VALUATION OF ECOSYSTEM SERVICES FOR WATER PROVISION, PURIFICATION, AND REGULATION IN CHILEAN REGIONS BASED ON A MULTIREGIONAL INPUT-OUTPUT MODEL

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Abstract

Water-related ecosystem services (WES) - including provision, purification, and physical regulation - are fundamental to regional sustainability but remain economically undervalued in Chile. This study addresses this gap by quantifying for the first time the economic value of these services across Chilean regions, employing an environmentally extended multiregional input-output model (MRIO-EE). The model integrates the economic structure of 15 regions (2014), sectoral water extractions and restitutions from surface and groundwater, and the additional water required for pollutant dilution and assimilation (gray water). Scarcity thresholds (ST) and the extended water exploitation index (EWEI) are calculated to evaluate regional hydroeconomic equilibrium (HEE) and its associated cost (CHEE). The analysis estimates water usage under overexploitation conditions, linking it to the opportunity cost of reallocating water to its most economically productive use—generating added value. Results indicate that the economic value of water services in overexploited regions ranges from 3 to 50 USD per cubic meter (2014). The total value of provision and purification services is 71.5 billion USD, with groundwater regulation services contributing an additional 10.7 billion USD. These findings highlight the significant regional variability and economic importance of WES in Chile. This study demonstrates that the MRIO-EE model, despite certain limitations, provides a robust framework for quantifying the economic value of water-related ES. The results offer critical insights for designing policies aimed at achieving sustainable and equitable water resource management in regions facing overexploitation.

Key words: Input-output, hydro-economic equilibrium, water ecosystem services, Chile

JEL Classification: C67, Q25, Q50

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CONTENTS

1 Introduction

Chile exhibits a notable spatial variance in socioeconomic conditions, characterized by significant discrepancies in population, productive arrangement, and developmental levels across its regions (Mieres, 2020). This scenario is further complicated by pronounced spatial climatic fluctuations that exert an influence on the availability of water resources (Fernández and Gironás, 2021). While the nation possesses a considerable volume of water resources, their distribution is uneven, ranging from scarcity in the north to abundance in the south (DGA, 2016). Industries reliant on substantial water usage, such as agriculture, mining, and water supply services, assume pivotal roles in the central and northern regions of the country. Many of these regions are grappling with severe water scarcity issues that are poised to be exacerbated by the impacts of climate change (Barría et al., 2021; IPCC, 2021).

This dual spatial heterogeneity and the incongruity between water availability and demand accentuate the significance of comprehending the spatial interplay between the economic framework and water assets. Furthermore, it underscores the importance of possessing tools to assess the ramifications of national and regional policies on regional water equilibriums, aimed at fostering development resilient to climate shifts, as underscored by the IPCC report (IPCC, 2022).

In this context, an interesting research question is: What are the virtual water flows between Chilean regions, and their content in terms of pollution, value added, and scarcity?

To address this research question, this article has the following main objectives: i) To determine water extractions and returns (volume and quality) from productive sectors in each region of Chile. ii) To estimate virtual water flows between regions, identifying their pollution content (grey water) and value added. iii) To determine the hydroeconomic equilibrium by region and the volume of water used beyond scarcity thresholds. iv) To estimate the scarcity content in virtual water flows. v) To determine the cost of the hydroeconomic equilibrium in Chilean regions (eliminating overexploitation), in terms of value added.

To scrutinize these intricate economic-environmental interdependencies, an environmentally extended multiregional input-output (MRIO-EE) model serves as a robust framework for studying the multifaceted linkages between economic endeavours and water sources. These models excel in capturing the complex dynamics of interactions spanning regions and sectors (Wood, 2017).

Within this framework, the present study utilizes the first and only MRIO matrix constructed for Chile (Haddad et al., 2018b), which includes the 15 regions existing in the country at that time and 12 economic sectors.

In delineating water demand, the framework adopts the concept of extended water demand (ED) introduced by Guan and Hubacek (2008). This concept encompasses surface and groundwater extractions net of returns (blue water), as well as the water required for pollutant dilution (grey water). Water extraction and return coefficients are estimated based on available data and indirect methodologies. The determination of grey water coefficients involves the use of a mixing model (Rocchi et al., 2024; Sturla and Rocchi, 2024; Xie, 1996). The estimation of virtual water flows (Allan, 2003) follows the methodologies proposed by Haddad (2020) and Sturla et al. (2023, 2024), incorporating a final demand matrix. Additionally, the study estimates the composition of regional water use by calculating the volume of virtual water exported from Chile.

