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Brief Report

Climate Change and Overuse: Water Resource Challenges during Economic Growth in Coquimbo, Chile

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Abstract: The arid Coquimbo region of Chile has experienced a significant economic growth in recent decades, fueled in large part by water-intensive activities such as mining and agriculture. Under this context, a monthly and annual trend analysis of precipitation, streamflow, and piezometric levels was carried out. Thus, 43 pluviometric stations, 11 fluviometric stations, and 11 wells were selected. These stations were evaluated for their temporal trends using the Mann–Kendall test. Results revealed a significant decrease in river flows, with negative and significant trends concentrated in the mean and maximum flows, both at annual and monthly levels. Likewise, positive trends were found in the depth to water table on wells, with significant trends in 81.8% of the monthly cases, and in 72.7% of the annual cases. While also decreasing over the same period, rainfall trends exhibit high variability and lacked significance. Although the amounts of precipitation have decreased, this does not seem to be the main factor responsible for the scarcity of water in the region, but rather an excessive consumption of this resource. This is endorsed by the increase in GDP (Gross Domestic Product), which is explained by activities that consume water (mining and agriculture). Similarly, an increase in the granting of underground water rights was verified, which speaks of the high demands for the resource. However, future modeling is advised to better understand the regional hydrology of the area and quantify the anthropic effects on water resources more precisely.

Keywords: Chile; land use planning; water management; anthropogenic effects; sustainable water resources management

1. Introduction

Water is a critical natural resource for social, economic, and environmental development of Chile [1]. In the 1990–2017 period, Chile's Gross Domestic Product (GDP) tripled, a growth fueled by industries reliant on water resources such as mining and agriculture [2]. Chile has a high degree of geographical variability in water supply [3]. From Santiago to the north, where arid and semi-arid zones are located, the availability is less than 1000 m^3/inhabitant/year [4], which results in a situation of water stress [3,5] in territories dedicated mostly to mining, agriculture, and tourism [5]. Surface water rights in the Coquimbo Region were massively privatized and allocated between the 1980s and 2000s, in such a way that as of 2004 the basins were declared closed to access this type of right, after 95% of those rights were granted in that same year. Consequently, new demands from the private sector have been supplied with groundwater [6]. Resulting pressure on the aquifers with excessive concession of groundwater rights between latitudes 17°29′ S and 35° S [7] has led to conflicts among users [8]. The Region of Coquimbo is located within this territory.

Recent studies have concluded that climate change has affected this area due to a decrease in water supply [9–11]. This necessitates temporal understanding of regional variables such as rainfall, average and minimum river flows, maximum flows (which are the product of floods due to intense rains or thaws), and changes in water table (which expresses the pressure of groundwater use). We hypothesized that precipitation changes might affect water resources in the region, but the increase in the demand is most likely the main factor explaining the decrease in water supply, especially when considering the reduction in the volume of groundwater aquifers.

2. Materials and Methods

2.1. Study Domain

The Coquimbo Region is located between latitudes 29° S and 32° S (Figure 1) and has an area of 40,579 km^2 (5.4% of the Chilean territory). The local climate is semi-arid (Figure 1) with a rainfall pattern defined by 2–3 wet months in the winter and a territorial gradient where rainfall increases from north to south and from the coast towards the Andes [12]. Annual rainfall ranges from 60 mm in the north of the region to 300 mm in the south [13].

