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Glacier contributions to river discharge during the current Chilean megadrought

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Key Points:

- Imbalance glacier ablation has strongly buffered the late-summer discharge of the Maipo River during the current Chilean megadrought.
- Between 2010 and 2018, almost a quarter of total ablation in the Maipo Basin was not balanced by new snowfall.
- By buffering river discharge during drought, glaciers, distinct from seasonal snow, provide a valuable hydrologic service to Santiago.

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Abstract

The current Chilean megadrought has led to acute water shortages in central Chile since 2010. Glaciers have provided vital fresh water to the region's rivers, but the quantity, timing and sustainability of that provision remain unclear. Here we combine in-situ, remote sensing and climate reanalysis data to show that from 2010 to 2018 during the megadrought, unsustainable imbalance ablation of glaciers (ablation not balanced by new snowfall) strongly buffered the late-summer discharge of the Maipo River, a primary source of water to Santiago. If there had been no glaciers, water availability would have been reduced from December through May, with a 31 ± 19% decrease during March. Our results indicate that while the annual contributions of imbalance ablation to river discharge during the megadrought have been small compared to those from precipitation and sustainable balance ablation, they have nevertheless been a substantial input to a hydrological system that was already experiencing high water stress. The water-equivalent volume of imbalance ablation generated in the Maipo Basin between 2010 and 2018 was 740×10^6 m^3 (19 ± 12 mm yr^{-1}), approximately 3.4 times the capacity of the basin's El Yeso Reservoir. This is equivalent to 14% of Santiago's potable water use in that time, while total glacier ablation was equivalent to 59%. We show that glacier retreat will exacerbate river discharge deficits and further jeopardise water availability in central Chile if precipitation deficits endure, and conjecture that these effects will be amplified by climatic warming.

Plain Language Summary

Since 2010, central Chile has experienced a long period of drought or 'megadrought'. There has been considerably less water in rivers and streams, causing a wide range of societal problems. In our study, we explore the role glaciers have played in maintaining river levels during the megadrought. We focus on the basin of the Maipo River, from which the Chilean capital Santiago derives a large portion of its water supply. Our results suggest that meltwater from the glaciers has been much less sustainable since the megadrought began in 2010, and that if there had been no glaciers, water availability during the megadrought would have been substantially reduced in late summer. We found that even without the seasonal snow that falls on them, glaciers provided enough meltwater from 2010 to 2018 to meet 14% of Santiago's potable water use. Given predictions of a drier future in central Chile, our results have implications for the water resilience of the Chilean capital, its agricultural sector, and the health of its upstream mountain ecosystems.

1 Introduction

Since 2010, central Chile has experienced a prolonged period of extreme dryness, the current Chilean megadrought, due to consecutive annual precipitation deficits of 25-45% against the 1970-2000 average (Garreaud et al., 2020). These deficits are estimated to be 25% attributable to anthropogenic climatic warming, and have been caused by the passage over the region of fewer than usual extratropical winter storms, which have instead been deflected polewards by a region of warm water and high atmospheric pressure in the Southeast Pacific (Garreaud et al., 2020, 2021; Boisier et al., 2016).

In response to the megadrought's profound environmental and socioeconomic impacts, the Government of Santiago has announced a plan to ration water in the capital for the first time ever (Government of Santiago, 2022), while the Chilean government has declared agricultural emergency in many regions (The Santiago Times, 2019). Vegetation productivity, snow cover and glacier albedo have decreased, while forest fire occurence and glacier mass loss have increased (CR2, 2015; Garreaud et al., 2017; González et al., 2018; Dussaillant et al., 2019; Shaw et al., 2021). The megadrought is perceived as having caused an increase in the cost of living, a decrease in quality of life, and as having negatively affected tourism and the labour market (Aldunce et al., 2017).

A major concern is the reduced availability of surface water that has been observed in the form of decreased river discharge, lake and reservoir volumes (CR2, 2015; Alvarez-Garreton et al., 2021). This is particularly problematic because unlike water stored in the ground, vegetation, ice and snow, this surface water is easily available for human use, and is essential for the healthy functioning of native riparian, riverine and lacustrine ecosystems.

Glaciers are an important source of surface water in central Chile, particularly in summer (Ayala et al., 2020), and have lost substantial mass and area in recent decades (Malmros et al., 2016; Braun et al., 2019; Dussaillant et al., 2019; Farías-Barahona et al., 2019, 2020). It is established that glacier mass change has been especially negative since the beginning of the megadrought in 2010 (Dussaillant et al., 2019; Farías-Barahona et al., 2020), that high-mountain runoff during the megadrought has been dominated by ice rather than snow melt (Burger et al., 2019), and that glaciers are likely to continue to retreat towards 2100 (Huss et al., 2017; Bocchiola et al., 2018; Ayala et al., 2020), partly due to their current climatic-geometric disequilibrium (Mernild et al., 2015) and partly due to future climatic change. However, the role of glaciers in buffering river discharge at the basin scale during the megadrought has yet to be explored in detail.

Here we quantified glacier contributions to the discharge of the Maipo River, the main source of water to Santiago, for periods before (2000-2010) and during the current Chilean megadrought (2010-2018). We did this using a mass-conserving, data-driven approach using in-situ and remote datasets, on both annual and seasonal bases. Extending the approaches of Kaser et al. (2010) and Pritchard (2019), we focused in particular on the sustainability of the contributions, assessing how much water supply is potentially to be lost due to glacier retreat, and at what time of year, in what is predicted to be a drier future (Garreaud et al., 2020).

2 Study area

The Maipo River is the main source of water to the Santiago Metropolitan Region of central Chile, which has a population of around 7 million people (Government of Chile, 2017). It provides approximately 70% of the region's drinking water and 90% of the water that is needed for irrigation, as well as being essential to local hydropower generation and industrial activities (DGA, 2004). Secondary water sources to Santiago are groundwater and the Mapocho River to the north (Bonelli et al., 2014). Originating on the western side of the central Andes, the Maipo River is situated in one of 25 global biodiveristy hotspots (Myers et al., 2000), and helps support a wide variety of species that are endemic to the Chilean Mediterranean Zone (Figueroa et al., 2013).

For the purposes of this study, we define the basin of the Maipo River such that its outlet is at the Maipo El Manzano gauging station (Figure 1). As such, the basin covers an altitudinal range of 850 to 6570 m a.s.l, and has an area of 4840 km^2. Bare rock with sparse vegetation is the dominant land-surface type in the mountains, while valley bottoms support grasses, shrubs and small areas of native forest (mixed but mostly evergreen). Most of the basin becomes snow covered in winter. According to the Randolph Glacier Inventory 6.0 (RGI-Consortium, 2017), the basin has 325 glaciers, covering an area of 350 km^2. Fractional glacier coverage is 7.2%.

