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20 years of mass balances on the Piloto glacier, Las Cuevas river basin, Mendoza, Argentina

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Abstract

Climatic changes of the 20th century have altered the water cycle in the Andean basins of central Argentina. The most visible change is seen in the mountain glaciers, with loss of part of their mass due to decreasing thickness and a substantial recession in the last 100 years. This paper briefly describes the results of glacier mass balance research since 1979 in the Piloto Glacier at the Cajón del Rubio, in the headwaters of Las Cuevas River, presenting new results for the period 1997–2003. Very large interannual variability of net annual specific balance is evident, due largely to variations in winter snow accumulation, with a maximum net annual value of +151 cm w.e. and a minimum value of - 230 cm w.e. Wet El Niño years are normally associated with positive net annual balances, while dry La Niña years generally result in negative balances. Within the 24-year period, 67% of the years show negative net annual specific balances, with a cumulative mass balance loss of - 10.50 m water equivalent (w.e.). Except for exceptions normally related to El Niño events, a general decreasing trend of winter snow accumulation is evident in the record, particularly after 1992, which has a strong effect in the overall negative mass balance values. The glacier contribution to Las Cuevas River runoff is analysed based on the Punta de Vacas River gauge station for a hypothetical year without snow precipitation (YWSP), when the snowmelt component is zero. Extremely dry years similar to a YWSP have occurred in 1968–1969, 1969–1970 and 1996–1997. The Punta de Vacas gauge station is located 62 km downstream from Piloto Glacier, and the basin contains 3.0% of uncovered glacier ice and 3.7% of debris-covered ice. The total glacier contribution to Las Cuevas River discharge is calculated as 82±8% during extremely dry years. If glacier wastage continues at the present trend as observed during the last 2 decades, it will severely affect the water resources in the arid central Andes of Argentina.

Keywords: glacier mass balance; glacier contribution to runoff; Argentinian Central Andes

1. Introduction

The receding process of glaciers during the last 100 years that appears to be coherent worldwide (IPCC, 2001) shows that mountain glaciers play an important role in drainage basins, particularly in Asia, North and South America, contributing the highest proportion of fresh water contribution of river systems in dry seasons (Meier, 1969). Monitoring glacier mass balance in these regions is important for studying changes in the hydrological cycle within a scenario of climate change, and could be used as well to infer climatic information from changes of glacier size (Oerlemans, 1994).

Mass balance studies at Piloto Glacier, Cajón del Rubio, located in the headwaters of Las Cuevas river, high central Andes of Argentina (Fig. 1) began in the

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1979–1980 austral summer. The Piloto glacier (32° 37′ S, 70° 09′W), was selected as a bench mark glacier to study mass balance, both due to its spatial representativeness and accessibility. At a later stage the ablation area of neighboring Alma Blanca glacier was added to the mass balance research programme. In map view, Piloto glacier is a U-shaped glacier with two-tongues (West and East) separated by a ridge, with a total area of 1.4 km^2 of relatively smooth glacier surface situated between 4185 and 4900 m a.s.l. (Fig. 2). Since 1985 only the Piloto East tongue (PE) has been studied because fields of penitentes and frequent avalanches that occur on the Piloto West tongue (PW) make field measurements very complicated. PE Glacier has an area of 0.504 km^2, and is located between 4185 and 4740 m a.s.l. PW Glacier mass balances have shown, when measured, a close correlation with those of PE (Leiva and Cabrera, 1996).

The mass balance of Piloto East Glacier from 1979–1980 until 1996–1997 has been described by Leiva (1999). This paper presents updated results of mass balance until 2002–2003 and a discussion of the influence of glaciers on water resources in this semi-arid basin of central Argentina.

