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Hydrological response of a headwater catchment in the semi-arid Andes (30°S) to climate change

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ABSTRACT

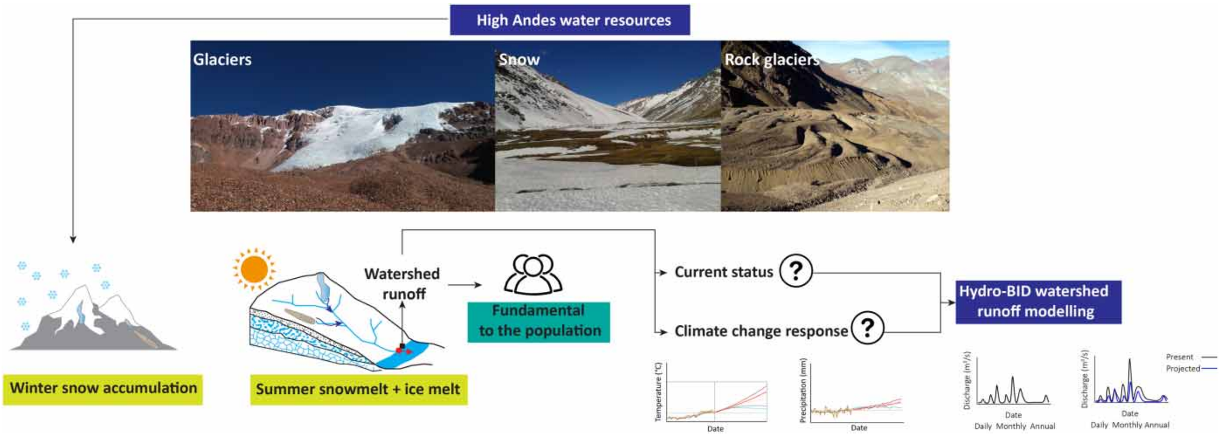
Globally, climate change has caused a significant reduction in snow cover in mountainous regions. To understand the impact of present and future snow changes on runoff in the semi-arid Andes, we applied the Hydro-BID hydrological model and associated datasets to the headwaters of the Elqui River basin (30°S) for current conditions and two Shared Socioeconomic Pathway (SSP) scenarios. Results show that model calibration at daily, monthly and annual time scales (R^2 0.7, 0.7 and 0.8) and validation (R2 0.6, 0.7 and 0.7) were satisfactory. Future climate change scenario SSP2-4.5 indicates for 2040–2059, 2060–2079 and 2080–2099 temperature increases of 1.2, 1.6 and 1.9 °C and precipitation reductions of 26, 29 and 36%. Discharge for SSP2-4.5 will reduce (the average annual flow decreases by 54, 58 and 66%). For the same periods, SSP5-8.5 projects temperature increases of 1.5, 2.6 and 3.7 °C and precipitation reductions of 28, 39 and 44%. Compared to SSP2-4.5, river discharge will experience a more acute reduction (projected annual decrease of 57, 70 and 77%). Model results indicate that the maximum flow will be reached 3 months earlier than today. Results reinforce the importance of snow for runoff in the semi-arid Andes and the applicability of Hydro-BID in mountainous regions.

Key words: cryosphere, Hydro-BID, hydrology modelling, mountain hydrology, snow, water resource

HIGHLIGHTS

- Snow is the main driver of streamflow in a semi-arid Andean catchment.
- Discharge will decrease by 50–77% under SSP2-4.5 and SSP2-8.5 in Elqui River (30°S).
- The Hydro-BID model for the Latin America and Caribbean hydrological database is suitable for use in mountain catchments.
- Understanding the precipitation dynamics and change in upper headwaters is imperative for hydrological management in the Andes.

GRAPHICAL ABSTRACT



INTRODUCTION

In many arid and semi-arid mountainous regions, the cryosphere is an important hydrological source (Jansson *et al.* 2003; Viviroli *et al.* 2011; Jones *et al.* 2018), in that the resultant meltwater can represent between 50 and 95% of the total streamflow during the summer (Viviroli & Weingartner 2004). This contribution is essential to meet the demand of ∼1.9 billion people that live in these regions, as well as the local ecosystems and other economic interests (Mills-Novoa *et al.* 2017; Immerzeel *et al.* 2020; Kellner & Brunner 2020; Viviroli *et al.* 2020). However, in the periods 1980–2018, air temperatures in mountain chains increased by ∼0.4 °C per decade (Yao *et al.* 2022), which has altered the timing, amount and type of winter precipitation as well as melt, thereby directly impacting streamflow resulting from glaciers and snow accumulation (Barnett *et al.* 2005; Immerzeel *et al.* 2010; Huss *et al.* 2017). Globally, most glaciers are experiencing accelerated retreat and permafrost degradation has progressively increased (Milner *et al.* 2017; Biskaborn *et al.* 2019; Zemp *et al.* 2019; Dimri *et al.* 2021). Added to this is the impact of changing land use on the quality and quantity of available water (e.g. Wamucii *et al.* 2021). The combination of these processes directly affects all sectors of primary industry, especially agriculture and horticulture, and has caused an increase in food availability concern both for the present and future (Mancosu *et al.* 2015; Qin *et al.* 2020).

As changes are occurring relatively rapidly, there is a need to use a range of tools to project possible outcomes that allow for the differences of data availability and process understanding across the globe (Clark *et al.* 2016). For instance, while modelling is a practical tool to study the hydrological processes of basins (Ragettli *et al.* 2016), glacio-hydrological simulation has become a major challenge. This is due to difficulties in installing and maintaining hydrometeorological and glaciological monitoring networks in isolated regions (Pellicciotti *et al.* 2012; Ragettli *et al.* 2014, 2016; Masiokas *et al.* 2020). Another factor is the difficulty of accurately representing spatial and temporal variability of hydrological processes (Ruelland *et al.* 2011; Ragettli *et al.* 2014; Scaff *et al.* 2017), which means that often models do not reproduce hydrological processes with a significant degree of realism (Dussaillant *et al.* 2012; Pellicciotti *et al.* 2012). These challenges have generally limited the understanding of the physical processes that control runoff generation in mountainous areas (Hewitt 2011; Stehr & Aguayo 2017).

For the semi-arid Andes, several studies have focused on melting and sublimation of glaciers (e.g. MacDonell *et al.* 2013; Ayala *et al.* 2016) and snow (e.g. Gascoin *et al.* 2013; Réveillet *et al.* 2020), with few considering the hydrological implications of these processes (Stehr *et al.* 2009; Ragettli *et al.* 2014; Omani *et al.* 2017; Navarro *et al.* 2023a). These studies have been instrumental in understanding specific controls on climate-cryosphere interactions, but of limited value for both quantifying streamflow expected downstream at present and into the future.

Some applications of hydrological models developed for the semi-arid Andes have tried to reproduce and project runoff behaviour (e.g. Araya & Hunt 2003; Trigos & Munizaga 2006; Souvignet *et al.* 2008; Ruelland *et al.* 2011; Hublart *et al.* 2013, 2014, 2015). However, some of the corresponding results have a significant degree of uncertainty, in some instances due to not considering the influence of accumulated snow in winter (e.g. Araya & Hunt 2003) or by only using a limited time period (e.g. Trigos & Munizaga 2006; Souvignet *et al.* 2008). On the other hand, hydrological models that have considered the effect of snow and a broader temporal range (~30 years), have managed to reproduce and project flows with a significant degree of realism (e.g. Ruelland *et al.* 2011; Hublart *et al.* 2014) and have made it possible to visualise the influence of snow on groundwater table dynamics (Ruelland *et al.* 2011). Undoubtedly, the contribution made by these works has had a significant impact on the knowledge and characterisation of runoff in their studied basins. However, these studies have not considered recent hydroclimatic variability, including the mega-drought of the last 13 years.

As long-term meteorological and hydrological datasets are largely absent from this region, and impacts of extreme weather events largely ignored, it is necessary to consider flexible alternatives to model water availability that can be used to develop water management plans that are widely applicable (Delpla *et al.* 2009; Beniston *et al.* 2011; Hill 2013). It is with these considerations in mind that the Inter-American Development Bank (IDB, or BID in Spanish) has developed the Hydro-BID for the Latin America and Caribbean (LAC) region (Andres *et al.* 2018). The advantages of this hydrological management model include that it can be applied in areas with data deficits and also to project the hydrological status of basins under climate change scenarios (Mena *et al.* 2021). Hydro-BID has been implemented in several countries in the LAC region (e.g. Moreda *et al.* 2014a; Wyatt *et al.* 2014; Moreda & Coli 2017). However, most studies have focused on basins with relatively regular relief and rainfall patterns (Arbuet *et al.* 2021; Mena *et al.* 2021). Given the utility of the tool for LAC generally, and that water generated in the Andes supplies >100 million people (Mills-Novoa *et al.* 2017), there is a need to evaluate how well Hydro-BID represents processes in Andean catchments. This paper represents the first step in this process by implementing the model in a relatively well-studied catchment in the semi-arid Andes of Chile. Here, the cryosphere plays an important role in water delivery (Navarro *et al.* 2023a), and so it is imperative that general models such as Hydro-BID are tested to evaluate their ability to represent these processes.

The main aims of this study are to analyse the hydrological contribution of snow in a semi-arid mountain system and how this may be impacted in future due to climate change and to evaluate the use of Hydro-BID in a high mountain environment. To address these aims, we use the Hydro-BID hydrological model to simulate daily, monthly and annual runoff in the upper Elqui River basin.

METHODS

Study site

The headwaters of the Elqui River catchment are located in the semi-arid Andes, Chile (30°S) (Figure 1), and cover an area of ca. 5,700 km^2. They include the sub-catchments of the Turbio River (ca. 4,118 km^2) and the Claro River (ca. 1,520 km^2). The Turbio River originates at the confluence of the Turbio and La Laguna rivers, while the Claro River is the result of the joining of the Derecho and Cochiguaz rivers. Daily discharge measurements between 1985 and 2018 indicate that the mean discharge for the Turbio, Claro and Elqui rivers is 5.7, 3.8 and 9.6 m^3 s^{-1}, respectively (Alvarez-Garreton *et al.* 2018).

This section of the semi-arid Chilean Andes is characterised by a strong altitudinal gradient between the Pacific Ocean and the Cordillera, such that 6,000 m high peaks are located within 150 km of the coast (Figure 1). Above 3,000 m asl, glacial landforms dominate the landscape (e.g. moraines, U-shaped valleys and rock glaciers) (Monnier *et al.* 2014). These landforms are the result of changing fluvial, glacial and slope processes caused by glacial–interglacial oscillations during the Quaternary period (Zech *et al.* 2008; Riquelme *et al.* 2011; Aguilar *et al.* 2013). The underlying geology is characterised by granite and fractured volcanic outcrops from the Palaeozoic and Cenozoic periods, carbonates and sedimentary-volcanic material from the Jurassic and Inferior Cretaceous periods, and alluvial deposits from the Quaternary (Velásquez *et al.* 2021).