3 Methods

To calculate glacier contributions to river discharge before and during the megadrought, we compared river discharge data with glacier runoff estimates, which we derived from satellite-based glacier mass balances and a meteorological dataset we generated from in-situ meteorological and climate reanalysis data. We define the two study periods: before and during the megadrought, by hydrological year, where the hydrological year in

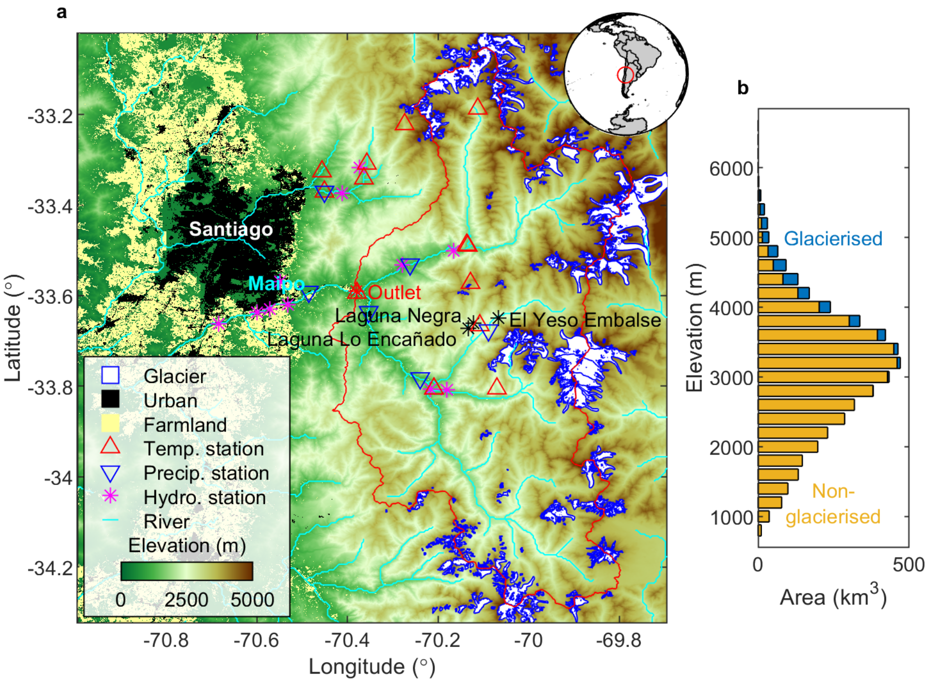

Figure 1. **The study area.** **a,** The basin of the Maipo River in central Chile. The basin is outlined in red. The outlet is the Maipo El Manzano gauging station. Major reservoirs are marked with black stars. Glacier outlines are from RGI-Consortium (2017), urban areas are from Marconcini et al. (2020), and farmland is from Thenkabail et al. (2021). Temperature and precipitation stations are from Alvarez-Garreton et al. (2018). The elevation model is from JAXA (2019). **b,** The basin's hypsometry.

the southern hemisphere begins on 1st April. As such, before the megadrought is 1st April 2000-31st March 2010 and during the megadrought is 1st April 2010-31st March 2018. The mathematical notation used in the following equations is given in the Notation section, but in particular we note that the subscripts $_{\mathrm{a}}$, $_{\mathrm{m}}$, $_{\mathrm{b}}$, and $_{\mathrm{g}}$ indicate annual, monthly, basin and glacier, respectively. We note also that comparing precipitation and river discharge for the period 2000-2010 with long-term precipitation and river discharge (1971-2000 and 1979-2000, respectively) shows that the 2000-2010 period is representative of 'normal' hydrological conditions (Supplementary Figure 7).

3.1 Meteorological data

We generated a daily 0.005° (approximately 500 m) meteorological dataset of air temperature and precipitation for the period 2000-2018 by temporally aggregating then statistically downscaling and bias correcting hourly ERA5-Land reanalysis data (Muñoz-Sabater, 2019; Muñoz-Sabater et al., 2021), using station data from Alvarez-Garreton et al. (2018). The temperature and precipitation stations we used are shown in Figure 1, while spatially distributed period averages of the two variables are shown in Figure 2 and Supplementary Figure 1. We performed the downscaling following the method proposed by Machguth et al. (2009) and the bias correction by empirical quantile mapping (e.g. Rye et al., 2010). To downscale precipitation, we used a constant altitudinal lapse rate of 0.18 mm yr^{-1} m^{-1} from the precipitation stations, while for air temperature we used daily altitudinal lapse rates from the reanalysis, the mean of which was -6.0 °C km^{-1} (Supplementary Figures 2-3). We computed air temperature and precipitation biases as the differences between the reanalysis and the station data for the 2000-2018 period, using 999 quantiles for each variable (Supplementary Figures 4-5). We then spatially interpolated those biases on a daily basis by inverse distance weighting. We temporally aggregated the temperature and precipitation data to daily resolution by taking the mean and sum of the hourly values respectively.

To correct the precipitation data from the stations for undercatch, we modified the approach of Masuda et al. (2019) and Yokoyama et al. (2003):

$$P = \frac{P_{\mathrm{obs}}}{CR} \tag{1}$$

where P is corrected precipitation (mm yr^{-1}), P_{obs} is observed precipitation (mm yr^{-1}) and CR is the catch ratio:

$$CR = \frac{1}{1 + mu + \lambda} \tag{2}$$

Here, m is a correction coefficient (0.0856 s m^{-1} for rain, 0.346 s m^{-1} for snow) for wind speed u (m s^{-1}), to account for wind-induced undercatch, and λ is a tuning parameter we added to account for undercatch induced by evaporation, wetting, splashing, missed and trace precipitation events and unrepresentative station locations. We calculated u from the reanalysis by aggregating from hourly to daily resolution, correcting from 10 m to 2 m above the surface using the logarithmic wind speed profile with a surface roughness length of 0.01 m (typical of bare soil Oke, 1987) and multiplying by 1.175 because precipitation typically falls during periods when wind speed is 15-20% higher than average (Sevruk, 1982). To determine whether precipitation fell as rain or snow, we followed the approaches of Yasutomi et al. (2011) and Matsuo et al. (1981), using the downscaled bias-corrected air temperature data, and relative humidity estimated from the reanalysis. That is, we assumed precipitation fell as snow if humidity and temperature were both relatively low, and as rain if humidity and temperature were relatively high. We tuned λ by minimising the residual of the mean annual water balance of the Maipo Basin $e_{\mathrm{a,b}}$ (mm yr^{-1}) for 2000-2018 (Supplementary Figure 6):