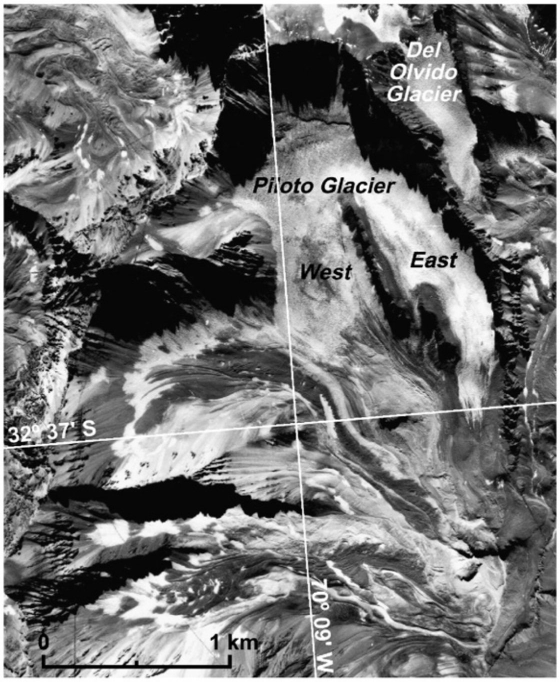

Fig. 2. Piloto Glacier. Aerial photograph showing the glacier in 1974.

2. Methodology

Direct measurements of mass balance have been carried out at Piloto Glacier since 1979 by the direct glaciological method (Østrem and Stanley, 1969; Østrem and Brugman, 1991). Snow pits, density profiles derived from RAM hardness (Keeler, 1969), and ablation stake data were used to obtain net mass balances for the period 1979–1984 (Leiva, 1982; Leiva et al., 1986; Leiva and Cabrera, 1996). Accumulation data were not obtained for the 1984, 1985, 1988, 1989 and 1990 winters. At the end of the 1986 and 1990 ablation seasons the net mass balances 1984/86 (cumulative biannual) and 1988/90 (cumulative triennial) were measured. The fact that mean ablation values are almost constant in time (Leiva, 1982) made possible the calculation of the corresponding accumulation for the two and three year-periods. These multiyear accumulation values were then distributed, using the correlation that exists between June–July precipitation of Santiago de Chile and the Piloto East accumulation, to reconstruct the 1984, 1985, 1988, 1989 and 1990 accumulation and net mass balance values (Leiva and Cabrera, 1996).

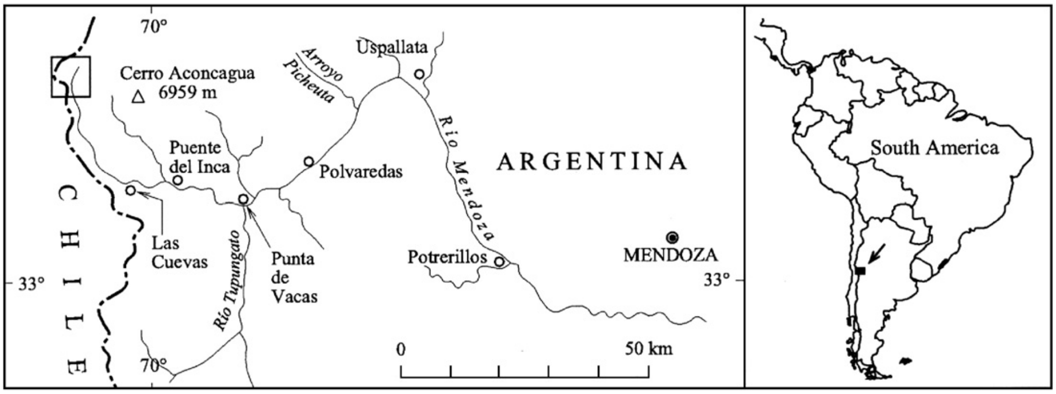

Fig. 1. Location map. The inset on the left corresponds to the location of Fig. 2.

