



## Research article

# The economics impacts of long-run droughts: Challenges, gaps, and way forward

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## ABSTRACT

Quantifying drought's economic impacts has been key for decision-making to build future strategies and improve the development and implementation of proactive plans. However, climate change is changing drought frequency, intensity, and durability. These changes imply modifications of their economic impact, as longer droughts result in greater cumulative economic losses for water users. Though the longer the drought lasts, other factors also play a crucial role in its economic outcomes, such as Infrastructure capacity (IC), the Amount of Water in Storage (AWS) in reservoirs and aquifers, and short- and long-term responses to it. This study proposes and applies an analytical framework for the economic assessment of long-run droughts, assessing and explaining central Chile megadrought economic effects through the factors that begin to influence the economic impact level in this setting. High levels of both IC and the AWS, as well as short- and long-term responses of water users, allow for high resilience to long-run droughts, tolerating extraordinary water disruption in its society with relatively low total economic impacts. Despite this adaptability, long-term droughts bring places to a water-critical threshold where long-term adaptation strategies may be less flexible than short-term strategies, escalating the adverse economic effects. This fact suggests that the economic evaluation of megadrought needs to focus on future tipping points (substantial water scarcity). The tipping point depends on the IC, how water users manage the AWS, and adaptation strategies. Establishing the tipping point should be a priority for future interdisciplinary research.

## 1. Introduction

Quantifying droughts' economic effects help evaluate future water scarcity strategies and enhance their planning, management, and implementation (Ding et al., 2011; Meyer et al., 2013). Many studies estimate the costs and impacts of droughts, especially in dry locations such as the Mediterranean Basin, California, and Australia (Borzi et al., 2021; Christian-Smith et al., 2011; Wittwer and Waschik, 2021). Most have focused on assessing the economic impacts of short-term droughts (less than three years) - assessing its current effects - rather than focusing

on potential future effects if the drought continues. (e.g., Carroll et al. (2009), Martin-Ortega et al. (2012); Wittwer and Waschik (2021)).

However, climate change (CC) has altered droughts' frequency, intensity, and duration (Chiang et al., 2021; Spinoni et al., 2014; Van Loon et al., 2016). Droughts have become more frequent, severe, and long-lasting (Prudhomme et al., 2014; Satoh et al., 2022), and all these factors are predicted to increase (Konapala et al., 2020). These changes increase the economic effect because more prolonged and severe droughts increase the cumulative economic loss for water users. Furthermore, long-run droughts (i.e., below-average precipitation

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lasting more than two or three years) include more complex natural and human dynamics than short-term droughts (Alvarez-Garretón et al., 2021; Van Loon et al., 2016).

As a response to these challenges, many authors have suggested new conceptualizations of droughts and how we assess their impacts (AghaKouchak et al., 2015; Van Loon et al., 2016). The latter aspect also relates to droughts' economic impacts. Even while the literature has thoroughly examined the methods for assessing the economic effects of droughts (Ding et al., 2011; Freire-González et al., 2017; Logar and van den Bergh, 2013; Meyer et al., 2013), it has a significant focus on short-term droughts. However, the outcome of a long-term drought will be influenced by factors related to the region's resilience and water users' adaptability that commonly have not been considered in short-term studies.

This paper summarizes these resilience- and adaptation-related characteristics in four factors that act as major drivers of long-term droughts' economic impacts: Infrastructure Capacity (IC), Amount of Water in Storage (AWS), and short- and long-term adaptation responses. IC includes production, treatment, storage, and distribution capacity for both "produced water" and water generated through desalination or recycling. A region's IC level and composition considerably impact the severity of droughts' economic effects by boosting resilience and reducing negative consequences. In the case of long-run droughts, the IC mitigates the economic impacts at the beginning of it. However, as the drought continues, the water depletion held in storage can trigger a tipping point with significant societal and economic consequences. In the context of long-run droughts, IC and the AWS interrelate, presenting challenges beyond the size of IC.

AWS, including surface reservoirs and underground aquifers, provides a buffer against water scarcity. However, storing water also requires self-discipline and restraint to leave water in storage as insurance against drought next year and the year after, as well as not wildly pumping groundwater and drastically lowering surface reservoirs. Several authors have highlighted the need for groundwater and surface water to be strongly linked and managed conjunctively as 'one water' (Famiglietti, 2014; Scanlon et al., 2023). However, it is also essential to consider that groundwater often takes a long time to replenish or is a non-renewable resource. At the same time, surface water is renewable but dependent on precipitation and streamflow. Unfortunately, the storage capacity of aquifers is often unknown. Satellite measurements can reveal changes in groundwater storage but not the depth of the water table and physical hydrogeologic characteristics. Therefore, managing water in storage, especially during long-run droughts, involves complex trade-offs between short-term and long-term goals and between sources and uses of water with different physical and economic characteristics.

Regarding short- and long-term adaptation responses, different public and private drought responses have been documented. Ding et al. (2011) refer to short-term responsive actions vs. proactive planning and mitigation strategies. The first is focused on smooth short-term disturbances and providing emergency supplies to maintain the basic functioning of industries and markets. In contrast, the second one is focused on increasing long-term social-economic resilience to future drought impacts. Christian-Smith et al. (2011) differentiate between mitigation (preparedness) and response. Mitigation refers to actions and programs taken before and in the early stages of drought to reduce drought-related risks. In contrast, response refers to actions taken immediately before, during, and after drought to reduce its impacts (Knutson et al., 1998). Freire-González et al. (2017) discussed short-term and long-term policy considerations. The first concerns decisions during a drought, such as which users should be subject to water restrictions, how much water should be restricted, and when to introduce restrictions. Long-term policy decisions involve public and private water storage and production investment.

Short- and long-term responses to a long-run drought can significantly define the economic impact extent. Because short-term and long-

term decisions are not the same, these reactions entail different options and trade-offs. Depending on AWS, short-term decisions occur with fixed infrastructure capacity during the drought. The range across which water users can employ short-term strategies is greater in an area with a high level of IC and where the AWS is large enough to meet water demand. In this sense, IC and sufficient AWS increase the flexibility in short-term adjustments of water users. These decisions involve a set of strategies that common assessment methods (e.g., programming or statistical models) fail to capture, understating the flexibility in the response of water users (Howitt et al., 2015; Medellín-Azuara et al., 2016). This could result in overestimating the immediate economic harm caused by the drought to water users, underestimating their adaptability.

In the case of long-term responses, they can involve changes to the IC, improved adaptation strategies by national and local governments, or behavioral changes (e.g., changes in consumption and investment patterns of private actors) that profoundly impact the economic system. These long-term responses represent a more substantial reaction to drought than short-term responses and imply significant investment costs. Long-term responses commonly appear after previous experiences with droughts to improve social-economic resilience to future drought impacts.

This study examines the economics of long-term droughts, describing how the IC, AWS (at surface and groundwater levels), and short- and long-term responses influence the economic impact on various economic sectors with high water requirements and national significance. As a case study, we examine the megadrought (MD) in central Chile, which has affected the country's most populous region since 2010 (Garreaud et al., 2019; Steiger et al., 2021).

The main contribution of this study is two-fold. First, we propose an analytical framework, in a context of a long-run drought. The economic impact assessment under this framework allows the incorporation of IC, the AWS, and short- and long-term responses as key determinants of long-term drought's economic impacts. Second, we discuss the methodological and political implications of using this framework as a source for science-based drought strategies for future, more severe and prolonged droughts.

The remainder of this article is organized as follows. Section 2 sets out the methodological framework elements, describing the methods used to estimate the drought economic impacts, considering different sectors, and summarizes the current MD context. Section 3 presents the drought's economic impacts on the sectors. Section 4 discusses the results considering IC, the AWS, and the relevance of short and long-term responses to droughts. Finally, section 5 concludes with policy recommendations and suggestions for future research.

## 2. Methodology

### 2.1. Conceptual framework

This conceptual framework extends Freire-González et al. (2017), which emphasizes Hydraulic Capital's importance in drought economics and how short-term responses can affect droughts' economic effects. Our framework differs in four ways: This framework is only centered on long-run droughts. Second, we used the framework to conduct an ex-post analysis to assess how IC, AWS, and water users' reactions affected long-term drought economics. Third, we separated AWS from IC, discussing the difficulties in managing surface and groundwater in storage due to their different physical and economic characteristics.

Fourth, we stress the importance of comprehending hydraulic stock level trends and cumulative economic losses. The Freire-González framework determined the optimal hydraulic capital investment based on marginal social costs and benefits, highlighting that at some point, the cost of investing in additional infrastructure will exceed its benefits. In this issue, we deepen the discussion as the optimal level could significantly change when observing the economic consequences before

or after passing specific water supply tipping points.

Fig. 1 depicts the overall methodological framework for this study. First, we establish the assessment's spatial and temporal framework. The spatial framework's definition is crucial since droughts produce winners and losers (Ding et al. (2011)). Thus, it is critical to determine the presence of zero-sum transfer between losers and winners throughout the outcomes analysis. On the other hand, defining the temporal framework is crucial due to the lag effects of droughts and the cumulative economic impacts as droughts persist.

Second, we define the economic framework, selecting economic sectors to evaluate based on water dependencies and regional economic relevance. The specific method used to assess the economic impact on each sector should consider data availability. After data collection and analysis, different methods estimate drought cost to each sector. These outcomes should reflect the economic decisions of different agents under continuous water scarcity. The IC, the AWS, and the short- and long-term responses affect these outcomes.

## 2.2. Case study

Chile is a rather narrow strip of land between the Andes cordillera and the Pacific coast of South America. Its central part extends from 30° to 38°S (Fig. 2 panel A), covering seven administrative regions (from the southern part of Coquimbo to Bio Bio), home to about 10 million inhabitants (nearly 78 percent of the country's population; INE (2017)) and hosting important economic activities. Its agricultural sector represents nearly 95% and 65% of the number of farms and the country's agricultural, livestock, and forestry area, respectively (ODEPA, 2019). Central Chile exhibits a semi-arid, Mediterranean-like climate where average precipitation (ranging from 100 to 1000 mm per year) is largely concentrated in austral winter. A seasonal snowpack over the Andes cordillera delivers water to the central valley during summer, when potable and agricultural water consumption is highest. Years of low precipitation are not uncommon, with moderate droughts (10–20% deficit) recurring every 5–10 years (Núñez Cobo et al., 2018). Nonetheless, since 2010 the region has experienced an uninterrupted sequence of dry years, with adverse and increasing environmental (Alvarez-Garretón et al., 2021; Garreaud et al., 2017) and social impacts (Aldunce et al., 2017; Boisier et al., 2016; Garreaud et al., 2017, 2019). Given its extraordinary duration and spatial pattern, unprecedented in the historical record, this event has been termed the central Chile megadrought (MD; Garreaud et al. (2017)). Fig. 2, panel A, shows the rainfall deficit from 2010 to 2020 across central Chile, ranging from 25% to 45%. Every year in this period has experienced less precipitation than the historical average, but the deficit's magnitude is variable. To display this variability, Fig. 2, panel B shows Santiago precipitation (Quinta Normal meteorological station) from 1900 to the present. The MD stands out in this record and include one extremely dry year (2019) when accumulated precipitation was only 82 mm, a fourth of an average year.

Since Central Chile has experienced an uninterrupted sequence of 13 dry years since 2010, we select a temporal framework between 2010 and 2020. The economic sectors analyzed were selected based on the quantification of their water requirements (FCH, 2019) and their importance at the national level. The sectors included in the analysis were agriculture, urban and rural water supply, forestry, electricity generation, and tourism. The specific methods used to assess the economic impact on each sector are described below.