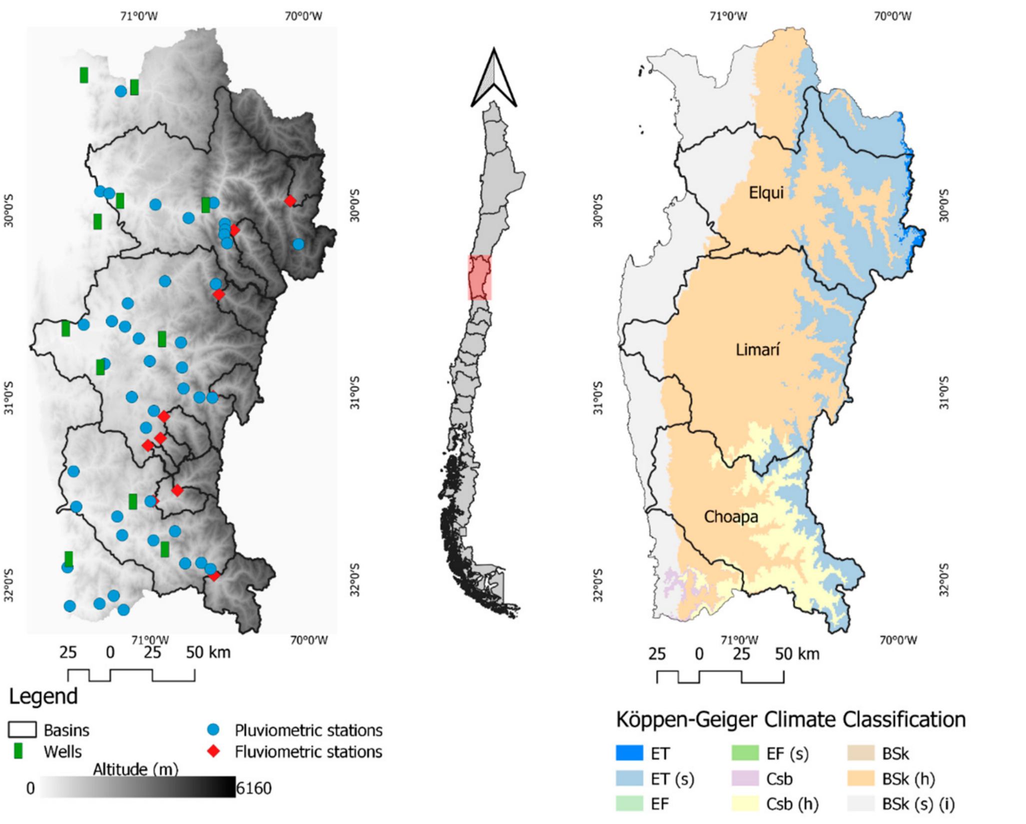

Figure 1. Location of the fluviometric, pluviometric, and piezometric stations, and climate classification of the Coquimbo Region in the Elqui, Limarí, and Choapa watersheds (layers available at: www.ide.cl and www.dga.cl. Accessed on 5 January 2020).

2.2. Data Synthesis and Trend Analysis

The study considered the 1984–2018 period based on public information gathered from the General Water Directorate (DGA, the Government agency in charge of water resources management) stations, with 43 rain gauges, 10 river flow stations, and 11 piezometers, as shown in Figure 1. It is noteworthily to point out that the periodicity of the water table level records is variable and can be between 6 and 12 measurements per year. For this reason, only the months whose records were present in a given studied year were evaluated, effectively reducing the annual number of months analyzed.

Temporal (monthly and annual) trend analyses were carried out using the Mann–Kendall statistical test [14,15] (Equation (1)). This test verifies the existence of trends and whether they are statistically significant for a given confidence level (5% significance). Furthermore, it has the advantage of not requiring the data to come from a parametric distribution [14,15].

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign\left(x_j - x_k\right) \quad (1)$$

where S is the Mann–Kendall statistic; the sign function $(x_j - x_k)$ will have the value "1" if $x_j - x_k > 0$; value "0" if $x_j - x_k = 0$; and value "−1" if $x_j - x_k < 0$. Similarly, x_j and x_k are consecutive values of the variable under study; n is the sample size; j and k represent two consecutive years; t_p represents the frequency of ties in a group; and q is the number of groups with ties (p). Then, the variance $VAR(S)$ is described in Equation (2).

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p\left(t_p - 1\right)\left(2t_p + 5\right)\right] \quad (2)$$

Finally, with both values, Z (the standardized test statistic) is calculated with one of the following expressions (Equation (3)), depending on the result from Equations (1) and (2) (see more details in Cabral and Lucena [16]):

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} \ ; \ if\ S > 0 \\ 0\ ; \quad if\ S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} \ ; \ if\ S < 0 \end{cases} \quad (3)$$

In addition to the above, the region's economic evolution was evaluated (and graphically correlated to groundwater rights given in the same period) based on activities that normally demand large amounts of water.

