isotopic and mineralogical composition was analyzed by PCA (Figure 5b). In the PCA biplot, PC1 explains
46.77% of the total variance. It displays strong positive loadings for $^{87}\text{Sr}/^{86}\text{Sr}$ and total clay minerals, and a distinct negative loading for quartz and mean grain size, providing evidence that Sr isotopes consistently covary with grain size. PC2, which accounts for 30.17% of the total variance, shows strong positive loadings for $\varepsilon_{\text{Nd}}$, K-feldspar, and pyroxene, and distinct negative loadings for amphibole and plagioclase. $\varepsilon_{\text{Nd}}$ is positively related to K-feldspar and pyroxene, but it is orthogonal with respect to mean grain size.

4.3 Sediment core subsamples

For the FC17-08 subsamples, the background sediments show relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ and high $\varepsilon_{\text{Nd}}$ values (Figure 6a). The subsamples representing the 2008–2017 Cachet II GLOF deposits at 17.0–17.5, 24.0–24.5, and 26.0–26.5 cm display similar $^{87}\text{Sr}/^{86}\text{Sr}$ and slightly lower $\varepsilon_{\text{Nd}}$ values (Figure 6a). The sample from the 66–70 cm turbidite shows very high $^{87}\text{Sr}/^{86}\text{Sr}$ and low $\varepsilon_{\text{Nd}}$ values, making it isotopically distinct from all the other subsamples. The subsample from the fine-grained and low-TOC deposit at 82–83 cm shows an isotopic composition similar to that of the 2008–2017 Cachet II GLOF deposits.

All seven sediment core subsamples are composed of clay- and silt-sized particles (Figure 4a). The background sediment samples are slightly coarser (mean: 7.73 ± 0.73 µm) than the other subsamples (Figure 4a), and those corresponding to the 2008–2017 Cachet II GLOFs are the finest (mean: 5.05 ± 0.46 µm). The two unknown event deposits are also fine-grained, with the subsample from the base of
the 66–70 cm turbidite being slightly coarser (mean: 7.40 µm) than the sample from
the 82–83 cm event deposit (mean: 6.04 µm). Surprisingly, the subsample
representing the turbidite is finer than the background sediments (Figure 4a).

5. Discussion

5.1 River suspended sediments

The \(^{87}\text{Sr} / ^{86}\text{Sr}\) and \(\varepsilon\text{Nd}\) composition of the river suspended sediments is
significantly correlated to the areal proportions of the PB and EAMC lithologies in
their respective watersheds (Figure 3b). The samples from the Huemules and
Colonia rivers, which drain a watershed predominantly composed of PB granitoids
(Figure 1), have \(^{87}\text{Sr} / ^{86}\text{Sr}\) and \(\varepsilon\text{Nd}\) signatures that superimpose on those of the PB
(Figure 3a). Likewise, the isotopic composition of the suspended sediment samples
from del Salto, los Ñadis, Bravo, and Pascua rivers reflects the EAMC that dominates
in their watersheds (Figures 1, 3a; Table 1). The Baker River suspended sediment
sample is the only one that seem in slight disagreement with the lithology of its
watershed. Its isotopic composition appears similar to that of the PB (Figure 3a),
although 58% of its watershed is composed of EAMC (Table 1; Figure 3b). This can
be explained by (1) the season of sample collection (summer), which likely resulted
in a proportionally higher contribution of meltwater, and therefore glacial sediments
from NPI proglacial rivers, (2) the high amount of sediment produced by glacier
erosion, compared to the non-glacierized part of the watershed, and (3) the
significantly (~3x) higher precipitation in the western part of the watershed. This is
supported by the high SSC values (57–96 mg/L) that were measured in NPI proglacial rivers (Colonia and Huemules) compared to those draining the weakly-glacierized sub-watersheds to the east of Baker River (4–32 mg/L; del Salto and los Ñadis; Supplementary Information Figure S1).