### 2.2.1. Agricultural sector

We analyzed drought's economic impact on agriculture through a mathematical programming modelling approach. National statistics on area, price, yields, and costs for 20 agricultural activities by region and commune in central Chile were used to simulate all years between 2010 and 2020 (baseline path). We calibrated using Positive Mathematical Programming (PMP) for all years (Howitt, 1995a, 1995b). In this case, the effects of IC, the AWS, and both short-term and long-term responses

are implicitly captured by data from the sector (baseline path) during the evaluation period (from 2010 to 2020). Calibrating the baseline path each year creates a baseline that matches national and regional statistics. So, for this baseline path, we assumed that "forces," such as prices, costs, yields, and water restrictions, affect how farmers allocate their input and the activity levels produced. In this case, we assumed that the baseline path shows that megadrought causes water restrictions to get tighter yearly. However, farmers and governments have different ways of dealing with these restrictions, depending on the infrastructure capacity (IC) and the amount of water in storage (AWS). Also, prices, costs, and yields change over time, which affects how farmers decide what to do. The results of these forces show how production activities are spread out each year on the baseline path and how inputs are allocated.

Then, to obtain an economical range of the MD impact, we constructed two scenario paths by simulating agricultural structure from 2010 to 2020 under the actual evolution of prices, costs, and yields in the following years "without" water scarcity. Scenario 1 represents the activity level of 2010 from the baseline path, but considering the evolution of prices and cost in the following years. Meanwhile, scenario 2, represents the same activity level from 2010 as starting point but in the following years, considering prices, costs and yield evolution from posterior years. The difference of these scenarios paths with the baseline path will give us a delta where the effects of prices, yields, and costs were isolated (Table 1 describes the scenarios used).

These simulations show how the allocation of inputs, and the level of production activities change based on the patterns of costs, prices, and yields that happened "without" taking other factors like the increase in water restrictions into account. The following differences (starting from 2010) will draw the upper threshold of drought's influence, ignoring prices, costs, and yield. We also included Chile's total agricultural emergency response expenditures, including drought-related public emergency responses (FAO, 2021). A detailed explanation of the model, data used, data treatment, and scenario construction stage is presented in Appendix A, section A1.

### 2.2.2. Urban drinking water sector

We assessed drought's economic impacts on urban drinking water by considering water supply from sanitation companies and household water demand. For the supply side, we estimate the induced costs based on the investments made by sanitation companies as a response to the MD<sup>1</sup>. The National Association of Sanitary Service Companies of Chile (ANDESS) provided 2010–2020 operational and capital expenditures for MD-related items. The investments were classified based on their stage within the process as an investment for production, distribution, or "others" (like studies or public awareness campaigns for rational use). The sanitation companies that share their data cover 61,4% of the country's total population and 73,6% of central Chile's population.

Secondly, we simulated household water demand based on climate-related variables such as temperature, precipitation, and the standardized anomaly of the cumulative Normalized Difference Vegetation Index (zcNDVI)<sup>2</sup> (Zambrano et al., 2018). We used the sample of 215 Central Chile communes for which there is data in the years 2010–2020. An Ordinary Least Squares (OLS) model and a fixed-effects (FE) panel data model were estimated. We used 2010–2020 sanitation company drinking water billing data to constrain estimates. The water demand model was used to predict the average household consumption, calculate the consumer surplus, and evaluate the rationing scenario's effect on household welfare based on the "Water Rationing Protocol for Greater

<sup>1</sup> Data used for calculations is unavailable for public use due to a confidentiality agreement with the participating firms.

<sup>2</sup> The zcNDVI correspond to the standardized anomaly of the cumulative NDVI (cNDVI) over the growing season, between start- and end-of season (see Zambrano et al., 2018). It can be calculated as:  $zcNDVI^S = \frac{cNDVI^S - \bar{cNDVI}}{\sigma(cNDVI)}$  where  $S$  is the season.

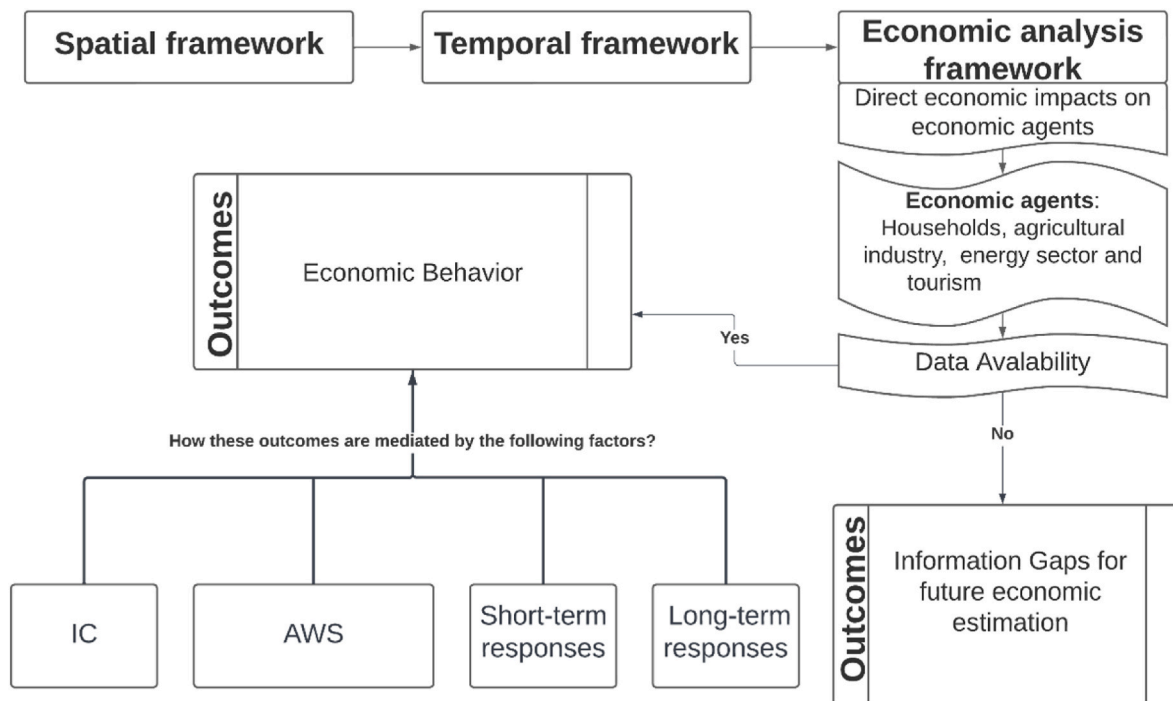


Fig. 1. Methodological framework (Source: Own elaboration).

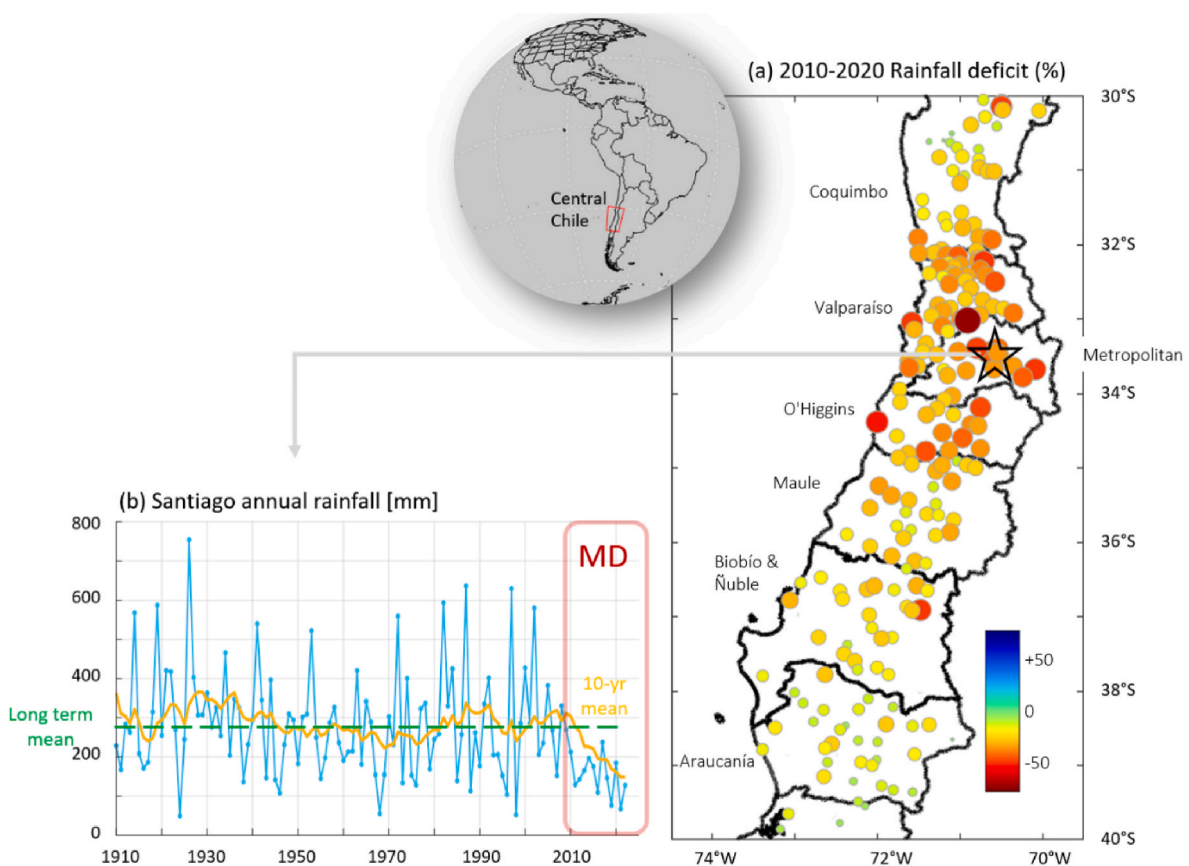


Fig. 2. The Central Chile Mega Drought. (a) Map of the rainfall deficit between 2010 and 2020 observed in meteorological stations along central Chile. The deficit is the difference between the average precipitation in that period and the climatology (1980–2010 mean) precipitation, expressed as percentage of the climatology. The map also shows the administrative regions considered in the present study. (b) Time series of the annual precipitation in Santiago (station Quinta Normal, start in panel (a)). The yellow line is the 10-year moving average. Data sources: Dirección Meteorológica de Chile and Dirección General de Aguas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 1**  
Scenario description for the Agricultural Sector.

Baseline path	Scenario 1	Scenario 2
Base on national and regional yearly agricultural statistics for 2010 until 2020	2010 activity level considering evolution of prices and cost from 2010 until 2020	2010 activity level considering evolution of prices, costs and yields from 2010 until 2020

Santiago” (SISS, 2022).

In this case, we assumed that in the initial situation (current situation in 2020), there is an equilibrium between the water demand and the water supply. This assumption implicitly includes short- and long-term responses of sanitation companies (investments as a response to mega-drought), which are also related to IC and the AWS in each region. The 20% rationing scenario represents the extreme situation where despite all the IC, the optimum management of the AWS, and the investments made by sanitation companies, the decrease in water availability is such that there is necessary a policy of water rationing.

A detailed explanation of the induced cost estimation on sanitation companies, the residential water demand estimation, and the MD cost estimation is presented in Appendix A, section A2.

### 2.2.3. Hydroelectricity power, rural water supply, forestry, and tourism

Secondary data was collected on drought’s economic effects on hydroelectricity, rural water supply, forestry, and tourism. Unlike agriculture and residential water demand, we could not simulate a behavioral pattern to evaluate the economic impact, so we used a descriptive approach.

We assess the hydroelectric sector’s temporal changes compared with other energy supply sources, using National Energy Commission statistics (CNE, 2022). Then, we assess hydroelectric sector installed capacity and system efficiency over time. We use both assessments as a temporal framework of analysis of the changes suffered from 2010 until 2020 and compare it with the pre-MD period (2000–2009). We examine how the current MD affects the installed capacity, electric generation, and efficiency of large dams, run of the river (RoR), and mini-hydroelectric sources (less than 3 MW). For rural water supply, we use the expenditure related to water trucks to estimate the economic impact on the rural water supply system. Data were obtained via the Transparency Law from the central and regional governments from 2011 to the end of 2019 on the State expenditures to private parties in contracts to ensure drinking water supply via cistern trucks (Vergara240, 2020). For the forestry sector, national statistics were gathered and complemented with literature related to Chilean forestry and the wildfire impacts and frequency in the central regions. Ski industry statistics, data, and literature were gathered for the tourist sector.