On the other hand, the Coquimbo Region is made up of three large basins that group other smaller ones. These are Elqui, Limarí, and Choapa (Figure 1). In this context, it was possible to evaluate the consumption of water for productive purposes (annual agricultural crops) and the origin of the water used for irrigation. In addition, the volume stored in two aquifers inside the Elqui River basin was evaluated, derived from the fact that the minimum necessary information was available for these. These analyses were carried out through the use of the WEAP (Water Evaluation and Planning) [17,18] model, adjusted for the Elqui river basin within the framework of the FIA PYT 2017–0215 Project [19]. This model is composed of the integration of demand nodes and their interaction with surface and groundwater, with data from the MAGIC model (Integrated Generic Analytical Model of Basins)—Elqui, from a study called "Diagnostic Master Plan for the water resources management, Coquimbo Region" [20]. Likewise, the model allows us to estimate the volume of aquifers, through the interaction between the demand and its recharge from inefficiencies. The water demand is supplied by two sources: surface and groundwater rights.

3. Results

Monthly rainfall trends (Mann–Kendall test) were mainly negative (53.1%) over the 34-year study period, but with little statistical significance (0.8%). Annual rainfall exhibited similar downward trends (72.1%), but none of these were significant (Table 1). Therefore, rainfall does not show significant temporal changes (Table 1 and Figure 2).

Table 1. Monthly and annual trends in rainfall, flows, and depth to water table in the Coquimbo Region (1984–2018). Significant values for an α < 0.05.

Variable	Component		Negative	Positive	Positive and Significant	Negative and Significant	No Trends
Rainfall	Monthly		274 (53.1%)	193 (37.4%)	4 (0.8%)	4 (0.8%)	41 (7.9%)
	Annual		31 (72.1%)	10 (23.3%)	0 (0%)	0 (0%)	2 (4.7%)
Streamflow	Monthly	Min	102 (85.0%)	4 (3.3%)	0 (0%)	13 (10.8%)	1 (0.8%)
		Mean	80 (66.6%)	0 (0%)	0 (0%)	40 (33.3%)	0 (0%)
		Max	85 (70.8%)	0 (0%)	0 (0%)	35 (29.2%)	0 (0%)
	Annual	Min	7 (70.0%)	1 (10.0%)	0 (0%)	1 (10.0%)	1 (10.0%)
		Mean	2 (20.0%)	0 (0%)	0 (0%)	8 (80.0%)	0 (0%)
		Max	5 (50.0%)	0 (0%)	0 (0%)	5 (50.0%)	0 (0%)
Depth to water Table	Monthly		0 (0%)	12 (18.2%)	54 (81.8%)	0 (0%)	0 (0%)
	Annual		0 (0%)	3 (27.3%)	8 (72.7%)	0 (0%)	0 (0%)