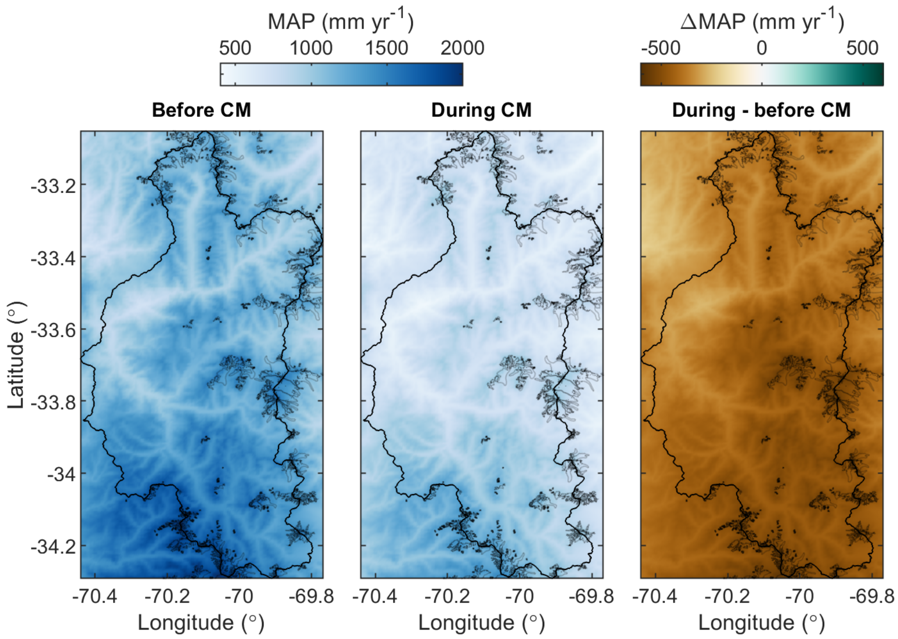

Figure 2. Mean annual precipitation (MAP) for the Maipo Basin at 0.005° spatial resolution, after downscaling and bias correction, for before (left) and during (middle) the current Chilean megadrought (CM). The rightmost panel shows the difference between the two periods. The basin is shown in black and the glaciers in grey.

$$\underset{\lambda}{\text{minimise}}\ |e_{\mathrm{a,b}}(\lambda)| \tag{3}$$

$$e_{\mathrm{a,b}} = P_{\mathrm{a,b}}(\lambda) - ET_{\mathrm{a,b}} - Q_{\mathrm{a,b}} - b_{\mathrm{a,b}} - \Delta S_{\mathrm{a,b}} \tag{4}$$

where $P_{\mathrm{a,b}}$ is mean annual precipitation over the basin (mm yr^{-1}) and $Q_{\mathrm{a,b}}$ is mean annual discharge from the basin (mm yr^{-1}), from Alvarez-Garreton et al. (2018). $ET_{\mathrm{a,b}}$ is mean annual evapotranspiration from the basin (mm yr^{-1}), which we estimated using ALEXI data for the period 2003-2016 from Hain and Anderson (2017), and $\Delta S_{\mathrm{a,b}}$ is mean annual change in water storage (mm yr^{-1}), which we assumed to be zero in the long term, because net storage change decreases as the integration period increases (Dingman, 2002), and the Maipo Basin has a relatively small storage capacity due to its steep slopes, shallow soil and largely impermeable basement rocks (Moreno & Gibbons, 2007). $b_{\mathrm{a,b}}$ (mm w.e. yr^{-1}) is the mean annual water-equivalent volume change of the basin's glaciers per basin area:

$$b_{\mathrm{a,b}} = \frac{\sum_{\mathrm{g}} b_{\mathrm{a,g}} A_{\mathrm{g}}}{A_{\mathrm{b}}} \tag{5}$$

where A_{g} is glacier area (m^2), A_{b} is basin area (m^2), and $b_{\mathrm{a,g}}$ is glacier-specific mean annual mass balance (mm w.e. yr^{-1}), which we calculated from the elevation difference dataset of Dussaillant et al. (2019):

$$b_{\mathrm{a,g}} = \Delta E_{\mathrm{a,g}} \frac{\rho_{\mathrm{i}}}{\rho_{\mathrm{w}}} \tag{6}$$

where $\Delta E_{\mathrm{a,g}}$ is glacier-specific mean annual elevation change (mm i.e. yr^{-1}), ρ_{i} is the density of glacier ice (850 kg m^{-3}) following Huss (2013), and ρ_{w} is the density of water (1000 kg m^{-3}). The value of λ that satisfied the water balance for 2000-2018 was 0.33, while catch ratios at the individual stations ranged from 0.67 to 0.71 (29% to 33% undercatch).

Using this approach, the meteorological dataset is informed by station observations and simultaneously solves the basin's water balance (Supplementary Figure 7). Importantly, we found that the main results of our study do not change if we calibrate λ instead for the periods 2000-2010 or 2010-2018 (Supplementary Figure 8). We take this as an indication of the robustness of our approach. However, we also note that there is uncertainty in each of the terms of the water balance, which we account for implicitly in the uncertainty assigned to precipitation, as described below.

Supplementary Figure 9 shows monthly discharge from the Maipo Basin in the period 2000-2018 (Alvarez-Garreton et al., 2018), average precipitation from our meteorological dataset in the same period, and annual glacier mass balances before and during the megadrought (Dussaillant et al., 2019).

3.2 Glacier contributions to discharge

For periods both before and during the megadrought, we calculated mean annual contributions of glacier ablation (Figure 4) to basin discharge $C_{\mathrm{a,b}}$ (%) as:

$$C_{\mathrm{a,b}} = \frac{a_{\mathrm{a,b}}}{Q_{\mathrm{a,b}}} \tag{7}$$

where $a_{\mathrm{a,b}}$ (mm w.e. yr^{-1}) is mean annual glacier ablation per basin area, assuming that as runoff leaves each glacier, it goes directly into a proglacial stream, and that evaporation and infiltration losses from there to the outlet, from rivers and lakes, are minimal (e.g. Huss & Hock, 2018), due to the minimal surface area of these features, the short transit times of the water they contain (0.74 days; see below), and the basin's low permeability geology. We calculated $a_{\mathrm{a,b}}$ as the difference between mean annual on-glacier solid precipitation per basin area $c_{\mathrm{a,b}}$ and $b_{\mathrm{a,b}}$:

$$a_{\mathrm{a,b}} = c_{\mathrm{a,b}} - b_{\mathrm{a,b}} \tag{8}$$

where:

$$c_{\mathrm{a,b}} = \frac{\sum_{\mathrm{g}} c_{\mathrm{a,g}} A_{\mathrm{g}}}{A_{\mathrm{b}}} \tag{9}$$

and $c_{\mathrm{a,g}}$ is mean annual on-glacier solid precipitation (averaged over the area of each glacier).