Differences in $^{87}$Sr/$^{86}$Sr and $\varepsilon$Nd compositions also exist between the river suspended sediments that drain watersheds of apparently similar lithology. This is particularly marked in $\varepsilon$Nd for the rivers draining the PB (Huemules and Colonia), but it is also clearly expressed in the $^{87}$Sr/$^{86}$Sr and $\varepsilon$Nd signatures of the four rivers that drain EAMC-dominated watersheds (del Salto, Pascua, Bravo, los Ñadis) (Figure 3). For the Huemules and Colonia rivers, this isotopic difference most likely results from the relatively large age, and therefore isotopic, variations that occur within the PB. The PB is indeed composed of granitoids formed throughout the Cretaceous (Pankhurst et al., 1999), which covers a timespan of almost 100 Ma. However, the clear isotopic difference between the Colonia and Huemules rivers could also be explained by a non-negligible EAMC contribution for the Colonia sample since this lithology accounts for 9% of its watershed but is absent from the Huemules River watershed (Table 1). This EAMC influence is however considered minimal since most of the sediment transported by Colonia River is of glacial origin, especially in summer, and that glaciers only occur in the western part of the Colonia River watershed, which is entirely composed of PB granitoids (Figure 1).

Likewise, there are two possible explanations for the isotopic differences between the four rivers that drain EAMC-dominated watersheds. One is that the
isotopic composition of the EAMC, which was formed during the Paleozoic (Weaver et al., 1990; Augustsson & Bahlburg, 2003; Moreno & Gibbons, 2007), varies across watersheds. This is however unlikely given that the samples that plot the most apart in the εNd vs. ⁸⁷Sr/⁸⁶Sr diagram (del Salto and los Ñadis; Figure 3a) are from rivers that drain watersheds that are adjacent (Figure 1) and that their bedrock was formed between 320–330 Ma (e.g., Augustsson & Bahlburg, 2008). The second and more likely explanation is that the suspended sediments from the del Salto and Pascua rivers receive a significant PB contribution. Indeed, the glacierized regions at the head of del Salto River and in the upper Pascua River watershed are underlain by the PB (Figure 1), and glaciers are known to significantly enhance erosion (Quinteros et al., 2004; Carretier et al., 2013), resulting in a disproportionate contribution from ice-covered lithologies (Liu et al., 2020). Therefore, the PB contribution is likely much higher than suggested by its low areal proportion, especially in summer when the suspended sediment samples were collected. The isotopic difference that exists between the del Salto and Pascua river suspended sediment samples likely results from the trapping of large amounts of glacial sediment of PB origin in Lake O’Higgins, since PB in the Pascua watershed only occurs in the upper sub-watershed (Figure 1).

5.2 End-member definition

The clear distribution of the PB and EAMC lithologies in the Baker River watershed and the overall agreement between the isotopic composition of the river suspended sediments and that of the bedrock lithologies allow us to use ⁸⁷Sr/⁸⁶Sr
and εNd to define the sources of the fjord sediments preserved at the head of Martinez Channel. The isotopic composition of the Huemules and Colonia River suspended sediments were used to represent sediment originating from the western side of Baker River. The del Salto, los Ñadis, Bravo, and Pascua River suspended sediments were selected to define the isotopic composition of sediments originating from the eastern part of the watershed (Figure 3a). The Baker River suspended sediment sample was not used for end-member characterization since it is composed of a mixture of sediment originating from both the PB and EAMC. Although this selection makes use of samples from rivers that do not flow into Baker River to define the end-members of sediments transported by Baker River, this choice is justified by the clear distribution of the bedrock lithologies (Figure 1), and the higher number of datapoints allows us to better reflect the possible spatial and temporal variations in the nature of the sediment sources. To account for the variable $^{87}$Sr/$^{86}$Sr and εNd signatures of the individual river suspended sediment samples, the range (min–max) of isotopic values was used to define the source end-members (Figure 3a).