Between 1970 and 2009, the mean annual precipitation rate was 167 mm at the La Laguna station (3,200 m asl) (Monnier *et al.* 2014) which is concentrated in 5–10 events per year during the winter months (Rabatel *et al.* 2011). During precipitation events, the 0 °C isotherm is generally between 1,800 and 2,500 m asl, and the snowline lies approximately 280 m below this level (Schauwecker *et al.* 2022), which means that in the headwaters, precipitation is mainly in the form of snow. In recent years, the position of the snow line has increased at a rate of 10–30 m a^{-1} (Saavedra *et al.* 2018) and during the last 50 years, the area where snow commonly falls has been reduced at an average annual rate of 12% per decade (Cordero *et al.* 2019). In the wider region (30–38°S), the last decade has been characterised by below-average precipitation rates and has been classified as a mega-drought (Garreaud *et al.* 2017, 2020).

Snow cover explains a large part of the annual variations in river flows in the semi-arid Andes (Masiokas *et al.* 2020). On an annual scale, snowmelt contributes between 66 and 93% of runoff in central Chile (Burger *et al.* 2019). Comparatively,

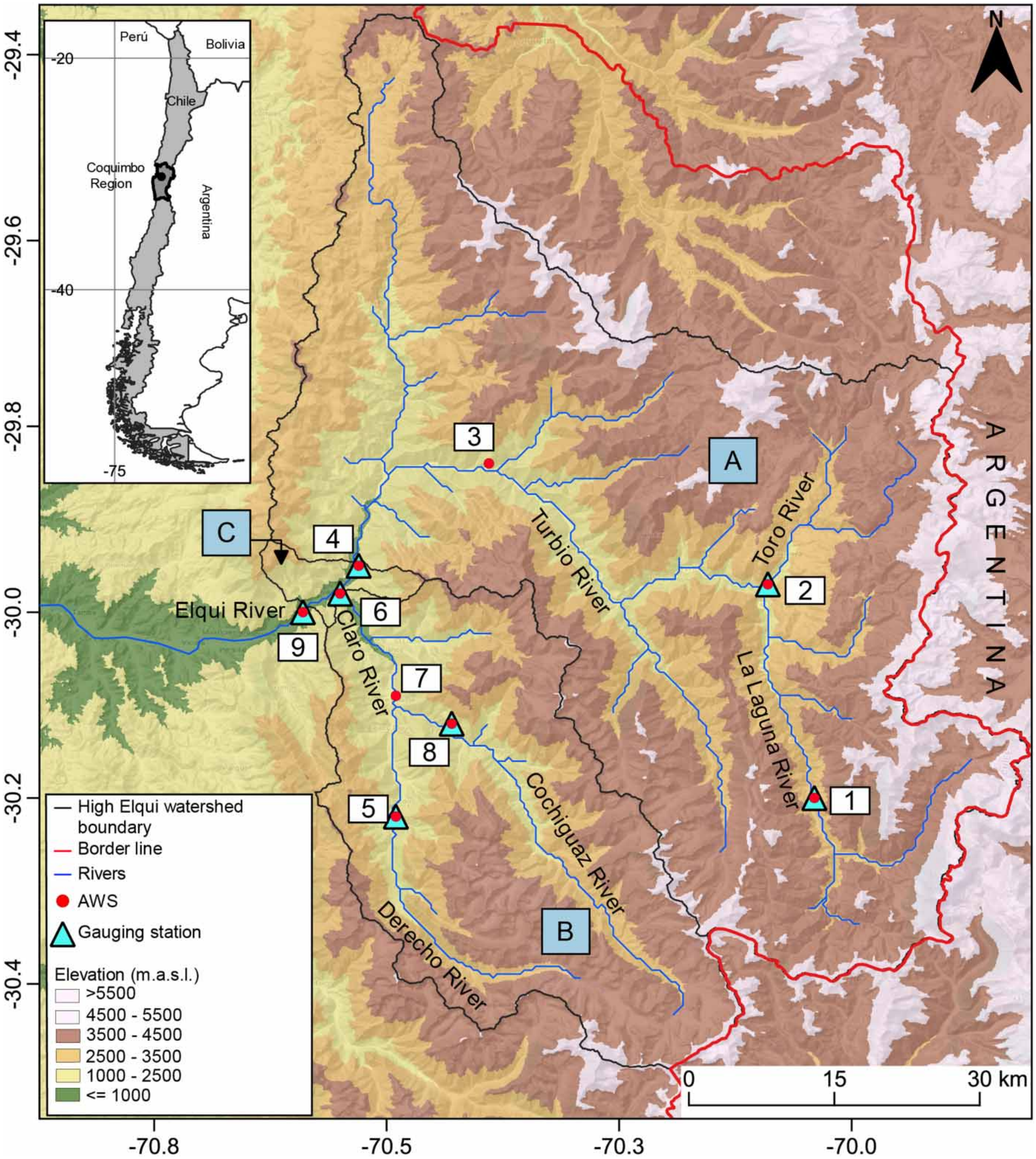


Figure 1 | Location of the Upper Elqui River basin. The top left corner is the South America map, and red is the region of Coquimbo, where the study area is located. A = Turbio River sub-basin, B = Claro River sub-basin, C = Elqui River discharge zone. AWS = Automatic Weather Station. 1 = Laguna River AWS and gauge station, 2 = Toro River AWS and gauge station, 3 = Turbio River in Huanta AWS, 4 = Turbio River in Varillar AWS and gauge station, 5 = Derecho River in Alcoguaz AWS and gauge station, 6 = Claro River in Rivadavia AWS and gauge station, 7 = Claro River in Montegrande AWS, 8 = Cochiguaz River AWS and gauge station, 9 = Elqui River in Algarrobal AWS and gauge station. Elevation data: SRTM Digital Model Elevation of 30 m of resolution. Please refer to the online version of this paper to see this figure in colour: https://doi.org/10.2166/wcc.2023.268.

during periods of drought, and the summer months, glaciers become more important for maintaining streamflow, and in central Chile, their contribution is equivalent to 67% of runoff in summer (Ayala *et al.* 2016). Sublimation from glaciers and snow is reasonably significant, and ranges from 36 to 86% (MacDonell *et al.* 2013; Voordendag *et al.* 2021), however, the ratio of sublimation to melt is dependent on elevation and seasonal conditions (Réveillet *et al.* 2019; Voordendag *et al.* 2021).

Hydro-BID model implementation

Hydro-BID is an integrated hydrology and water management model developed specifically for the LAC to simulate and project surface runoff under different climate scenarios (Mena *et al.* 2021). This study only uses the hydrological modelling component of the system, rather than the water management submodule. The implemented model uses the Analytical Hydrographic Dataset (AHD), which supplies information on land use, soil types, precipitation, temperature and drainage networks for ~230,000 LAC watersheds (Nalesso & Coli 2017; Figure 2). Catchment-specific information is accessed by including the catchment of interest serial number (COMID) into an AHD plugin compatible with QGIS 2.18 (Figure 2) an Open Source Geographic Information System (Rosas-Chavoya *et al.* 2022). In the case of the study area, the COMIDs of interest were the La Laguna, Toro, Turbio, Derecho, Cochiguaz and Claro rivers plus the Elqui River discharge zone (Figure 1).

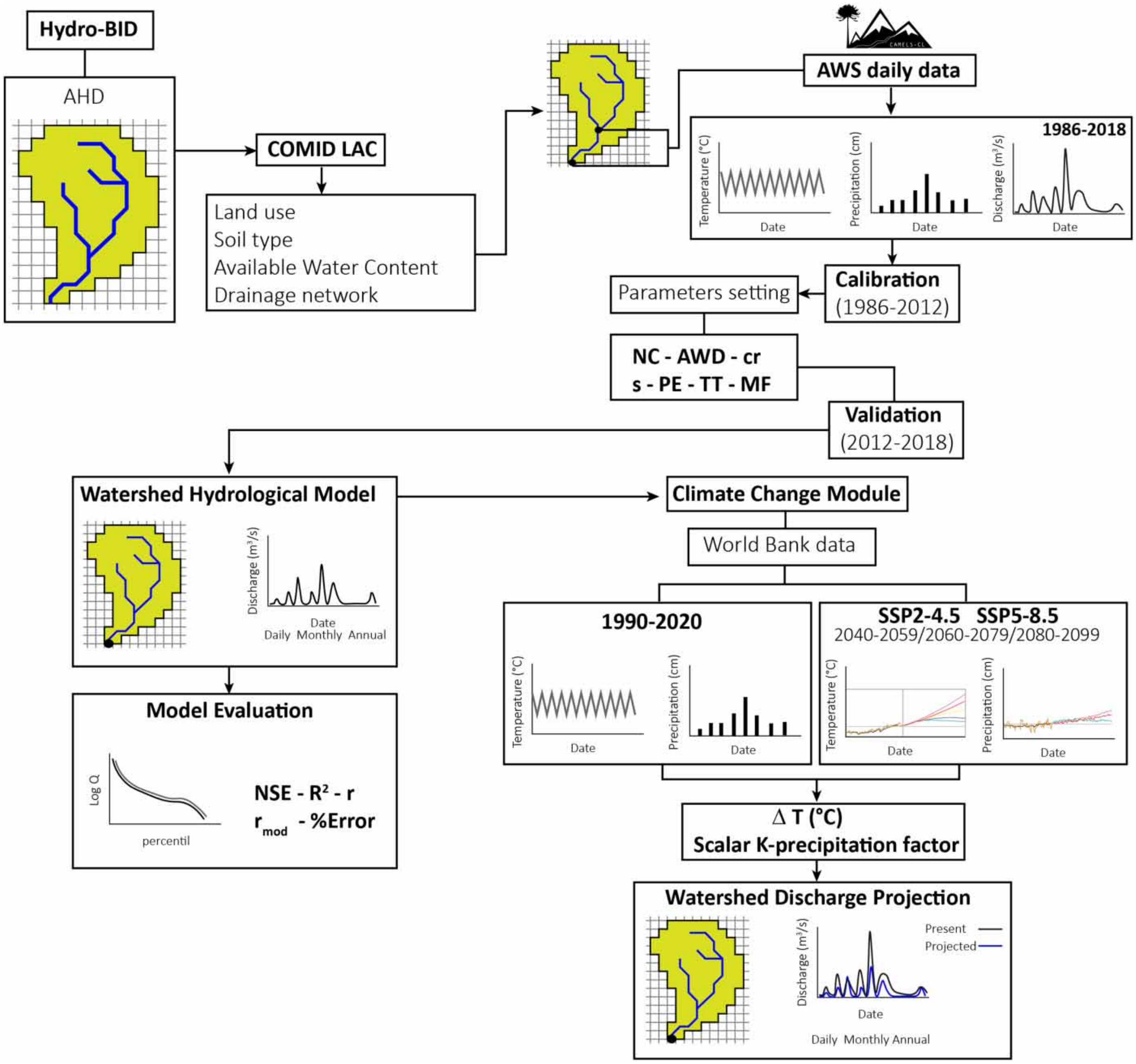


Figure 2 | Flowchart of the methodology used to simulate daily, monthly and annual runoffs in the upper Elqui River. AHD, analytical hydrographic dataset; COMID LAC, unique identifier of each basin of Latin America and Caribbean database; NC, curve number; AWD, available water content; cr, recession coefficient; S, seepage; PE, potential evapotranspiration logistic; TT, temperature threshold; MF, melting factor; NSE, Nash–Sutcliffe coefficient; R^2, determination coefficient; r, correlation coefficient; r_{mod}, modified correlation coefficient.