In order to assess the sustainability of these contributions, we define balance ablation, $\min(c_{\mathrm{a,g}} - b_{\mathrm{a,g}}, c_{\mathrm{a,g}})$, as ablation that is balanced over the domain of each glacier on a multi-annual basis by snowfall, and is therefore sustainable in the current climate, and imbalance ablation, $\max(0, -b_{\mathrm{a,g}})$, as that which is not balanced by snowfall, and is therefore unsustainable (e.g. Pritchard, 2019; Miles et al., 2021). Another way to conceptualise this is that unsustainable imbalance ablation is the portion of ablation that would not exist if the glaciers did not exist; a useful concept because it allows the hydrological importance of glaciers to be quantified independent of seasonal snow. Since some glaciers in the Maipo Basin gained mass in the early 21st century (Dussaillant et al., 2019), we apply the same logic to partition balance and imbalance accumulation such that balance accumulation is accumulation that is balanced by ablation (equal to balance ablation), and imbalance accumulation, $\max(0, b_{\mathrm{a,g}})$, is that which is not balanced by ablation. According to this convention, imbalance ablation can occur only for glaciers that are losing mass and imbalance accumulation only for glaciers that are gaining mass. Imbalance ablation contributes to runoff and river discharge, while imbalance accumulation does not. These concepts are explained schematically in Figure 3.

We calculated mean monthly contributions of glacier ablation to discharge $C_{\mathrm{m,b}}$ (%) according to:

$$C_{\mathrm{m,b}} = \frac{a_{\mathrm{m,b}}}{Q_{\mathrm{m,b}}} \tag{10}$$

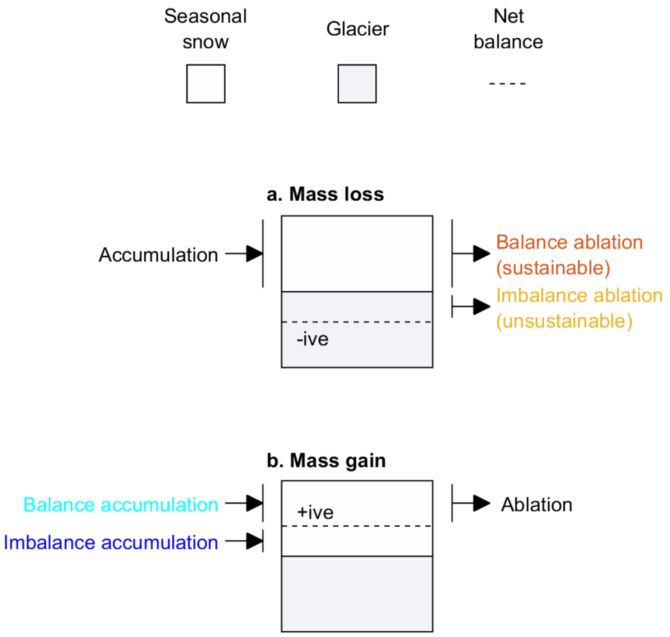

Figure 3. Schematic describing key terminology used in the study. a, For glaciers that are losing mass, balance ablation equals accumulation; imbalance ablation is unsustainable. -ive is negative. **b,** For glaciers that are gaining mass, balance accumulation equals ablation. +ive is positive. The directions of the arrows indicate mass going into and coming out of the glacier-snow system.

where $a_{\mathrm{m,b}}$ is mean monthly glacier ablation per basin area (mm w.e. mo^{-1}) and $Q_{\mathrm{m,b}}$ is mean monthly discharge per basin area (mm mo^{-1}). Here:

$$a_{\mathrm{m,b}} = \frac{\sum_{\mathrm{g}} a_{\mathrm{m,g}} A_{\mathrm{g}}}{A_{\mathrm{b}}} \tag{11}$$

where we calculated $a_{\mathrm{m,g}}$, mean monthly ablation per glacier (mm w.e. mo^{-1}), following Kaser et al. (2010) and Pritchard (2019), according to:

$$a_{\mathrm{m,g}} = (c_{\mathrm{a,g}} - b_{\mathrm{a,g}}) \frac{\phi_{\mathrm{m,g}}}{\phi_{\mathrm{a,g}}} \tag{12}$$

Here, $\phi_{\mathrm{m,g}}$ is mean monthly positive degree day (PDD) sum and $\phi_{\mathrm{a,g}}$ is mean annual PDD sum. This way, ablation was attributed to the warmest months of the year proportionally to how warm those months were compared to others. For each glacier, we calculated mean monthly and annual PDD sums at the terminus, using the air temperature data.

Monthly ablation per glacier comprises i) seasonally-delayed ablation, $\max(0, a_{\mathrm{m,g}} - c_{\mathrm{m,g}})$, which is the ablation during warm months later in the year of snow fallen during cold months earlier in the year; and ii) ablation of freshly fallen snow, which happens instantly in the warm months of the year, $a_{\mathrm{m,g}} - \max(0, a_{\mathrm{m,g}} - c_{\mathrm{m,g}})$. Monthly accumulation per glacier comprises i) seasonally-stored accumulation, $\max(0, c_{\mathrm{m,g}} - a_{\mathrm{m,g}})$, which is snow fallen during cold months of the year, and which is later melted; and ii) snow fallen during warm months of the year, and which melts instantly (equal to ii) above).

Extending the methods of Kaser et al. (2010) and Pritchard (2019), we asserted that on a monthly basis, imbalance ablation must occur at the end of the ablation season, after all the on-glacier seasonal snow has melted. As such, we assigned imbalance ablation from the geodetic mass balances to the end of the period during which seasonally-delayed ablation occurred (Figure 5). The corollary to this is that imbalance accumulation must occur at the beginning of the accumulation season; young snow at the top of the snowpack must melt first at the beginning of the ablation season, while old snow at the bottom of the snowpack must melt last at the end of the ablation season, and any unmelted snow must be from the very beginning of the accumulation season. We therefore assigned imbalance accumulation from the geodetic mass balances to the beginning of the period during which seasonally-stored accumulation occurred. We made these assignments numerically such that mass was conserved.