Appendix A details data used, methods, and characteristics of each sector. When data was insufficient to estimate cost, a brief discussion was presented, identifying information gaps. Finally, using the framework proposed we discuss our results.

## 3. Results

### 3.1. Agriculture

Within the calibrated baseline path, net water use decreased by 15.3%, and total agricultural land decreased by 13.5% from 2010 to 2020 (Table 2). At disaggregated levels, our model shows that dryland and irrigated land decrease a 3.1% and 15.7%, respectively. While we can’t establish causality, drought is likely key in decreasing irrigated land, where surface irrigation areas (laying and furrows) have presented marked losses. In contrast, sprinkler and micro-irrigation areas have increased (Donoso, 2021). By subsector, our model shows significant decreases in cereal (19%), legume (81.9%), and industrial crop surfaces (63%), while fruit trees grow by over 21,000 ha.

**Table 2**  
Agricultural changes comparing 2010 and 2020 base years.

Description	2010	2020	% change
<b>Net water use (10<sup>9</sup> m<sup>3</sup>)</b>	<b>67.05</b>	<b>10,27 reduction</b>	<b>−15.3%</b>
<b>Total land (ha)</b>	<b>472,762</b>	<b>63,919 loss</b>	<b>−13.5%</b>
<b>By system</b>			
Irrigated land (ha)	388,189	61,258 loss	−15.7%
Dryland (ha)	84,572	2661 loss	−3.1%
<b>By subsector</b>			
Cereals (ha)	246,326	47,169 loss	−19.1%
Fruits (ha)	175,656	21,144 increase	+12.0%
Legumes and tubers (ha)	30,916	25,351 loss	−81.9%
Industrial (ha)	19,863	12,543 loss	−63.1%
<b>Income (million USD)</b>	<b>3.59</b>	<b>6.66 increase</b>	<b>+ 185%</b>
<b>By subsector</b>			
Cereals (million USD)	1.58	0.62 increase	+37.1%
Fruits (million USD)	1.88	4.9 increase	+326.2%
Legumes and tubers (million USD)	0.09	0.06 loss	−69.1%
Industrial (million USD)	0.04	0.004 loss	−10.1%
<b>Labor Demand (Working days/year)</b>	<b>20,587,618</b>	<b>1,309,189 increase</b>	<b>+6.3%</b>

Despite most subsector dropping land, agricultural income rose 185% from 3,6 million USD<sup>3</sup> to 10.3 million USD, and labor demand increased by 6.3%. By subsector, our model shows “Legumes and tubers” (69.1%) and “Industrial” crops (10.1%) lost relative income, while cereals (37%) (despite area reduction) and fruits gained income (326%).

Our baseline path aligns 2010–2020 national agricultural statistics. The latest Agricultural and Forestry Census (INE, 2022), shows an 8.1% decline in agricultural land since 2007 (4,165,209 ha). Similarly, irrigated area has dropped nearly 19% since 2007. However, Chile’s agricultural GDP rose from 4810 to 5361 (million USD) between 2010 and 2020, keeping its 3% sectoral contribution to the country’s GDP throughout the current MD (Banco Central, 2021).

To estimate the MD’s economic impact, we tested the isolated and combined effects of crop prices, costs, and yield evolutions from 2010 to 2020. Fig. 3 compares the baseline path’s agricultural income to both scenarios, which assume 2010’s activity levels and the evolution of prices, costs, and yields from 2011 to 2020. Without considering costs, prices, or yields, we assume that the gap between the baseline path and the scenarios’ paths represents the agricultural sector’s income losses due to MD.

Fig. 3 shows that the difference between the baseline path and scenarios (Scen1 and Scen2) increases over time. Since 2016, the distance between the baseline and the two scenarios has widened. This is related to the IC and the pool of responses available to cope with the MD. In the MD’s first year, the income losses appear minor, likely due to water systems (such as groundwater or dams) having sufficient reserves. As maintained, the possibilities to achieve the potential income become more distant, reflecting how water reserves become scarcer. The accumulated income losses ranged from 90.45 million USD (Scen 1) to 86.74 million USD (Scen 2).

Additionally, Chile spent 160 million USD on agricultural emergency response between 2008 and 2017, with 64% going to drought response (FAO, 2021). In this sense, our estimate could rise to 196.45 million USD, 3.7% of 2020 Agricultural GDP.

### 3.2. Urban drinking water sector

#### 3.2.1. Sanitation companies’ induced costs

Due to MD, sanitation companies increased capital and operational costs from 2010 to 2020. Figure B1 in Appendix B shows the trend of these investments as a percentage of the inversion.

These costs include expenditures for new water sources (e.g.,

<sup>3</sup> Average value between January and April 2022 \$1USD = CLP\$806.

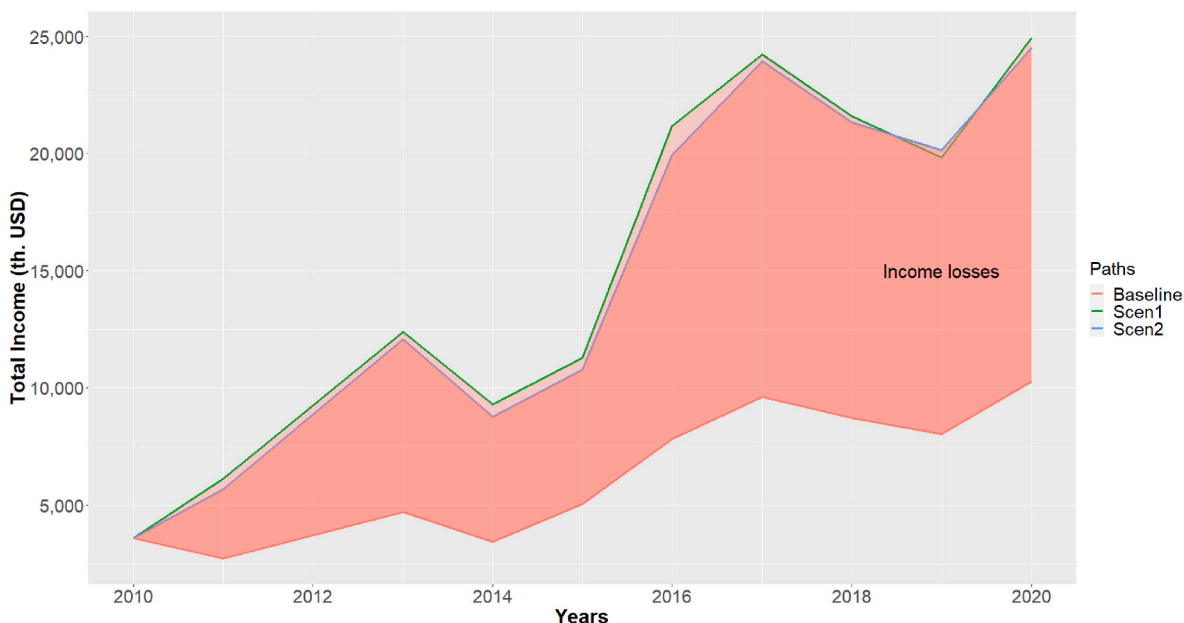


Fig. 3. Total agricultural income 2010–2020 for the baseline path and both scenarios (The area between the baseline path and scenarios indicates income losses).

desalination), storage facilities, increased water volumes by water treatment, buying and leasing water rights, pipe extension, pumping capacity, and other water transport activities. Each company depending on its location, weighs categories differently. New water sources (desalination plant) and groundwater treatment capacity increase production costs for northern zone companies (related to water salinity in these regions). Surface storage, surface water treatment capacity, and well deepening and drilling account for 39% of costs in the Central zone. Southern companies spend 36% of their production costs on transport, water rights, and wastewater treatment. Between 2010 and 2020, capital expenditure was 1119 million USD. However, when operational costs for the drought are included, the amount comes to 318 million USD, for a total of 1437 million USD. Considering only the facilities in Chile’s Central area that took part in this study, the capital expenditure was 660 million USD. Operational expenses were 155 million USD, implying total expenditures of 815 million USD.

3.2.2. Urban water consumption – avoided costs

Table 3 shows water demand OLS and RE model results. The direction of the price effect on residential water use is as expected in all models. According to previous research (Acuña et al., 2020; Fercovic et al., 2019; Vásquez-Lavín et al., 2017), all elasticities are inelastic (from -0.16 to -0.35).

The effect of income is positive and significant for the samples analyzed, consistent with the assumption of considering water as a normal good. The climatic variables of interest have the expected signs. Precipitation has a negative effect, and temperature increases positively affect residential water use. Specifically, temperature increases raise water demand by 9% (i.e., average temperature between 10° and 20° Celsius) to 15% (i.e., average temperature above 20°Celsius) compared to average temperatures between 0° and 10° Celsius. In contrast, a positive precipitation evolution would reduce water consumption by 2%–4%. The results suggest that accumulated rainfall between 100 and 200 mm reduces water demand by about 4% compared to the base category (i.e., between 0 and 100 mm of accumulated rainfall). On the other hand, for accumulated rainfall between 200 and 300 mm, demand decreases by 2% concerning the base category. In this line, accumulated rainfall above 300 mm decreases water demand by approximately 3% concerning low levels of rainfall (i.e., between 0 and 100 mm of accumulated rainfall).

Table 3 Estimation results. Standard errors are in parentheses. \*\*\*p < 0.01, \*\*p < 0.05, \*p < 0.1.

Variable	Spatial framework (30°-38°S)	
	OLS	Panel RE
<b>Price</b>	-0.35*** (0.01)	-0.16*** (0.00)
<b>Income</b>	0.35*** (0.01)	0.08*** (0.01)
<b>Population</b>	0.01*** (0.00)	0.09*** (0.01)
<b>Rainfall</b>		
Between 100 and 200	-0.09*** (0.01)	-0.04*** (0.00)
Between 200 and 300	-0.04*** (0.01)	-0.02*** (0.01)
Greater than 300	-0.03** (0.01)	-0.03** (0.01)
<b>Temperature</b>		
Between 10 and 20	0.06*** (0.01)	0.09*** (0.00)
Greater than 20	0.07*** (0.01)	0.15*** (0.01)
<b>zcNDVI</b>		
Less than -1	0,03*** (0.01)	-0.01** (0.00)
Between -1 and -0.1	0,06*** (0.01)	-0,01 (0.00)
Between 0.1 and 1	0,03*** (0.01)	0,00 (0.00)
Greater than 1	0,01** (0.01)	0,02*** (0.01)
<b>Constant</b>	0,39*** (0.01)	1,58*** (0.08)
Observations	23538	23538
N		215

Source: Own elaboration

The zcNDVI variable represents water consumption behavior in the face of a vegetational drought. As zcNDVI is an indirect indicator of plant water status, a higher zcNDVI is related to higher water consumption. We use it here as an indicator of human water consumption related to the irrigation of yards, gardens, and green areas in urban areas. Thus, reaching a higher vegetation index zcNDVI (>1), the plants

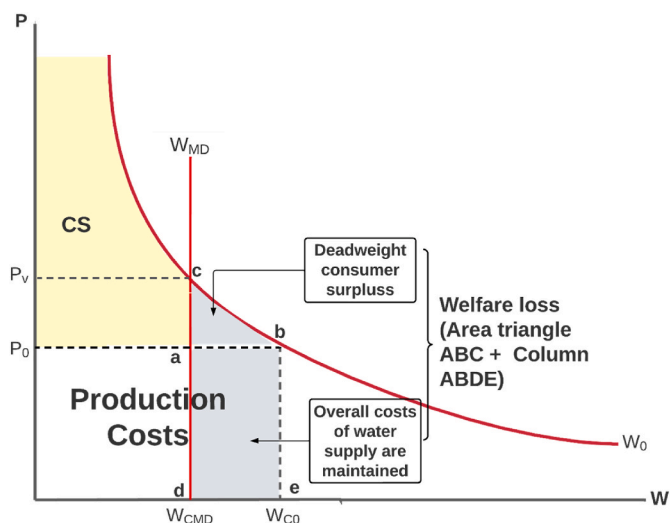


Fig. 4. Household-level water demand and consumer surplus.

would increase residential water consumption by approximately 2%. In contrast, for low levels of vegetation index (<1), water consumption is reduced by approximately 1%.