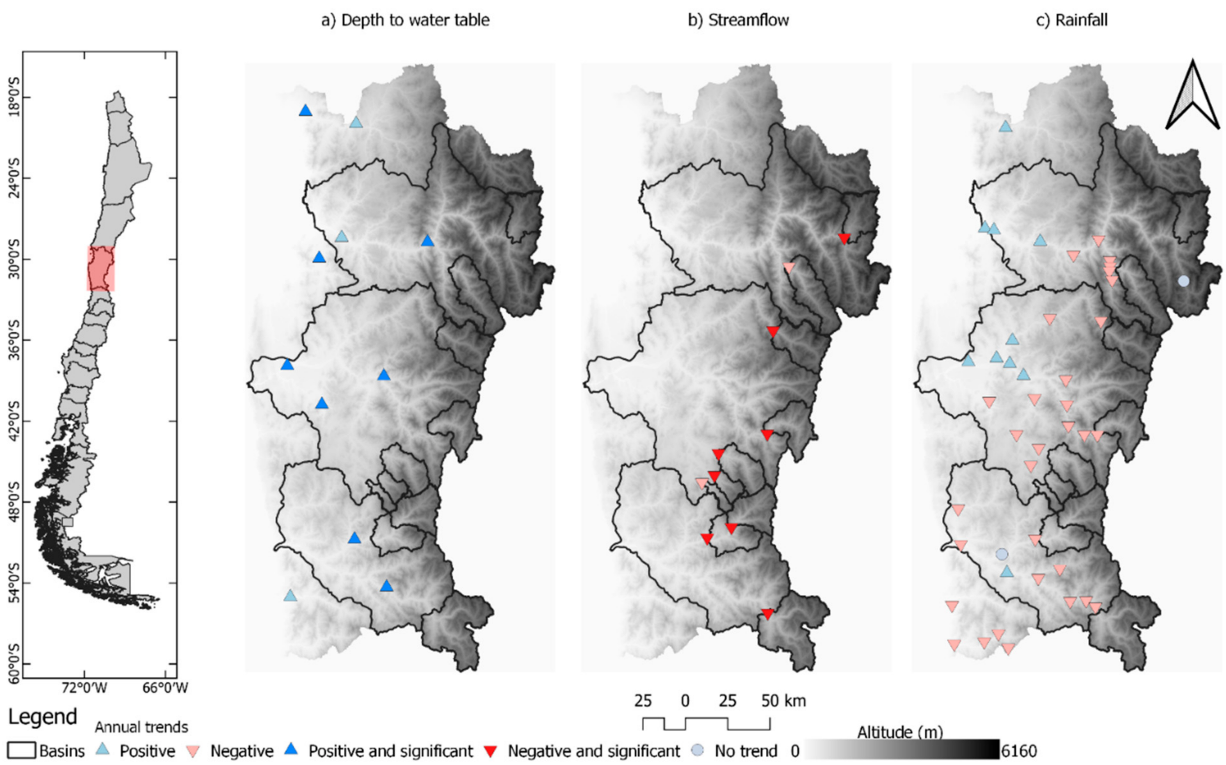

Figure 2. Annual trends on (**a**) distance to water tables; (**b**) average flow rate; and (**c**) accumulated rainfall (Source: own work).

Monthly flows, on the other hand, showed negative and significant trends (10.8%, 33.3%, and 29.2% for the minimum, average, and maximum flows, respectively (see Table 1)). Similarly, annual flows showed negative and significant trends (10.0%, 80.0%, and 50.0% for minimum, mean, and maximum values, respectively (see Table 1)). This is a concern for water resource sustainability because maximum flows are fed by floods (which are sporadic in semi-arid areas such as Coquimbo), and mean flows are fed mainly from waters previously stored in the basin as groundwater.

Groundwater tables in the study area also exhibited a temporal decrease in static levels. On a monthly basis, all trends showed a decrease in groundwater levels, and 81.8% of those were statistically significant, agreeing with Valois et al. [21], who found that 80% of the wells in the region show a significant decrease in their levels.

In addition to the above, the Coquimbo Region has seen a strong increase in GDP and water consumption, mostly from agriculture and mining industries (Figure 3, top).