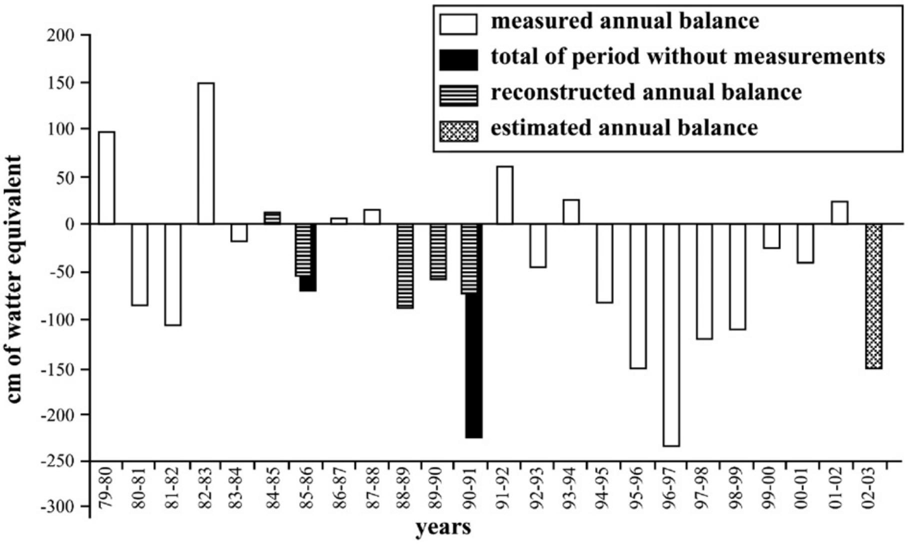

Fig. 3. Mean specific mass balances of Piloto East Glacier since 1979.

The studies were based on a detailed topographic map at 1:10 000 scale with 10 m-interval contour lines, developed at IANIGLA (Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales) in 1983. Ten years later accurate GPS measurements were performed in the field and were recently improved using IANIGLA's permanent GPS station located in the city of Mendoza (MZAC). Standard glaciological measurements of mass balance supported by GPS-technology would permit to make more systematic and consistent measurements in future studies.

The processing of the stake data from the Cajon del Rubio glaciers, and some theoretical considerations (Cabrera, 1986a,b), allowed us to verify the existence on each glacier of a zone where the local specific mass balance is representative of the mean net balance of the entire glacier. This representative zone remains stable notwithstanding the value and sign of this balance. Stake measurements in these zones were done in order to determine the corresponding mass balance, the altitude distribution of the mass balance and the mean ablation value that appears to be invariant year to year (Leiva, 1982; Cabrera, 1984). Thus, after several years of extensive mass balance measurements on a network of many stakes and pits distributed over the entire glacier area, it was found that the extensive network could be substituted by several stakes located within a representative zone close to the 4500 m elevation. This experimental result achieved at Piloto glacier verifies the theoretical consideration that the equilibrium line altitude (ELA_0), where the specific mass balance is zero in steady-state conditions, is a representative zone of the entire glacier in which the specific balance at any given time equals the mean specific mass balance for the entire glacier. This "characteristic altitude" does not vary in time – within a year and year to year – no matter the balance value and its sign (Cabrera, 1984). The authors have found that this simplification has not reduced the accuracy of the glacier mass balance calculations.

Since 1987 discrete measurements of the specific mass balance have been carried out at Piloto East Glacier twice a year, once at the end of the accumulation season and once at the end of the ablation season, within a reduced area around the characteristic altitude. The winter balance in late spring was obtained mainly by density data obtained from rammsonde hardness results that were converted to density values by statistical correlation (Keeler, 1969), adjusted with density measurements in a pit profile (Leiva et al., 1986). The summer balance has been determined in the autumn. This method has been used in years with positive balance. In years with negative mass balance only the ablation data from stakes has been measured because there is no snow accumulation on the glacier during spring.

3. Mass balance

The mean net annual specific balances since 1997 are the following:

1997–1998 balance: −120 (±30) cm water equivalent (w.e.)
1998–1999 balance: −110 (±30) cm w.e.

Table 1
Piloto East glacier mass balance data. c_n mean accumulation, a_n mean ablation, b_n annual mean balance and Σb_n cumulative mass balance since 1979

	c_n (cm w.e.)	a_n (cm w.e.)	b_n (cm w.e.)	Σb_n (cm w.e.)
1979–80	100	0*	100	100
1980–81	30	116	−86	14
1981–82	20	127	−107	−93
1982–83	270	119	151	58
1983–84	95	116	−21	37
1984–85	215	200	15	52
1985–86	129	200	−71	−19
1986–87	135	125	10	−9
1987–88	143	124	19	10
1988–89	111	200	−89	−79
1989–90	140	200	−60	−139
1990–91	124	200	−76	−215
1991–92	180	116	64	−151
1992–93	70	119	−49	−200
1993–94	105	79	26	−174
1994–95	25	106	−81	−255
1995–96	50	200	−150	−405
1996–97	0	230	−230	−635
1997–98	80	200	−120	−755
1998–99	40	150	−110	−865
1999–00	75	100	−25	−890
2000–01	46	85	−39	−929
2001–02	65	95	29	−900
2002–03	50	200	−150	−1050

* Frequent *graupel* storms occurred during the 1979–1980. These storms did not contribute to the annual accumulation significantly but they whitened the whole glacier surface, increasing the albedo and made the mean annual ablation negligible. The 1979–1980 summer was an exceptional summer in the whole 1979–2003 period (Leiva, 1982).