As in those previous studies, we note that there is no initial condition to be imposed on the variables of the monthly glacier mass balance equations. Seasonally-delayed and monthly imbalance ablation, as well as seasonally-stored and monthly imbalance accumulation, are 'forced' retrospectively, and can therefore only be estimated in hindcast. Further, glaciers are treated in a simplified way, in that their mass balances and the runoff they generate vary in time but not in space. As such, the method we use here is suited to providing estimates of the importance of glacier runoff for water availability at the basin scale and over long time periods, rather than providing mechanistic insights at the local scale and over short time periods (Kaser et al., 2010; Pritchard, 2019). Sublimation, which can be a considerable mechanism of mass loss from glaciers in central Chile (Ayala et al., 2017), is not accounted for.

To calculate imbalance ablation contributions to discharge, we used Equations 7 and 10, replacing $a_{\mathrm{a,b}}$ and $a_{\mathrm{m,b}}$ with annual and monthly imbalance ablation respectively.

Following Van Nieuwenhuyse (2005) and Huss and Hock (2018), we estimated the transit time of glacier runoff to the basin outlet as a function of basin area, mean river discharge and slope, finding a value of 0.74 days. As this is only a small fraction of a month, we considered its impact on our calculations of monthly glacier contributions to discharge to be negligible.

3.3 Uncertainties

We considered uncertainties in glacier contributions to discharge to derive primarily from uncertainties in the precipitation, discharge, and mass balance data, which we consider to be independent of one another.

As such, we quantified uncertainty in $C_{\mathrm{a,b}}$ according to:

$$\sigma_{C_{\mathrm{a,b}}} = C_{\mathrm{a,b}}\sqrt{\left(\frac{\sigma_{a_{\mathrm{a,b}}}}{a_{\mathrm{a,b}}}\right)^2 + \left(\frac{\sigma_{Q_{\mathrm{a,b}}}}{Q_{\mathrm{a,b}}}\right)^2} \tag{13}$$

where we estimated the relative uncertainty in mean annual discharge to be 15% (McMillan et al., 2012), and where:

$$\sigma_{a_{\mathrm{a,b}}} = \sqrt{\sigma^2_{c_{\mathrm{a,b}}} + \sigma^2_{b_{\mathrm{a,b}}}} \tag{14}$$

Here, we estimated the relative uncertainty in $c_{\mathrm{a,b}}$ to be 40% (McMillan et al., 2012; Pritchard, 2019), so $\sigma_{c_{\mathrm{a,b}}} = 0.4c_{\mathrm{a,b}}$, and the relative uncertainty in $b_{\mathrm{a,b}}$ to be 60% (Dussaillant et al., 2019), so $\sigma_{b_{\mathrm{a,b}}} = 0.6b_{\mathrm{a,b}}$.

We quantified uncertainty in $C_{\mathrm{m,b}}$ according to:

$$\sigma_{C_{\mathrm{m,b}}} = C_{\mathrm{m,b}}\sqrt{\left(\frac{\sigma_{a_{\mathrm{m,b}}}}{a_{\mathrm{m,b}}}\right)^2 + \left(\frac{\sigma_{Q_{\mathrm{m,b}}}}{Q_{\mathrm{m,b}}}\right)^2} \tag{15}$$

where we assumed the relative uncertainties in $a_{\mathrm{m,b}}$ and $Q_{\mathrm{m,b}}$ to be equal to the relative uncertainties in $a_{\mathrm{a,b}}$ and $Q_{\mathrm{a,b}}$, respectively.

We quantified uncertainties in the contribution of imbalance ablation to discharge using Equations 13 and 15, replacing relative uncertainties in $a_{\mathrm{a,b}}$ and $a_{\mathrm{m,b}}$, with relative uncertainties in basin-scale mean annual and mean monthly imbalance ablation, respectively, assuming the latter two to have the same relative uncertainty as $b_{\mathrm{a,b}}$ (i.e. 50%).

4 Results and discussion

4.1 Annual glacier contributions to discharge

On an annual basis, our calculations show that the glaciers of the Maipo Basin generated slightly less runoff during the megadrought than before, but became considerably more important as a source of water to the Maipo River (Figure 4c). Mean annual runoff from glacier ablation at the basin scale decreased from 90 ± 39 mm yr^{-1} to 81 ± 28 mm yr^{-1}, probably due to lower air temperatures. However, the mean annual contribution of glacier ablation to discharge at the Maipo El Manzano outlet increased relatively, from 11 ± 5% to 16 ± 6%, primarily due to a large decrease in discharge from the basin, from 830 ± 120 mm yr^{-1} to 520 ± 80 mm yr^{-1}. For comparison, (Ayala et al., 2020) reported a mean annual glacier contribution to discharge of 16 ± 7% for 1955-2016 based on 1955 glacier areas (which are 35 ± 5% larger than today's glacier areas) and 17% for 2010-2016, also based on 1955 glacier areas.

Importantly, imbalance ablation increased greatly as a fraction of total glacier ablation, from 3.2% to 24% (Figure 4b), so ablation was much less sustainable during the megadrought than it was before (i.e. much less melt was being balanced by snowfall). Indeed, imbalance ablation generated more runoff during the megadrought and became a more important source of water. Mean annual runoff from imbalance ablation increased from 2.9 ± 1.7 mm yr^{-1} to 19 ± 12 mm yr^{-1}, while the mean annual contribution of imbalance glacier ablation to discharge increased from 0.35 ± 0.22% to 3.7 ± 2.3%.

On average, the basin's glaciers underwent a net mass gain before the megadrought and a net mass loss during (Figure 4a) (Dussaillant et al., 2019), indicating that the megadrought

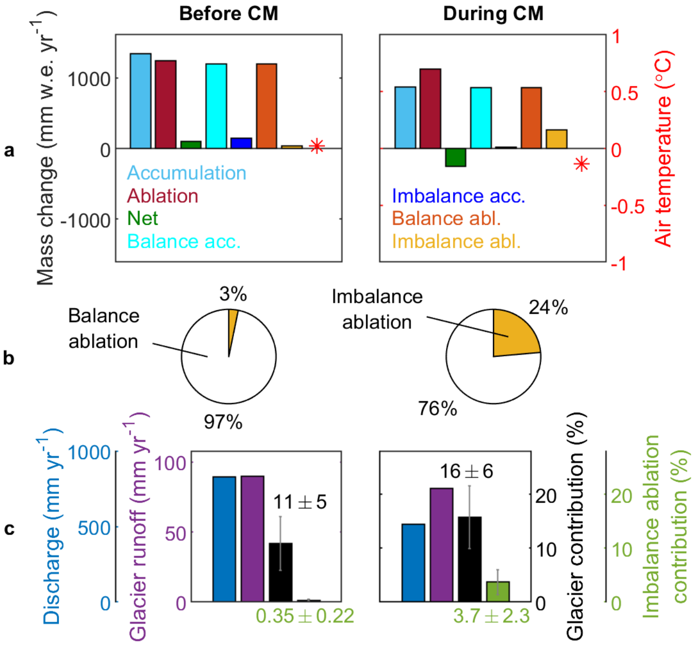

Figure 4. Annual glacier contributions to the discharge of the Maipo River before and during the current Chilean megadrought (CM). a, Annual water-equivalent volume changes per glacier area of glaciers in the Maipo Basin, and mean annual air temperatures at glacier terminuses (red asterisk). **b,** Percentages of total ablation that are balanced or not by accumulation. **c,** Mean annual discharge and glacier runoff volumes per basin area at the Maipo El Manzano outlet, and relative contributions of glacier and imbalance ablation to mean annual discharge.