Hydro-BID calculates runoff originating from precipitation, actual evapotranspiration, percolation, baseflow, deep percolation and stored water volumes in the saturated and unsaturated zones. These calculations are based on the generalised basin loading function (GWLF) (Haith *et al.* 1992), which integrates processes associated with snow melt (SM), potential evapotranspiration (PET), runoff (R) and percolation (P) (Nalesso & Coli 2017). R is calculated through the curve number (NC). PET is estimated with daily temperature data and a coverage factor that depends on land use and vegetation cover. Baseflow and P are obtained from the groundwater recession and percolation constants, respectively. The volume of stored water is calculated from the daily hydrological balance, which enables runoff volume to be calculated at the basin and sub-basin scales (Moreda *et al.* 2014b). Limiting factors for the use of this model for applications in the semi-arid Andes is that it does not use an energy balance approach to model snow melt, and ignores sublimation, the direct contribution of glaciers and the effect of snow transport by wind.

Hydroclimatic datasets

Hydro-BID uses hydroclimatic forcing data derived from daily time series of temperature (°C), precipitation (mm or cm) and discharge (m^3/s) (Figure 2). In the present study, these datasets were obtained from nine meteorological stations and seven flow monitoring stations, from the CAMELS-CL database (Alvarez-Garreton *et al.* 2018; Barría *et al.* 2021; Figure 2).

Both mean air temperature (MAT) and daily precipitation have continuous records over a 41-year period (1979–2020), however, the daily flow time series contains some gaps over that timeframe (see Supplementary Table S2). To avoid periods of poor data availability, the study period was shortened to 1986–2018, as it corresponded to the time period where discharge values were available from at least one station within the wider network (see Supplementary Table S2). The problem of temporal discontinuity in discharge measurements was mainly confined to the Derecho, Claro, Turbio and Elqui river stations (Figure 1). To replace missing data, linear regression models were used to fill missing discharge values based on stations that recorded values (see Supplementary Figure S1). Only regression models with R^2 values > 0.6, adjusted $R^2 > 0.6$, and standard error $<10\%$ were considered valid.

Climate change projections

Shared Socioeconomic Pathways (SSPs) are climate change scenarios proposed by the IPCC that describe possible social, demographic and economic projections to the end of the century (Chen *et al.* 2020). The IPCC (2021) has proposed five potential scenarios based on the level of greenhouse gas emissions, mitigation measures and socioeconomic elements (denominated SSP1 through SSP5). SSP1 relates to a scenario where the use of green energy is encouraged (van Vuuren *et al.* 2014). Under SSP1, the air temperature will increase by less than 1.5 °C by 2100 (IPCC 2021). SSP2 is an intermediate pathway between SSP1 and SSP3 (Fricko *et al.* 2017). SSP3 is the result of the lack of global cooperation to face the climate crisis (Fujimori *et al.* 2017). In SSP3, a lower amount of greenhouse gas emissions is expected compared to SSP5. However, under SSP3, it is projected that by 2100 greenhouse gas emissions will be twice as high as today (IPCC 2021). Comparatively, the SSP4 scenario relates to the increase in inequality within, and between, countries (Calvin *et al.* 2017). Finally, SSP5 is the opposite extreme of SSP1 and is characterised by the indiscriminate use of fossil fuels, a rapidly growing economy and no implementation of mitigation measures (Kriegler *et al.* 2017).

The Hydro-BID climate change module (Figure 2) enables the simulation of hydrological response to changes in temperature and precipitation associated with the SSP proposed in the most recent IPCC report (IPCC 2021). For this study, precipitation data (1990–2020), monthly and annual temperature and precipitation projections were downloaded for SSP2-4.5 and SSP5-8.5, for the Coquimbo region from the World Bank database (Figure 2) (World Bank Group, Climate Change Knowledge Portal). The selected projection periods corresponded to 2040–2059, 2060–2079 and 2080–2099. Since the conditions projected by SSP1-1.9 and SSP1-2.6 are highly unlikely to occur, only scenarios SSP2-4.5 and SSP5-8.5 were used. SSP2-4.5 represents the best of the worst scenarios that could be achieved based on current conditions, whereas SSP5-8.5 is the worst possible future climate scenario.

For each SSP and respective time period, projected monthly temperature data were incorporated into the Hydro-BID climate change module. For precipitation, a scalar factor was calculated between the 1990–2020 precipitation data with respect to the monthly precipitation data projected by each SSP and the time period to be simulated. This was done by first comparing the mean precipitation of the selected SSP for the relevant time period (P_t) to the mean monthly precipitation between 1990 and 2020 (P_p). The scalar factor corresponded to:

$$F = 1 + D \tag{1}$$

where F represents the reduction factor or precipitation increase according to the selected SSP and D is the precipitation ratio between P_t and P_p.

Model calibration and validation

The model was calibrated in the Turbio River sub-basin for the 1986–2012 periods, which included part of the mega-drought (Garreaud *et al.* 2017, 2020). During calibration, several parameters were adjusted to account for regional processes (Figure 2). These included: curve number (NC), which characterises the use and hydrology of the soil; available water content (AWC), which refers to water available to plants in the soil; recession coefficient (CR), which determines groundwater contribution to streamflow following precipitation events in which discharge increases; losses (S), which is the exchange of water between groundwater units; evapotranspiration factors during periods with and without cultivation; temperature threshold (TT) and the snow melting factor (SMF). The validation of the calibrated model was carried out in the same sub-basin of the Turbio River and for the entire upper part of the Elqui River basin for 2012–2018.

The evaluation of model effectiveness included statistical and graphical techniques. These included analysing correlation coefficients (r), modified correlation coefficients (r_{mod}), Nash–Sutcliffe coefficients (NSE), the general volume error and a sensitivity analysis. For the coefficients r, r_{mod} and NSE (Figure 2), when their values are close to 1, they indicate that the degree of adjustment between the modelled discharge and the observed discharge is high. Comparatively, the general volume error indicates the mean error percentage between the simulated and observed values. In terms of error, an overall error of $\leq \pm$ 15% was considered acceptable (Moriasi *et al.* 2015). Note that the Hydro-BID model framework calculates these indices for daily and monthly runoff calculations, but to calculate annual values of the performance indices, the hydroGOF R package was used (Bigiarini 2020). Graphical model evaluation included evaluating the degree of fit between the simulated and observed water volume curve (Figure 2). The sensitivity analysis considered the value of the root mean square error (RMSE). For this, the minimum and maximum values of the range of values for each parameter as suggested by Nalesso & Coli (2017) were evaluated.

RESULTS AND DISCUSSION

Model calibration and validation

The calibration resulted in new values of several parameters (see Supplementary Table S3), such that all except for NC, S and TT were adjusted within the range recommended by Nalesso & Coli (2017). Of those outside the normal range, the adjusted value of TT was the most notable, such that a value of 4 °C was used which reflects the fact that precipitation in the mountainous region of Elqui is predominantly snow. While outside the suggested range, this adjustment is in line with other studies in similar environments (e.g. Ruelland *et al.* 2011; Kraaijenbrink *et al.* 2021).

The calibrated model results for the Turbio River sub-basin show that Hydro-BID accurately simulates measured streamflow (see Supplementary Figure S2), as seen in the R^2 of ~0.7 for the daily and monthly flows, while for the annual flow is ~0.8 (see Supplementary Table S4). This means there is a high degree of fit between the values of the simulated daily, monthly and annual hydrographs with the observed data (see Supplementary Figure S2(a)–S2(c)). However, the maximum flows related to periods with higher precipitation are underestimated by the model (see Supplementary Figure S2(a) and S2(b)). Regarding r_{mod}, the values are >0.5, which indicates that the model explains relatively well a large part of the variance of the simulated discharge with respect to the observed discharge. Comparatively, the NSE value is ~0.7 for the simulated daily, monthly and annual flow data and the results of the calibrated model show an overall error of $\sim\!-2$, $\sim\!-1$ and ~2% for the simulated daily, monthly and annual flows, respectively. Finally, Supplementary Figure S2(d) shows the degree of fit between the simulated and adjusted water volume curves is high.

Validated model results for the upper Elqui River basin are summarised in Supplementary Table S4 and Figure 3. In this part of the basin, the value of R^2 is ~0.6 for the daily and monthly flow data, while for the annual flow is ~0.7 (Table 1), which connects to the high degree of fit between the simulated daily, monthly and annual hydrograph values with measured streamflow (Figure 3(a)–3(c)). However, the model underestimates maximum flows associated with periods of abundant precipitation during the six validation years (Figure 4(a) and 4(b)). The r_{mod} and NSE values suggest that the model explains