1999–2000 balance: −25 (±3) cm w.e.
2000–2001 balance: −39 (±15) cm w.e.
2001–2002 balance: +29 (±3) cm w.e.

Winter balance 2002: +50 (±3) cm w.e. The 2002–2003 summer balance data are not available, and it is estimated to be - 2.0±0.2 m as observed by the authors during previous years (e.g. Leiva, 1999). Thus, the 2002–2003 balance was estimated as −1.50±0.23 m w.e.

Using the above information, the 2000–2003 cumulative mass balance can be estimated as - 1.50± 0.41 m w.e. Fig. 3 (modified from Leiva and Cabrera, 1996) and Table 1 show the specific mass balance of Piloto East Glacier since 1979. The 1979–2003 cumulative mass balance of the Piloto East glacier (Fig. 4, modified from Leiva and Cabrera, 1996) and Table 1 shows a mass loss of 10.50 m w.e. In general the mass balance values are negative for the period, particularly since 1988–89, with 67% of the years showing negative net annual specific balances. In years with strongly negative balance the entire glacier consisted of ablation area, with an accumulation/ablation area ratio AAR = 0. Positive balances show in general an AAR ≅ 58%.

A very large interannual variability of net annual specific balance is shown in the data record, being due largely to variations in winter snow accumulation. Within the period, the maximum balance value is +151 cm w.e., and a minimum of −230 cm w.e. As shown by Leiva (1999), strongly positive annual balances correspond to years with very high winter snow accumulation, which are in turn closely correlated with El Niño Southern Oscillation (ENSO) events, such as in 1982–1983, 1987–1988 and 1991–1992. In contrast, strongly negative mass balance years correspond normally to dry La Niña events, such as in 1988–1989 and 1998–1999. A general decreasing trend of winter snow accumulation is evident, particularly after 1992, which has a strong impact in the overall negative mass balance record.

4. Glacier contribution to Las Cuevas River runoff

Considering that rainfall contribution is negligible in the basin (Milana and Maturano, 1997; Milana, 1998), a simple model for the runoff of Las Cuevas River can be established as:

$$\begin{aligned}\text{Runoff} &= \text{Snowmelt in the basin}\\ &\quad + \text{glacier ice melt} - (\text{Evaporation}) + B\end{aligned}$$

where B represents the base flow, which is the runoff observed at the outlet of the drainage basin (or at the gauge station) during long periods when no precipitation or snowmelt occur, being composed of groundwater runoff and delayed subsurface runoff.

Data from the Punta de Vacas River gauge station, located 62 km downstream from Piloto Glacier, and the glacier surface area in the basin obtained from the Glacier Inventory of Mendoza River Basin (Corte and Espizúa, 1981), were used to establish the magnitude of glacier contribution to Las Cuevas river runoff. The whole area of the basin, 654 km^2, contains 19.58 km^2 (2.99%) of uncovered (debris-free) ice and 24.41 km^2 (3.73%) of debris-covered ice. The Punta de Vacas runoff time series shows that the mass balance data of the Piloto Glacier covers a very interesting time period when Las Cuevas river runoff data have high variability.

Assuming a hypothetical year without snow precipitation on the cordillera (YWSP), the mean net annual balance of the glacier equals the annual ablation. Therefore the snowmelt component of the water balance equation for the YWSP is zero. For this YWSP the