is depleting the region's glaciers. This transition was accompanied by a slight decrease in mean air temperature at glacier terminuses, from 0.02 to -0.14 C, and a large decrease in solid on-glacier precipitation, from 1340 ± 540 mm yr^{-1} to 870 ± 350 mm yr^{-1}, indicating that changes in snowfall during the megadrought, rather than changes in temperature, have driven glacier mass loss. However, there was considerable variability between glaciers—something that is demonstrated by the fact that both imbalance accumulation and imbalance ablation occurred in both periods.

Analysis of the basin's water balance (Supplementary Figure 7) demonstrates that mean annual discharge was closely related to mean annual precipitation during the two periods. However, while the mean annual precipitation deficit was 34%, the discharge deficit was slightly greater at 38%. Further, it is interesting to note that based on the ALEXI data, mean annual evapotranspiration from the basin increased from 370 mm yr^{-1} before the megadrought to 400 mm yr^{-1} during, and that the phase of precipitation falling in the basin remained relatively constant, from a snowfall fraction of 71% to 72%.

4.2 Seasonal glacier contributions to discharge

On a monthly basis, glaciers have clearly been an important water source to the Maipo River in summer, and were particularly important in summer during the megadrought (Figure 5e and f). Both before and during the megadrought, glacier runoff was highest, on average, from January to March, while discharge was highest from November to January. However, mean monthly discharge was markedly lower in summer during the megadrought than before, while glacier runoff was relatively similar. Discharge peaked at 140 ± 20 mm mo^{-1} before and 71 ± 11 mm mo^{-1} during the megadrought, while glacier runoff peaked at 20 ± 9 mm mo^{-1} before and 20 ± 6 mm mo^{-1} during the megadrought. As a result, glacier contribution to discharge peaked in March in both periods, but at 29 ± 14% before the megadrought and 43 ± 16% during. Ayala et al. (2020) report a maximum summer glacier contribution to discharge during 1955-2016 of 59 ± 23% and an average of 55% from 2010-2016 based on the larger 1955 glacier areas.

Strikingly, glacier ablation was predominantly unsustainable in March during the megadrought, after all the on-glacier seasonal snow had melted, when imbalance ablation reached a maximum of 73% of the total (Figure 5d). Before the megadrought, a maximum value of 19% was reached slightly later, in April, likely because there was more snow on the glaciers in early to mid summer. Because discharge is typically quite low by the end of summer—42 ± 6 mm mo^{-1} in April before the megadrought and 40 ± 6 mm mo^{-1} in March during—the contributions of imbalance ablation to discharge peaked at and around these times. Specifically, mean monthly runoff from imbalance ablation increased from a peak value of 1.6 ± 0.7 mm mo^{-1} in April to 13 ± 4 mm mo^{-1} in March, while the mean monthly contribution of imbalance glacier ablation to discharge increased from a peak of 3.8 ± 2.3% to 31 ± 19% in the same months. That is, imbalance ablation strongly buffered late-summer river discharge.

The seasonality of the mass changes of the region's glaciers is shown in Figures 5b and c. Net mass change was positive, on average, from mid-April to mid-October in both periods. However, peak accumulation was considerably lower during the megadrought, at 170 ± 70 mm mo^{-1} in June, than before, at 350 ± 140 mm mo^{-1} in June, as was peak imbalance accumulation, at 7.6 ± 3 mm mo^{-1} during and 81 ± 33 mm mo^{-1} before the megadrought. Ablation-season air temperature was slightly lower during the megadrought (Figure 5a), which may partly explain why runoff was slightly lower in this season, while precipitation phase remained very similar between the two periods in both ablation and accumulation seasons.