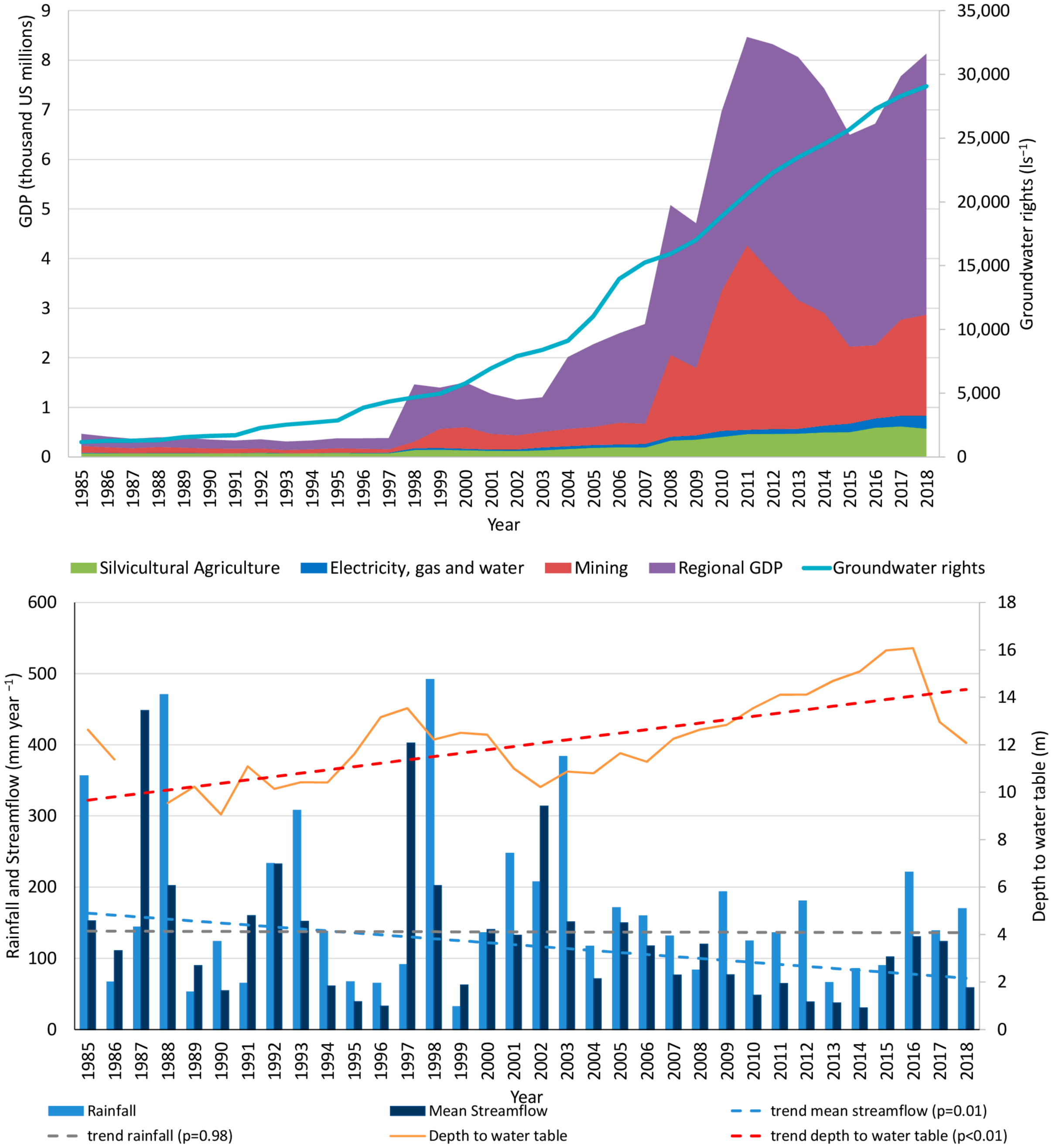

Figure 3. (**Top**): Evolution of GDP and groundwater rights for the Coquimbo Region, Chile. Source: Water Rights Granted in the Coquimbo Region (DGA, 2021) and Central Bank of Chile. (**Bottom**): Regional mean precipitation, surface flows, and depth to water tables in the Coquimbo Region, and their respective trends (Sen Slopes).

Figure 4 shows the water sources used for irrigation of annual crops in the coastal part of the Elqui river basin, revealing a sustained increase in the use of groundwater for this purpose. Similarly, when evaluating the stored volume of two aquifers inside the Elqui river basin, a sustained decrease in its volume is appreciated (Figure 5).