Fig. 4 presents the situation with and without potential rationing and the associated welfare loss.  $W_0$  represents the current household water demand and  $W_{MD}$  represents the water supply constraint considering a 20% rationing scenario,  $p_0$  is the water price (assumed to be fixed due to institutional constraints).  $W_{c0}$  represents the consumption of households in commune c in the initial scenario. In contrast,  $W_{cMD}$  represents the water consumption of households in commune c under the rationing scenario. Therefore, considering a 20% rationing, households will use less water. Thus, household water consumption in this scenario is  $W_{MD}$ . Since  $p_0$  is assumed fixed, a virtual water price  $p_v$  is needed to calculate consumer surplus loss in commune c.

The triangle abc represents household welfare loss under resource rationing scenario. Household welfare decreases by 122 USD per year. Additionally, it is important to mention that column abde is generally not a saving in production costs. This is because variable costs comprise only a small portion of water supply costs. Thus, the conventional assumption that if less water is delivered, the cost of water supply operations falls in approximately the same proportion is unlikely to hold in this case. The column abde amounts to a welfare loss of 94 USD, bringing the total to 217 USD of annual welfare loss per household. Considering the spatial framework of interest, the avoided cost per year, represented by the total loss of surplus, corresponds to 542.40 million USD per year.

We compare the company’s investments in the study area’s most populous region with the expected annual economic impact under the 20% rationing scenario. Considering the 217 USD/household/year of welfare loss under the 20% restriction, our results show that a dollar invested in drought preparedness can prevent approximately 8,3 dollars in economic losses.

Table 4  
Summary of the cost estimated and the percentage of national GDP.

Sector <sup>a</sup>	Estimated cost (million USD)	Avoided cost - 5 years (million USD)	Avoided cost - 10 years (million USD)
Agriculture	196.45		
Urban Water supply	815	2712	5424
Rural Water Supply	191		
Total cost (million USD)	1202.45	2712	5424
Percentage of National GDP*	0.475%	1.07%	2.14%

<sup>a</sup> Hydropower, Forestry, and Tourism were left out because there was not enough information to come up with an estimate of the total economic impact; \* (252.9 billion USD - 2020).

### 3.3. Rural water supply

The Rural Potable Water Program of the Waterworks Directorate (DOH) of the Public Works Ministry (MOP) provides rural residents with potable water in quantity, quality, and continuity under current regulations (Fuster and Donoso, 2018). The program licenses committees and cooperatives to manage, operate and maintain a rural potable water infrastructure (APR for its acronym in Spanish).

Water supply disruptions have affected several APRs during the MD period. Molinos-Senante and Donoso, 2021 show that the rural population facing water supply cuts between 2014 and 2017 ranged from 8.7% to 22.5%. Additionally, records indicate that communes from the central regions have been the most affected. The response to this problem has been the supply of water with water trucks, the purchase of storage tanks, and the financing of emergency activities by the central government to supply water in the affected areas (Fernández and Gironás, 2021). We use as a proxy the expenditure related to water trucks to estimate the economic impact on the rural water supply system.

Data obtained via the Transparency Law from the central and regional governments show that from 2011 to the end of 2019, at least 275 million USD have been paid by the State to private parties in contracts to ensure some drinking water supply via cistern trucks (Vergara240, 2020). Considering only those communes within central Chile, the expenditure reaches 191 million USD.

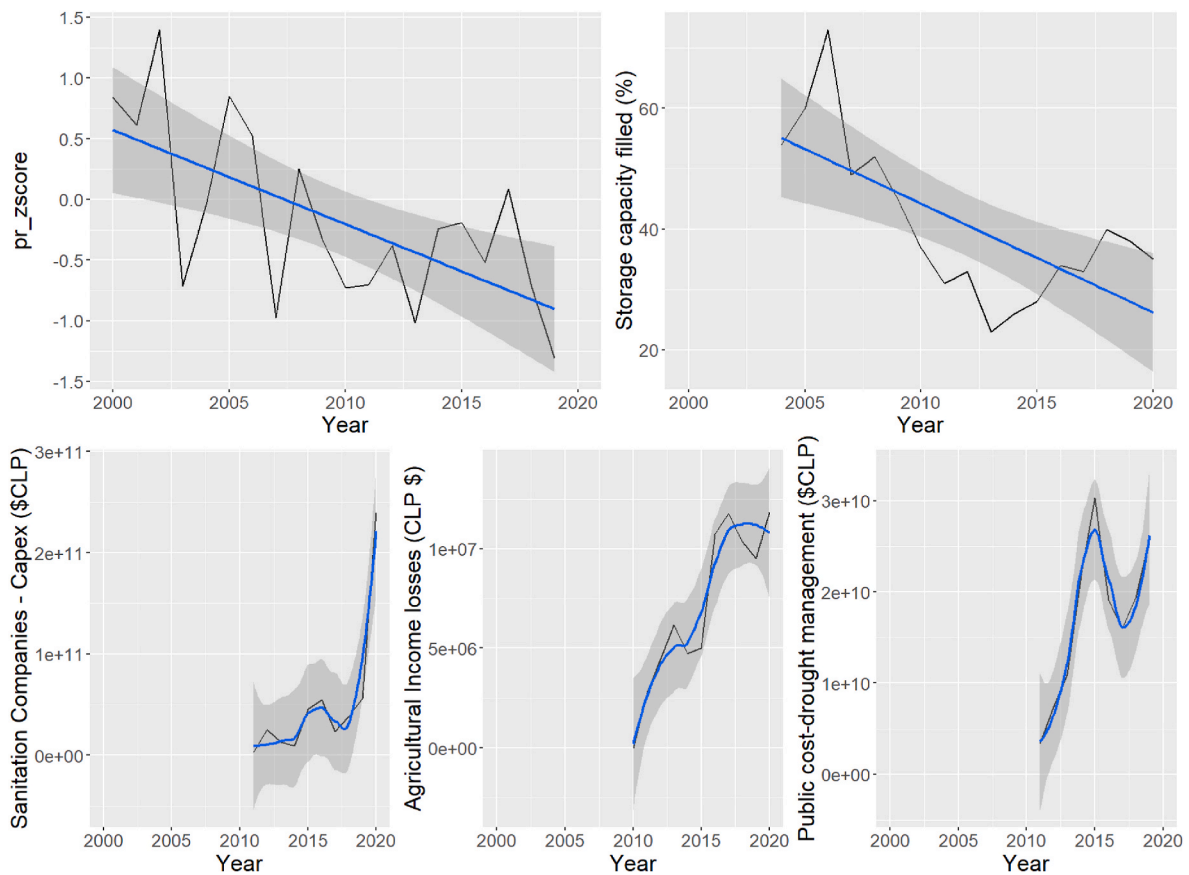
Among the region affected, most of the expenditure is concentrated between the regions of Biobío and Coquimbo, followed by the regions of Valparaíso, Maule, Metropolitana, and O’Higgins, respectively (Vergara240, 2020). Appendix B, Figure B2, shows the regional expenditure on water trucks between 2011 and 2019.

### 3.4. Total economic impact

Among all the sectors, we gathered enough data to evaluate the economic impacts of drought in the agricultural, drinking water, and sanitation sectors. With this, we covered most of the country’s water demand, representing approximately 95% of it (FCH, 2019). Appendix C details the data gathered and their assessment for the other sectors (hydroelectric, forestry, and tourism), highlighting the gaps in data available to assess the economic impact on each.

Table 4 shows the estimated cost by sector and the avoided cost estimated for the urban water supply sector. Over Ten years (2010–2020), economic losses totaled nearly \$1202 million USD or 0.475% of the national GDP. Our results show that there has been significant economic adaptability and robustness to deal with the current MD. Notably, when only considered avoided cost for the urban drinking water sector, the negative impact exceeds the total estimated costs for the agriculture, urban, and rural water supply sectors.

Despite central Chile MD’s marginal economic effect over 2010–2020, when we look at historical precipitations, the depletion of the water in storage, and the trends in economical cost in different sectors, we observe a strong negative association between them. Fig. 5 shows these trends and how, within the first years of the drought, the economic costs are lower as the AWS is at nearly total capacity.



**Fig. 5.** Water supply (precipitation and stored water) and economic impacts (sanitation companies’ investments; Agricultural income losses and public investments on drought emergency plans). *pr\_zscore*: precipitation z-scores calculated as  $(pp_y - \overline{pp}_{1979-2019}) / s_{1979-2019}$ .

However, as the drought continues, reserves deplete, and the economic costs increase. Moreover, given the results obtained in the urban water supply sector through the avoided costs, the economic impact is expected to skyrocket when water restrictions arise as a policy option. This fact suggests that the MD economic evaluation needs to focus on the future tipping points (substantial water scarcity) because the economic cost will increase substantially when we approach it. The tipping point depends on the IC, the AWS, and adaptation strategies, but unfortunately, due to a lack of hydrological information, we cannot situate that tipping point appropriately in the future. This gap should be a priority for future interdisciplinary research.

**4. Discussions**

The economic damage estimate for the Chilean MD seems to be very low. While this value underestimates the actual total value due to information gaps, this general conclusion is likely accurate. Previous droughts influenced Chile’s ability to adapt to the current MD. Droughts have changed management institutions, policies, infrastructure, water storage conditions, and sector water demands. On the other hand, water managers and stakeholders from different sectors have acted, assuming the current MD will not end mid-term. All these responses can be summarised into those actions related to IC, the AWS, and the short- and long-term responses taken by water users.

**4.1. Infrastructure capacity**

We found that Chile has accounted for sufficient IC to mitigate the current drought conditions. Chile’s IC level and composition have steadily increased over 120 years (Haindle, 2022). Past droughts have

pushed authorities to take long-term decisions that have impacted the amount and composition of the hydraulic stock of capital, translating into a region with high resilience to the current drought.

The construction of reservoirs in Chile has mainly served three purposes: storing drinking water, storing water for hydroelectric generation, and storing water for irrigation. Until 2020, three medium and large reservoirs in Chile were dedicated exclusively to drinking water storage, eight reservoirs allowed hydroelectric power generation, and twenty-two reservoirs were dedicated only to irrigation. All these reservoirs have helped store up to 13,158 Hm<sup>3</sup> of water, translating into high resilience levels under drought conditions. Nevertheless, after 13 years of drought, despite this high level and composition of IC, the MD has drastically reduced the AWS at the surface level (Fig. 5).

As of July 12, 2022, the reservoirs were at 28% capacity, adding to the central North’s 20–70% rainfall deficit, according to the General Directorate of Water (DGA). In January 2022, the global storage corresponded to only 37.1% of the total capacity (DGA, 2022). Table 5 shows the storage volumes of Central Chile’s main reservoirs during the drought’s even years (2010–2020), showing that the AWS by some reservoirs is below its capacity and historical average.

The reservoirs had less stored water and reduced deliveries as the drought continued. In February 2022, some reservoirs in the Coquimbo region (e.g., The Cogotí reservoir) only had systemic water. That is, the supply is so small that it is no longer possible for it to come out through the valves to be used by farmers. On the same date, the sanitation company of the Valparaíso region revealed that the Peñuela reservoir (until a few years ago, the region’s primary water reserve) accumulated around 170 m<sup>3</sup>, representing only 0.2% accumulation of a total capacity of 95 Hm<sup>3</sup>.

In current years, the length and severity of the MD have shown that

**Table 5**  
Stored Volumes (millions of m<sup>3</sup>).

Reservoir	Region	Use	Capacity	Historical Average	2010	2012	2014	2016	2018	2020
Puclaro	IV	Irrigation	209	135	138	32	20	134	207	141
Recoleta	IV	Irrigation	86	67	73	24	4	58	86	55
La Paloma	IV	Irrigation	750	404	273	102	29	241	569	312
El yeso	RM	Drinking Water	220	176	201	113	105	220	135	118
Conv. Viejo	VI	Irrigation	237	140	70	208	156	169	223	219
Rapel	VI	Generation	695	517	415	544	425	484	413	416
Colbún	VII	Generation and Irrig.	1544	1135	629	756	688	677	766	881
Lago Laja	VIII	Generation and Irrig.	5582	3193	1235	1033	532	802	1045	889

Source: Own elaboration based on hydrometeorological reports (<https://dga.mop.gob.cl/>)

the current IC (mainly in the northern regions of Central Chile) is reaching a tipping point where the available stored water will not be enough to satisfy current and future demand. Within this scenario, the first policy restrictions have appeared to be used to manage and allocate these reserves. The economic impacts after these restrictions will likely be more harmful than those calculated in the present study.

