https://doi.org/10.5194/hess-2023-246
Preprint. Discussion started: 24 October 2023

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The influence of human activities on streamflow reductions during the megadrought in Central Chile

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Abstract. Central Chile has experienced a protracted megadrought since 2010 (up to date), with annual precipitation deficits ranging from 25% to 70%. Drought propagation has been intensified during this time, with streamflow reductions up to 30% larger than those expected from historical records. This intensification has been attributed to the cumulative effect of precipitation deficits associated to catchment memory in near-natural basins of central Chile. However, the additional effect of water extractions on drought intensification in disturbed basins remains an open challenge. In this study, we assess the effects of climate and water use on streamflow reductions during the last three decades in four major agricultural basins in central Chile, with particular focus on the ongoing megadrought. We address this by contrasting streamflow observations with near-natural streamflow simulations representing the discharge that would have occurred without water extractions. Near-natural streamflow estimations are obtained from rainfall-runoff models trained over a reference period with low human intervention (1960-1988). We characterise hydrological droughts driven by precipitation and human activities during the evaluation period (1988-2020) in terms of the frequency, duration and intensity of near-natural and observed seasonal streamflow deficits, respectively.

Our results show that before the megadrought onset (1988-2009), streamflow in the four basins was 2 to 20% lower than the streamflow during the undisturbed period. Between 81 to 100% of these larger deficits were explained by water extractions. During the megadrought (2010-2020), streamflow was reduced in a range of 47 to 76 % among the different basins, compared to the reference period. During this time, the climatic contribution to streamflow reductions increased and water extractions had a lower relative contribution, accounting for 27 to 51% of streamflow reduction. During the complete evaluation period, human activities have amplified the propagation of droughts, with more than double the frequency, duration, and intensity of hydrological droughts in some basins, compared to those expected by precipitation deficits only. We conclude that while the primary cause of streamflow reductions during the megadrought has been the lack of precipitation, water uses have not

diminished during this time, causing an exacerbation of the hydrological drought conditions and aggravating their impacts on human water consumption, economic activities, and natural ecosystems.

1 Introduction

The fluxes of the water cycle vary and change in time and space, as well as the anthropic activities affecting those fluxes, leading to a co-evolving hydrosocial cycle (Linton and Budds, 2014; Budds, 2012) that defines the state of the hydrological system (Van Loon et al., 2016). Observational evidence in different regions indicates that hydrological cycles are being affected by climate change and human activities. Climate change has led to changes in precipitation patterns worldwide (Fleig et al., 2010; Kingston et al., 2015), while human activities have altered the spatiotemporal distribution of water resources (Van Loon et al., 2022). This can potentially generate water scarcity problems, particularly when precipitation deficits occur in regions that concentrate water consumption requirements.

While meteorological droughts (precipitation deficits) are mainly controlled by regional climate, hydrological droughts (streamflow, and groundwater deficits) are also influenced by catchment characteristics and water uses. In this way, under similar meteorological conditions, the severity of hydrological droughts and their impacts on society can vary significantly within the territory (Van Lanen et al., 2013).

Most drought analyses consider climate variability as a main driver of drought, however, increasing focus has been given to assessing the compounding effects of climate variability and human activities on water resources and drought propagation (Van Loon et al., 2016; Wanders and Wada, 2015; Zhao et al., 2014). Anthropogenic activities, such as irrigation, urbanization, land use changes, and water infrastructure (e.g., reservoirs or water transfer channels) affect runoff mechanisms (Huang et al., 2016) and can lead to a higher frequency of hydrological droughts (Alvarez-Garreton et al., 2021; Ward et al., 2020). A notable example of this is the Yellow river basin in China, where despite not significant rainfall deficits have occurred in recent years, a hydrological drought with historical minimum flow levels is being observed, which has been mainly dominated by anthropic uses in the basin (Huang et al., 2016; Kong et al., 2016; Li et al., 2019; Liu et al., 2016; Zhao et al., 2014).

Advancing our understanding of hydrological droughts as a complex process depending on the interaction between climatic, biophysical, and anthropic drivers is critical to assess a catchment's vulnerability to droughts, mitigate their occurrence, and design adaptation plans. While all these drivers influence the propagation and impacts of droughts, adaptation and mitigation water management plans mainly influence on human activities. Therefore, it is critical to address the scientific challenge of understanding the influence of human activities on the hydrological cycle and quantifying their impacts.

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To address this challenge, in this paper we focus in central Chile (29°-35°S; Fig. 1), a region where the signal of anthropogenic climate change is leading to an increase in mean temperature, increasing of heatwaves events, and a sustained decrease in precipitation (Boisier et al., 2018; Bozkurt et al., 2017; Garreaud et al., 2017, 2020; González-Reyes et al., 2023). The drying trend has led to the so-called megadrought, affecting the country since 2010, with annual precipitation deficits ranging between 25% and 70% (Garreaud et al., 2020, 2017). This meteorological drought in central Chile has propagated across the terrestrial system, leading to hydrological droughts and water scarcity problems that vary across the territory (Alvarez-Garreton et al., 2021; Duran-Llacer et al., 2020; Muñoz et al., 2020; Barría et al., 2021b).

For example, in the Petorca river basin, Muñoz et al. (2020) found that during the megadrought, streamflow, and water bodies of the upper parts of the basin were less affected than the mid and low areas of the valley, where most of the agriculture is located. However, the authors did not make a formal attribution study to disentangle the role of water consumption and climate on streamflow reduction. Another study was conducted on the Aculeo Lake, a natural reservoir in central Chile that dried up during the ongoing megadrought. Barría et al (2021b) performed an attribution exercise and used the Water Evaluation and Planning System (WEAP) hydrological model and concluded that climate was the primary factor explaining the lake's drying, while water demand has remained stable over the past few decades. Furthermore, higher than expected streamflow reductions during the megadrought have also been observed in near-natural basins. Alvarez-Garreton et al. (2021) reported the effects of catchment memory in snow-dominated catchments in Central Chile, where the accumulation of the persistent precipitation deficits led to less streamflow than expected from observations during previous single-year meteorological droughts. Although there have been some insights of the role of catchments and anthropic characteristics in the megadrought's propagation, the impact of human activities on streamflow reduction and drought conditions in the major basins of central Chile remains unclear.

In this article, we quantify the relative effects of climate and water extractions on streamflow reduction during the megadrought (2010-2020) and before it (1988-2010) in four major agricultural basins in central Chile. Additionally, we assess the influence of water extractions on the intensity, frequency, and duration of hydrological droughts for the same period. To achieve this, we follow the approach proposed by Van Loon et al. (2022) and compare streamflow observations with a near natural simulated flow representing the discharge that would have occurred without human influences.

2 Methods and data

2.1 Study area

The study was conducted in four major basins located between 29º and 33°S (Fig. 1): The Elqui, Limarí, and Choapa basins in the Coquimbo region, and the Aconcagua basin in the Valparaíso region. These basins fall within semi-arid (Coquimbo region) and mediterranean (Valparaiso region) climate zones, which are particularly vulnerable to droughts due to the majority of annual precipitation occurring during a few winter events (Garreaud et al., 2017).

All catchments feature a snow-rain-fed hydrologic regime. The Aconcagua basin also has a large glacier area (192 km^2) that contributes to runoff, especially during dry summers (Crespo et al., 2020). The study basins have experienced precipitation deficits of 25-70% and streamflow deficits of up to 70% during the megadrought that has affected the region since 2010 (Alvarez-Garreton et al., 2021; Garreaud et al., 2020, 2017).

According to the data provided by the water security platform from the Center for Climate and Resilience Research (www.seguridadhidrica.cl), agriculture is the primary productive sector and the main consumer of water resources within these basins. Agricultural lands cover areas of 152 km^2, 605 km^2, 313 km^2, and 582 km^2, and their annual water consumption at present corresponds to 3.25 m^3/s, 14.3 m^3/s, 6.48 m^3/s, and 15.72 m^3/s, in the Elqui, Limarí, Choapa, and Aconcagua basins, respectively. Avocado and table vine species are the main consumers in the Aconcagua basin, while the Limarí basin has a higher demand from permanent forage species, table vine, and citrus plantations.