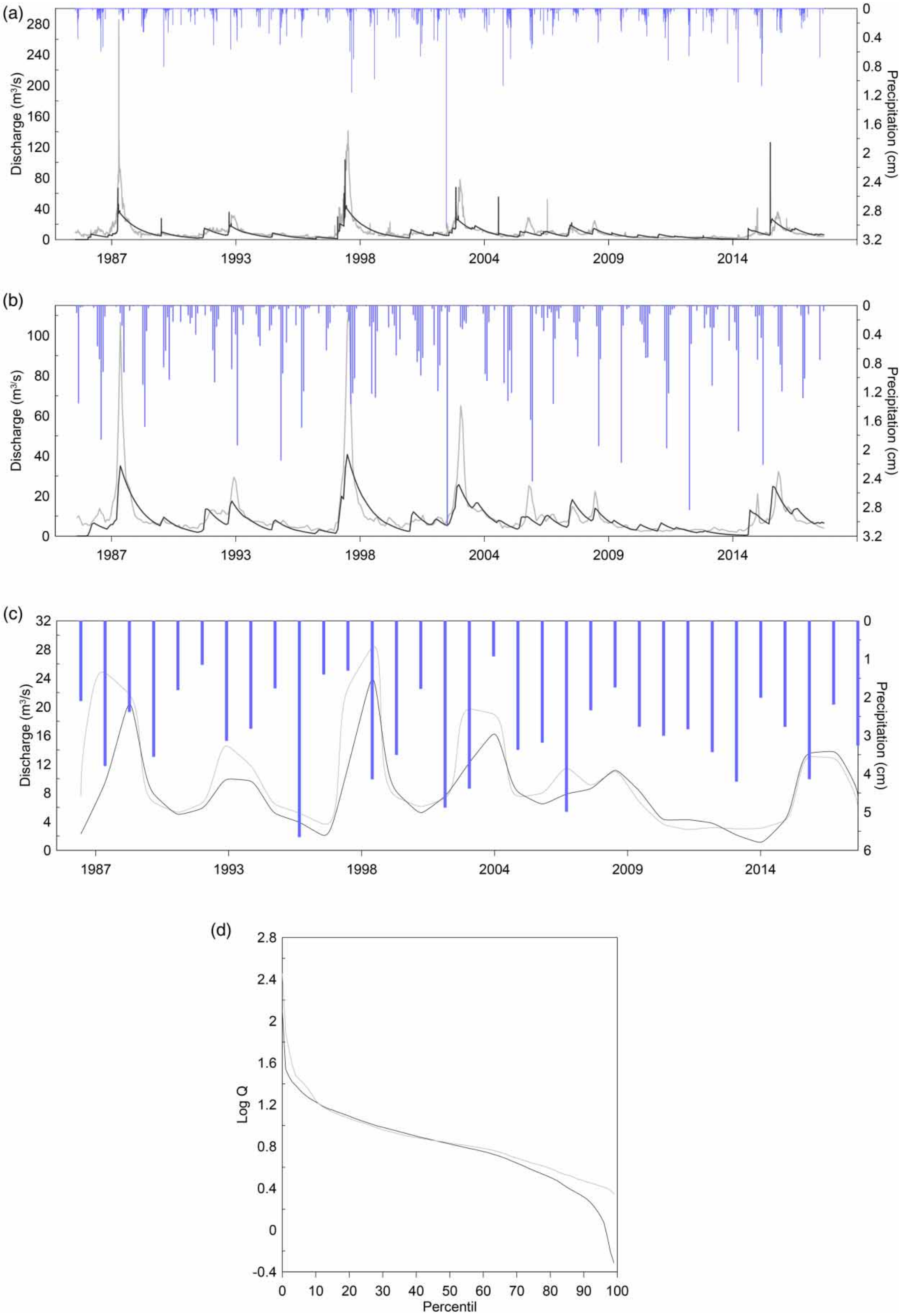


Figure 3 | Results of model validation in Elqui River discharge zone. (a) Daily simulated and observed curves, (b) monthly simulated and observed curves and (c) annual simulated and observed curves. Blue bars represent precipitation data, the black line represents modelled discharge and the grey line represents observed discharge. (d) Water volume graph, modelled (black) and observed (grey). Please refer to the online version of this paper to see this figure in colour: https://doi.org/10.2166/wcc.2023.268.

Table 1 | Discharge (*Q*) projection results summary for SSP2-4.5 and SSP5-8.5 climate scenarios

***Q* mean (m^3/s) (1986–2018)**		***Q* mean SSP2-4.5 (m^3/s)**			***Q* mean SSP5-8.5 (m^3/s)**		
		2040–2059	**2060–2079**	**2080–2099**	**2040–2059**	**2060–2079**	**2080–2099**
Daily	10	4.5 (–55%)	4.1 (– 58%)	3.3 (– 67%)	4.2 (– 58%)	2.9 (– 71%)	2.3 (– 77%)
Monthly	10	4.7 (–51%)	4.2 (– 55%)	3.4 (– 64%)	4.3 (– 57%)	3.0 (– 70%)	2.4 (– 76%)
Annual	121	56 (–54%)	51 (– 58%)	41 (– 66%)	52 (– 57%)	36 (– 70%)	28 (– 77%)

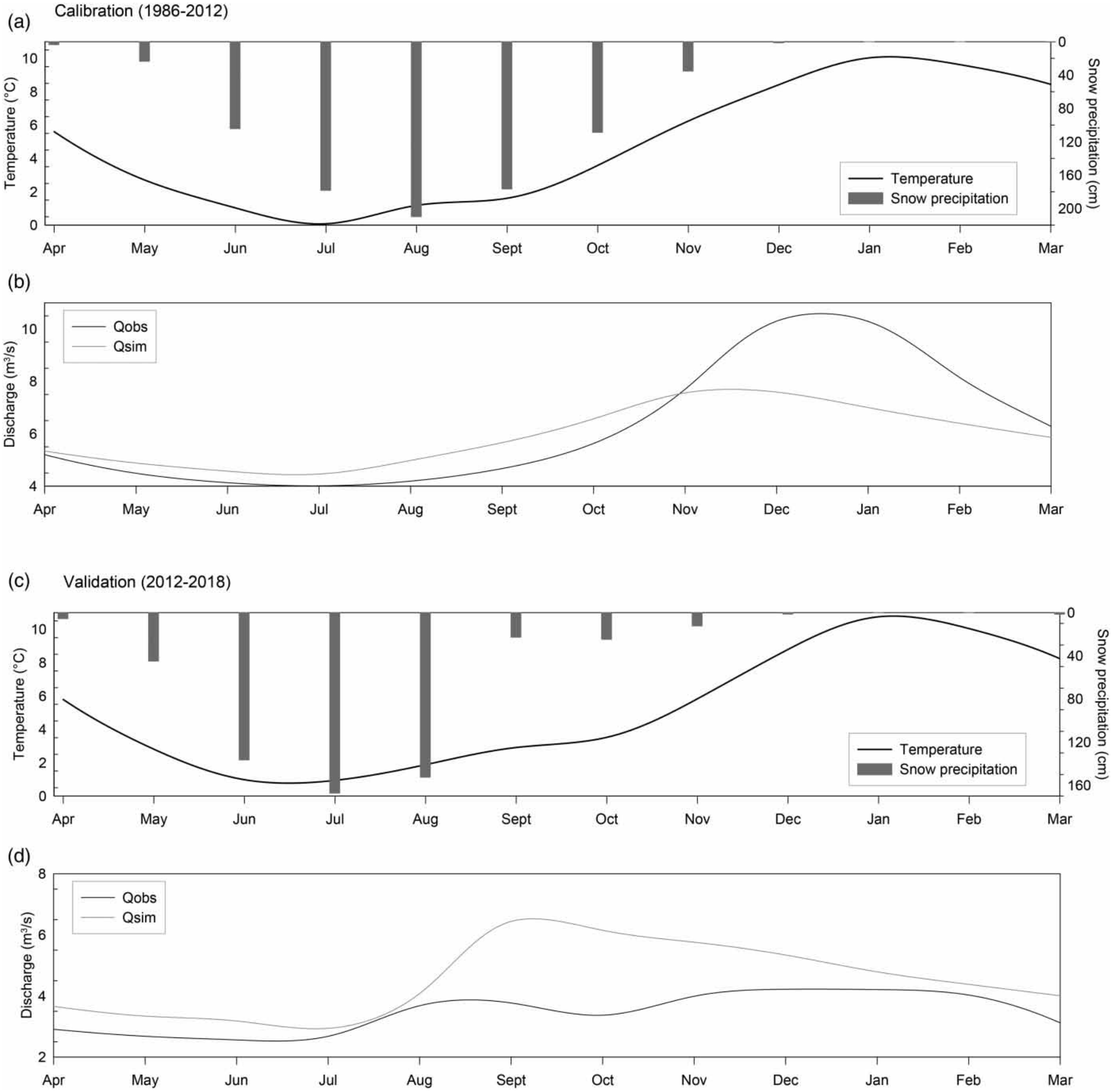


Figure 4 | Data and modelled results of precipitation, temperature and discharge averaged over the hydrological year for the calibration and validation model runs. (a and b) Datasets are based on the calibration period for the Turbio River sub-basin. (c and d) Datasets correspond to the validation time periods for the Turbio River sub-basin.

a large part of the variance of the simulated monthly flow reasonably well, but not for the daily flow. Overall error is relatively low, however (see Supplementary Table S4), and the graphical analysis suggests the degree of fit between the simulated and fitted water volume curve is relatively high (Figure 3(d)). Finally, the sensitivity analysis results (see Supplementary Table S5) confirmed the final parameter choice, as there is high sensitivity to parameter selection which results in the lowest RMSE corresponding to the implemented parameter array.

Moriasi *et al.* (2015) showed that the daily, monthly or annual results of a basin-scale hydrological model can be defined as ‘satisfactory’, when the value of $R^2 > 0.6$, NSE > 0.5 and the general error is $\leq \pm$ 15%. According to this standard, the calibrated and validated model results can be classified as satisfactory. This is supported by the low RMSE value, and the high degree of fit shown in Figure 3 and Supplementary Figure S2.

Future scenarios

SSP2-4.5

For the SSP2-4.5 scenario, the mean annual temperature in the wider region is projected to increase by 1.2, 1.6 and 1.9 °C for the periods 2040–2059, 2060–2079 and 2080–2099, respectively. Comparatively, precipitation is projected to decrease by 26% (2040–2059), 29% (2060–2079) and 36% (2080–2099). For these combinations, significant changes in streamflow are observed on annual, monthly and daily time scales. Under SSP2-4.5 for 2040–2059, 2060–2079 and 2080–2099, the annual average discharge is projected to decrease by 54, 58 and 66%, respectively (Table 1). In the case of mean monthly flows (Figure 5), for the periods 2040–2059, it is estimated that they will decrease by 51% (Figure 5(a)). Whereas, for the periods 2060–2079, a reduction of 55% is projected (Figure 5(b)), and for 2080–2099, a decrease of 64% is estimated

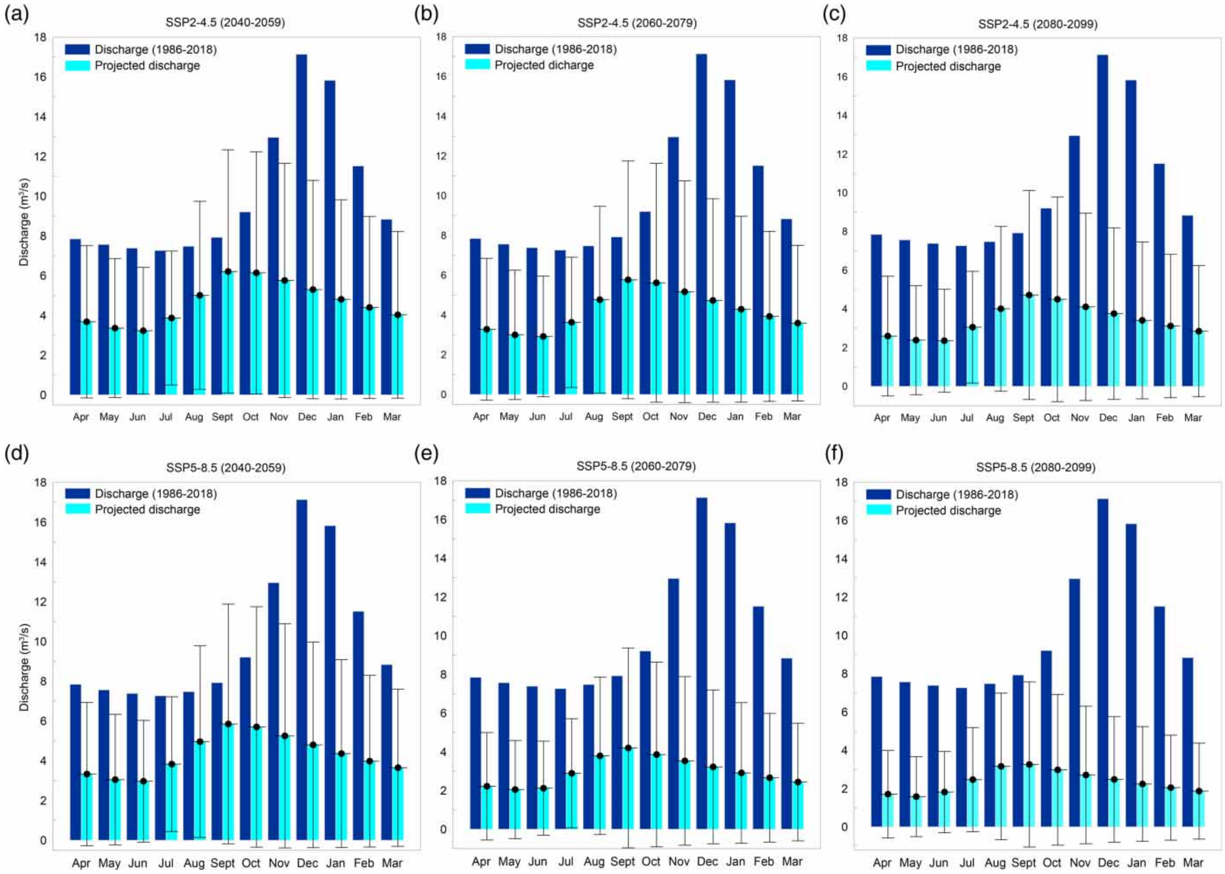


Figure 5 | Discharge projections for the Elqui River basin. The top panels are SSP2-4.5 results for (a) 2040–2059, (b) 2060–2079 and (c) 2080–2099. The bottom panels are SSP5-8.5 results for (d) 2040–2059, (e) 2060–2079 and (f) 2080–2099. The vertical line with the black point is the standard deviation of projected results.