#### 4.2. Amount of water in storage

Water stored in reservoirs and underground aquifers has provided an essential buffer against water scarcity during the current central Chile MD. However, during the last years, despite some regions' storage capacity (especially the northern ones), the water stored has not been recharged and, in the end, has not been enough to satisfy users' water demand. The changes in precipitation patterns and the increasing extremes of drought highlight the need to rethink current management strategies of water storage. However, managing water in storage during long-run droughts, involves complex trade-offs between short-term and long-term goals and between sources and uses of water with different physical and economic characteristics in supply and use.

Groundwater takes a long time to replenish, is a non-renewable resource, and the storage capacity of aquifers is often unknown. Additionally, groundwater exploitation is generally carried out on a more individual scale than surface water withdrawal because the economies of scale in surface water abstraction and conveyance are much larger than in groundwater. In this sense, aquifers are more prone to over-exploitation than surface water because they are inherently harder to manage on a big scale. Some examples have been observed in northern regions of Chile, where groundwater storage has been depleting due to the combined effect of drought and the rise of water demand (Suárez et al., 2014), which has implied more energy required for pumping (Meza et al., 2015).

The agricultural sector, in particular, has significantly buffered the MD economic impacts through groundwater use (Donoso, 2021). Groundwater use increased during the MD period, even though its importance as an alternative to surface water began before 2010 (Barría et al., 2021; Garreaud et al., 2017). The relationship between Chilean agriculture and groundwater use is explained mainly by the development of intensive activities in natural resources that led to significant increases in water demand and the surface water imbalance. This promoted agriculture under irrigation, increasing its surface (Martin and Saavedra, 2018) and representing 82% of the total consumptive water use (Donoso, 2021). Additionally, irrigation efficiency has increased its average efficiency between 1997 and 2007 from 48.6% to 56.9% (Martin and Saavedra, 2018). This efficiency also increases the area with technical irrigation, with which the sector's water demand has continued to increase. This last, combined with surface water imbalance, has put pressure on agriculture's use and overuse of groundwater (Donoso et al., 2020). Fig. 6 shows the groundwater level within three selected wells of three basins of Central Chile, where agriculture plays an important role.

Groundwater has helped farmers adjust to surface water imbalance in the short term. However, farm structural costs and resource

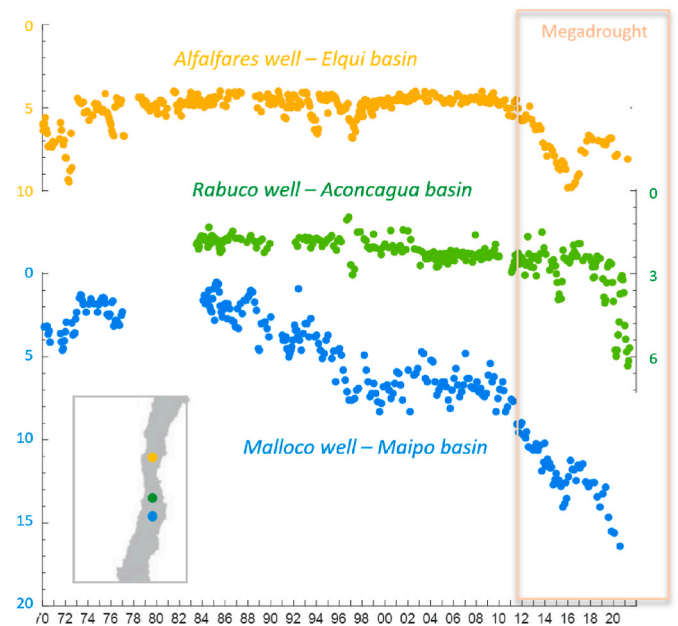


Fig. 6. The groundwater level in selected wells from northern regions of Central Chile.

management have changed. As groundwater storage decreases, farm pumping costs rise (Rinaudo and Donoso, 2018; Suárez et al., 2014). On the other hand, resources have been allocated more efficiently economically to higher-value crops. For example, Donoso (2021) documents that there has been an increased transaction of groundwater rights to the high-value agricultural export sector during the MD period with resulting efficiency gains.

Regarding surface water in storage, it is renewable, we can know its storage capacity, and it is dependent on precipitation and streamflow. Large volumes of water are stored in reservoirs, but these are more vulnerable to long-term droughts than aquifers (Scanlon et al., 2023). The Limarí basin, for instance, despite having more than 900 Hm<sup>3</sup> of storage capacity, the development in irrigated areas, especially with permanent crops, has made it harder to withstand long-term droughts since the system cannot supply the water needs of permanent crops. This has caused people to cut down trees and leave vineyards out of production (Scott et al., 2014). The drought has persisted, and reservoirs have drained instead of cutting water delivery. Thus, in March 2022, the Cogotí reservoir, which irrigates 25,000 ha in the Limarí valley, had no water for farmers.

The above examples show the need to rethink managing stored water, especially in a prolonged drought (Famiglietti, 2014; Milly et al., 2008). Several studies have highlighted that conjunctive surface water and groundwater management can resolve temporal disconnects between supply and demand caused by climate extremes (Scanlon et al., 2023). In the same way that the need for these changes is recognized, it

is necessary to change the form of economic analysis of these prolonged phenomena related to stored water.

A common notion in economics is the Le Chatelier Principle (Samuelson, 1948), according to which the economic cost of an adverse shock (e.g., lost profit) is lower in the long run than in the short run because the long-run provides more time to make adjustments that can mitigate the shock. However, the Principle does not hold when the short-run response involves drawing down limited reserves which are not automatically replenished, such as emptying reservoirs or increasing groundwater overdraft. If the shock persists, the economic loss is greater in the long run than in the short run. As we observed within the Limarí valley, while the reservoirs contain water and the depth of the water table is high, pulling water out of them did not imply enough high costs to restrict its use. Indeed, this was translated into an expansion of water-intensive fruit trees area during the beginning of the MD period, accompanied by a continuous intensification that increased water being used for irrigation but caused a drastic decrease in groundwater recharge (Nauditt et al., 2021). This overexploitation of surface and groundwater resources led to reservoirs close to the dead pool and lower groundwater tables, increasing pumping costs over time, reaching the point that farmers were forced to cut down their trees or leave crops unharvested.

The challenge with an MD is to maintain sufficient self-control to leave enough AWS as insurance against drought continuing in the following years and to refrain from pumping excessive amounts of groundwater and too rapidly emptying surface reservoirs. Water scarcity is affected by human control of the resource expressed in the AWS. Only water under human control is considered economically useful and thus reducing water scarcity (Zegarra, 2002). If AWS cannot be controlled, high levels of IC do not mean low scarcity in economic terms.

#### 4.3. Short- and long-term responses

The present MD has provided an excellent opportunity to examine agents' immediate responses to the drought situation at hand as well as the results of long-term decisions made in the past that have improved the region's economy's resilience. Despite being given at different times, both responses are connected.

Short-term disturbances due to drought are more related to severity than length. The MD's severity had not reached the levels of 1924, 1998, or 1968 droughts until 2019 and then, although to a lesser extent, in 2021 (see Fig. 2) (Garreaud et al., 2017, 2019). Our results show that despite its duration, the current MD has had similar economic impacts as the driest but shorter droughts mentioned above (e.g., Fernández et al. (1999)). Although these differences could be due to methodological differences, we argued that two factors are key to explaining our results. First, the current MD has not had the severity of the past droughts until 2019 (the final period of this assessment). In this sense, the economic agents' reactive responses (short-term responses) have had better effects on impact reduction because they face a more prolonged but less severe drought. Second, as discussed above, an important investment has been focused on increasing the country's level and composition of the IC in the last few years. Under this scenario, joined with the groundwater reserves, the capacity for authorities and private actors to implement drought management options has increased.

The agricultural sector is an excellent example of how public and private short-term responses succeeded in reducing the negative impacts of drought. Farmers planted less than their full acreage (Díaz, 2019), harvested less than the total area planted (Mayorga, 2021), used deficit irrigation application (Pizarro et al., 2022); the increase groundwater pumping (Donoso, 2021; Donoso et al., 2020); and reallocated water to higher-value crops (Meza et al., 2021). These measures have been accompanied by short-term public responses that have helped mitigate the economic impact of drought (agricultural insurance of cereals in drylands, technological transfers, irrigation law, agricultural emergency due to water deficit, and drought risk management).

On the other hand, long-term historical actions have provided the region with the conditions necessary to face the current megadrought. Chile's extensive history of droughts has resulted in more resilient infrastructure, institutions, and water requirements. In addition, the region's robust response to the MD is also attributable to the utilization of alternative energy sources (non-hydro). All these have translated into the successful preparation of the energy sector to the current MD impacts contrasting with the drought's impacts of 1967–1968 and 1997–1999 on the same sector.

Past droughts (1968 and 1998) had significant impacts on hydroelectric generation. They forced the State and the private sector to rethink the development of the national energy matrix toward a more resilient system for events like this. During 1968, most hydroelectric plants operated below their total capacity, producing 16% less energy than in 1967. The first energy rationing measures were announced at the end of the winter of that year, which continued until the first months of 1969 (de Montmollin, 2021). Although despite the rationing measures, more hydroelectric plants were built (Bauer, 2009). The experience was a wake-up call that pushed stakeholders to conduct long-term studies of historical rainfall patterns and consider valuing and managing the water stored in the reservoirs. At the end of 1998, the Chilean Central Interconnected System (CIS) had an average hydroelectric generation of 77%. The lack of rain and snow reduced hydroelectric generation so much that the CIS suffered power outages and frequent blackouts for months, causing severe economic losses for many people and organizations (Bauer, 2009). The emergency dramatically revealed the drawbacks of the central grid's reliance on hydropower. Political reactions and proposed reforms followed immediately.

In 1999, an important reform was made to the General Law of Electric Services, which implied that electric companies had to respond to any damage caused by power cuts, even if the cuts were caused by drought (Serra, 2022). In 2004 and 2005, Congress amended the Act to lower barriers to entry for power generation. However, given the environmental restrictions and citizen opposition, this did not have the expected response in the short term, making it challenging to build conventional power plants. In response to the above, the government deepened the previous modifications to the Law in favor of competition. It promoted non-conventional renewable energies (NCRE), except for hydroelectric plants with more than 20 MW. Consequently, hydropower dependence today is close to 27% (Serra, 2022).

Likewise, although past droughts encouraged the adoption of long-term policies that today have helped to face the current drought, long-term responses to future droughts have also been derived from it. Baeza (2018) indicates that the National Policy for Water Resources 2015 and the National Water Resources Strategy 2012–2025 defines the approaches, strategic axes, and actions to address the problems of drought and water scarcity, from legal to technological, among other actions. The legal sphere and institutional coordination changes have resulted in actions such as recovering and building reservoirs, recharging aquifers, saving water, and improving the practices of those sectors that use the resource (Ministerio del Interior y Seguridad Pública de Chile, 2015; MOP, 2012).

The current MD brought about a series of innovations to mitigate future events. In particular, the MOP, through the national plan for large reservoirs, considers the construction of works between 2015 and 2025 to provide a solution to the drought in rural areas of the country, with a focus on vulnerable agricultural sectors (MOP-DOH, 2016). At the same time, the government has aimed to improve monitoring and tend towards integrated management of water resources at the basin level. This has led to the approval of laws regulating rural sanitation services, water control and sanctions, and water collection (MOP, 2012). Similarly, from 2000 to the present, the evolution of groundwater management has been marked by the development of groundwater regulation and the search for co-management between the State and groundwater associations (Baeza, 2018; Donoso, 2021).