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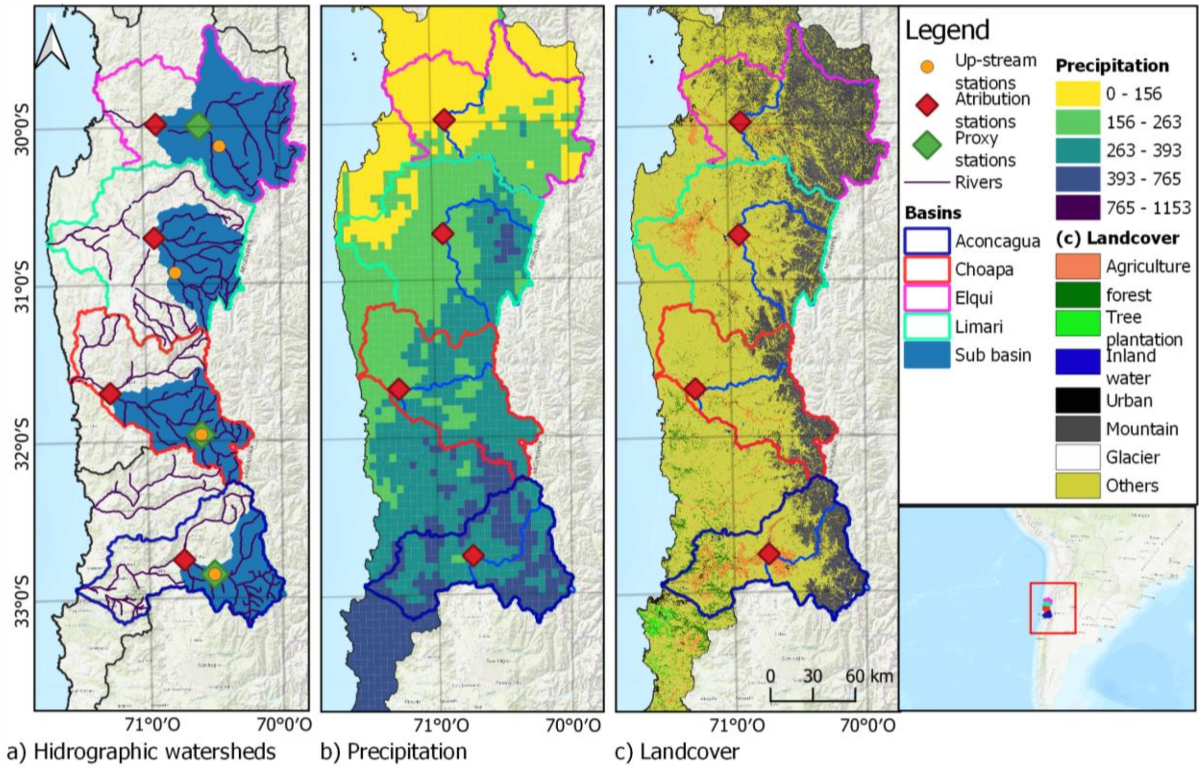

Figure 1. Panel a) shows the four main basins of the study area and the streamflow gauges used for the analyses. The red diamonds indicate the stations used to characterise each basin; the green diamonds are the gauges used as predictors for filling in monthly streamflow data (Sect. 2.2); and the orange circles are the up-stream stations used in the rainfall-runoff ratio analysis (Sect. 2.3). The basin area covered by the red diamond gauge is painted blue. Panel b) presents the mean annual precipitation (mm/yr) from the CR2MET dataset for the period 1980-2010. Panel c) shows the gridded land cover dataset from Zhao et al. (2016). Base map source: Esri, 2017.

2.2 Data

Times series of monthly streamflow and runoff (streamflow normalised by catchment area) were obtained from the CAMELS-CL dataset (Alvarez-Garreton et al., 2018; available at: https://camels.cr2.cl/) for the period April 1960 – March 2020. Catchment-scale monthly precipitation for the same period was obtained from the CR2MET dataset version 2.5 at a 5 x 5 km grid resolution (Boisier, 2023) and averaged across the basin polygons. Catchment-scale monthly evapotranspiration (ET) was computed based on the ECMWF surface re-analysis ERA5-Land dataset, available at a horizontal resolution of 10 km (Muñoz-Sabater et al., 2021) from April 1960 to March 2020. For each study basin, we selected the most downstream streamflow gauge station having more than 80% of streamflow records for the 1960-2020 period (see Fig. 1). Gaps in monthly streamflow of downstream gauges (red diamonds in Fig. 1a) were filled based on linear regression models, using the basin's precipitation and the streamflow of an upstream gauge with a strong correlation with the considered station (green diamonds in Fig. 1a) as

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predictors. The linear regressions resulted in coefficients of determination larger than 0.8 in Elqui, Choapa, and Aconcagua basins.

Streamflow and basin-averaged precipitation and ET were computed for hydrological years (April to March in Chile) and for wet and dry seasons. The wet season is defined from April to August, while the dry season corresponds to the months between September and March. Annual (seasonal) streamflow values were computed when the 12 (6) months had valid data.

To account for human intervention within the basins, we analysed annual water uses from industry, energy, mining, livestock, drinking water sectors, as well as water evaporation from lakes and reservoirs for the period 1960-2020 obtained from the water security platform from the Center for Climate and Resilience Research (www.seguridadhidrica.cl). All variables with a different spatial resolution than the basin (whether gridded or associated with an administrative unit) were calculated for the basin considering the weighted average of the variable within the basin surface.

2.3 Near-natural streamflow modelling and attribution exercise

The attribution exercise to quantify the climatic and human contributions on streamflow reductions is schematized in Fig. 2. Near-natural streamflow simulations were obtained by rainfall-runoff statistical models trained in periods when anthropic activities had low water consumption (Sharifi et al., 2021; Zhao et al., 2014).

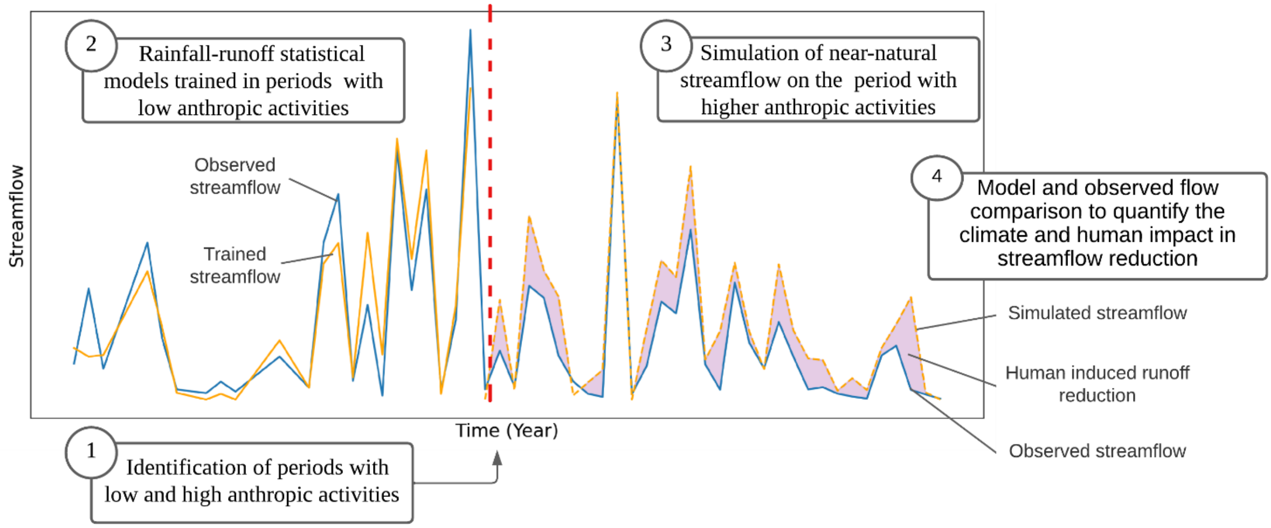

Figure 2. Flowchart of the steps to quantify the human contribution to streamflow reduction based on comparing a near-natural simulated streamflow with the observed streamflow on a period of high anthropic activities.

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2.3.1 Selection of low-influence training periods

For each basin, we identified low human intervention periods based on the regime shifts of streamflow, precipitation, and anthropic variables (Sect. 2.2). The non-parametric Buishand break point test (Buishand, 1982) was applied to identify regime shifts. Buishand is a statistical homogeneity test method that checks if two (or more) datasets come from the same distribution. In this way, the test can detect breakpoints where the distribution of a dataset changes. We applied the Buishand test to each time series during the 1960-2020 periods. To identify multiple breakpoints, we iterated the test in the sub-periods before and after the previous breakpoint until no breakpoints with a significance level at p-value < 0.05. For the Buishand test, we used the pyHomogeneity Python library (Shourov, 2020).