5.3 Grain-size influence on Sr and Nd isotopes

In addition to provenance, the Sr and Nd isotopic composition of sediments is also known to be influenced by grain size (Revel-Rolland et al., 2005; Bouchez et al., 2011; Meyer et al., 2011; Jonell et al., 2018). Being able to estimate the extent of the grain-size influence on the Sr and Nd isotopic composition of sediment samples is particularly important in paleohydrology since flood deposits are typically identified by their distinctive grain-size signature (e.g., Schillereff et al., 2014; Xu et al., 2014;
This also applies to the deposits interpreted as representing GLOFs in the sediments of the Martínez Channel since these event deposits are systematically finer than the background sediments (Vandekerkhove et al., 2021) (Figure 2).

The $^{87}$Sr/$^{86}$Sr values of the Baker River sediment subsamples almost systematically decrease with grain size (Figure 5a). This trend is also visible in the PCA biplot (Figure 5b), where $^{87}$Sr/$^{86}$Sr negatively covaries with mean grain size. A similar relation has been observed in other environments (e.g., Feng et al., 2009; Bouchez et al., 2011; Gili et al., 2017; Jonell et al., 2018), where it was explained by one or a combination of the following reasons: (1) mineralogical sorting during sediment transport (e.g., Garçon et al., 2013, 2014), (2) chemical weathering (e.g., Feng et al., 2009), and/or (3) differences in the provenance of the different grain-size fractions (e.g., Singh et al., 2008). For the Baker River sediments, the most plausible hypothesis is mineralogical sorting. This is supported by the covariance between $^{87}$Sr/$^{86}$Sr and total clays (Figure 5b). As Rb is preferentially associated with clay minerals, the decay product of $^{87}$Rb, i.e., $^{87}$Sr, tends to be enriched in clays (e.g., Wedepohl, 1978), leading to high $^{87}$Sr/$^{86}$Sr values in fine-grained sediments. It is also possible that the relation between $^{87}$Sr/$^{86}$Sr and grain size reflects changes in the provenance of the different grain-size fractions. As shown in Figure 4b, finer sediments seem to be enriched in particles from the metamorphic complex. This hypothesis, however, is not supported by the grain size of the river suspended sediment samples, as the finest particles transported by Baker River tend to be
produced by glacial erosion of the PB. Chemical weathering is the least likely reason since northwestern Patagonia has experienced limited chemical weathering, due to the cold climate and the relatively recent deglaciation (e.g., Bertrand et al., 2012b).

By comparison, the highest $\varepsilon$Nd values occur in the finest (0–4 µm) and coarsest (63–90 and 90–125 µm) fractions, with lower values in-between (Figure 5a). This trend is also reflected in the PCA biplot, which shows a weak positive covariance between $\varepsilon$Nd and mean grain size (Figure 5b). In sediments, most of the Nd isotopic budget is thought to originate from monazite/allanite (e.g., Garçon et al., 2014; Jonell et al., 2018). These two dense accessory minerals commonly occur in granites but are rare in low-grade metamorphic rocks (Anthony et al., 2000). In Baker River sediments, these two minerals therefore most likely originate from the PB. The rest of the Nd isotopic budget is generally associated with clay minerals, mostly mica (Nelson, 1988; Pankhurst et al., 1999), which is also abundant in the granitoids of the PB (Hervé et al., 1993). Therefore, the high $\varepsilon$Nd value in the finest grain-size fraction of RS11-05 likely reflects the predominant PB origin of this fraction, mostly produced by glacial erosion (cf. the grain-size distribution of the Colonia River suspended sediment sample in Figure 4a). As the grains become coarser, the dense monazite/allanite originating from the PB tend to enrich, resulting in higher $\varepsilon$Nd values in the coarsest grain-size fractions. In-between these two extremes, the sediment is likely dominated by minerals of EAMC origin, explaining the lower $\varepsilon$Nd values of the intermediate grain-size fractions. This relation is also visible in the PCA biplot, in which $\varepsilon$Nd positively covaries with K-feldspar and pyroxene, i.e., two
minerals that are more abundant in the PB than in the EAMC (Güettner Oportus, 2017; Liu et al., 2020). It is also in agreement with the isotopic signatures of the lithological end-members, which show that the finest and coarsest grain-size fractions of RS11-05 are isotopically similar to the PB-dominated “West of Baker River” end-member (Figure 4b). Interestingly, the higher PB contribution in the finest grain-size fraction is not observed in $^{87}\text{Sr}^{86}\text{Sr}$, implying that the influence of mineralogical sorting on $^{87}\text{Sr}^{86}\text{Sr}$ overwhelms that of provenance of the individual grain-size fractions. This suggests that $\varepsilon\text{Nd}$ is a better provenance indicator than $^{87}\text{Sr}^{86}\text{Sr}$, in agreement with previous results obtained in different sedimentological settings (e.g., Meyer et al., 2011; Gili et al., 2017; Awasthi et al., 2018; Jonell et al., 2018). Those studies indeed indicate that $^{87}\text{Sr}^{86}\text{Sr}$ is relatively sensitive to grain size whereas $\varepsilon\text{Nd}$ is not and is therefore better suited to investigate sediment provenance.