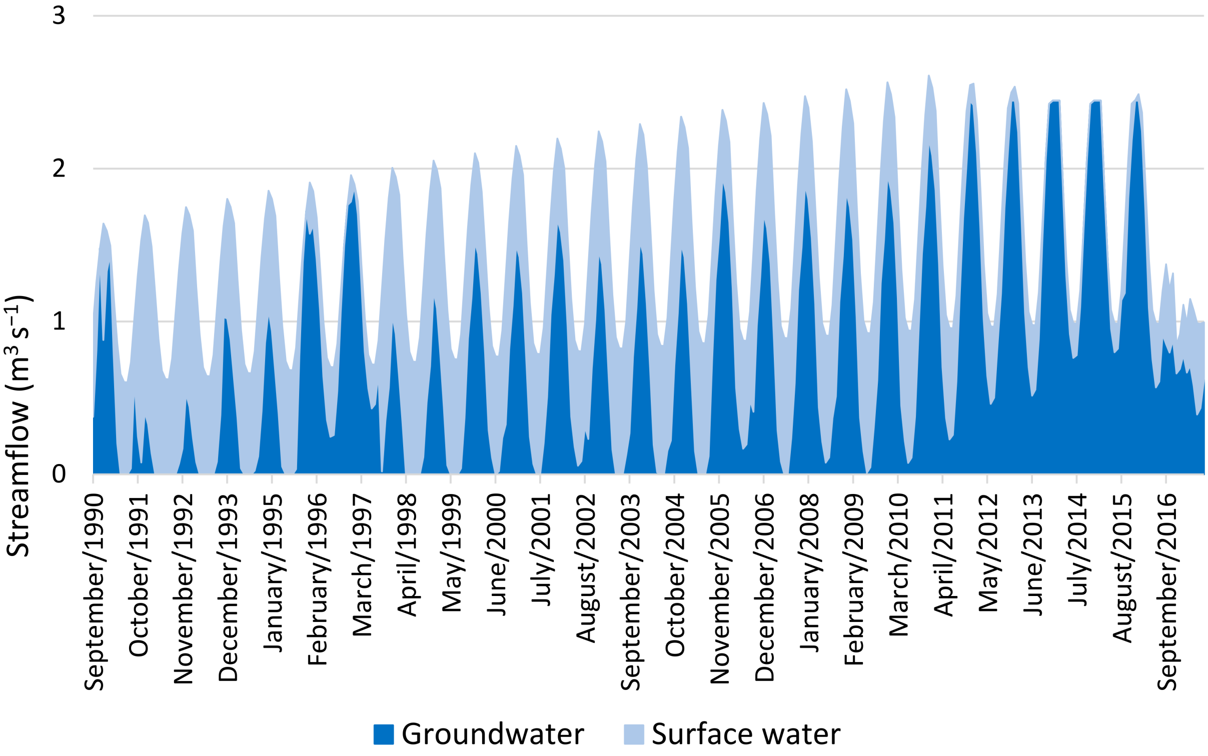

Figure 4. Water supply for annual crops in the coastal zone of the Elqui river basin.