Subsequently, a singular training period was selected across basins based on the identification of concurrent breaking points in both streamflow and human activities time series, while ensuring the absence of discernible precipitation shifts. By employing this approach, we ensure the selection of streamflow breakpoints that are not predominantly influenced by climatic variations.

To ensure that the chosen period of analysis is not dependent on the specific statistical test employed, we conducted a sensitivity analysis using the Sequential T-test Analysis of Regime Shifts (STARS) at a monthly time scale for both precipitation and streamflow time series (Rodionov, 2004). The STARS V6.3 Excel macro application, available at https://sites.google.com/view/regime-shift-test was utilized to perform the Rodionov test.

2.3.2 Climate and human contribution to streamflow reduction

Assuming that the effects of climate and local human activities on streamflow generation are independent, the observed streamflow (Q_{obs}) can be disaggregated as follows (Kong et al., 2016):

$$Q_{obs} = Q_{nn} + \Delta Q_{human} \quad (1)$$

Where Q_{nn} corresponds to a climatic-induced streamflow, referred as near-natural streamflow in this paper, and ΔQ_{human} is the human-induced effect on streamflow. In this study, near-natural streamflow in Eq.1 is estimated from linear rainfall-runoff regressions trained in the low-influence reference period defined in Sect. 2.3.1. To account for pluvial and snowmelt runoff generation processes, we implemented seasonal rainfall-runoff models. In several snow-dominated basins in central Chile, the winter flows continue to be fed by the snow accumulation of the previous hydrological year, especially when the previous year was wetter than normal (Alvarez-Garreton et al., 2021). Given this, to model winter flows, winter precipitation of the previous year is added as a predictor as follows:

$$Q_{summer}(t) = a_0 + a_1 P_{winter}(t) \quad (2)$$

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$$Q_{winter}(t) = b_0 + b_1 P_{winter}(t) + b_2 P_{winter}(t-1) \quad (3)$$

The coefficients in Eq. 2 and 3 were obtained by least square errors method during the training period. Based on this, the human influence during an evaluation (high-influence) period is obtained as:

$$\Delta Q_{human} = Q_{obs} - \widehat{Q_{nn}} \pm \varepsilon \quad (4)$$

where $\widehat{Q_{nn}}$ is the simulated near-natural streamflow (Eq. 2 and 3) and ε represents the uncertainty of the regression model. The attribution exercises were performed by applying Eq. 4 during the evaluation period. Noteworthy that multiple regression equations with different functional forms and variables -including evapotranspiration and temperature- were tested for representing near-natural streamflow during the reference period. The linear rainfall-runoff regressions from equations (2) and (3) were those with a higher r^2, and all variables statistically significant at a p-value of 0.05.

It should be noted that the near-natural streamflow estimations from Eq. 2 and 3 assume a stationary rainfall-runoff relationship. However, recent evidence has shown that, under protracted drought conditions, there is a non-stationary catchment response modulated by catchment memory that causes larger streamflow reductions to those expected from single-year precipitation deficits before the megadrought (Alvarez-Garreton et al., 2021). This evidence corresponds to the headwater near-natural basins located upstream of the human influenced basins selected in this study. To assess whether our analyses over the complete basins are potentially biased by non-stationary catchment responses, we compare the rainfall-runoff ratios (mean annual runoff normalised by mean annual precipitation) during the evaluation period before (1988-2010) and after the megadrought onset (2010-2020), in both the upper and lower sections of each basin, defined by the streamflow gauges highlighted in orange circles and red diamonds in Fig. 1, respectively.

2.4 Hydrological drought characterisation

To quantify the impact of human activities on hydrological droughts, we compared the characteristics of the observed and the near-natural streamflow deficits during drought events, including their frequency (number of drought events), duration (average, maximum and total), and intensity (i.e., deficit of volume) across the evaluation period. In this way, we can assess the relative influence of climate and human activities on the observed streamflow deficits, as schematised in Fig. 3.

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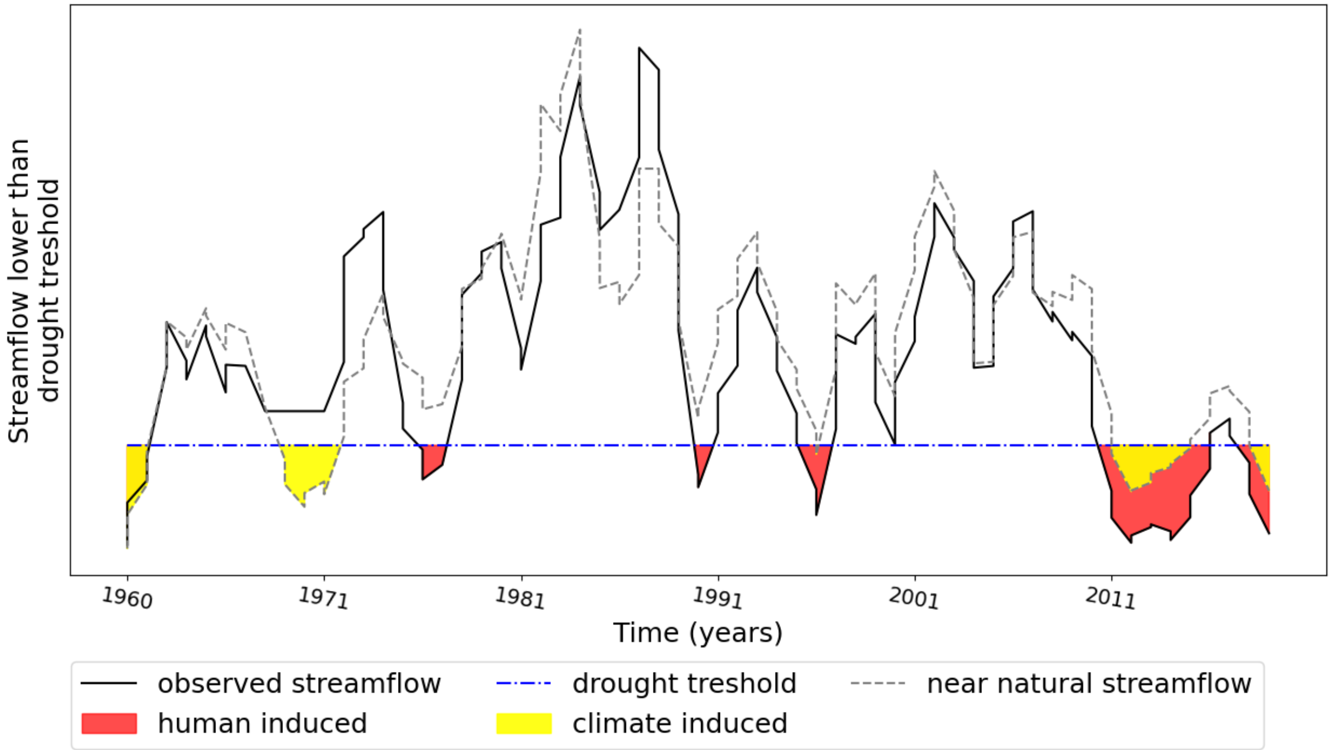

Figure 3. Example of drought periods with annual streamflow lower than a drought threshold. Three types of droughts are identified: climate-induced droughts, when near-natural streamflow simulations are below the threshold; human-induced droughts, where only observations are below the threshold; and human and natural induced, where both observatinos and near-natural estimations are below the threshold (adapted from Van Loon et al., 2016).

To identify drought events, thresholds based on percentiles of the flow duration curve are commonly used. For daily or monthly time series, a recommended threshold falls between the 70th and 90th percentile (Rangecroft et al., 2019; Van Loon et al., 2016; Van Loon, 2015). In this study, the 80th percentile of the seasonal flow series is adopted to define hydrological droughts. The threshold can be fixed or variable; we used the variable threshold to incorporate seasonality into the threshold (Rangecroft et al., 2019; Van Loon et al., 2019).

To allow for a strict assessment of human influence on hydrological drought, the selected threshold should not account for human activities (Rangecroft et al., 2019). If streamflow observations for the complete period were considered, human activities would be included. On the other hand, if only the training low-influence periods were used to calculate the threshold, the climate variability and drying trend of the complete period would not be represented by the threshold. Therefore, following the approach of Rangecroft et al. (2019), we define the drought threshold using the entire period of records (1960-2020) but

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considering a naturalised regime. To this end, we used the observed streamflow during the training period and the near-natural simulated streamflow during the evaluation period to establish the 80th percentile of the seasonal threshold.