(Figure 5(c)). Comparatively, projections of average daily discharge indicate that for 2040–2059 streamflow will decrease by 55% (Table 1), for 2060–2079 a decrease of 58% and for 2080–2099 a 67% decrease.

In the context of the hydrological year, the observed data (April to March 1990–2020) show that the maximum flow is reached during December (Figure 5). However, at different time periods under the SSP2-4.5 trajectory, peak flow will be reached during September.

SSP5-8.5

Following SSP5-8.5, the mean annual temperature is projected to increase by 1.5, 2.6 and 3.7 °C for the periods 2040–2059, 2060–2079 and 2080–2099, respectively, whereas precipitation will decrease by 28% (2040–2059), 39% (2060–2079) and 44% (2080–2099). In the case of SSP5-8.5, the projected results also show significant annual, monthly and daily changes in streamflow in the study area. In the context of SSP2-4.5 for 2040–2059, 2060–2079 and 2080–2099, the annual average discharge is projected to decrease by 57, 70 and 77%, respectively (Table 1). In the case of monthly average flows, a decrease of 57% is estimated for the periods 2040–2059 (Figure 5(d)), a decrease of 70% for 2060–2079 (Figure 5(e)) and a reduction of 76% for 2080–2099 (Figure 5(f)). For daily average discharge, the periods 2040–2059 experience a reduction of 58% (Table 1), while for 2060–2079, the reduction is 71% and for 2080–2099 it decreases by 77%.

In the case of the hydrological year, the same trend is observed as modelled in SSP2-4.5 (Figure 5). That is, in the different periods analysed for the SSP5-8.5 trajectory, the maximum flow during the hydrological year will be reached during September.

The role of snow in semi-arid headwaters

Hydrological modelling using Hydro-BID for a site with abrupt morphology such as the semi-arid Andes of Chile is not a simple task to undertake, mainly because morphological parameters cannot be adjusted in the model set-up. However, Hydro-BID has other elements that make it possible to simulate runoff for a mountain context, which enables the implementation of the model in Andean catchments. In this study, that meant adjusting some parameters outside the standard ranges and made it possible to improve model performance (see Supplementary Table S2). However, it was not until the modification of TT that the model was able to satisfactorily model the hydrology of the study region. The TT parameter defines the temperature at which precipitation is liquid or solid, and during the calibration stage, it was increased iteratively from 1 °C (default) to 4 °C. The modification of TT was based on two considerations. The first was related to the recognition that the hydrological system is driven predominantly by a snow regime in the Elqui River basin (Favier *et al.* 2009; Hublart *et al.* 2014; Balocchi *et al.* 2017). Secondly, most of the meteorological stations used in this study are located at relatively low elevations, and record events below the snow-rain transition zone (Schauwecker *et al.* 2022). By increasing TT, Hydro-BID was forced to incorporate a higher proportion of solid precipitation. This meant that the hydrological model reproduced with a greater degree of reality the natural precipitation process that dominates in the headwaters of Chilean semi-arid Andean basins. By allowing for this process, Hydro-BID simulates reasonably accurately the effect of snowmelt on the outflow of the upper part of the Elqui River (Figure 4). This coincides with what has been proposed by other studies (Ruelland *et al.* 2011; Hublart *et al.* 2013) and demonstrates the influence of snow on runoff from the upper part of the Elqui River basin. However, unlike previous studies in the area, Hydro-BID allows this process to be reproduced considering solid precipitation, not only liquid precipitation (Figure 4).

The results of the discharge projections show that for all scenarios streamflow decreases, which is consistent with the trend projected for South America by the IPCC (2021). However, Figure 5 also shows an evident change in the timing of annual peak flow. At present (1990–2020), the maximum annual flow is achieved in December (Figures 4(b) and 5), however, in future, the annual maximum will be reached during September (Figure 5). It is likely that this change is due not only to a decrease in precipitation rates, but also to a switch in the fraction of precipitation falling as snow and as rain. Given that snow melt is likely the dominant control in semi-arid Andean basins (e.g. Ayala *et al.* 2016; Burger *et al.* 2019; Masiokas *et al.* 2020), any modification to snow processes will have an immediate impact on discharge (Barnett *et al.* 2005; Huss *et al.* 2017). This is consistent with work carried out in the semi-arid Andes, where the reduction in snow covered area and permanence has already been observed (Saavedra *et al.* 2018; Cordero *et al.* 2019). In fact, the model results already show indications of these changes. In Figure 4(c) and 4(d), it is observed that between 2012 and 2018, the maximum snow accumulation was lower and was reached in July. This has meant that, during this period, the maximum flow is lower and often occurs in September, which is 3 months earlier than what was observed between 1986 and 2012 (Figure 4(a) and 4(b)). This change is likely due to the mega-drought that has affected the wider region (Garreaud *et al.* 2017, 2020). The local effect of the mega-drought has been compounded by the increase in mean annual temperature related to climate change (Souvignet *et al.* 2012). The results of Hydro-BID in the Elqui River basin are evidence that a lower amount of snowfall, both now and in the future, significantly influences the amount of water available for the population, ecosystem and economic activities.

Future water reserves

Due to ongoing water scarcity in the region, the Watershed Sustainability Index (WSI) categorises the Elqui River basin as having an intermediate degree of sustainability (Cortés *et al.* 2012). Following Hublart *et al.* (2013), ongoing scarcity will also be extended to annual flows in the future. For the periods 2041–2060, Hublart *et al.* (2013) estimated that the maximum flow will be reached in November and the annual volume of water will be reduced from 30 to 70%. This range is relatively wide, and less constrained than the results of Hydro-BID for the periods 2040–2059, where a reduction in the annual flow is projected to be 54 and 57% for SSP2-4.5 and SSP5-8.5, respectively (Table 1). In contrast to the work of Hublart *et al.* (2013), the Hydro-BID results show that the maximum t will be reached in September (Figure 5). These differences between both models respond to two main drivers. The first is related to the fact that Hydro-BID was considered part of the effect of the mega-drought in its calibration period, a period not yet experienced in the dataset used in Hublart *et al.* (2013). Secondly, the input forcing data used in Hydro-BID are derived from climate projection models that have a lower degree of uncertainty than those used by Hublart *et al.* (2013). However, both models project significant decreases in streamflow in the Elqui River basin at daily, monthly and annual time scales (Figure 5 and Table 1). With such a result, it is also necessary to reflect on the contribution of water derived from other sources in the catchment headwaters.

This study has focused on seasonal snow contribution to streamflow, but snow also relates to the hydrological role of glaciers, rock glaciers, snow and aquifers over a variety of timeframes. For instance, without snowfall events, it is not possible for some of these mountain components to be generated or preserved in the long term (Gascoin *et al.* 2013; Kinnard *et al.* 2020). Therefore, precipitation is the fundamental water source and the engine of the hydrological system in a catchment (Levizzani & Cattani 2019). Mountain water resources fulfil the function of redistributing precipitation accumulated in winter to runoff during spring and summer (Viviroli *et al.* 2011). Therefore, glaciers, rock glaciers, snow and aquifers fall into the category of freshwater reserves (Immerzeel *et al.* 2020; Viviroli *et al.* 2020), which can be categorised as medium or long term. The former has the potential to cover the demand for water on a daily, monthly and annual scale (e.g. snow) (Jansson *et al.* 2003). Long-term reserves have the capacity to contribute water for a period of time that varies from months to centuries (e.g. glaciers) (Jansson *et al.* 2003). The role of rock glaciers in this context is largely unclear (Jones *et al.* 2018, 2019).

Hydro-BID projects a decrease in the medium-term reserve (snow) in the study area. Therefore, the long-term freshwater reserves of the Elqui basin will become essential to face a future with less precipitation and snow accumulation. The presence of glaciers in the Elqui basin is limited and most ice is contained within one glacier, the Tapado Glacier, which is located in the upper part of the Elqui basin (Robson *et al.* 2022). Pourrier *et al.* (2014) identified that the hydrological contribution from the Tapado Glacier complex is important to meet the demand in the lower areas of the Elqui River basin, especially during the summer and periods of drought. However, on a global scale, glaciers have been progressively losing mass (Zemp *et al.* 2019) and glaciers in the semi-arid Andes are no exception (e.g. Kinnard *et al.* 2020; Masiokas *et al.* 2020). In the case of the Tapado Glacier, during the last ~64 years, its surface has been reduced by 20–30% and the mega-drought has increased the frequency and size of negative mass balances (Robson *et al.* 2022). As precipitation is the main driver of mass balance change in these systems (Kinnard *et al.* 2020), the reduction in the amount of accumulated snow projected by Hydro-BID implies greater pressure on permanent ice masses such as Tapado. This increased pressure will further contribute to the loss of glacier mass, and increase the probability that a long-term water reserve such as the Tapado Glacier will become a medium-term water reserve in the future.