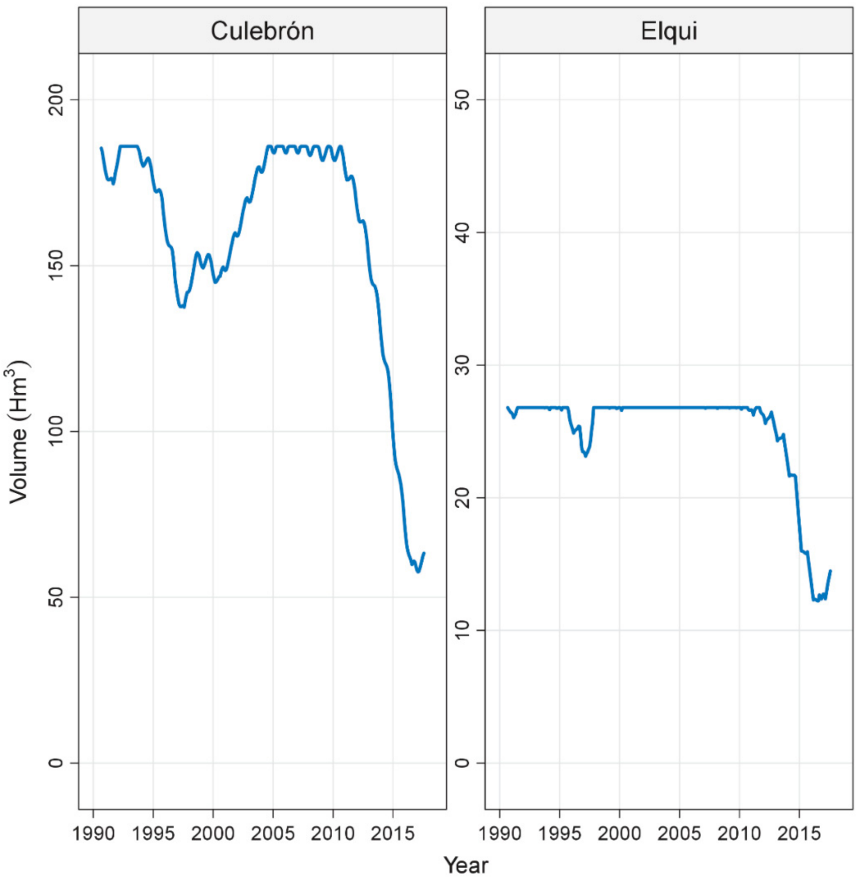

Figure 5. Temporal variation of the Culebrón and Elqui aquifers's volume (Elqui basin).

4. Discussion

Based on the above, it can be seen that rainfall does not show significant changes in the last 34 years, according to the Mann–Kendall test and the Sen slopes, which agree with the conclusions by Souvignet et al. [22] and Favier et al. [23], who found that rainfall in recent decades has not presented clear trends for the Coquimbo Region. However, although the trends do not show a significant decrease, lower amounts of accumulated precipitation have been documented during the last decade due to the presence of a megadrought that lasted for more than 5 years [24]. Another factor to consider is presented in the interannual variability of rainfall, which fluctuates depending on the ENSO phases and can explain up to 32% of the variations in average rainfall for the region [25]. These variations are cyclical with durations between 3 and 5 years [26] and by oscillating between high and low periods can affect the detection of climatic trends; however, if the length of the data is at least 3 times the size of the cycle, trend detection should not be affected [27].

Groundwater demand for crop irrigation has increased steadily, reaching parity between the use of surface and groundwater resources as of 2010 (Figure 4). In addition, when verifying the volume stored in two aquifers of the Elqui basin, a sustained decrease in the accumulated volume was found, a decrease that has accelerated since 2010 (Figure 5). The above results coincide with what was found by Valois et al. [21], who identified a significant decrease in the piezometric levels of 80% of regional wells. Moreover, the authors found a 0.5-to-1 m per year decrease water table levels at the Culebrón aquifer, explained by the increase in water consumption for agricultural purposes.

It is noteworthily to mention that water table decreases coincide with the beginning of the megadrought in Chile [24]. Based on the foregoing, it is possible to point out that despite the presence of a sustained megadrought in the last decade, the amounts of precipitation in the area do not show a significant decrease, so precipitation is most likely not the main factor responsible for the decrease in the flows and the increase in the depth to water tables. Above all, considering that the reduction of water in the region occurs in conjunction with an increase in productive activities (mainly mining and agriculture), sectors that require thousands of cubic hectometers per year and that are expected to change by −2.5% and 71.2%, respectively, by the year 2040 [28].

Considering that the main economic activities of the region require water for their execution, it is verified that this natural resource acts as a limiting factor of production [29], and therefore, by reducing surface water sources in the case of agriculture to maintain and increase cultivated areas, underground water tables have been exploited and this would explain in part the increase in the depth to water tables. Notwithstanding the foregoing, Gu et al. [30] and Hemati et al. [31] point out that economic development and water consumption can be modeled as an inverted "U", where economic growth increases together with water consumption, to later stabilize and decrease, depending on the optimization of production processes and the implementation of new technologies [30]. However, Duarte et al. [32] concluded that despite greater efficiency in the use of water, this model of growth and water consumption is not sustainable over time. The foregoing becomes relevant when considering that groundwater is slow to recover and, therefore, its exploitation must be done under a sustainable model.