3 Results

3.1 Low-influence periods

The series of annual streamflow, precipitation, total evapotranspiration (ET), and runoff coefficients (runoff normalised by precipitation) are shown in Fig. 4. The Buishand test resulted in significant change points only in streamflow and ET. Three change points were detected in all basins, the first between the years 1977-1978, the second one in 1988, and the last one between years 1998-2010 years for the streamflow in all basins (Fig. 4), while a single change point was detected in 1973-1975 for ET in all basins except Aconcagua. The Rodionov STARS test detected similar three change points in streamflow in 1977 -1981, 1988, and 2010, with the 1988 breakpoint presenting the higher R-shift index value.

In order to select periods with minimal human activities, it is important to identify breakpoints in the streamflow time series that are not primarily explained by climate shifts. The streamflow breakpoint of 1977-1978 is disregarded since it is mainly due to climate drivers, as indicated by the single ET breakpoint during that period. We can relate this to the great Pacific shift and the warm cycle of the Pacific Decadal Oscillation (PDO) between 1977 and the mid-1990s (Kayano et al., 2009; Jacques-Coper and Garreaud, 2015; González-Reyes et al., 2017). Additionally, the 2010 Aconcagua streamflow breakpoint is likely driven by the onset of the megadrought, which also affected the 2004 change points in the Limarí and Choapa Basins where lower precipitation was observed even before the megadrought.

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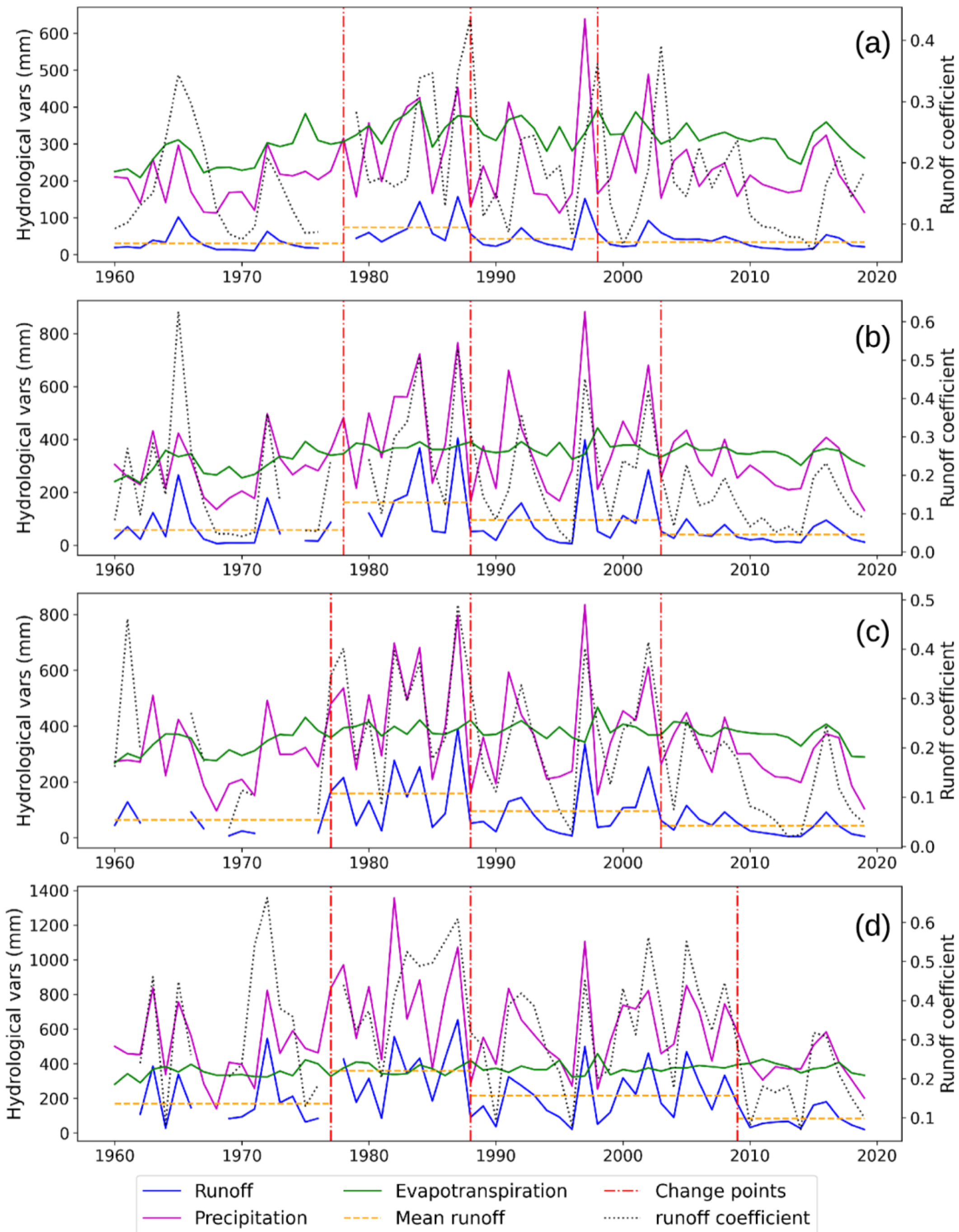

Figure 4. Annual streamflow, precipitation, evapotranspiration, and runoff coefficient during the complete period (1960-2020) for Elqui (a), Limarí (b), Choapa (c), and Aconcagua (d) Basins, respectively. The vertical red line indicates the years where significant change points (P value < 0.05) on streamflow distribution are detected by the Buishand test.

Regarding water use, breakpoints were observed in Elqui and Limarí in 1988 and 1992, respectively, mainly associated to the growth of the agricultural sector (Fig. 5). In the Aconcagua basin, a breakpoint occurred in 1985 due to intensified water use by the mining and agriculture sectors. Meanwhile, in the Choapa basin, a significant increase in mining water consumption since 2000 explains the time series breakpoint observed in that year. The 1998 Elqui Basin streamflow breakpoint may be attributed to the construction of a dam upstream from the gauge station considered in this study (Fig. 5). Based on these results, we used the 1988 streamflow breakpoint observed in all basins to define the low-influence period of 1960-1988. In consequence, the evaluation period was defined between 1988 and 2020, characterised by greater anthropogenic intervention and by the megadrought in its second half.

By comparing the hydroclimatic conditions of the study basins during the low-influence and evaluation periods, we see that the mean annual precipitation declined between 0 to 18% during these periods (Table 1). In contrast, the mean annual streamflow decreased by a range of 14 to 35%. If we examine summer streamflow, when agricultural water consumption is more intense, a reduction of 24 to 46% is observed. While the Aconcagua basin features the largest decrease in precipitation, the Choapa basin has the largest decrease in streamflow.

Basin	**Mean annual precipitation (mm)**			**Mean annual runoff (mm)**			**Mean summer runoff (mm)**		
	Low-influence period	Evaluation period	Difference	Low-influence period	Evaluation period	Difference %	Low-influence period	Evaluation period	Difference %
Elqui	232.83	232.73	0.0%	45.53	39,17	-15.9%	28.66	21.71	-24.3%
Limarí	355.13	336.78	-5.2%	95.91	66,92	-30.2%	54.50	33.87	-37.9%
Choapa	371.16	327.76	-11.7%	106.41	66,77	-37.2%	68.09	36.70	-46.1%
Aconcagua	634.61	533.76	-16%	258.42	173,87	-32.7%	193.29	119.82	-38.0%

Table 1: Average annual precipitation, average annual streamflow, and average summer season streamflow for each basin in the low-influence (1960-1988) and evaluation periods (1988-2020).