An important observation is that the influence of grain size on the $^{87}\text{Sr}^{86}\text{Sr}$ and $\varepsilon\text{Nd}$ compositions of the Baker River bulk sediments is relatively limited compared to the isotopic differences between the two end-members (Figure 4b). According to the standard deviation of (a) the eight RS11-05 grain-size fractions, and (b) the end-members, the isotopic differences between the grain-size fractions of sample RS11-05 only account for 15% of the isotopic differences between the end-members. The real influence of grain size on the isotopic composition of the fjord sediment samples is probably lower than that since the mean grain size of the FC17-08 subsamples varies between 4.55 and 8.25 µm, which only covers the finest RS11-05 subsamples. The influence of grain-size on the isotopic composition of these
samples mostly corresponds to the two finest RS11-05 subsamples (Figure 4b),
which reduces the influence of grain size to 8 and 14% of the provenance signal for
Sr and Nd isotopes, respectively. With this in mind, we consider that the isotopic
composition of the fjord sediment samples mostly represents provenance.

5.4 Reconstructing the provenance of flood deposits

The two subsamples representing the background sediment of core FC17-08
have Sr and Nd isotopic signatures that correspond to the “West of Baker River” end-
member (Figure 6). This suggests that the western part of the lower Baker River
watershed constitutes the main source of sediments to the fjord, in agreement with
the observation that glacierized sub-watersheds contribute relatively more to
sediment budgets than their non-glacierized counterparts, due to efficient bedrock
erosion by glaciers (Liu et al., 2020). For the Baker watershed, this is supported by
the sediment budgets of Vandekerkhove et al. (2020b), which suggests that the rivers
draining the western part of the watershed contribute roughly 15 times more to the
Baker River sediment load than the eastern rivers.

The $^{87}\text{Sr}/^{86}\text{Sr}$ and $\epsilon$Nd signatures of the three samples corresponding to the
2008–2017 GLOF deposits at 0–27.5 cm confirm that these deposits represent the
abrupt drainage events that have affected Lake Cachet II, as they almost perfectly
correspond to the isotopic signature of the Colonia River (Figure 6b). More
importantly, these results confirm that Sr and Nd isotopes can be used to reconstruct
the provenance of GLOF deposits, despite the minor influence of grain-size on the
The sample representing the 66–70 cm turbidite that was deposited between 1990–2000 displays an isotopic signature that is clearly distinct from all the other samples (Figure 6b). Both isotopes plot in the “East of Baker River” end-member area, which suggests that this turbidite is predominately composed of sediment originating from the eastern side of Baker River. This result is in agreement with the hypothesis of Vandekerkhove et al. (2021) that this turbidite represents a rain-on-snow event that occurred in August 1992. In this case, the rain-on-snow event would have primarily affected the eastern part of the watershed since it happened in winter, when precipitation most likely fell as snow in the western part of the watershed, but as rain in the east (Figure 7a).