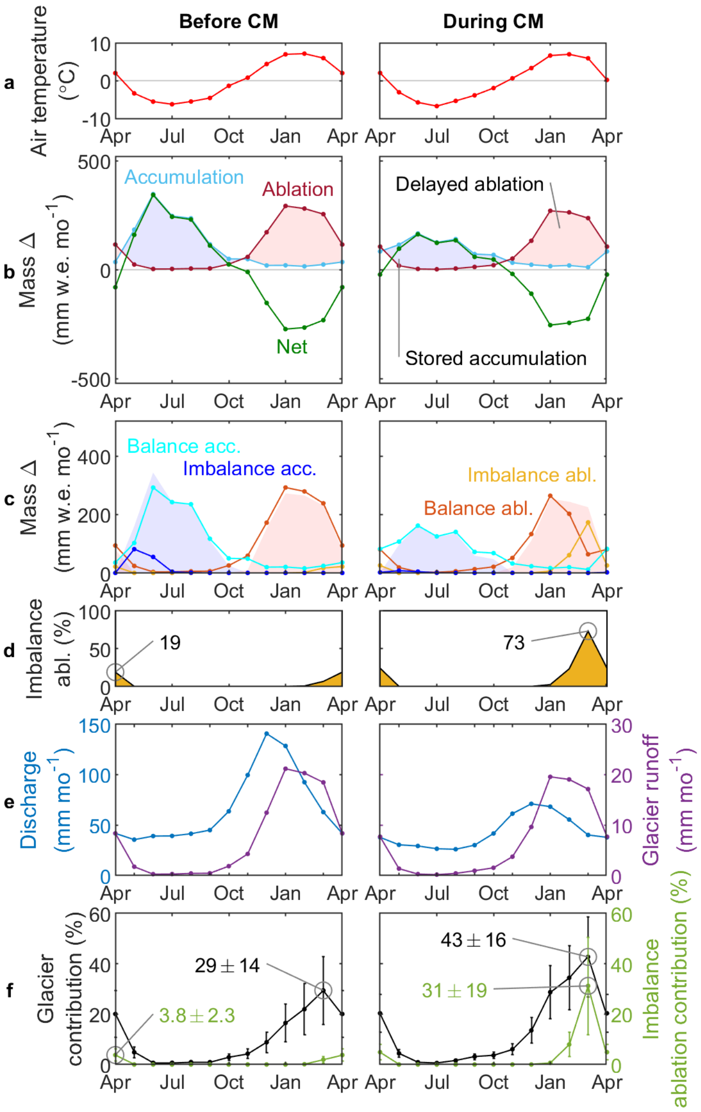

Figure 5. Seasonal glacier contributions to the discharge of the Maipo River before and during the current Chilean megadrought (CM). a, Mean monthly air temperatures at glacier terminuses. **b,** Mean monthly water-equivalent volume changes per glacier area of glaciers in the Maipo Basin, showing accumulation, ablation and net mass balance. **c,** Mean monthly water-equivalent volume changes per glacier area of glaciers in the Maipo Basin, showing balance and imbalance components of ablation and accumulation. **d,** Percentages of total ablation that are balanced or not by accumulation. **e,** Mean monthly discharge and glacier runoff volumes per basin area at the Maipo El Manzano outlet. **f,** Relative contributions of glacier and imbalance ablation to mean monthly discharge.

4.3 Implications for water availability in a changing climate

By partitioning glacier ablation into balance and imbalance components, we can estimate what the discharge of the Maipo River would have been during the megadrought if there had been no glaciers. In such a hypothetical situation, balance ablation would still have occurred, but simply as snowmelt, while imbalance ablation would not have occurred at all. That is, discharge without glaciers can be approximated as discharge with glaciers minus imbalance ablation, which can be thought of as a 'deglaciation discharge dividend' (Collins, 2008). As such, our results indicate that on an annual basis, discharge would have been 3.7 ± 2.3% less during the megadrought if there had been no glaciers (Figure 4), while on a monthly basis, it would have been 31 ± 19% less during March (Figure 5). Discharge deficits would have been considerably greater in late summer (Figure 6b), and 50% greater, on average, in March (Figure 6c). This perspective is useful for considering the possible impacts on the Maipo River, and therefore on water supply to Santiago, of a drier future, given that precipitation in central Chile is expected to see only partial recovery in the coming decades (Garreaud et al., 2020), and that glacier retreat will be rapid (Huss et al., 2017). Indeed, projected drying in central Chile is 3-30% against the 1976-2005 mean (Bozkurt et al., 2018), with precipitation reductions (especially in winter) a robust result amongst general circulation models (Hodnebrog et al., 2022; Zazulie et al., 2018), while glaciers in the sub-tropical Andes are projected to lose 80 ± 10% of their current ice volume by 2100 under RCP 4.5 (Huss et al., 2017). Importantly, because peak water from the region's glaciers is thought already to have passed (Huss & Hock, 2018; Ragettli et al., 2016), our results suggest that glacier retreat in a warming climate (e.g. Bocchiola et al., 2018) will exacerbate future discharge deficits, especially in late summer, as present-day imbalance ablation will be substantially reduced as a buffer.

On an annual basis, the contributions of glacier ablation to river discharge were small compared to those from precipitation in both the before and during megadrought periods (Figure 4c). Precipitation, including off-glacier snowmelt, contributed 8.2 times more to the discharge of the Maipo River than total glacier ablation before the megadrought and 5.4 times more during. Further, it contributed 290 times and 26 times more than imbalance glacier ablation. However, because central Chile has been experiencing high water stress (Gassert et al., 2013; Biancalani & Marinelli, 2021), even these relatively small contributions have been important components of total water supply, and this was especially true during the megadrought. For example, Figure 6a shows that between 2010 and 2018, imbalance ablation contributed a sum total of 740 × 10^6 m^3 of water to the Maipo River (93 × 10^6 m^3 yr^{-1}, or 19 ± 12 mm yr^{-1}), equivalent to 14% of the potable water use of the Santiago Metropolitan Region during that time, given a potable water use of 670 × 10^6 m^3 (DGA, 2017), or 5% of total consumption, given a consumptive water use of 2100 × 10^6 m^3 yr^{-1} (DGA, 2017). Total ablation contributed 3100 × 10^6 m^3 during the megadrought, equivalent to 59% of potable water use, and 19% of total. Moreover, these glacier contributions to river discharge are comparable in volume on decadal timescales to the capacities of the region's three major reservoirs (Figure 6a), and supply enough water from January through March to sustain environmental flows (Supplementary Figure 10; DGA, 2008; Alvarez-Garreton et al., 2022).

Compensating for the impacts of glacier retreat on water availability in a drier future in central Chile will not be straightforward. To some extent, it will be possible to offset changes in the seasonality of downstream river discharge by increasing reservoir capacity, and indeed the Chilean government plans to build 26 new reservoirs over the whole of Chile over the coming decades (Government of Chile, 2019). However, it is clear that this will not help protect vulnerable upstream ecosystems from reduced baseflow (Miller et al., 2021), and that reservoirs cannot replace present-day deglaciation discharge dividends from imbalance ablation (e.g. Farinotti et al., 2016). To deal with the latter of these issues, the region will instead have to change its water demand—which will be

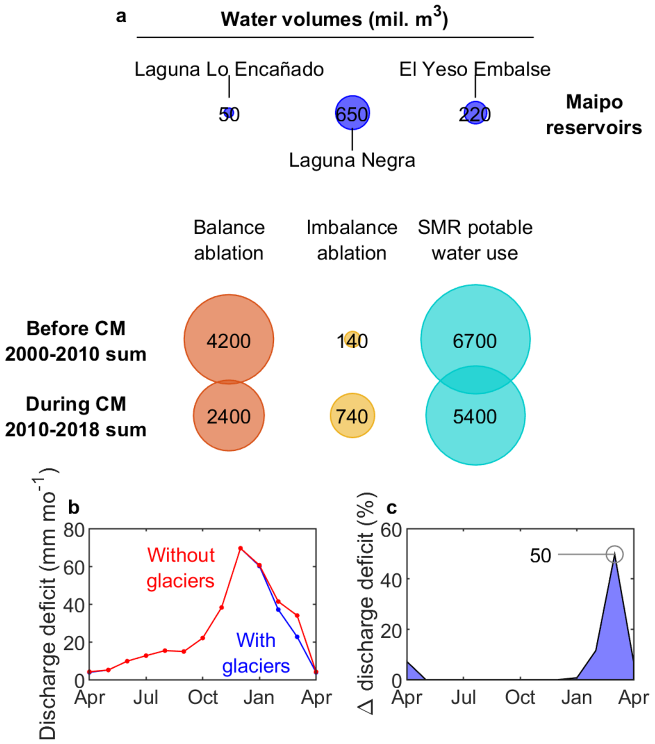

Figure 6. The importance of glacier runoff as a source of water. a, Water volumes of Maipo Basin reservoirs at full capacity, balance and imbalance ablation sums for the before and during the current Chilean megadrought (CM) periods, and the potable water use of the Santiago Metropolitan Region (SMR) in these periods. **b**, Comparison of the discharge deficits between before and during megadrought periods in the real world, with glaciers, and in a hypothetical world, without glaciers (i.e. without imbalance ablation). **c** The relative difference between the with and without glaciers curves of panel b.