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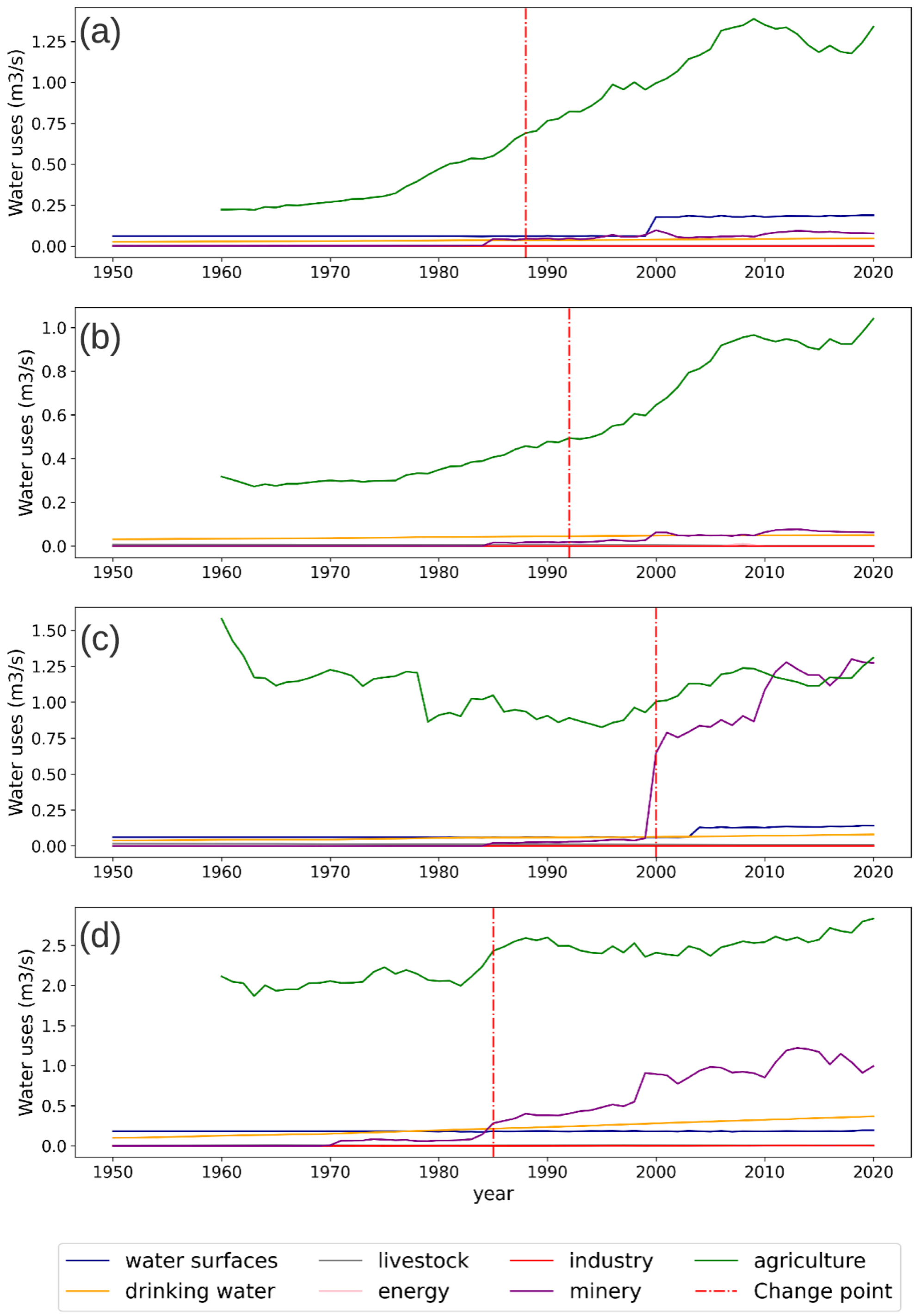

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238 **Figure 5. Time series of water uses from different human activities in Elqui (a), Limarí (b), Choapa (c), and Aconcagua (d) basins,**
239 **respectively. These time series include water uses for industrial, agriculture, mining, energy, animals, water surfaces, and drinking**
240 **water sectors. The red line indicates a breakpoint in the total water use distribution.**

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3.2 Near-natural streamflow estimation

Near-natural simulated streamflow during the low-influence and evaluation periods for each basin is presented in Fig. 6. The summer season estimations obtained from Eq. 2 had good performances during the training period, with mean biases of 0 to 5% and r^2 ranging from 0.8 to 0.89 for the different basins. The winter season models resulted in lower performance, with mean biases of 0 to 0.63% and r^2 ranging from 0.61 and 0.93 among the study basins (Table 2).

Basin	Season	r^2	Mean bias
Elqui	Summer	0.81	-0.01%
	Winter	0.69	0%
Limari	Summer	0.84	-5%
	Winter	0.86	0.63%
Choapa	Summer	0.89	-0.05%
	Winter	0.93	0.06%
Aconcagua	Summer	0.81	0%
	Winter	0.61	0%

Table 2: Seasonal model results in the calibration period.

To test the potential biases induced by non-stationary catchment response during the megadrought, Table 3 shows the rainfall-runoff ratios during the evaluation period before (1988-2010) and after the megadrought onset (2010-2020), in the upper and lower sections of each basin, respectively. These results indicate that the mean rainfall-runoff ratios declined across all sections and basins during the megadrought, however, the reduction in the upper sections, mostly attributed to endogenous runoff mechanisms and hydrological memory, is less significant than that those observed downstream. Specifically, the changes in downstream rainfall-runoff ratios are nearly four times greater than the upper stream changes in the Aconcagua and Elqui basins, more than twice as much in Choapa, and 1.6 times greater at the Limarí station, which is the sub-basin with the lowest level of human activity in our attribution exercise. This indicates that while endogenous runoff mechanisms, such as hydrological memory, may contribute to larger streamflow deficits during prolonged drought in near-natural basins, human activities in the downstream basins are inducing a larger impact in runoff generation during the megadrought.

	Basin	**Elqui**		**Limarí**		**Choapa**		**Aconcagua**	
	Section	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**
Period	1988 -2010	0.42	0.19	0.41	0.18	0.58	0.21	0.75	0.33
	2010 -2020	0.38	0.12	0.31	0.11	0.43	0.09	0.66	0.18
	Difference	9.03%	34.3%	25.2%	40.4%	24.94%	58.33%	11.94%	46.21%

Table 3: Average annual runoff coefficient during the change period without major climate events (1988-2010) and during the megadrought (2010-2020) for the upper and lower sections of each basin. The difference between the two periods relative to 1988-2010 is shown in the third row.

3.3 The impacts of climate and human activities on streamflow

During the evaluation period, the near-natural streamflow is higher than the observed streamflow in all the cases (Fig. 6) with mean biases in annual simulated streamflow ranging from 65% in the Limarí basin (simulated annual runoff of 55 mm and observed annual runoff of 36,7 mm) to 30% in the Aconcagua basin (simulated annual runoff of 155,4 mm and observed annual runoff of 119,8 mm).

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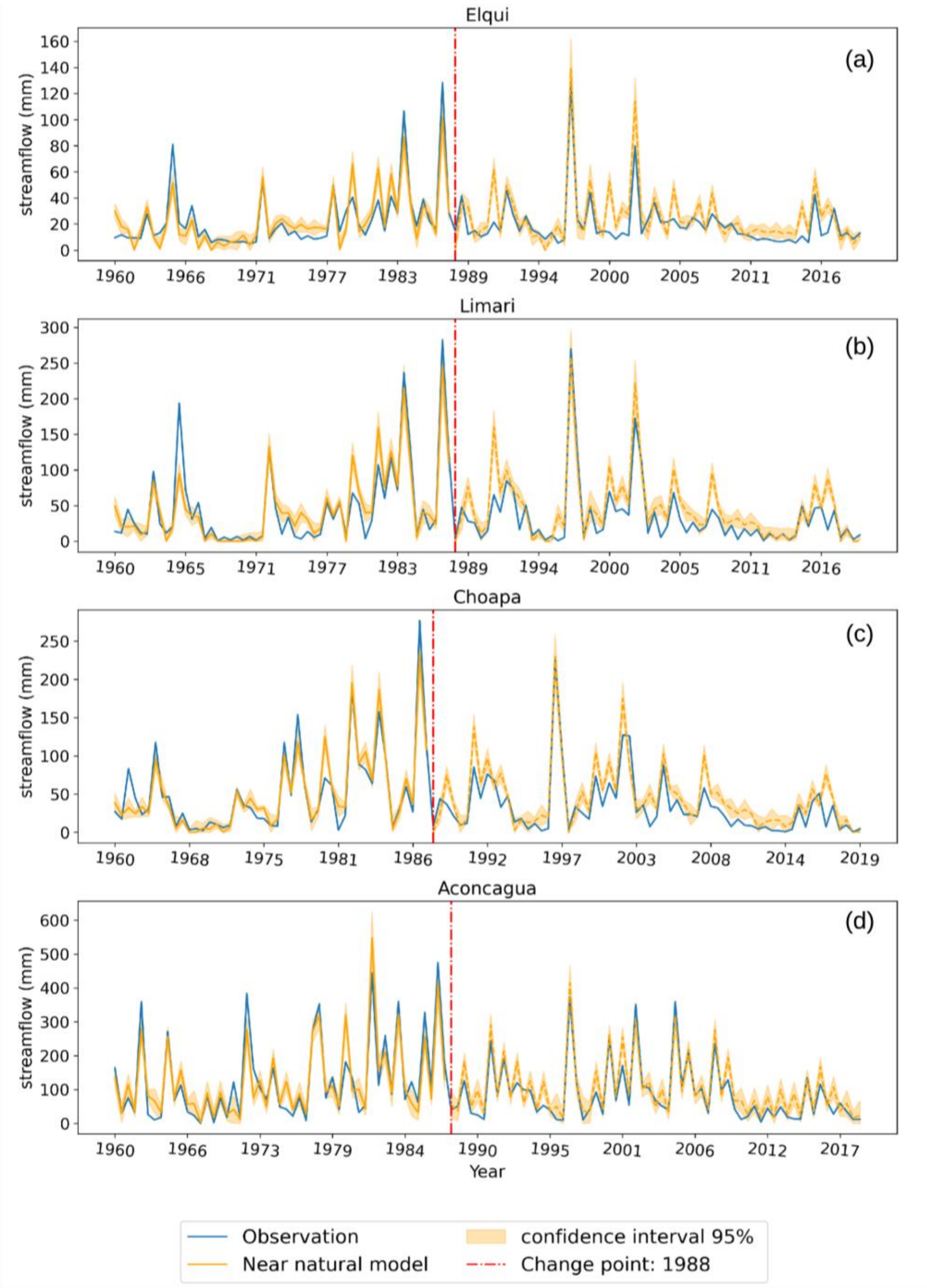