The isotopic signature of the fine-grained and organic-poor deposit at 82–83 cm undoubtedly shows that it originated from the western side of the Baker River watershed (Figure 6b). This contradicts the hypothesis of Vandekerkhove et al. (2021) that it represents the 1988 Las Lengas GLOF, which would have a clear EAMC signature (Figure 1). A more likely candidate is the rain-on-snow event that happened in December 1989 (Dussaillant et al., 2012). Since this rain-on-snow event happened in early summer, snow cover, and therefore erosion, predominantly occurred in the western part of the watershed (Figure 7b). As a result, this intense rain-on-snow event reworked glacier rock flour of PB origin, resulting in the deposition of fine-grained sediments with a PB geochemical signature in Martínez Channel. This interpretation is additionally supported by the association of a similar
fine-grained low-TOC layer occurring deeper in two other sediment cores from the
same fjord with a flood caused by an intense rain-on-snow event in December 1976
(Vandekerkhove et al., 2021).

The association of the 82–83 cm fine-grained deposit and 66-70 cm turbidite
with the December 1989 and August 1992 rain-on-snow events, respectively,
validates the $^{210}$Pb chronology of sediment core FC17-08 made by Vandekerkhove et
al. (2021) since both events are within the error bars of their modeled age (Figure 2).
The real age of the events is consistently older (1–2 years) than their modeled age.
This slight overestimation is confirmed by the modeled age (1980) of the December
1976 rain-on-snow event that was observed in the deepest sediments of the deepest
cores (Vandekerkhove et al., 2021), resulting in a 3-year offset. This offset does not
represent the delay between flood occurrence and formation of flood deposits since
signal propagation in the Baker River system is typically in the order of days (Amann
et al., submitted). This implies a slight (<10%) overestimation of the sedimentation
rates by the CFCS model.

5.5 Implications for the sedimentary signature of GLOFs vs. meteorological floods

The striking similarities between the sedimentary and isotopic signatures of
the early summer 1989 and 1976 rain-on-snow flood deposits with those of the
2008–2017 Cachet II GLOF deposits suggest that deposits due to GLOFs and rain-
on-snow events occurring in summer may be difficult to differentiate based on their
sedimentological characteristics. Although our results confirm that all Cachet II
GLOFs are recorded as fine-grained and organic-poor deposits and that none of them was able to trigger a turbidite at site FC17-08, they also suggest that not all fine-grained and organic-poor deposits can be interpreted as GLOFs. They can also represent rain-on-snow events occurring in (early) summer, i.e., when the only snow left in the watershed is over its mostly-glacierized western side (Figure 7b).

Differentiating between these two types of floods remains challenging based on the existing sedimentological and isotopic criteria.

The association of the 66–70 cm organic-rich turbidite with the winter 1992 rain-on-snow event additionally shows that seasonality plays an important role in controlling how rain-on-snow events are recorded in fjord sediments. This issue probably affects all sedimentary basins receiving sediments from partially-glacierized watersheds, or at least watersheds with highly variable snow cover. Locations in the watershed where rain falls on snow produces more sediment than locations where rain falls directly on the ground.

Finally, our results also imply that the 1988 Las Lengas GLOF was not recorded at site FC17-08. This observation is supported by the lack of a discharge peak in the Baker River hydrographs, which was explained by Vandekerkhove et al. (2021) by the low (daily) resolution of the hydrographs, despite the 1301 m³/sec discharge peak that was estimated for los Ñadis River (Iribarren Anacona et al., 2014). Both the water discharge and sediment yield of the 1988 Las Lengas GLOF were likely too low to significantly affect Baker River and therefore be recorded in the fjord’s sediments.
6. Conclusions

This study confirms the ability of Sr and Nd isotopes to reconstruct sediment provenance in the Baker River watershed. Both isotopes can successfully differentiate sediments originating from the western and eastern sides of the watershed, suggesting that either isotope is powerful enough for provenance reconstruction in the Baker region. This excellent discrimination potential reflects the clear distribution of rocks of different age (Mesozoic granitoids and Paleozoic metamorphic complex) within the Baker River watershed. In addition, our results suggest that $\varepsilon_{Nd}$ is less affected by grain size than $^{87}$Sr/$^{86}$Sr. Despite a minor influence of grain size on the isotopic results (<15% of the provenance signal), $^{87}$Sr/$^{86}$Sr and $\varepsilon_{Nd}$ can reliably be applied to flood deposits, whether they are mud layers or turbidites.