#### 4.4. Challenges, gaps, and way forward

This study calls to rethink how we assess the economic impact of long-run droughts. As droughts become more severe and prolonged, this inevitably implies taking charge of the tipping points. Central Chile megadrought -lasting more than a decade now-motivated this analysis beyond the academic exercise, since the current condition offers a grim prospect of the country's future climate, not dissimilar to the projections for other Mediterranean-like climates (e.g., California and South Africa). Past long-term responses move the water tipping point towards high levels of resilience, where water users have more flexibility to respond and adapt to a normal changing situation. However, if the drought persists, it is unclear how fast these adaptations will take place and whether tipping points will be passed. Our results show that despite the resilience shown by Central Chile to the current MD, stricter water restrictions have emerged, particularly in recent years. Parallel to this, several studies have issued warnings about the approaching availability thresholds for water supplies (such as groundwater or reservoirs) (Donoso et al., 2020; Rinaudo and Donoso, 2018), which might cause the economic cost of the existing MD to increase quite substantially. This fact poses a new paradigm for the economic impact assessment of droughts and their adaptation when we face droughts persisting for several years and even decades. The economic notion that adaptive responses are more flexible in the long run than in the short run (thus, implying lower economic cost) generally does not hold when groundwater depletion and rapid emptying of surface water reservoirs are the short-run responses. Our results show that within the first years of the drought, as water reserves are at nearly total capacity, the economic costs of short-run responses are lower. However, as the drought continues, reserves deplete; thus, long-run responses are no longer flexible, and the economic costs increase. Even more, the economic impact skyrockets when water restrictions arise as a policy option. This is especially evident when the avoided cost is calculated in urban drinking water.

The above also implies new challenges for policymakers and the private sector. As a policy and private decision implication, generally, policymakers make decisions about future drought strategies, justifying them based on the economic impact of past or current droughts (among other criteria). It is important to ask not only about the current economic impacts but also the economic impacts if the IC and the AWS levels are close to their limits. Our results highlight that in a context of a long-run drought, despite the IC or the flexibility to adapt, when a rationing scenario is getting closer, the cost could be much higher than those costs calculated as current economic impacts. In this context, deciding what value is used for justifying a policy strategy or a private measure could have a tremendous effect on the type and the level of the adaptation measure to choose and the investment it implies. Once again, the urban drinking water sector provides a grim example: the total expenditure to mitigate (and avoid) water rationing in a city like Santiago (ca 6 million inhabitants) is likely order of magnitude of the social and economic catastrophe that a water shortage -for days or weeks-may bring.

Another point to rethink in a context of a long-run drought is the increasing complexity of the interaction of natural and human processes (Van Loon et al., 2016). As the drought persists, this relation comprises complex and dynamic feedback resulting in a strongly non-linear response of the hydrological system. As discussed, short-term responses to drought can include water use reductions, water-saving technologies, planting less water-demanding crops, using other water sources, and increasing groundwater abstraction because of surface water shortage. These measures could affect (positively or negatively) water storage and fluxes within a particular water system. These effects, frequently overlooked in short-term droughts, must be considered in the context of long-term droughts. If the drought persists, actions taken to lessen the immediate local economic impact may push us closer to water tipping points, exacerbating the economic impacts in the years to come.

## 5. Conclusions

This paper analyses the economics of long-run droughts, assessing the economic impacts of the MD in Central Chile (2010-present) within an analytical framework that sets out essential characteristics of a drought, such as IC, the AWS, and the short- and long-term responses. Our study shows that the different economic sectors have adapted autonomously to the MD, buffering their economic impacts. In this context of low economic impacts, despite the magnitude and extension of the current MD, the level of IC and the AWS, the temporality of the phenomenon, and the short- and long-term responses are key factors to explain what a first sight could seem striking. However, the long-term drought could lead the region to water-critical levels, which may skyrocket the negative economic impacts. The latter is observed in our results when avoided cost for the urban drinking water sector is 208% and 515% greater than the inversion made by sanitary companies, in scenarios of 5 and 10 years of avoided costs, respectively.

In economics, the less flexible response in the short run than the long-run response implies that the economic cost is lower in the long run than in the short run. However, in a long-run drought, as we near a scenario when water reserves are nearly depleted, long-run responses become more costly. When countries or regions have a long history of short-run droughts, they have accumulated knowledge and infrastructure to adapt. However, long-run droughts may overcome this acquired adaptability. Our findings highlight how important it is to ensure enough water supply to fill storage capacity and maintain a resilient water system during drought. While the different economic sectors in Central Chile have adapted to the MD and buffered its impacts, further research is needed to better understand the available water supply, especially from groundwater reserves, and to determine the tipping point at which resilience may be lost.

Moreover, although the economic impacts estimated in our study could be helpful information for policymakers, it is important to indicate a few caveats. First, we have focussed on estimating the economic impacts for specific economic sectors without considering the effects of droughts on ecosystem services. The non-inclusion of these intangible costs could underestimate the actual cost. Second, the geographic coverage of this assessment involved several regions, provinces, and communes with different characteristics. In this sense, local economic impacts, for instance, at the commune level, were cancelled since zero-sum transfers of losses or gains were not excluded between different communes. In this sense, the low aggregated economic impact may hide significant local economic impacts.

Finally, this study underscores the need for policymakers to prioritize measures that ensure a sufficient water supply to fill storage capacity and maintain a robust water system during drought. Given the potential consequences of long-run droughts, more research is urgently needed to better understand the available water supply and the threshold at which regions may lose their resilience.

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### Credit authors statement

**Francisco Fernández:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Visualization. **Felipe Vásquez-Lavín:** Conceptualization, Supervision, Writing – review & editing, Funding acquisition. **Roberto D. Ponce:** Writing – review & editing, Funding acquisition. **Rene Garreaud:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Francisco Hernández:** Data curation, Formal analysis, Investigation, Methodology, Writing-original draft. **Oscar**

**Link:** Data curation, Formal analysis, Investigation, writing - review.  
**Francisco Zambrano:** Data curation, Formal analysis, Investigation, writing - review.  
**Michael Hanemann:** Conceptualization, Formal analysis, – review & editing.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

### Appendix A. Methodological details

#### A.1 Agricultural sector

##### A.1.1. Mathematical programming model for the agricultural sector

In this model, the representative farmer is modeled at the commune level. Each commune is considered an economic agent whose objective is to maximize profit given its particular resource constraints, where 177 communes were considered between Coquimbo and Bio Bio. The main decision variable is the area assigned by 20 agricultural activities (Common Beans, Potatoes, Wheat, Corn, Sugar-beet, Rice, Oats, Cherry, Walnut, Red Apple, Green Apple, European Plum, Japanese Plum, Orange, Avocado, Olive, Pear, Asian Pear, Grape, Peach) and cropping system (rainfed or irrigated) represented by  $X_{c,a,s}$ . In this case,  $X_{c,a,s}$  describes the area (ha) of commune  $c$  assigned to activity  $a$  with cropping system  $s$ .

The objective function of the model is the benefit of the national agricultural sector ( $Z$ ) considering the agricultural income generated by each of the communes ( $Z_c$ ). Thus, the objective function is defined as:

$$\max Z = \sum_c Z_c \quad (\text{Eq.A1})$$

The agricultural income of each of the communes ( $Z_c$ ) is defined as:

$$Z_c = \sum_a \sum_s ((P_a * y_{c,a,s}) * X_{c,a,s}) - \sum_a \sum_s \alpha_{c,a,s} * (X_{c,a,s})^{\beta_{c,a,s}} \quad (\text{Eq.A 2})$$

Where,  $P_a$  is the price for activity  $a$ ,  $y_{c,a,s}$  is the yield of crop  $a$ , under system  $s$  in commune  $c$  and  $X_{c,a,s}$  is the decision variable. On the other hand,  $\sum_a \sum_s \alpha_{c,a,s} * (X_{c,a,s})^{\beta_{c,a,s}}$  represents the nonlinear cost function whose parameters  $\alpha_{c,a,s}$  and  $\beta_{c,a,s}$  were estimated using a variant of the PMP approach (Blanco et al., 2008).

On the other hand, the resource constraint is defined as:

$$\sum_a \sum_s r_{i,c,a,s} * X_{c,a,s} \leq b_{i,c} \quad (\text{Eq. A3})$$

$$X_{c,a,s} \geq 0 \quad (\text{Eq. A4})$$

Where in equation [A3]  $r_{i,c,a,s}$  represents the matrix of coefficients in the resource constraints. That is, the resource requirements of each of the activities, by commune and by production system. While  $b_{i,c}$  represents the vector of amounts of resources available per commune. While equation [A4] represents the non-negativity restrictions in the distribution of land.

The proposed model reproduces the activity levels observed for all years from 2010 to 2020. The model allows to compare the observed activity levels for each year reflecting the responses of agricultural producers in each of these years (from 2010 to 2020). The model incorporates all the available information and uses calibrated parameters to model all the conditions that –due to the lack of information– cannot be made explicit.

The base information used (area, production, yield) and how data from different sources was treated is presented in Table A1. For fruits, area and yield data was obtained from “Catastro Frutícola” (CIREN, 2020), for all regions considered in this study (from Coquimbo to Bio Bio region) and from year 2010–2020. Yield data (average production per hectare according to reported production) was obtained from the latest yield data reported by the Catastro Frutícola 2010–2020 or nearby years. If there is no information for a specific tree, informed production is considered divided by the area in production. Missing data for area and yield was imputed using the imputeTS package (Moritz, and Bartz-Beielstein, 2017) in R, which specializes on univariate time series imputation. Moreover, administrative changes regarding the region and communes’ organizations were considered until 2010. After this year new administrative organization were not considered (e.g., constitution of Nuble region in 2018). For annual crops, legumes and industrial crops, area and yield data from Ponce et al. (2014) and 2007 Census was updated using the Indexes of Annual crops from ODEPA (2021). These Indices help to reflect the

variation in area and yield between 2007 and 2010 and regional variations between 2010 and 2020. The information on the costs by commune, activities and irrigation systems (irrigation, rainfed), as well as the intensity of work is the same used in the study of the Office of Agrarian Studies and Policies (ODEPA, 2010). From this and based on information from FAO (FAO, 2020) on area, yields and prices, the data was updated to all years. Finally, the elasticities used to calibrate the model were collected from previous studies (Quiroz et al., 1995; CAPRI Model, 2008; Foster et al., 2011).

**Table A1**  
Data used for agricultural model

Data source	Crops	Years	Variable	Scale	Data treatment
Catastro Frutícola	Cherry, European plum, Japanese plum, Fresh consumption peach, Table grape, Red apple, Green apple, Olive, Avocado, Asian pear, Pear, Walnut, Orange	2002–2020	Fruit Area	Region/Province/Commune – from Coquimbo to Bio Bio region	We use ImputeTS package in R to impute the missing values Marga Marga province was created in 2009 (We consider Olmue and Limache communes within it since 2002) Since September 6, 2018, the Nuble region has been constituted, formed by twenty-one communes made up the province of Nuble, of the Biobío Region. For this study, the current communes of the Nuble region were still considered within the Biobío region. Latest yield data reported by Catastro frutícola 2010–2020 or nearby years Yield information (Average production per hectare according to reported production) If the fruit tree is not present, it is considered informed production/Area in the production
Ponce et al. (2014)/ Índices de Cultivos Anuales Regionales/ Census 2007	Wheat, Maize, Oat, Potato, Rice, sugarbeet, Common bean	2010 to 2020	Annual crops, legumbres and industrial crops Area and yields	Regional	Historical regional area and yield data regarding ODEPA 2021 annual crops are considered. Indices are determined to reflect the variation in area and yield between 2007 and 2010 and regional variations between 2010 and 2020. With these indices, it is corrected database used in Ponce et al. (2014), whose initial source is based on data from the 2007 Census
Ponce et al. (2014)	All crops	2010 to 2020	Labor and Total Cost	Region/Province/Commune – from Coquimbo to Bio Bio region	Information used in the study of Chilean Agrarian Policies and Studies Bureau (ODEPA, 2010). Updated cost using price variation from FAOSTAT (2010–2020)
Agrimed	All crops	2010 to 2020	Crop Irrigation Requirement (CIR)	Region/Province/Commune by specie	Original data in mm/m <sup>2</sup> /yr, Crop Irrigation requirements at the Base Line(th m <sup>3</sup> /h/yr) For those crops without CIR information the associated figure is: Rice = 15 tho m <sup>3</sup> /h/yr cherry, plum, walnut and pear uses 8 tho m <sup>3</sup> /year = used by peach Olive uses 5 tho m <sup>3</sup> /year = used by maize Avocado uses 10 tho m <sup>3</sup> /year = used by orange
FAOSTAT	All crops	2010 and 2020	Prices	Country	Real prices for all years (from 2010 to 2020) for all crops considered in this study,

**A.1.2. Scenarios**

For this case, where the ex-post economic effect of the drought in the sector is evaluated, we calibrated the model for each year, meaning for 2010, 2011 and so on until 2020, assuming a profit-maximizing equilibrium in all years considering sectorial statistics at the national and regional level. We called the evolution of these years calibrated, the baseline path, which represent what actually happened in each of these years in terms of activity levels. The comparison between each year of the baseline path reflects the structural changes in the agricultural sector of the Central region, represented in land allocation, water demand, labor demand, and income. The differences between years will be compared with national and regional statistics to explain the observed changes and look for drought contribution.