Figure 6. The observed and near natural simulated seasonal streamflow for Elqui (a), Limarí (b), Choapa (c), and Aconcagua (d) basins, respectively. The continuous yellow line represents the simulated streamflow on the reference period whose r^2 is presented on the legend. The dashed yellow line is the simulated streamflows on the change period after the breakpoint (red line). the yellow ban represents the 95% confidence interval.

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The relative impacts of climate and human activities on summer streamflow reductions during the evaluation period is presented in Fig. 7. This figure shows the annual anomalies of precipitation, observed and near-natural simulated streamflow, as well as the human-induced streamflow reduction obtained as the difference of the latter two (Eq. 4). The results for the annual fluxes are presented in Appendix A (Fig. A1).

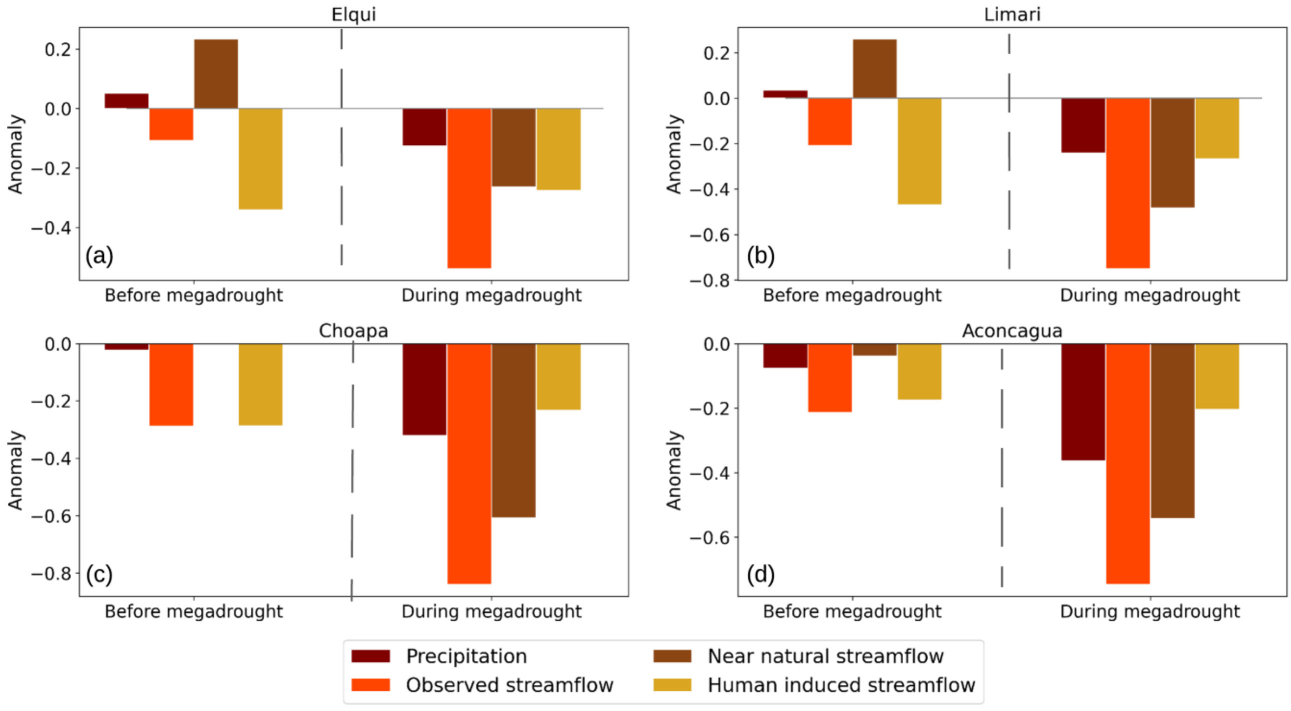

Figure 7: Anomalies in annual precipitation, observed summer streamflow and simulated near-natural summer streamflow, with the derived human-induced streamflow change for Elqui (a), Limarí (b), Choapa (c), and Aconcagua (d) basins. The anomalies are presented for the evaluation period before and after the megadrought onset (1988-2009 and 2010-2020, respectively). For each flux, the anomalies are computed as the percentage difference with respect to their mean values during the reference period (1960-1988).

Before the megadrought onset, annual precipitation varied between 5 to -7.6% with respect to the 1960-1988 reference period among the study basins. The resulting near-natural summer streamflow during that period followed the direction of the annual precipitation anomalies, with anomalies between 23 to -4% across basins. During that period, the observed summer streamflow accounting for full climatic and human influences decreased by 10-28%. This indicates that water uses for human activities were the driver factor of summer streamflow reduction before the megadrought onset, causing up to 100% of reduction in Elqui, Limarí and Choapa, and 82% in the Aconcagua Basin, respectively. The human-induced decrease on Aconcagua accounts for 33.8 mm over the total streamflow deficit of 41.3 mm.

After the megadrought onset, the relative impact of precipitation deficits and human activities on streamflow depletion changed. The annual precipitation anomalies during the megadrought varied between -13 to -36% across basins, while the near natural streamflow estimates present anomalies between -26% to - 61% with respect to the 1960-1988 reference period. During that period, the observed summer streamflow accounting for full climatic and human influences featured anomalies of -54% to -84%. This indicate that precipitation deficits dominate the streamflow reduction, however, there is still a relevant reduction of 7.9 mm, 11.9 mm, 15.5mm, and 39.5 mm attributed to human activities, representing 51%, 29%, 27%, and 27% of the total summer streamflow reduction in Elqui, Limarí, Choapa, and Aconcagua Basin, respectively.

Particularly noteworthy is the Aconcagua basin case, where the human induced total streamflow reduction during the megadrought (39.5 mm) is higher than in the period before the megadrought (33.8 mm) despite considerably less water availability (near natural summer streamflow estimates of 88.6 mm during the megadrought and 185,7 mm before the megadrought).

Consistently with the summer seasons, near-natural annual streamflow before the megadrought followed precipitation patterns, with anomalies between 22 to -5% across basins (Fig. A1). During that period, the observed annual streamflow varied between -2 to -20% across basins. Water uses for human activities were the driver factor of streamflow reduction before the megadrought onset, causing up to 100% of reduction in Elqui, Limarí and Choapa, and 71% in the Aconcagua Basin, respectively. After the megadrought onset, the observed streamflow featured anomalies of -47 to -71%. From these streamflow deficits a 44% to 75 % of the reduction is attributed to climatic-factors (i.e., anomalies represented by the near-natural simulated streamflow), while the remaining 25 to 56% is attributed to human activities.