challenging if Chile's economic growth rate over recent decades (IMF, 2021) continues—or rely increasingly on i) water trucks bringing water from elsewhere, which is already common (CR2, 2015) ii) desalination of seawater from the coast, or iii) inter-basin water transfers from regions with lower water stress, all of which are associated with considerable financial cost and environmental problems (e.g. Herrera-Leon et al., 2019).

While we are able to assess in this study the hydrological role of glaciers in central Chile during the megadrought, and make inferences about how glaciers have affected, and will affect, water availability in the region, many questions remain as to how the megadrought has affected water availability more broadly, and how water availability in the region might change in the future. For example, recent research has suggested that reduced snow cover has resulted in a decrease in groundwater recharge during the megadrought, via a decrease in infiltration (Alvarez-Garreton et al., 2021). Yet it is unclear how snow cover changes have affected evapotranspiration, and whether vegetation response to the megadrought, via evapotranspiration, has acted to increase or reduce discharge deficits (e.g. Berghuijs et al., 2014; Mastrotheodoros et al., 2020). Indeed, our solution of the water balance for the Maipo Basin suggests evapotranspiration may have increased, and may therefore be increasing discharge deficits, albeit with considerable uncertainty (Supplementary Figure 7). Further, it is unclear how runoff generation has changed over short spatial and temporal scales within river basins, and what the hydrological origin of water has been at points of human and ecosystem use (e.g. Buytaert et al., 2017). To understand future water availability, these questions need to be asked in a context of increasing air temperatures and changing precipitation phase. We expect that progress in these directions will be made using physical hydrological or land-surface models that are able to simulate feedbacks among hydrological and vegetation processes (Fatichi, Pappas, & Ivanov, 2016), and are less susceptible than conceptual models to problems associated with climatic non-stationarity (Fatichi, Vivoni, et al., 2016).

5 Conclusions

In this article, we show that glaciers have been a reliable source of surface water for central Chile since the beginning of the century. They store water as snow during winter and release it as runoff to rivers during summer, when it is most needed downstream because precipitation is scarce. However, while sustainable balance ablation dominated the contributions of glacier runoff to river discharge before the current Chilean megadrought, unsustainable imbalance ablation comprised a considerable fraction of river discharge during the megadrought, especially in late summer (March, April). This shift of the region's glaciers towards a regime of less sustainable ablation was caused by the precipitation deficits that have characterised the megadrought, i.e. by reduced accumulation due to reduced snowfall, instead of by increased ablation, and is likely to be maintained in concomitance with the precipitation deficits that are predicted for the coming decades. While glacier runoff decreased slightly during the megadrought, fractional glacier contribution to river discharge increased relatively by more.

The implications of our results for water availability in central Chile, in what is likely to be a drier future, are threefold. Firstly, glacier retreat will exacerbate river discharge deficits caused by precipitation deficits, especially in late summer. Secondly, river discharge deficits due to glacier retreat could be of societally relevant magnitudes, and, for example, similar in magnitude on multi-annual timescales to water volumes held in existing water-storage infrastructure. Thirdly, compensating for the impacts of glacier retreat on river discharge would have to include not only increases in reservoir capacity, but also reduced water demand and/or increased water supply from other sources or locations, e.g. via water trucks, desalination at the coast, or inter-basin transfers. Importantly, these mitigation strategies are not necessarily financially or environmentally desirable, and will not protect dependent upstream alpine ecosystems from reduced baseflow. To build a picture of how the megadrought has affected water availability in the region more broadly, and how water availability might change in the coming decades, future work should assess changes in water supply, relative to changes in water demand and accessibility, using physically-based land-surface models.

Notation

$\boldsymbol{c}$	Accumulation
$\boldsymbol{a}$	Ablation
$\boldsymbol{b}$	Mass balance
$\boldsymbol{P}$	Precipitation
$\boldsymbol{ET}$	Evapotranspiration
$\boldsymbol{Q}$	River discharge
$\boldsymbol{S}$	Water storage
$\boldsymbol{e}$	Water balance residual
$\boldsymbol{\phi}$	Positive degree day sum
$\boldsymbol{A}$	Area
$\boldsymbol{C}$	Glacier contribution to discharge
$\boldsymbol{u}$	Wind speed
$\boldsymbol{CR}$	Precipitation catch ratio
$_{\mathbf{g}}$	Glacier
$_{\mathbf{b}}$	Basin
$_{\mathbf{a}}$	Mean annual
$_{\mathbf{m}}$	Mean monthly
$_{\mathbf{i}}$	Ice
$_{\mathbf{w}}$	Water
$_{\mathbf{obs}}$	Observed
$\boldsymbol{m}$	Undercatch correction parameter
$\boldsymbol{\lambda}$	Undercatch tuning parameter

Data availability

The ERA5-Land data are available from the Climate Data Store via `https://doi.org/10.24381/cds.e2161bac` (Muñoz-Sabater et al., 2021). The in-situ temperature data are available from CR2 via `https://www.cr2.cl/datos-de-temperatura/` (Alvarez-Garreton et al., 2018). The in-situ precipitation data are available from CR2 via `https://www.cr2.cl/datos-de-precipitacion/` (Alvarez-Garreton et al., 2018). The in-situ river discharge data are available from CR2 via `https://www.cr2.cl/datos-de-caudales/` (Alvarez-Garreton et al., 2018). The glacier elevation change data are available from PANGAEA via `https://doi.pangaea.de/10.1594/PANGAEA.903618` (Dussaillant et al., 2019). The glacier outline data are available from the National Snow and Ice Data Center via `https://doi.org/10.7265/4m1f-gd79` (RGI-Consortium, 2017). All processed data, including the downscaled temperature and precipitation data and derivative ALEXI evapotranspiration data for the study area (Hain & Anderson, 2017), along with the MATLAB scripts used to produce the main results of the study, and the main results themselves, are available from Zenodo via `https://doi.org/10.5281/zenodo.7034647`.

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