To obtain an economical range of the megadrought impact, we tested the isolated and combined effects of activity prices, costs, and yield evolutions from 2010 to 2020 compared to the 2010 year. We try to answer here what the main changes would have been if observed activity levels in the year of 2010 were subjected to the prices, costs, and yields observed in all the posterior years until 2020. Scenario 1, represent the activity level of the year 2010 from the baseline path, but considering the evolution of prices and cost in the following years. Meanwhile, scenario 2, represents the same activity level from 2010 as starting point but in the following years, considering prices, costs and yield evolution from posterior years. The difference of these scenarios paths with the baseline path will give us a delta where the effects of prices, yields, and costs were isolated. Assuming that drought has had a negative impact on the agricultural sector, comparing scenarios results with the baseline path will draw the upper threshold of drought’s influence, discarding the price, cost, and yield effects.

## A.2. Urban drinking water

### A.2.1. Analysis of Changes in Water Supply

For the supply side, we estimate the induced costs based on the investments made by sanitation companies as a response to the MD. Data was provided by the National Association of Sanitary Service Companies of Chile (ANDESS), including operational and capital expenditures from 2010 to 2020 for items considered explicitly as a response to the megadrought. The investments were classified based on their stage within the process as an investment for production, distribution, or “others” (like studies or public awareness campaigns for rational use). Data used for calculations is unavailable for public use due to confidentiality agreement with the participating firms.

### A.2.2. Urban drinking water demand

**A.2.2.1 Residential Water Demand Estimation.** For the estimation of water demand at the residential level, the same approach described by [Fercovic et al. \(2019\)](#) was used, where an estimate of the demand of an average household at the commune level is made. This water consumption is a function of economic variables (price and income), climatic-related variables (precipitation and temperature) and vegetational drought index. The water consumption considered in these estimates includes all possible consumptions within the household: kitchen (washing dishes, cooking, drinking, laundry), bathroom (sinks, toilets, showers) and gardens (swimming pool, garden). The available data do not allow distinguishing between these uses, however, the Observatory of Cities of the Catholic University (OCUD) in its 2019 report projects these consumptions for different socioeconomic sectors. In the highest income segments, consumption outside the home (garden and swimming pools) represented 63% of the group of households with a house, while in the most vulnerable sectors this consumption represented at most 7%. Therefore, in a scenario of water stress, it is reasonable to think about restricting consumption for non-essential uses such as irrigation of gardens and swimming pools.

For the estimation of demand, a log-log functional form is assumed<sup>4</sup>:

$$\ln(w_{it}) = Z_{it}\delta + \alpha \ln(P_{it}) + \gamma(Y_{it}) + \varepsilon_{it} \quad (\text{Eq. A5})$$

Where  $w_{it}$ , is the average water demand in commune  $i$ , in period  $t$ ;  $Z_{it}$  is the vector of socio-demographic variables of commune  $i$  in period  $t$ , among which we have: climatic variables (temperature and precipitation) and vegetational drought index;  $Y_{it}$  is the income of commune  $i$  in period  $t$ ;  $P_{it}$  is the average price of water in commune  $i$  in period  $t$  and  $\varepsilon_{it}$  represents the error term. For the estimation, an unbalanced panel was constructed based on the sample of [Acuña et al. \(2020\)](#) that considers aggregated information at the level of municipalities. In particular, according to the spatial framework of interest, 215 municipalities are considered, during the period 2010–2020, which was estimated using a standard fixed effect (OLS) estimator and the standard errors are clustered at the municipality level.

Water consumption and price data were obtained from [Acuña et al. \(2020\)](#) in complement with information from the Superintendency of Sanitation Services (SISS), which was complemented with information on climate variables obtained from CR2 (CR2, 2020). The specification used for water demand follows a simplified form of the model of [Fercovic et al. \(2019\)](#), where the sub-indices  $i$  and  $t$  represent the commune and the period (month) respectively:

$$\ln(w_{it}) = \beta_0 + \beta_1 \ln(P_{it}) + \beta_2 \ln(Y_{it}) + \beta_3 \ln(H_{it}) + \beta_4 \ln(T_{it}) + \beta_5 \ln(Pr_{it}) + \beta_6 \ln(ZCNDVI_{it}) + \mu_t + v_i + \varepsilon_{it} \quad (\text{Eq. A6})$$

Where  $w_{it}$  represents the average residential water use in commune  $i$  in period  $t$ ;  $P_{it}$  is the average water price;  $Y_{it}$  represents the household income;  $H_{it}$  is the number of habitants of commune  $i$  in period  $t$ ;  $T_{it}$  is the average monthly temperature;  $Pr_{it}$  is the average monthly precipitation;  $ZCNDVI_{it}$  represents the commune-level vegetational drought index;  $\mu_t$  denotes seasonal variables per year;  $v_i$  are fixed effects; and  $\varepsilon_{it}$  is the error term. The model was estimated with the sample of all communes with available data that are in the spatial framework of interest and with a subsample of the same 43 communes used by [Fercovic et al. \(2019\)](#). A standard fixed effects (OLS) estimator is used and standard errors are clustered at the commune level. Once the water demand is estimated, the results are used to evaluate consumption in the megadrought scenario.

**A.2.2.2. Megadrought Cost Estimation.** As shown in [Figure A1](#), the economic cost of the megadrought scenario is obtained by valuing the potential loss of household welfare in the event of a rationing scenario in the supply of the resource. For this purpose, the following assumptions are considered. In the first place, it is assumed that in the initial situation there is an equilibrium between the water demand of the various municipalities and the water supply available in each of them. It is also assumed that the drinking water sector is the only water consumer in each of the municipalities. With respect to the expected change in water availability in the megadrought scenario, a 20% rationing scenario is assumed, which could affect water consumption and household welfare. Additionally, is important to mention that column ABDE is generally not a saving in production costs. This is due to variable cost represent a small fraction of the overall cost of water supply, thus the conventional assumptions that, if less water is delivered, the costs of water supply operations fall in the same proportion is not considered in this case.

<sup>4</sup> The log-log functional form together with the linear functional form, is one of the most widely used in the literature. It has two advantages over the linear functional form: (1) it delivers the price elasticity directly, i.e., it is simple to interpret the estimated parameter and (2) it has no exclusion price, i.e., there is no price at which water consumption can be zero, which is consistent with an essential good such as water. Other functional forms less commonly used in the literature are the semilogarithmic functional form and the Stone-Geary functional form. For more details on the functional forms of water demand, see [Vásquez-Lavín et al., 2017](#).

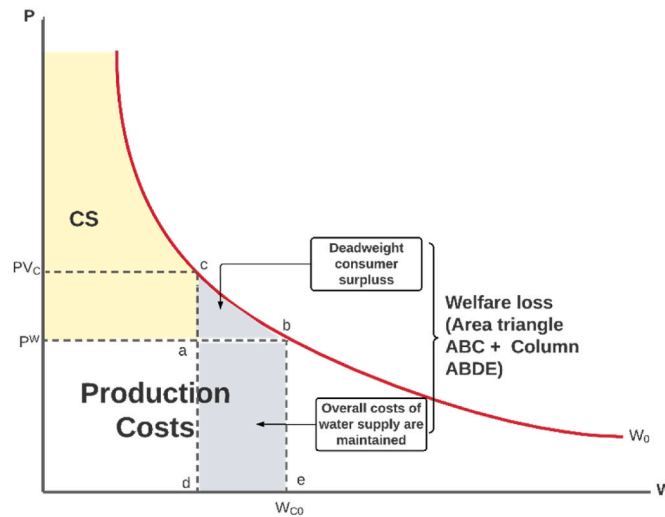


Fig. A1. Megadrought Household-level water cost estimation

### A.3. Hydroelectricity power, rural water supply, forestry, and tourism

For the hydroelectricity, rural water supply, forestry, and tourism sectors, secondary data was collected on how drought affects each sector's economy. We couldn't simulate a behavior pattern like we could with agriculture and residential water demand to figure out the economic impact, so we used a more descriptive method. Table A2 gives a brief summary of each method used in each industry and its main features.

Table A2

Summary of methods used by each sector

Sector	Type of method	Method Characteristics
Agriculture	Mathematical Programming Model	Supply Model to evaluate ex-post income losses as a proxy of drought costs
Urban Water supply	Residential Water Demand Model and Supply investments	Direct assessment of Induced Costs on national water companies
Rural Water Supply	Secondary information	Avoided Costs considering potential water shortages scenario (consumer surplus)
Hydropower		Direct Costs
Tourism		Descriptive
Forest		Descriptive

## Appendix B. Secondary Figures

### B.1. Urban drinking water sector

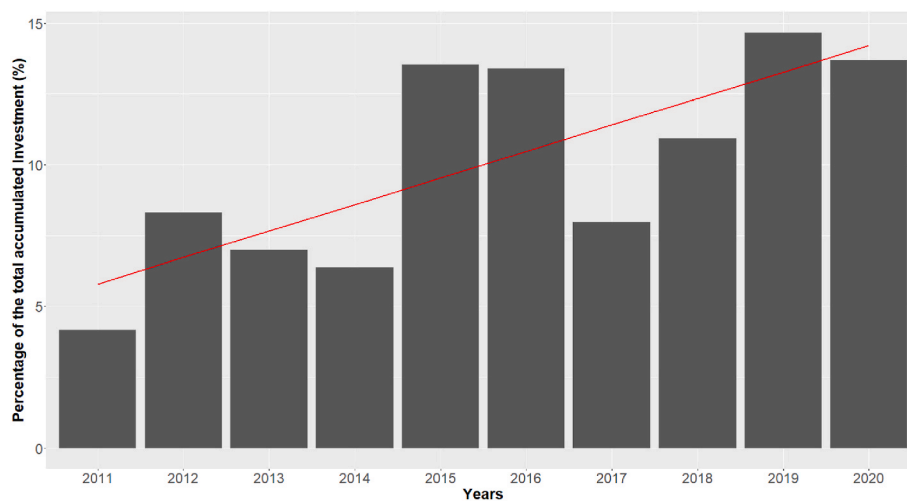


Fig. B1. Annual percentage of the accumulated investments during the period 2010–2020. The Red line represents the trend of the annual percentage of the accumulated investment.