3.4 The impacts of human activities on hydrological drought events

The hydrological drought events selected based on a seasonal threshold of 80th percentile of the near-natural streamflow (Sect. 2.4) are shown in Fig. 8. By contrasting the observed and near-natural time series, the climate-induced and human-induced droughts are distinguished. The meteorological megadrought (2010-2020) is identified as a series of hydrological drought events in the observed streamflow. In contrast, it does not seem as persistent and intense in the near-natural streamflow scenario.

The largest human impact on hydrological droughts is observed in the total seasons in drought and the total deficit (Table 4). Elqui, Choapa, and Aconcagua have 13, 8, and 10 extra seasons of drought, respectively, and more than double (triple in Choapa's case) deficit concerning the near natural scenario. Additionally, more drought events with a larger average time duration and average deficit have occurred in the observed scenario on the three basins previously mentioned. The largest drought event in each basin occurred during the megadrought. Across all basins, the human activities led to an increase in the maximum duration of hydrological droughts, with maximum values ranging between 4 to 10 seasons, in contrast to 1 to 4

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316 seasons experienced in the near-natural cases. In particular, this translates to five years of continuous streamflow below the
317 Q80 threshold on the Aconcagua basin.

Basin	**Hydrological Droughts**	**frequency**	**duration (seasons)**			**deficit (mm)**		
			Total season	Max duration	Average duration	Total deficit	Max deficit	Average deficit
Elqui	Near natural	5.0	5.0	1.0	1.0	21.1	10.5	4.2
	Observed	9.0	18.0	9.0	2.0	56.1	29.8	6.2
Limarí	Near natural	3.0	9.0	4.0	3.0	41.4	20.9	13.8
	Observed	6.0	13.0	4.0	2.2	47.5	20.4	7.9
Choapa	Near natural	5.0	10.0	4.0	2.0	36.1	19.6	7.2
	Observed	6.0	18.0	7.0	3.0	110.1	51.0	18.3
Aconcagua	Near natural	6.0	14.0	4.0	2.3	337.1	134.5	56.2
	Observed	10.0	24.0	10.0	2.4	732.0	276.7	73.2

318 **Table 4: drought characteristics for each basin considering the observed and simulated near natural streamflow during the**
319 **evaluation period (1988-2020).**

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Preprint. Discussion started: 24 October 2023

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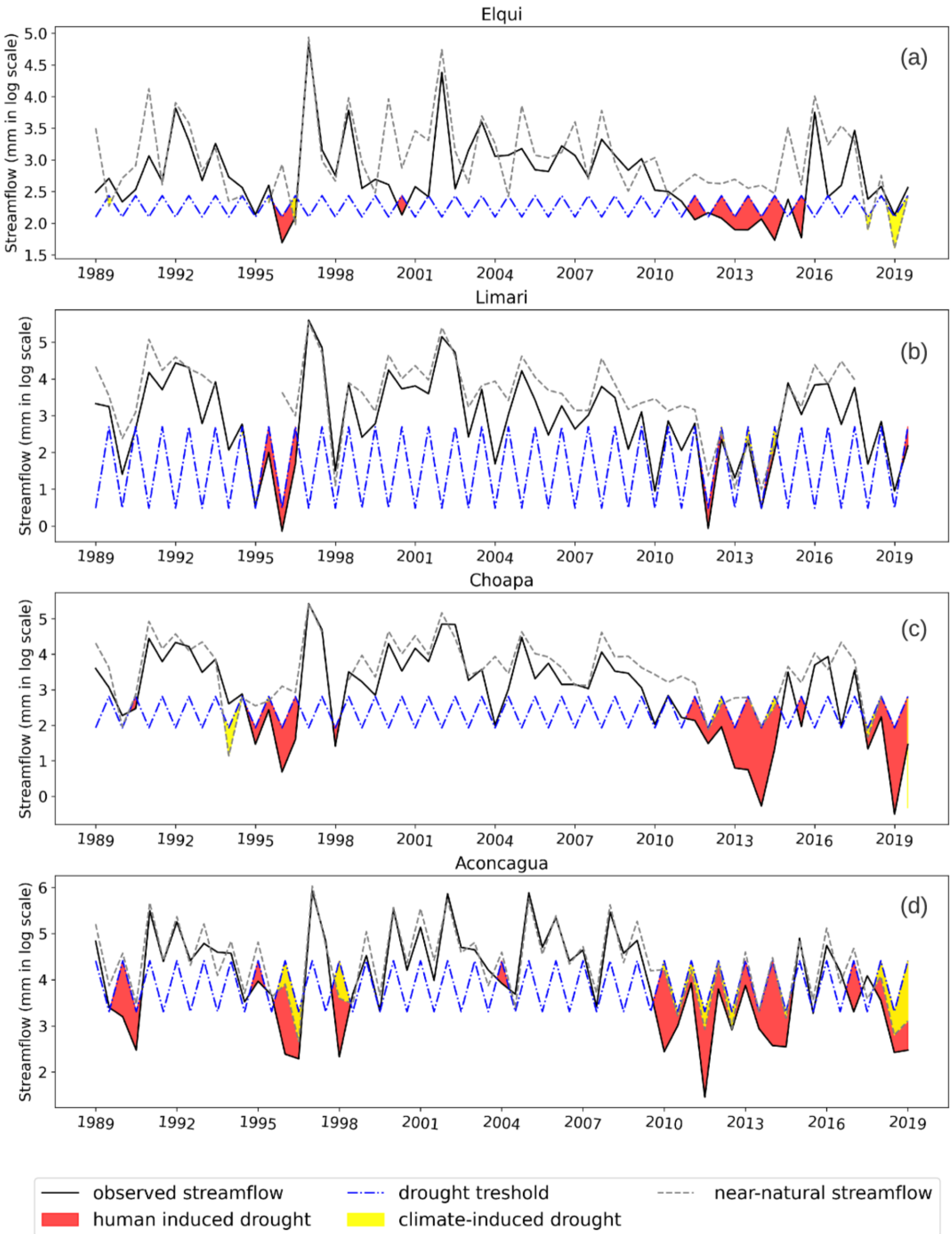

Figure 8. Observed and near-natural streamflow and hydrological drought events during the evaluation period (1988–2020) for Elqui (a), Limarí (b), Choapa (c), and Aconcagua (d) basins, respectively.

4 Discussion

4.1 Impact of increased human activities on water availability

During the megadrought, precipitation deficits have played a more significant role on the decrease in streamflow than anthropogenic factors, however, human activities still account for approximately 27 to 29% of the streamflow reduction in the Aconcagua, Choapa, and Limarí basins and 51% in Elqui, the basin least affected by the meteorological megadrought.

Human activities have intensified since the 1980s and 1990s, driven by rising water demand from economic activities, population growth, and land use changes (Fig. 5a), despite the precipitation deficits and streamflow reduction during the megadrought. This suggest that total water consumption has been inelastic to the surface water deficits. In the Aconcagua basin, the total water consumption increased during the megadrought, while in the other three basins, the human-induced streamflow reduction expressed as mm is slightly smaller during the megadrought, compared to the period prior to the megadrought (Fig. 7). This finding could be explained by an initial reduction in agricultural water consumption during the first years of the megadrought, which was later reversed (Fig. 5a) by higher extractions of groundwater sources in the subsequent years (Taucare et al., 2020; Duran-Llacer et al., 2020).

Human activities account for approximately 25% of the reduction in streamflow during the evaluation period in most basins, and their effects on hydrological droughts have been significant. Despite experiencing lower precipitation deficits, the Elqui basin shows a similar pattern of hydrological drought recurrence, total seasons, and maximum duration compared to the Choapa and Aconcagua basins. During the megadrought, this basin was the most affected by increased human activities, with the number of drought seasons increasing from 5 in the near natural scenario to 18 in the observed data. This suggests that increased and inelastic human water demands are particularly relevant in semi-arid basins with limited precipitation and high interannual variability in terms of precipitation regime, such as Elqui, making them more prone to experience a more severe hydrological drought during precipitation deficits. This is consistent with Huang (2016), who highlighted that sustainable agricultural development is threatened in arid and semi-arid regions due to limited available water resources, and with Saft et al. (2016), who demonstrated that aridity is a crucial factor influencing sensitivity to interdecadal climate variability.