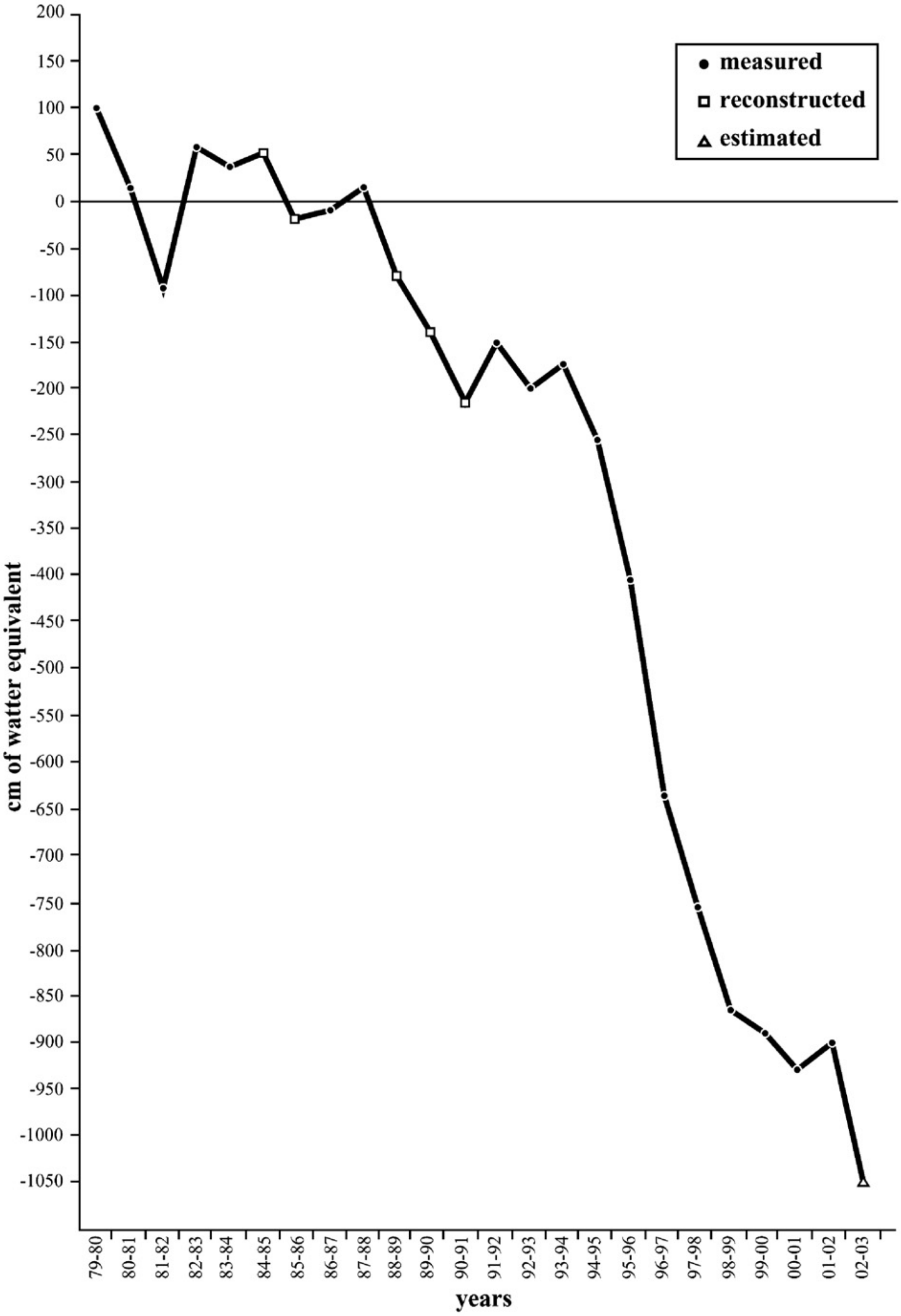

Fig. 4. Cumulative mass balances of Piloto East Glacier.

glacier contribution to the Las Cuevas total river runoff has been calculated by multiplying the debris-covered and debris-free ice surface areas of the basin by corresponding ablation values (Leiva, 1982) as it is shown in Table 2.

In order to estimate realistically dry conditions and their effect on the total runoff of Las Cuevas River we have taken minimum values of monthly average runoff data for the 1955–2001 period. Table 3 shows that such minimum data occurred during hydrological years 1968–1969, 1969–1970 and 1996–1997 (the rest of the table is omitted). Half of those minimum values belong to the 1996–1997 hydrological year, 4 to 1968–1969 and 2 to the 1969–1970 hydrological year.