Under a similar context, Valdés-Pineda et al. [33] studied the causes leading to the disappearance of the Aculeo lagoon (central Chile), finding that, although the effects of less precipitation on the amount of available water are manifested, this ecological disaster occurred mainly as a consequence of overconsumption of the resource, used mainly for agricultural purposes. A similar situation is described by Muñoz et al. [34] in the Petorca basin (Valparaíso Region), where the reduction of the Petorca river is not fully explained by climatic variability, but mostly water withdrawals for agricultural purposes, whose high evapotranspiration rates play an important role in the water scarcity of the basin. Similarly, Duran-Llacer et al. [35] analyzed groundwater withdrawals in the La Ligua and Petorca basins (Valparaíso Region), finding that the decrease in piezometric levels is mainly due to the use of groundwater to maintain and increase the area planted with avocado trees in the region (agricultural uses). Finally, Aitken et al. [3] analyzed the scarcity of water in Chile, concluding that the main consumer of water in the Antofagasta Region (north of Chile) is mining, in addition to being the main factor contributing to the region's water scarcity. In the other regions of the country, it was found that agriculture is the main consumer of water and, therefore, an increase in irrigation efficiency would be beneficial in terms of water availability.

When considering the results altogether, it is possible to point out that the Coquimbo Region has been affected by the effects of climate change, reducing the amount of available surface water. However, agricultural and mining production in the area are activities that require tremendous amounts of water, and in the case of agriculture, its demand is projected to increase (as previously mentioned), a situation that is not sustainable with current water availability in the region (Figure 5). Similar conclusions were obtained by Alam et al. [36], who analyzed groundwater consumption in the central valley of California, finding that the decrease in piezometric levels can be explained by an increase in agricultural areas, a greater need for irrigation due to high temperatures, and the implementation of crops with higher water demands. In the case of the Coquimbo Region, temperatures have risen [19], together with an increase in the area occupied by fruit trees (e.g., lemon, cherry, and clementine trees, among others) [37] and a megadrought has been present in the last decade, a situation that has required increasing pressure on groundwater resources to meet agricultural needs and whose water demands exceed the natural recharge rate of the aquifers of the northern and central macrozones of the country [38].

Despite the above, one limitation of this study is not having enough information to model water consumption and economic development in the Coquimbo Region. However, the increase in water rights requested from DGA, together with the rise in GDP (Figure 3), seem to indicate that the study area has not yet reached the point of stabilization in water consumption, derived from the fact that both still show increasing trends. Additionally, only the modeled Elqui river basin is available, and for this reason, it was the only one used to evaluate the relationship between water consumption and its origin (surface or underground). However, it is expected that the behavior in the Choapa and Limarí basins (the other two large basins of the Coquimbo Region) will be similar to that of the Elqui River basin, derived from the fact that the three basins have similar climates and land uses, in terms of mining and agriculture.

5. Conclusions

The results achieved and the analysis carried out allow us to conclude that, although rainfall shows a decline in the studied period for the Coquimbo Region in Chile, these falls are not significant. It follows that the lower supply in mean and maximum flows could not be directly attributed to climatic factors, but to other variables. It was verified and concluded that the economic activities have grown strongly in the period studied and, since they are highly demanding of water, these are most likely the main causes of the decrease in water supply. This fact is corroborated by the increase in the use of groundwater and the depth between the surface and the piezometric level of the various analyzed wells. Moreover, human activities and overuse are rapidly depleting water resources (especially groundwater) in the region, and the problem is further complicated by a changing climate and decreasing precipitation. However, the overall trend is stronger for overconsumption compared to climate variability, affecting the long-term productivity and water resource sustainability of this area of the country.

Results show that the main cause of this concerning situation is excessive consumption, and there is an urgent need to know (model) how to adequately quantify water availability, as well as current uses, before authorizing new water withdrawals. This is also applicable to current productive activities that, apparently, might not have enough water in the future for them to function. Therefore, if this is not considered properly, the region could be facing a critical situation that will condition its productive future and, most importantly, its environmental future, which is the basis of all human sustainability.

Considering the above, future modeling is advised to better understand the regional hydrology of the area and quantify the anthropic effects on water resources more precisely.

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