4.2 Drought vulnerability

Hydrological drought vulnerability is associated with those conditions that cause an increase in the frequency, duration, and intensity of the hydrological droughts when a precipitation deficit threat is faced. Vulnerability should be addressed by looking for sensitivity variables that come from the biophysical basin's characteristics, such as aridity, location, geomorphology,

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Preprint. Discussion started: 24 October 2023

hydrological regime, natural land cover, and snow and glacier cover (Saft et al., 2015; Van Loon and Laaha, 2015), and human activities such as management and extraction of water, land use, land cover changes, urbanisation, between others (Barría et al., 2021a; Van Loon et al., 2016, 2022). Although several articles have assessed hydrological drought vulnerability by evaluating biophysical basin characteristics (Alvarez-Garreton et al., 2021; Van Loon and Laaha, 2015; Saft et al., 2015; Van Lanen et al., 2013), there is still a gap in understanding how human activities contribute to basin's vulnerability to drought.

As discussed in Sect. 4.1, human activities have intensified streamflow deficits during the megadrought. Although our results correspond to four basins in central Chile, the large streamflow deficits have been reported over a wider region, with a range of impacts on society and ecosystems. For example, (Miranda et al., 2020) reported that watercourses stopped flowing at certain periods of the year during the megadrought, while a significant effect has been observed on forest productivity with high tree mortality. Additionally, thousands of people have lost access to domestic water services (Muñoz et al., 2020). National statistics indicate that spending on cistern trucks to deliver potable water to rural communities in the six main watersheds of Coquimbo and Valparaíso regions reached US$56 million during 2010-2020. Human activities that affect catchment vulnerability in central Chile include groundwater extractions (Taucare et al., 2020), overallocation of water use rights (Alvarez-Garreton et al., 2021; Barría et al., 2021a), and continuous land use change for agricultural purposes (Madariaga et al., 2021). For example, agriculture is sometimes established on hillsides with high slopes, exacerbating water consumption problems and changing runoff mechanisms. In the entire Aconcagua basin, the water consumption of avocado plantations has increased 15% between 2014 and 2020, reaching almost 4.8 M3/s, while citrus plantations have increased 67-70% in the Elqui and Limarí basins since 2010, reaching 1.8 M3/s of water consumption in the Limarí basin. This reveals that water use for agriculture activities has been inelastic to the precipitation deficits during the megadrought. Human activities in these basins are adapting to less water availability in ways that are leading to aggravated water scarcity problems, which is consider in the literature as maladaptation (Schipper, 2020).

5 Conclusions

The megadrought in central Chile corresponds to the longest dry period over the last centuries. The study basins featured a range of 16-41% in mean annual precipitation deficits during this period, whereas the deficits in streamflow were significantly larger. The Elqui, Limarí, Choapa, and Aconcagua Basin experienced deficits in summer streamflow of 54%, 75%, 84%, and 75%, respectively.

Our findings indicate that human activities were the main driving factor of streamflow reduction before the megadrought began in 2010. During the megadrought, human activities still accounted for a significant portion of streamflow reduction, ranging from 27 to 51%. The impact of human activities on hydrological drought characteristics was substantial, leading to more than double the recurrence, duration, and intensity of droughts in some basins. Furthermore, our results show that human activities have dominated the decline of the rainfall-runoff ratios during the megadrought in the study basins.

Human activities in these basins show limited adaptation to the decreasing water availability. During the megadrought, new surface and underground water use rights have been granted (Barría et al., 2021b). The increase in human water demand, often inelastic to the decreased surface water availability, makes basins more vulnerable to severe hydrological droughts when precipitation deficits are faced, especially on semi-arid basins with water availability constraints.

This paper demonstrates that during long and persistent dry periods, human activities within the catchment strongly influence the intensity and duration of hydrological drought. To effectively adapt to climate change and avoid maladaptation measures, it is necessary to consider the feedback between water use, anthropogenic activity, and the hydrological system. These considerations are particularly important in Chile and other territories around the world, where the dry signal is consistent and expected to persist.

Data availability

The CR2MET dataset were obtained from the Center for Climate and Resilience Research website at https://www.cr2.cl/datos-productos-grillados (last access: 20 September 2023). The water use data was obtained upon request from the Center for Climate and Resilience Research website at https://seguridadhidrica.cr2.cl (last access: 20 September 2023). The streamflow data were obtained from CAMELS-CL dataset (Alvarez-Garreton et al., 2018), available at the Center for Climate and Resilience Research website at https://camels.cr2.cl (last access: 20 September 2023).

Author contributions

NA, CAG and AM conceived the idea of the research. NA performed the analyses. NA and CAG wrote much of the manuscript. All the authors reviewed early manuscript drafts and the final draft.

Competing interests

The contact author has declared that none of the authors has any competing interests.

Acknowledgements:

This research has been developed within the framework of the Center for Climate and Resilience Research (CR2, ANID/FONDAP/1522A0001), the research project ANID/FSEQ210001 and ANID/FONDECYT/1201714

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https://doi.org/10.5194/hess-2023-246
Preprint. Discussion started: 24 October 2023

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Appendix 1

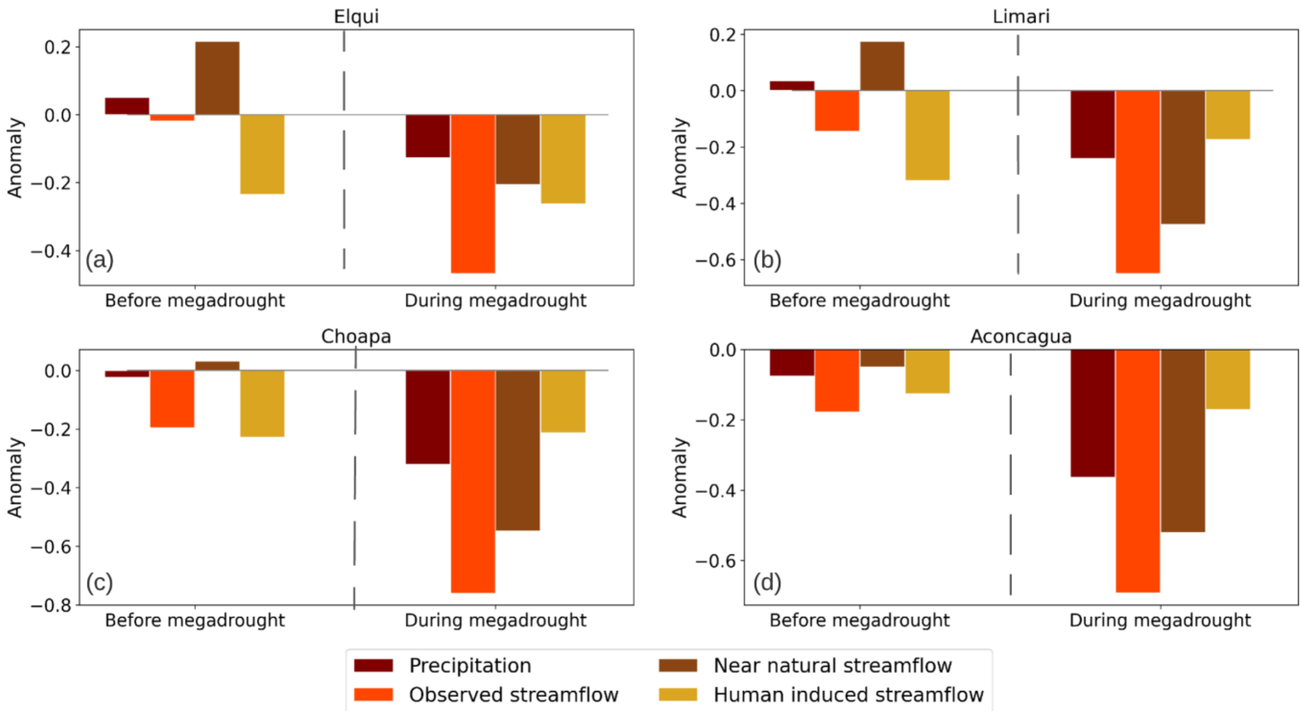

Figure A1: Anomalies in annual precipitation, observed streamflow, simulated near-natural streamflow and human-induced streamflow change. The anomalies are presented for the evaluation period before and after the megadrought onset (1988-2009 and 2010-2020, respectively). For each flux, the anomalies are computed as the percentage difference with respect to their mean values during the low-influence reference period (1960-1988). The graphs show these results for Elqui (a), Limarí (b), Choapa (c), and Aconcagua (d) Basins, respectively