For rock glaciers, the outlook is different, as they are a form of periglacial landform composed of a mixture of water, ice and debris (Berthling 2011). Their categorisation as potential long-term freshwater reserves (Jones *et al.* 2018, 2019), responds more to their detrital coverage than necessarily their ice content. As sediment acts to insulate the massive or interstitial ice stored inside from positive air temperatures and the effects of radiation, it is likely that these landforms will be less affected by the effects of climate change (Jones *et al.* 2018; Schaffer & MacDonell 2022). Another advantage of the rock cover is that it causes the hydrological discharge of water to be gradual during the summer (Krainer & Mostler 2002; Harrington *et al.* 2018). In the case of the upper part of the Elqui River basin, rock glaciers are distributed in large numbers and, therefore, occupy a significant surface area (Barcaza *et al.* 2017; Schaffer *et al.* 2019). It has been estimated that the exposed glaciers and rock glaciers in the upper part of the Elqui basin represent 0.1 and 0.5 km^3 of water equivalent, respectively (Schaffer *et al.* 2019). In terms of contribution, it has been estimated that rock glaciers can contribute between 9 and 20% of the annual discharge of the La Laguna sub-basin (Schaffer *et al.* 2019). Likewise, in the study area, geophysical data indicate that rock glaciers can have significant ice and liquid water content (de Pasquale *et al.* 2022; Navarro *et al.* 2023b). In fact, Monnier & Kinnard (2015) estimated an average ice fraction of 66% in a rock glacier located in the La Laguna sub-basin.

Processes related to glaciers and mountain permafrost are not directly considered by Hydro-BID. It is clear that the significant decrease in the Elqui River basin discharge (Table 1 and Figure 5) can be associated with reduced snow accumulation. However, looking forward, it is possible that the projected decrease in flow (Figure 5) will not be as severe in the mid-term due to the presence of glaciers and rock glaciers. However, to substantiate this hypothesis, it is essential to develop more studies that allow quantifying the hydrological significance of rock glaciers and permafrost environments (Hilbich *et al.* 2022). A better understanding of permafrost processes and the interaction between snow and the underlying terrain will greatly improve the application of hydrological models in high mountain environments.

Hydro-BID as a high mountain hydrology model

Hydro-BID is a hydrological model developed to support water management in low-lying catchments in LAC (e.g. Arbuet *et al.* 2021; Mena *et al.* 2021). However, the results of this work have demonstrated its applicability in a mountainous region such as the semi-arid Andes (Figures 3 and 4). This suggests that Hydro-BID has the capacity to estimate and project runoff in mountainous regions of LAC, which could help to refine water management plans in, and stemming from, these areas. The applicability of Hydro-BID is primarily related to the AHD, which enables Hydro-BID to be applied in areas where there is limited data availability (Mena *et al.* 2021). The AHD has made it possible to compensate for the data deficit of other models and integrate their results with Hydro-BID (e.g. Mena *et al.* 2021).

In general, in the Andes, semi-distributed and distributed hydrological models have been used to solve water management and research problems (Ragettli *et al.* 2014). The former is simple and only need temperature data to differentiate solid from liquid precipitation (Omani *et al.* 2017). However, their results may be altered as a result of compensation errors, since there is no total reproduction of high mountain processes (Pellicciotti *et al.* 2012; Ragettli *et al.* 2014). Distributed models guarantee accuracy and less dependency on calibration (Pellicciotti *et al.* 2012). However, they are subordinate to the availability of data (Ragettli & Pellicciotti 2012). The results of the present study show that, unlike distributed models that have been applied in the Andes (e.g. Ragettli & Pellicciotti 2012; Krogh *et al.* 2015; Ayala *et al.* 2016; Ragettli *et al.* 2016; Mernild *et al.* 2018; Burger *et al.* 2019), Hydro-BID cannot directly quantify the contribution derived from snow and glaciers. However, using a simplified approach, it has demonstrated the importance of snow for runoff in the region and has the ability to project flow based on future climate scenarios (Figure 5). In fact, Hydro-BID satisfactorily reproduces the flows observed in the Elqui River basin to the same degree as other semi-distributed hydrological models applied in the Andes (Stehr *et al.* 2009; Ruelland *et al.* 2011; Ragettli *et al.* 2014; Omani *et al.* 2017; Escanilla-Minchel *et al.* 2020).

Model simplicity enables Hydro-BID to provide an indication of the general behaviour of runoff from a mountain basin in a short timeframe. Hydrological characterisation using Hydro-BID can be used as an initial step, before addressing more complex high mountain hydrological problems with distributed hydrological models (e.g. TOPKAPI, SnowModel, CRHM). Similarly, due to its extensive database, Hydro-BID offers the opportunity to solve the problems that some models have presented regarding the availability of local data on land use and type (e.g. Stehr *et al.* 2009). Considering that Hydro-BID is a flexible model to which climate change, reservoirs, sediment transport and groundwater modules have been incorporated (Moreda & Coli 2016), for mountainous regions, it would be good to develop a specific mountain module or set of parameterizations that incorporate glaciers and permafrost to make Hydro-BID an even more complete high mountain hydrological model.

CONCLUSIONS

This study has reinforced the importance of snow for runoff in the semi-arid Andes of Chile (32°). Additionally, it has demonstrated that the Hydro-BID model can satisfactorily simulate and project runoff in a catchment that is highly dependent on the contribution of snowmelt over the course of a hydrological year. In addition, despite being a relatively simple model, Hydro-BID has the ability to reproduce both solid and liquid precipitation in a basin and the resultant hydrological implications. This suggests that Hydro-BID can be used as a simple tool to understand the general behaviour of runoff in a high mountain, Latin

American basins. Therefore, Hydro-BID can support water management planning in areas where water is generated in the mountains, and where projections of future inputs are required.

The modelled projections for both SSP2-4.5 and SSP5-8.5 scenarios indicate that for the next 40, 60 and 80 years, the daily, monthly and annual runoffs will decrease between 50 and 77%. However, the most significant change is the month that the maximum flow is reached. In future, the peak flow will be reached 3 months earlier than the present. This means that there will likely be greater hydrological pressure on other long-term water reserves present in the semi-arid Andes, such as glaciers and rock glaciers.

This study reinforces the need to ensure even simple hydrological modelling platforms such as Hydro-BID include modules or parameters that consider cryospheric processes. This consideration will strengthen the simulation of high mountains that are easily integrated into a water management framework. However, there is additionally an opportunity to improve the current performance of the model. At present, the meteorological station data used to drive Hydro-BID is primarily based on stations located in valley floors. These datasets are used to create interpolated climate datasets, therein creating additional uncertainty due to station location bias. Exploration of new ways to interpolate climate datasets should be explored, which may include the use of virtual stations in summit areas. The drawback of this solution is the need to use reanalysis data (e.g. ERA5). However, with a robust method of bias correction, the data from these potential virtual stations will have the potential to better represent the temperature and precipitation rates of headwater regions and therein decrease the uncertainty of the Hydro-BID results.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Aguilar, G., Riquelme, R., Martinod, J. & Darrozes, J. 2013 Rol del clima y la tectónica en la evolución geomorfológica de los Andes Semiáridos chilenos entre los 27–32 S. *Andean Geology* **40** (1), 79–101.

Alvarez-Garreton, C., Mendoza, P. A., Boisier, J. P., Addor, N., Galleguillos, M., Zambrano-Bigiarini, M., Lara, A., Puelma, C., Cortes, G., Garreaud, R., McPhee, J. & Ayala, A. 2018 The CAMELS-CL dataset: catchment attributes and meteorology for large sample studies–Chile dataset. *Hydrology and Earth System Sciences* **22** (11), 5817–5846.

Andres, L., Boateng, K., Borja-Vega, C. & Thomas, E. 2018 A review of in-situ and remote sensing technologies to monitor water and sanitation interventions. *Water* **10** (6), 756.

Araya, A. & Hunt, J. 2003 *Aplicación del Sistema de Modelación Hidrologica SHERTAN a la Cuenca del rio Elqui*. *Undergraduate Thesis*, University of La Serena, La Serena, Chile.

Arbuet, A., Pusineri, G., Mazzón, R., Bianchi, H. H., Scioli, C., Paris, M., Corrales, J. & Nalesso, M. 2021 Implementación del modelo HydroBID en la Cuenca Los Padres-Santa Fe-Argentina. *Aqua-LAC* **13** (1), 81–96.

Ayala, A., Pellicciotti, F., MacDonell, S., McPhee, J., Vivero, S., Campos, C. & Egli, P. 2016 Modelling the hydrological response of debris-free and debris-covered glaciers to present climatic conditions in the semiarid Andes of central Chile. *Hydrological Processes* **30** (22), 4036–4058.

Balocchi, F., Pizarro, R., Meixner, T. & Urbina, F. 2017 Annual and monthly runoff analysis in the Elqui River, Chile, a semi-arid snow-glacier fed basin. *Tecnología y Ciencias del Agua* **8** (6), 23–35.

Barcaza, G., Nussbaumer, S. U., Tapia, G., Valdés, J., García, J. L., Videla, Y., Albornoz, A. & Arias, V. 2017 Glacier inventory and recent glacier variations in the Andes of Chile, South America. *Annals of Glaciology* **58** (75pt2), 166–180.

Barnett, T. P., Adam, J. C. & Lettenmaier, D. P. 2005 Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438** (7066), 303–309.

Barría, P., Sandoval, I. B., Guzman, C., Chadwick, C., Alvarez-Garreton, C., Díaz-Vasconcellos, R., Ocampo-Melgar, A. & Fuster, R. 2021 Water allocation under climate change: a diagnosis of the Chilean system. *Elementa: Science of the Anthropocene* **9** (1), 00131.

Beniston, M., Stoffel, M. & Hill, M. 2011 Impacts of climatic change on water and natural hazards in the Alps: can current water governance cope with future challenges? Examples from the European 'ACQWA' project. *Environmental Science & Policy* **14** (7), 734–743.

Berthling, I. 2011 Beyond confusion: rock glaciers as cryo-conditioned landforms. *Geomorphology* **131** (3–4), 98–106.

Bigiarini, M. 2020 hydroGOF: Goodness-of-fit functions for comparison of simulated and observed hydrological time series. R package version 0.4-0. doi:10.5281/zenodo.839854. Available from: https://github.com/hzambran/hydroGOF.

Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E., Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., Guglielmin, M., Ingeman-Nielsen, T., Isaksen, K., Ishikawa, M., Johansson, M., Johannsson, H., Joo, A., Kaverin, D., Kholodov, A., Konstantinov, P., Kröger, T., Lambiel, C., Lanckman, J., Luo, D., Malkova, G., Meiklejohn, I., Moskalenko, N., Oliva, M., Phillips, M., Ramo, M., Sannel, A., Sergeev, D., Seybold, C., Skryabin, P., Vasiliev, A., Wu, Q., Yoshikawa, K., Zheleznyak, M. & Lantuit, H. 2019 Permafrost is warming at a global scale. *Nature Communications* **10** (1), 1–11.

Burger, F., Ayala, A., Farias, D., Shaw, T. E., MacDonell, S., Brock, B., McPhee, J. & Pellicciotti, F. 2019 Interannual variability in glacier contribution to runoff from a high-elevation Andean catchment: understanding the role of debris cover in glacier hydrology. *Hydrological Processes* **33** (2), 214–229.

Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., Kim, S., Kyle, P., Link, R., Moss, R., McJeon, H., Patel, P., Smith, S., Waldhoff, S. & Wise, M. 2017 The SSP4: a world of deepening inequality. *Global Environmental Change* **42**, 284–296.