The provenance results indicate that the background sediments deposited at the head of Martínez Channel mostly originate from the western, glacierized, part of the watershed, reflecting the high erosion capacity of glaciers. In terms of event deposits, our results confirm the Cachet II origin of the fine-grained and organic-poor deposits preserved in the upper 27.5 cm of the sediment core. They also provide evidence that a similar deposit previously associated with the 1988 Las Lengas GLOF instead represents a rain-on-snow event that occurred in early summer 1989. In addition, our provenance analysis demonstrates that the turbidite at 66–70 cm originated from the eastern part of the watershed, allowing us to associate it with a rain-on-snow event that occurred in winter 1992.
These results have important implications for the sedimentary signature of GLOFs vs. meteorological floods. They confirm that GLOFs are systematically recorded as fine-grained organic-poor layers, as shown by Vandekerkhove et al. (2021), but they suggest that rain-on-snow flood events occurring in (early) summer may have the same signature, which reflects the glacial origin of the sediment transported by both flood types. Rain-on-snow floods occurring in winter, on the other hand, are recorded as regular meteorological floods (organic turbidites) since they only affect warmer (non-glacierized) sub-watersheds. In other words, the sedimentological signature of rain-on-snow events depends on snow cover distribution, and therefore on the season during which the flood occurs. Our results also suggest that GLOFs from smaller glacial lakes, such as Las Lengas, may not be recorded in downstream fjord sediments. We anticipate that these results will constitute a strong basis for the interpretation of flood deposits from sediment archives located in partially glacierized watersheds.
7. References


SERNAGEOMIN. 2003. Mapa Geológico de Chile, escala 1:1,000,000.