B2. Rural water supply

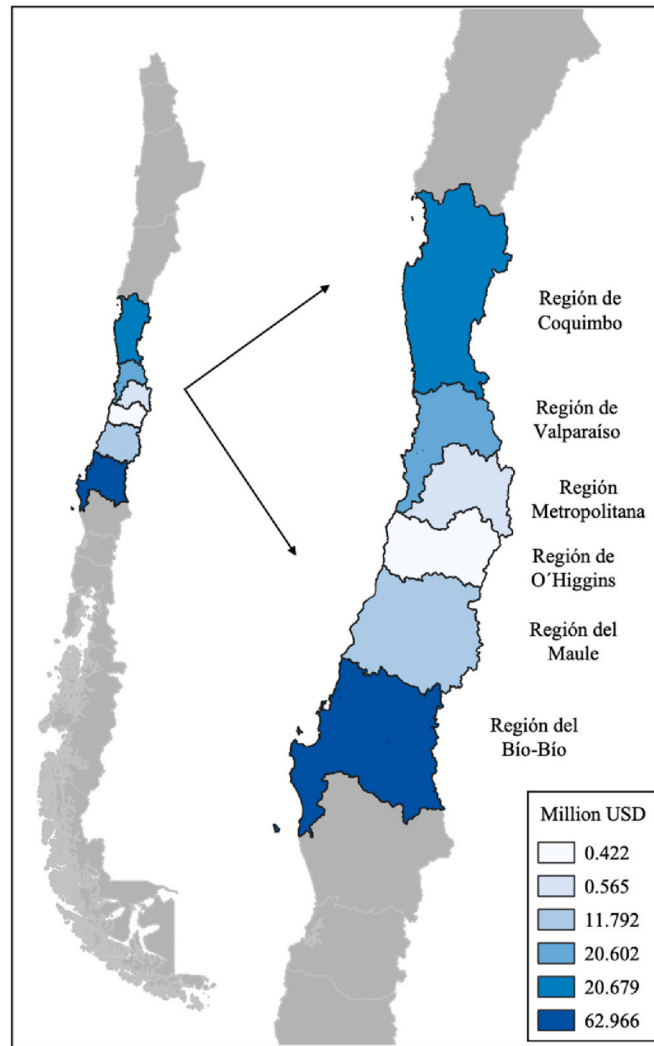


Fig. B2. Regional expenditure in water trucks between 2011 and 2019

Appendix C. Detailed results

C.1. Hydropower

Energy production in Chile depends significantly on water availability. The central interconnected system (SIC for its acronym in Spanish), the most extensive electrical system supplying energy to Chile, feeds 92.2% of the national population (CEN, 2022). The National Energy Commission (CNE) (2017) indicates that by 2015, 45% of Chile's generation was obtained from reservoir power plants.

Although several factors have played an important role in changing the country's energy supply structure, the high dependence on energy imports with volatile prices puts significant pressure to start considering alternative energy sources (de Montmollin, 2021; Nasirov et al., 2018). Droughts and reduced rainfall have hampered the country's energy supplies. The energy sector's sources have changed dramatically, especially hydropower. Figure C1 illustrates the energy mix from 2000 to 2017.

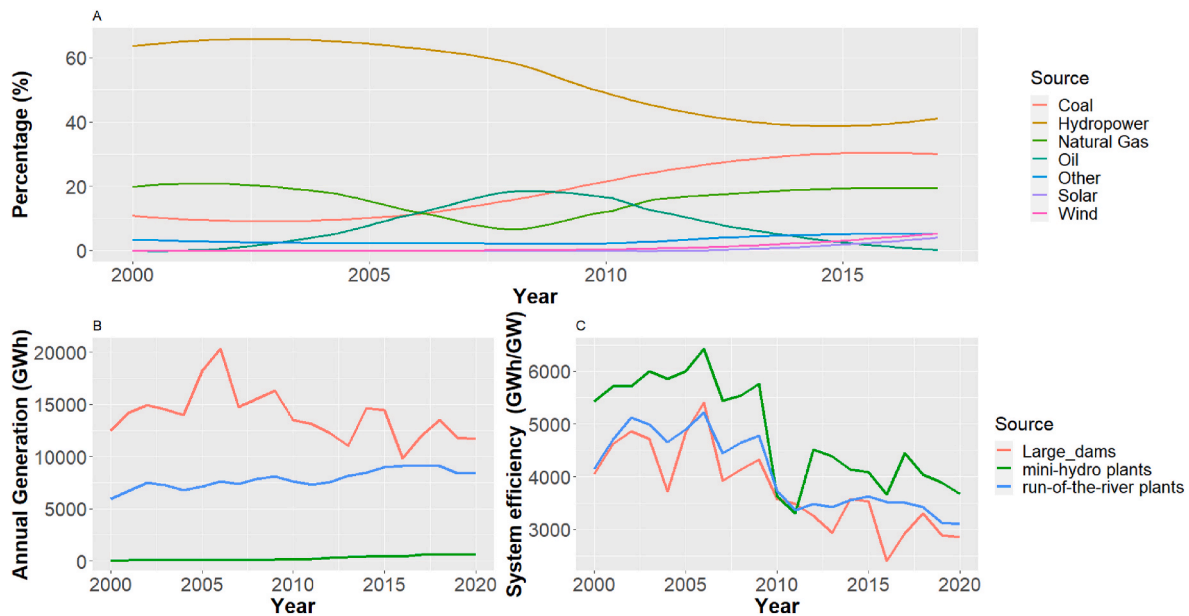


Fig. C1. Percentage of energy generation. Source: Own elaboration

Figure C1 indicates that hydroelectric power corresponds to the primary energy generated in the country. However, the contribution of hydroelectric energy to the total generated has decreased from nearly 70% in the early 2000s to approximately 35% in 2017. Although several factors have influenced these changes, the drop in the hydroelectric share is consistent with the uninterrupted sequence of dry years with average deficits of between 20% and 40% that Chile has experienced since 2010 (Aldunce et al., 2017; Garreaud et al., 2020). It is important to highlight that the drop in hydroelectric involvement in the matrix over the previous 20 years, called “carbonization,” is a multifactor response not only to the drought, such as the falling price of fossil fuels on the worldwide market. 1998’s drought led to more thermal power plants to reduce rain reliance. Later, import prices explain the rise of thermal power plants.

In the hydroelectric sector, the installed capacity is dominated by large dams, followed by middle size and mini-hydro projects. All these sources present an increase in their installed capacity from 2000 to 2021, highlighting the capacity of run-of-the-river plants during the drought. Although the growth of these sources’ installed capacity, they also exhibit important variations between different years (see Panel B and C of Figure C1). Large dams produced significantly more energy than smaller plants during the pre-megadrought period (2000–2010). During the MD period (2010–2020), run-of-the-river plants practically equaled the energy production of large dams (Panel B). Probably, the drought produced a change in the dominant favored production mode (i.e., large dam, run-of-the-river, or mini-hydro), where run-of-the-river plants become increasingly important with the drought compared to large dams.

Regarding the system efficiency (the ratio between annual generation and installed capacity), all three hydropower sources exhibit a clear tendency to decrease in time, which translates to increased installed capacity to produce additional energy in time. This trend is more pronounced than in the predrought period after 2010 (i.e., drought increase the marginal cost of hydropower) (Panel C).

Despite the evidence that has been provided here indicating the influence of the MD on the development of the hydropower industry, it is not possible to eliminate confounding variables using the data at hand. Therefore, the national data trend cannot be solely attributed to it.

### C.2. Forest

The Chilean Statistical Yearbook of Forestry 2021 warns about the decline in some species’ yield in the last few years, especially in Eucalyptus globulus plantations, due to, among other factors, the megadrought in the central zone of the country, affecting the plantation growth (INFOR, 2021). In addition, the increase in the frequency and magnitude of wildfires, as a secondary effect of the current megadrought, has become an important socio-economic issue in the country (Garreaud et al., 2020). The fires in 2017 damaged 198,000 ha of standing plantations in the O’Higgins, Maule, and Biobío regions, of which 79% corresponded to radiata pine plantations and the remaining 21% to eucalyptus plantations (INFOR, 2021).

The direct economic costs of how the lack of water has affected the forest industry (e.g., on species’ yield) have not been estimated. Regarding wildfires, as a secondary effect of droughts, Vásquez-Lavín et al., 2017 informed that during the 2017 fire season, around 570,000 ha distributed in 12 regions of the country were affected, which was translated to more than US\$ 362 million of costs incurred by the State during that season. Regarding private spending on forest fires reported by the Chilean Wood Corporation (CORMA), during the 2017–2018 fire season, forestry companies increased their investment to almost USD 80 million, and the amount allocated to prevention reached 18 million USD. Moreover, according to CORMA’s reports for 2013–14, 2014–15, 2015–16, and 2016–17, leading forestry companies allocated 50 million USD to fire prevention and combat.

Although these data represent key information to estimate the possible economic (accounting) impacts of forest fires, they would underestimate the actual cost by not including the impact on flora, fauna, soil, human health, and other relevant ecosystem services (Vásquez-Lavín et al., 2017).

### C.3. Tourism

Megadrought also has affected outdoor recreation, especially those related to the ski industry. Aldunce et al. (2017) interviewed ski industry informants in Chile about the MD’s effects on the industry. Most agreed that the main economic impact of the drought was higher expenditures for trip

companies, particularly artificial snow for ski resorts (Central-Chile). Moreover, the same authors mentioned the shortened ski season as a major drought impacting the industry. Vanat (2021) also mentioned this last point in the 2021 International Report on Snow & Mountain Tourism, indicating that the 2019 season was 17% shorter than the year 2018.

Although no reports have estimated the MD's economic impact on the ski industry in Chile, information has been compiled that can serve as a starting point for this. The Agency for Sustainability and Climate Change (ASCC), within the framework of the project "Territorial Agreement for Adaptation to Climate Change in Cordillera and Precordillera Areas," reviewed the international experience regarding the socio-economic implications of the lack of snow in ski resorts due to climate change (ASCC, 2018). This review identified the investment and operating costs associated with snowmaking. For example, Duglio and Beltramo (2016) indicate that 1 m<sup>3</sup> of artificial snow (including amortization, energy, and personnel costs) would be between 3 and 5 euros, while the unit cost of a snow gun would be US\$131,000.

Considering the above information, and, as an example, Table C1 presents an approximate estimate of the costs induced by the drought in two of the main ski centers in the central zone by 2021. For the estimation, the skiable surface of each center, the historical snow level, and the level of snow falling in 2021 are considered. Then, we determine the difference between the historical snow volume and the current volume for the skiable surface. On this difference, we apply two assumptions. First, the volume of snow is applied only in particular months, for which we assume only 50% of the calculated difference. Second, the center seeks to reach snow levels that allow them to carry out sports activities and not reach the historical snow averages, for which they only seek to generate a percentage of the previous 50% (for this, we also assume a 50%).

**Table C1**  
Cost induced on Ski centers

Item/Ski center	Portillo	Valle Nevado
Skiable surface (mt <sup>2</sup> )	5000000	9000000
Historical snow level (mts/year)	1,12	1,27
Snow falling (2021) (mts/year)	0,01	0,00
Volume snow (2021) (Skiable surface * Snow falling) (mt <sup>3</sup> )	50000	0
Volume snow (historical) (Skiable surface * Historical snow level) (mt <sup>3</sup> )	5600000	11430000
Volume Difference (mt <sup>3</sup> )	5550000	11430000
1st assumption (Seasonality): 50% of the year (mt <sup>3</sup> )	2775000	5715000
2nd assumption (Sport): 50% of the snow just for sport (mt <sup>3</sup> )	1387500	2857500
Total Operational Cost (assuming 4,16 USD/mt <sup>3</sup> ) (million USD)	5,77	11,88
Capital expenditure (snow gun)	0,131	0131
Total cost (million USD)	<b>5901</b>	<b>12,011</b>

With the above data, we estimate nearly 18 million USD as a cost of generating artificial snow for the main Ski resorts, which is considered one of the main drought's economic impacts. Assuming, a similar economic impact during the entire mega drought period, we estimate an accumulated economic impact of nearly 180 million USD between 2010 and 2020.

Currently, snowmaking is a regular practice in Chile for different ski centers. Identifying whether the operating costs and capital investments are like the international literature is key to determining the economic impacts of the megadrought on the industry and having data regarding the amount of m<sup>3</sup> of snow generated during periods of drought. Additionally, information regarding changes in ski season and the effects on the number of visitors may be key information to evaluate the economic effects of the megadrought.

#### Appendix D. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2023.118726>.

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