Clark, M. P., Wilby, R. L., Gutmann, E. D., Vano, J. A., Gangopadhyay, S., Wood, A. W., Fowler, H. J., Prudhomme, C., Arnold, J. R. & Brekke, L. D. 2016 Characterizing uncertainty of the hydrologic impacts of climate change. *Current Climate Change Reports* **2** (2), 55–64.

Cordero, R. R., Asencio, V., Feron, S., Damiani, A., Llanillo, P. J., Sepulveda, E., Jorquera, J., Carrasco, J. & Casassa, G. 2019 Dry-season snow cover losses in the Andes (18–40 S) driven by changes in large-scale climate modes. *Scientific Reports* **9** (1), 1–10.

Cortés, A. E., Oyarzún, R., Kretschmer, N., Chaves, H., Soto, G., Soto, M., Amézaga, J., Oyarzún, J., Rötting, T., Señoret, M. & Maturana, H. 2012 Application of the watershed sustainability index to the Elqui river basin, North-Central Chile. *Obras y Proyectos* **12** (2), 57–69.

Delpla, I., Jung, A. V., Baures, E., Clement, M. & Thomas, O. 2009 Impacts of climate change on surface water quality in relation to drinking water production. *Environment International* **35** (8), 1225–1233.

de Pasquale, G., Valois, R., Schaffer, N. & MacDonell, S. 2022 Contrasting geophysical signatures of a relict and an intact Andean rock glacier. *The Cryosphere* **16** (5), 1579–1596.

Dimri, A. P., Allen, S., Huggel, C., Mal, S., Ballesteros-Canovas, J. A., Rohrer, M., Shukla, A., Tiwari, P., Maharana, P., Bolch, T., Thayyen, R. J., Stoffel, M. & Pandey, A. 2021 Climate change, cryosphere and impacts in the Indian Himalayan Region. *Current Science*.

Dussaillant J, A., Buytaert, W., Meier, C. & Espinoza, F. 2012 Hydrological regime of remote catchments with extreme gradients under accelerated change: the Baker basin in Patagonia. *Hydrological Sciences Journal* **57** (8), 1530–1542.

Escanilla-Minchel, R., Alcayaga, H., Soto-Alvarez, M., Kinnard, C. & Urrutia, R. 2020 Evaluation of the impact of climate change on runoff generation in an Andean glacier watershed. *Water* **12** (12), 3547.

Favier, V., Falvey, M., Rabatel, A., Praderio, E. & López, D. 2009 Interpreting discrepancies between discharge and precipitation in high-altitude area of Chile's Norte Chico region (26–32°S). *Water Resources Research* **45** (2).

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D. L., Obersteiner, M. & Riahi, K. 2017 The marker quantification of the shared socioeconomic pathway 2: a middle-of-the-road scenario for the 21st century. *Global Environmental Change* **42**, 251–267.

Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D. S., Dai, H., Hijioka, Y. & Kainuma, M. 2017 SSP3: AIM implementation of shared socioeconomic pathways. *Global Environmental Change* **42**, 268–283.

Garreaud, R. D., Alvarez-Garreton, C., Barichivich, J., Boisier, J. P., Christie, D., Galleguillos, M., LeQuesne, C., McPhee, J. & Zambrano-Bigiarini, M. 2017 The 2010–2015 megadrought in central Chile: impacts on regional hydroclimate and vegetation. *Hydrology and Earth System Sciences* **21** (12), 6307–6327.

Garreaud, R. D., Boisier, J. P., Rondanelli, R., Montecinos, A., Sepúlveda, H. H. & Veloso-Aguila, D. 2020 The central Chile mega drought (2010–2018): a climate dynamics perspective. *International Journal of Climatology* **40** (1), 421–439.

Gascoin, S., Lhermitte, S., Kinnard, C., Bortels, K. & Liston, G. E. 2013 Wind effects on snow cover in Pascua-Lama, Dry Andes of Chile. *Advances in Water Resources* **55**, 25–39.

Haith, D. A., Mandel, R. & Wu, R. S. 1992 *Generalized Watershed Loading Functions Version 2.0 User's Manual*. Department of Agricultural and Biological Engineering, Cornell University, Cornell University, Ithaca, New York, p. 62.

Harrington, J. S., Mozil, A., Hayashi, M. & Bentley, L. R. 2018 Groundwater flow and storage processes in an inactive rock glacier. *Hydrological Processes* **32** (20), 3070–3088.

Hewitt, K. 2011 Glacier change, concentration, and elevation effects in the Karakoram Himalaya, Upper Indus Basin. *Mountain Research and Development* **31** (3), 188–200.

Hilbich, C., Hauck, C., Mollaret, C., Wainstein, P. & Arenson, L. U. 2022 Towards accurate quantification of ice content in permafrost of the Central Andes – Part 1: Geophysics-based estimates from three different regions. *The Cryosphere* **16** (5), 1845–1872.

Hill, M. 2013 Adaptive capacity of water governance: cases from the Alps and the Andes. *Mountain Research and Development* **33** (3), 248–259.

Hublart, P., Ruelland, D., Dezetter, A. & Jourde, H. 2013 Modelling current and future trends in water availability for agriculture on a semi-arid and mountainous Chilean catchment. *Cold and Mountain Region Hydrological Systems Under Climate Change: Towards Improved Projections*, vol. 360, pp. 26–32. IAHS-AISH P.

Hublart, P., Ruelland, D., Dezetter, A. & Jourde, H. 2014 Assessing the capacity to meet irrigation water needs for viticulture under climate variability in the Chilean Andes. *Hydrology in a Changing World: Environmental and Human Dimensions*. IAHS Publishing 363.

Hublart, P., Ruelland, D., Dezetter, A. & Jourde, H. 2015 Reducing structural uncertainty in conceptual hydrological modelling in the semi-arid Andes. *Hydrology and Earth System Sciences* **19** (5), 2295–2314.

Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R. S., Clague, J. J., Vuille, M., Buytaert, W., Cayan, D. R., Greenwood, G., Mark, B. G., Milner, A. M., Weingartner, R. & Winder, M. 2017 Toward mountains without permanent snow and ice. *Earth's Future* **5** (5), 418–435.

Immerzeel, W. W., Van Beek, L. P. & Bierkens, M. F. 2010 Climate change will affect the Asian water towers. *Science* **328** (5984), 1382–1385.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., Nepal, S., Pacheco, P., Painter, T. H., Pellicciotti, F., Rajaram, H., Ruppe, S., Sinisalo, A., Shrestha, A. B., Viviroli, D., Wada, Y., Xiao, C., Yao, T. & Baillie, J. E. M. 2020 Importance and vulnerability of the world's water towers. *Nature* **577** (7790), 364–369.

IPCC 2021 Climate change 2021: the physical science basis. In: *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R. & Zhou, B., eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA. In press. doi:10.1017/9781009157896..

Jansson, P., Hock, R. & Schneider, T. 2003 The concept of glacier storage: a review. *Journal of Hydrology* **282** (1–4), 116–129.

Jones, D. B., Harrison, S., Anderson, K. & Betts, R. A. 2018 Mountain rock glaciers contain globally significant water stores. *Scientific Reports* **8** (1), 1–10.

Jones, D. B., Harrison, S., Anderson, K. & Whalley, W. B. 2019 Rock glaciers and mountain hydrology: a review. *Earth-Science Reviews* **193**, 66–90.

Kinnard, C., Ginot, P., Surazakov, A., MacDonell, S., Nicholson, L., Patris, N., Rabate, A., Rivera, A. & Squeo, F. A. 2020 Mass balance and climate history of a high-altitude glacier, Desert Andes of Chile. *Frontiers in Earth Science* **8**, 40.

Kraaijenbrink, P. D., Stigter, E. E., Yao, T. & Immerzeel, W. W. 2021 Climate change decisive for Asia's snow meltwater supply. *Nature Climate Change* **11** (7), 591–597.

Krainer, K. & Mostler, W. 2002 Hydrology of active rock glaciers: examples from the Austrian Alps. *Arctic, Antarctic, and Alpine Research* **34** (2), 142–149.

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Leon Bodirsky, B., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J. P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F. & Edenhofer, O. 2017 Fossil-fueled development (SSP5): an energy and resource intensive scenario for the 21st century. *Global Environmental Change* **42**, 297–315.

Krogh, S. A., Pomeroy, J. W. & McPhee, J. 2015 Physically based mountain hydrological modeling using reanalysis data in Patagonia. *Journal of Hydrometeorology* **16** (1), 172–193.

Levizzani, V. & Cattani, E. 2019 Satellite remote sensing of precipitation and the terrestrial water cycle in a changing climate. *Remote Sensing* **11** (19), 2301.

MacDonell, S., Kinnard, C., Mölg, T., Nicholson, L. & Abermann, J. 2013 Meteorological drivers of ablation processes on a cold glacier in the semi-arid Andes of Chile. *The Cryosphere* **7** (5), 1513–1526.

Mancosu, N., Snyder, R. L., Kyriakakis, G. & Spano, D. 2015 Water scarcity and future challenges for food production. *Water* **7** (3), 975–992.

Masiokas, M. H., Rabatel, A., Rivera, A., Ruiz, L., Pitte, P., Ceballos, J. L., Barcaza, G., Soruco, A., Bown, F., Berthier, E., DussailLant, I. & MacDonell, S. 2020 A review of the current state and recent changes of the Andean cryosphere. *Frontiers in Earth Science* **8**, 99.

Mena, D., Solera, A., Restrepo, L., Pimiento, M., Cañón, M. & Duarte, F. 2021 An analysis of unmet water demand under climate change scenarios in the Gualí River Basin, Colombia, through the implementation of Hydro-BID and WEAP hydrological modeling tools. *Journal of Water and Climate Change* **12** (1), 185–200.

Mernild, S. H., Liston, G. E., Hiemstra, C. A., Yde, J. C. & Casassa, G. 2018 Annual river runoff variations and trends for the Andes Cordillera. *Journal of Hydrometeorology* **19** (7), 1167–1189.

Mills-Novoa, M., Borgias, S. L., Crootof, A., Thapa, B., De Grenade, R. & Scott, C. A. 2017 Bringing the hydrosocial cycle into climate change adaptation planning: lessons from two Andean mountain water towers. *Annals of the American Association of Geographers* **107** (2), 393–402.

Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., Cauvy-Fraunié, S., Gíslason, G. M., Jacobsen, D., Hannah, D. M., Hodson, A. J., Hood, E., Lencioni, V., Ólafsson, J. S., Robinson, C. T., Tranter, M. & Brown, L. E. 2017 Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences* **114** (37), 9770–9778.

Monnier, S. & Kinnard, C. 2015 Internal structure and composition of a rock glacier in the dry Andes, inferred from ground-penetrating radar data and its artefacts. *Permafrost and Periglacial Processes* **26** (4), 335–346.

Monnier, S., Kinnard, C., Surazakov, A. & Bossy, W. 2014 Geomorphology, internal structure, and successive development of a glacier foreland in the semiarid Chilean Andes (Cerro Tapado, upper Elqui Valley, 30 08′ S., 69 55′ W.). *Geomorphology* **207**, 126–140.