Figure 1. Geological map of the study region in Patagonia (based on SEGEMAR, 1998, SERNAGEOMIN, 2003, and Gómez et al., 2019), showing the location of the Baker River, its tributaries, and the fjord in which it discharges (Martínez Channel). The Northern Patagonian Icefield (NPI), Southern Patagonian Icefield (SPI), San Lorenzo icefield, and Cordón de los Ñadis icefield are also shown. The two proglacial lakes that are at the origin of the Baker River historical GLOFs are indicated using dark blue rectangles. The location of the river bulk (Baker; RS11-05) and suspended (Colonia, del Salto, los Ñadis, Huemules, Baker, Bravo and Pascua River) sediment sampling sites, as well as of sediment core FC17-08, are also indicated.
Figure 2. Lithology of sediment core FC17-08 (from Vandekerkhove et al., 2021) and location of the subsamples used in this study. The downcore variations in mean grain size and total organic carbon (TOC) confirm the identification of fine-grained organic-poor event deposits (uppermost 27.5 cm of the core and 82–83 cm) and of a relatively organic fine-grained turbidite (66–70 cm). The age-depth model (also from Vandekerkhove et al., 2021) shows that
the sediment core covers the period 2017 to 1974–1991. The modeled ages of the event deposits are shown to the right.
Figure 3. $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ composition of the river suspended sediment samples and comparison with the isotopic signature of the dominant bedrock lithologies (cf. Table 1). (a) $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ compositions of the river suspended sediments samples compared to those of the Patagonian Batholith (PB) (Pankhurst et al., 1999) and Eastern Andean Metamorphic Complex (EAMC) (Weaver et al., 1990). (b) Isotopic signatures ($^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$) of the river suspended sediments plotted against the relative areal proportion of the two main lithologies in their respective watersheds (Table 1). In all plots, the error bars are smaller than the size of the dots. In (a), the $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon_{\text{Nd}}$ signatures of the Huemules and Colonia river suspended sediment samples are used to characterize the “West of Baker River” end-member, which is dominated by the PB, whereas those from Pascua, del Salto, Bravo and los Nadis rivers are used to define the “East of Baker River” end-member, which is dominated by the EAMC. The Baker River suspended sediment sample is not used to define sources since it represents a mixture of both sources. The source end-members are defined using the
isotopic range (min–max values; represented as colored rectangles) of the river suspended sediment samples. The sub-watersheds used to define the “West of Baker River” and “East of Baker River” end-members are represented on the inset map in green and peach, respectively.
Figure 4. Evaluation of the influence of grain size on sediment provenance reconstruction. (a) Grain-size distributions of the river suspended sediments and of the FC17-08 sediment core subsamples. In (b), the isotopic composition of the eight grain-size fractions (0–4, 4–8, 8–16, 16–32, 32–45, 45–63, 63–90, and 90–125 µm) of river sediment sample RS11-05 (red dots) are compared to the isotopic signature of the two source end-members (West vs. East of Baker River) defined in Figure 3. The error bars are smaller than the size of the dots. Note that most of the fjord sediment samples are finer than ~10 µm and therefore correspond in grain size to the two finest sub-samples from RS11-05.
Figure 5. Variations in the $^{87}\text{Sr}/^{86}\text{Sr}$, $\varepsilon\text{Nd}$, and mineralogical composition of river sediment sample RS11-05 (Baker River) with grain size. (a) $^{87}\text{Sr}/^{86}\text{Sr}$ and $\varepsilon\text{Nd}$ composition of the eight RS11-05 grain-size fractions plotted vs. grain size. The error bars are smaller than the size of the dots and are therefore not visible. (b) PCA biplot of $^{87}\text{Sr}/^{86}\text{Sr}$, $\varepsilon\text{Nd}$, grain-size mean, and mineralogy of the same eight grain-size fractions.
Figure 6. Provenance of the subsamples from sediment core FC17-08. The $^{87}$Sr/$^{86}$Sr and $\varepsilon$Nd composition of the subsamples is (a) compared to the composition of the sources defined in Figure 3 ($\varepsilon$Nd vs. $^{87}$Sr/$^{86}$Sr biplot), and (b) plotted against depth. The depth of the fine-grained organic-poor deposits identified by Vandekerkhove et al. (2021) is marked in blue and that of the turbidite is in orange. The isotopic values of the suspended sediment sample collected in proglacial river Colonia is indicated in (b) using dashed lines as this river is the outflow of proglacial lake Cachet II, which is at the origin of the 21st century Baker River GLOFs.
Figure 7. Schematic models illustrating the differences between rain-on-snow flood events occurring in winter vs summer. (a) In winter, the entire watershed is snow-covered but precipitation falls as snow in its western part. Therefore, rain-on-snow events primarily affect the eastern part of the watershed and are recorded in downstream fjord sediments as intense rainfall events, i.e., organic-rich turbidites of Eastern Andean Metamorphic Complex (EAMC) origin. (b) In (early) summer, only the western part of the Baker River watershed is snow-
Rain-on-snow events are therefore recorded in downstream fjord sediments as fine-grained organic-poor layers, representing glacial material of Patagonian Batholith (PB) origin.
Table 1. Proportions of the two main lithologies (Patagonian Batholith [PB] and Eastern Andean Metamorphic Complex [EAMC]) in the watersheds of the seven sampled rivers, based on SEGEMAR (1998), SERNAGEOMIN (2003), and Gómez et al. (2019). For the Baker and Pascua River watersheds, calculations were made for the lower parts the watersheds only since sediments derived from the upper sub-watersheds are filtered by lakes General Carrera and Cochrane, and by Lake O’Higgins, respectively (Figure 1). The lithology under the NPI was assumed to be entirely PB. Only the PB and EAMC lithologies were considered in the calculation since the other lithologies are limited to minor occurrences in the upper (drier) part of the lower Baker River sub-watershed along Chacabuco River (Fig. 1).

<table>
<thead>
<tr>
<th>Watershed</th>
<th>PB (%)</th>
<th>EAMC (%)</th>
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<tbody>
<tr>
<td>Huemules</td>
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<tr>
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