Table 2
Glacier contribution to total annual discharge of Las Cuevas River in a YWSP

Type of glacier	Surface (10^6 m^2)	Mass balance in a YWSP (m w.e.)	Annual water discharge contribution (10^6 m^3)
Uncovered	19.58	−2.0±0.2	39.16±3.9
Debris-covered	24.41	−1.0±0.1	24.41±2.4

Historically 1968–1969 is known in the press and in common knowledge as “a year with no snow precipitation in the Cordillera”. This observation is also confirmed by snow-course data from Dirección General de Aguas (DGA), General Water Administration — Chile, measured in September 1968 at Portillo station, (32°50′ S, 70°07′W, 2885 m a.s.l.) and at Laguna Negra station (33°40′ S, 70°06′W, 2768 m a.s.l.), both on the Chilean side of the Andes, showing no snow accumulation. Snow-course data from Subsecretaría de Recursos Hídricos (SSRRHH), Water Resources Administration — Argentina, measured at Laguna del Diamante (34°14′S, 69°41′ W, 3310 m a.s.l.) on August 1968 on the Argentinean side of the Andes also shows no snow accumulation.

Using these minimum runoff data (hachured in Table 3) as possible monthly runoff in a hypothetical YWSP, the annual total discharge of Las Cuevas River would be 77.9×10^6 m^3. The contribution of uncovered-ice glaciers to Las Cuevas River runoff in such a YWSP (Table 2) is $39.16\pm3.9\times10^6$ m^3, which is 50.3±5.0% of the total river discharge in a YWSP. Adding the meltwater from the debris-covered glaciers, the total glacier contribution to the Las Cuevas River discharge increases to 81.6±8.1% in extremely dry years with nearly no precipitation.

Similar results have been obtained at the San Juan River basin. According to Milana (1998) glacier contribution to runoff has increased during the last 40 years due to decrease in the precipitation amount. Glacier contribution was 70% in the 1996–1997 summer, and in more severe drought conditions glaciers may contribute more than 75% of the total river discharge (Milana and Maturano, 1997).

Since 1914 (Leiva et al., 1989; Llorens and Leiva, 2000; Leiva, 2002), when historical data of glacier variations are first available, glaciers have lost substantial volume and have receded in the Mendoza river basin. In the last 2 decades this wastage trend is confirmed by our mass balance observations at Piloto Glacier. Increased glacier melt should result first in an increase in the glacier runoff contribution, but as the glaciers waste beyond a critical ice volume the total river runoff should decline, as has been modelled, for example, by Juen et al. (2007-this issue).

5. Conclusions

The mass balance series of the Piloto East Glacier shows a very negative trend in the 1979–2003 period, particularly since 1988–1989. The 1979–2003 cumulative mass balance is equivalent to a mass loss of 10.5 m w.e. and shows that the general receding process of the glaciers, that has taken place worldwide since at least the beginning of the 20th Century (IPCC, 2001), prevails as well in this basin of the central Argentinian Andes. It also indicates that if this trend continues, this small glacier that in 1979 had a maximum ice depth of 60 m (Leiva, 1982) will disappear in the near future, similar to what may happen to many other small glaciers of the Central Andes of Mendoza and San Juan provinces in central Argentina.

The snowmelt contribution to Las Cuevas River runoff is important, but the snow precipitation amount is highly variable, and has been decreasing since the beginning of the glacier mass balance studies as shown by the predominantly negative mass balances, except for strong El Niño years when precipitation values are very high. The relative area of glaciers in the entire river basin is small, but glacier contribution to river runoff, which is small in years with normal or above-normal snow precipitation, increases enormously in periods of drought, exceeding in such years 70% of the total river runoff.

Since 1914 (Leiva et al., 1989; Llorens and Leiva, 2000), and also since the start of our mass balance observations, glaciers have wasted substantially in the

Table 3
Mean monthly runoff for Las Cuevas River (m^3/s) and total annual discharge Q (10^6 m^3) observed during the three driest years within the period 1955–2001 (complete data series not shown). The minimum monthly values for the 1955–2001 period are hachured

Year	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Q
68–69	2.3	1.9	2.1	2.3	3.8	3.5	4.5	4.6	4	2.1	1.9	1.6	90.7
69–70	1.8	1.7	2.3	2.4	8.1	15.3	9.1	6.8	5.2	4	3.3	2.8	165.0
96–97	2.24	2.48	2.41	2.14	2.75	2.83	3.85	4.06	2.92	2.81	2.35	2.01	86.1

Mendoza river basin. This glacier behavior should lead firstly to an increase in glacier runoff, but consequently to a decrease in the total river runoff as the glaciers waste beyond a critical volume. This will have an important impact in the availability of future water resources in the semi-arid basins of central Argentina.

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