Moreda, F. & Coli, P. 2017 *Hydro-BID Case Study No. 5: Impact of Climate Change on Proposed Water Investments in Chalpi Basin, Ecuador*. Report IDB-TN-1365. Water and Sanitation Division, Inter-American Development Bank.

Moreda, F., Miralles-Wilhelm, F., Muñoz Castillo, R. & Coli Valdes Daussa, P. 2014a *Hydro-BID Case Study No. 2: Modeling the Impact of Climate Change on Flows of the Rio Piura Using Hydro-BID*. Report IDB-TN-1362. Infrastructure and Environment Department Water and Sanitation Division, Inter-American Development Bank.

Moreda, F., Mirallesm, W. & Muñoz, R. 2014b *Hydro-BID: An Integrated System for Modeling Impacts of Climate Change on Water Resources*. Report IDB-TN-529. Infrastructure and Environment Department Water and Sanitation Division, Inter-American Development Bank.

Moriasi, D. N., Gitau, M. W., Pai, N. & Daggupati, P. 2015 Hydrologic and water quality models: performance measures and evaluation criteria. *Transactions of the ASABE* **58** (6), 1763–1785.

Moreda, F., Lord, B., Nalesso, M., Coli, P. & Corrales, J. 2016 *Hydro-BID: New Functionalities (Reservoir, Sediment and Groundwater Simulation Modules)*. Report IDB-TN-1126. Water and Sanitation Division, Inter-American Development Bank.

Nalesso, M. & Coli, P. 2017 *Hydro-BID Step by Step Guide Hydro-BID Manual*. Water and Sanitation Division, Inter-American Development Bank.

Navarro, G., MacDonell, S. & Valois, R. 2023a A conceptual hydrological model of semiarid Andean headwater systems in Chile. *Progress in Physical Geography: Earth and Environment*. 03091333221147649.

Navarro, G., Valois, R., MacDonell, S., de Pasquale, G. & Díaz, J. P. 2023b Internal structure and water routing of an ice-debris landform assemblage using multiple geophysical methods in the semiarid Andes. *Frontiers in Earth Science* **11**, 1102620. doi:10.3389/feart.2023.1102620.

Omani, N., Srinivasan, R., Karthikeyan, R. & Smith, P. K. 2017 Hydrological modeling of highly glacierized basins (Andes, Alps, and Central Asia). *Water* **9** (2), 111.

Pellicciotti, F., Buergi, C., Immerzeel, W. W., Konz, M. & Shrestha, A. B. 2012 Challenges and uncertainties in hydrological modeling of remote Hindu Kush–Karakoram–Himalayan (HKH) basins: suggestions for calibration strategies. *Mountain Research and Development* **32** (1), 39–50.

Pourrier, J., Jourde, H., Kinnard, C., Gascoin, S. & Monnier, S. 2014 Glacier meltwater flow paths and storage in a geomorphologically complex glacial foreland: the case of the Tapado glacier, dry Andes of Chile (30 S). *Journal of Hydrology* **519**, 1068–1083.

Qin, Y., Abatzoglou, J. T., Siebert, S., Huning, L. S., AghaKouchak, A., Mankin, J. S., Hong, C., Tong, D., Davis, S. J. & Mueller, N. D. 2020 Agricultural risks from changing snowmelt. *Nature Climate Change* **10** (5), 459–465.

Rabatel, A., Castebrunet, H., Favier, V., Nicholson, L. & Kinnard, C. 2011 Glacier changes in the Pascua-Lama region, Chilean Andes (29 S): recent mass balance and 50yr surface area variations. *The Cryosphere* **5** (4), 1029–1041.

Ragettli, S. & Pellicciotti, F. 2012 Calibration of a physically based, spatially distributed hydrological model in a glacierized basin: on the use of knowledge from glaciometeorological processes to constrain model parameters. *Water Resources Research* **48** (3).

Ragettli, S., Cortés, G., McPhee, J. & Pellicciotti, F. 2014 An evaluation of approaches for modelling hydrological processes in high-elevation, glacierized Andean watersheds. *Hydrological Processes* **28** (23), 5674–5695.

Ragettli, S., Immerzeel, W. W. & Pellicciotti, F. 2016 Contrasting climate change impact on river flows from high-altitude catchments in the Himalayan and Andes Mountains. *Proceedings of the National Academy of Sciences* **113** (33), 9222–9227.

Réveillet, M., MacDonell, S., Gascoin, S., Kinnard, C., Lhermitte, S. & Schaffer, N. 2020 Impact of forcing on sublimation simulations for a high mountain catchment in the semiarid Andes. *Cryosphere* **14**, 147–163.

Riquelme, R., Rojas, C., Aguilar, G. & Flores, P. 2011 Late Pleistocene–Early Holocene paraglacial and fluvial sediment history in the Turbio valley, semiarid Chilean Andes. *Quaternary Research* **75** (1), 166–175.

Robson, B. A., MacDonell, S., Ayala, Á., Bolch, T., Nielsen, P. R. & Vivero, S. 2022 Glacier and rock glacier changes since the 1950s in the La Laguna catchment, Chile. *The Cryosphere* **16** (2), 647–665.

Rosas-Chavoya, M., Gallardo-Salazar, J. L., López-Serrano, P. M., Alcántara-Concepción, P. C. & León-Miranda, A. K. 2022 QGIS a constantly growing free and open-source geospatial software contributing to scientific development. *Cuadernos de Investigación Geográfica* **48** (1), 197–213.

Ruelland, D., Brisset, N., Jourde, H. & Oyarzun, R. 2011 Modelling the impact of climatic variability on the groundwater and surface flows from a mountainous catchment in the Chilean Andes. *Cold Regions Hydrology in a Changing Climate*, IAHS-AISH Publishing, vol. 346, pp. 171–179.

Saavedra, F. A., Kampf, S. K., Fassnacht, S. R. & Sibold, J. S. 2018 Changes in Andes snow cover from MODIS data, 2000–2016. *The Cryosphere* **12** (3), 1027–1046.

Scaff, L., Rutllant, J. A., Rahn, D., Gascoin, S. & Rondanelli, R. 2017 Meteorological interpretation of orographic precipitation gradients along an Andes west slope basin at 30 S (Elqui Valley, Chile). *Journal of Hydrometeorology* **18** (3), 713–727.

Schaffer, N. & MacDonell, S. 2022 Brief communication: a framework to classify glaciers for water resource evaluation and management in the Southern Andes. *The Cryosphere* **16**, 1779–1791. doi:10.5194/tc-16-1779-2022.

Schaffer, N., MacDonell, S., Réveillet, M., Yáñez, E. & Valois, R. 2019 Rock glaciers as a water resource in a changing climate in the semiarid Chilean Andes. *Regional Environmental Change* **19** (5), 1263–1279.

Schauwecker, S., Palma, G., MacDonell, S., Ayala, Á. & Viale, M. 2022 The snowline and 0°C isotherm altitudes during precipitation events in the dry subtropical Chilean Andes as seen by citizen science, surface stations, and ERA5 reanalysis data. *Frontiers in Earth Science* **10**, 875795.

Souvignet, M., Gaese, H., Ribbe, L., Kretschmer, N. & Oyarzun, R. 2008 *Climate Change Impacts on Water Availability in the Arid Elqui Valley, North Central Chile: A Preliminary Assessment*. IWRA World Water Congress, Montpellier, France.

Souvignet, M., Oyarzún, R., Verbist, K. M., Gaese, H. & Heinrich, J. 2012 Hydro-meteorological trends in semi-arid north-central Chile (29–32 S): water resources implications for a fragile Andean region. *Hydrological Sciences Journal* **57** (3), 479–495.

Stehr, A. & Aguayo, M. 2017 Snow cover dynamics in Andean watersheds of Chile (32.0–39.5 S) during the years 2000–2016. *Hydrology and Earth System Sciences* **21** (10), 5111–5126.

Stehr, A., Debels, P., Arumi, J. L., Romero, F. & Alcayaga, H. 2009 Combining the soil and water assessment tool (SWAT) and MODIS imagery to estimate monthly flows in a data-scarce Chilean Andean basin. *Hydrological Sciences Journal* **54** (6), 1053–1067.

Trigos, H. & Munizaga, I. 2006 *Análisis de Modelos Hidrológicos de Bases Físicas Para Cuencas Semiáridas y Estructuración Sistema de Simulación Cuenca rio Elqui*. Undergraduate Thesis, University of La Serena, La Serena, Chile.

Van Vuuren, D. P., Kriegler, E., O'Neill, B. C., Ebi, K. L., Riahi, K., Carter, T. R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R. & Winkler, H. 2014 A new scenario framework for climate change research: scenario matrix architecture. *Climatic Change* **122** (3), 373–386.

Velásquez, R., Coloma, F., Murillo, I., Merino, R. N. & Ortiz, M. 2021 Geología de las áreas Pisco Elqui y Paso del Agua Negra, región de Coquimbo. *Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica* 211–212: 201 p., 1 mapa escala 1:100.000.

Viviroli, D. & Weingartner, R. 2004 The hydrological significance of mountains: from regional to global scale. *Hydrology and Earth System Sciences* **8** (6), 1017–1030.

Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., Huang, Y., Koboltschnig, G., Litaor, M. I., López-Moreno, J. I., Lorentz, S., Schadler, B., Schreier, H., Schwaiger, K., Vuille, M. & Woods, R. 2011 Climate change and mountain water resources: overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences* **15** (2), 471–504.

Viviroli, D., Kummu, M., Meybeck, M., Kallio, M. & Wada, Y. 2020 Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability* **3** (11), 917–928.

Voordendag, A., Réveillet, M., MacDonell, S. & Lhermitte, S. 2021 Snow model comparison to simulate snow depth evolution and sublimation at point scale in the semi-arid Andes of Chile. *The Cryosphere* **15** (9), 4241–4259.

Wamucii, C. N., van Oel, P. R., Ligtenberg, A., Gathenya, J. M. & Teuling, A. J. 2021 Land use and climate change effects on water yield from East African forested water towers. *Hydrology and Earth System Sciences* **25** (11), 5641–5665.

Wyatt, A., Moreda, F., Miralles-Wilhelm, F. & Muñoz Castillo, R. 2014 *Caso de Estudio de Hydro-BID N 1: Modelo de Gestión del Recurso Hídrico en la Cuenca del Río Grande en Argentina*. Report IDB-TN-1361. Infrastructure and Environment Department Water and Sanitation Division, Inter-American Development Bank.

Yao, T., Bolch, T., Chen, D., Gao, J., Immerzeel, W., Piao, S., Thompson, L., Wada, Y., Wang, L., Wang, T., Wu, G., Xu, B., Wei Yang, W., Zhang, G. & Zhao, P. 2022 The imbalance of the Asian water tower. *Nature Reviews Earth & Environment* 1–15.

Zech, R., May, J. H., Kull, C., Ilgner, J., Kubik, P. W. & Veit, H. 2008 Timing of the late Quaternary glaciation in the Andes from ∼15 to 40° S. *Journal of Quaternary Science: Published for the Quaternary Research Association* **23** (6–7), 635–647.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S. U., Gärtner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S. & Cogley, J. G. 2019 Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature* **568** (7752), 382–386.

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