To characterize the water balance, the study employs the concept of hydroeconomic equilibrium (HEE) introduced by Sturla and Rocchi (2022). A region is considered to be in HEE when the extended water exploitation index (EWEI) doesn’t exceed the scarcity threshold (ST). The EWEI is the ratio of extended demand (ED) to feasible supply (FS), where the latter represents water availability adjusted for environmental, physical, and institutional considerations. The calculation of the ST incorporates groundwater resource management capacity, along with the inclusion of surface water management capacity in the present study. Based on the above, the excess ED, that is the of water used by the economic system beyond the scarcity threshold, is calculated for each region, allowing to weight for scarcity virtual water flows. Finally, the cost of HEE (CHEE) is determined based on an optimization problem to determine the maximum value added in the economy compatible with water scarcity constraints.

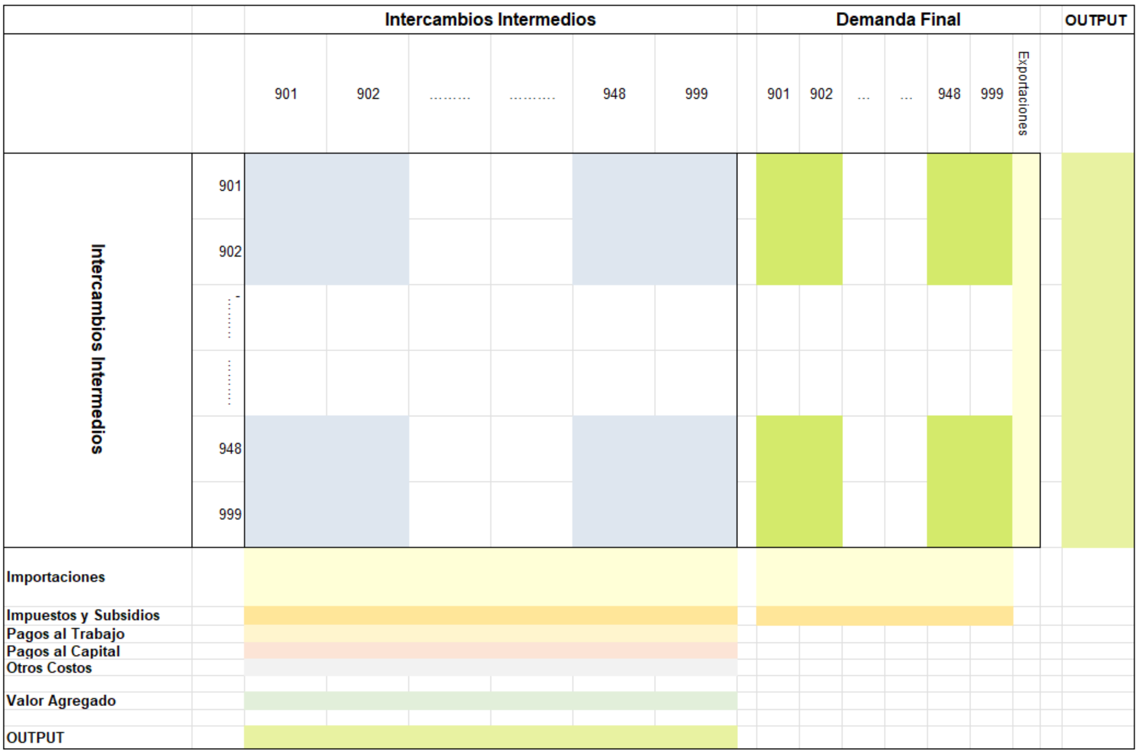
This study represents an innovation in the literature for five fundamental aspects: i) It constitutes the first accounting of extractions, returns, and grey water by region and productive sector in Chile. ii) It is the first estimation of interregional virtual water flows for Chile, determining the national structure of the regional water footprint. iii) A methodology is proposed to estimate the value added in virtual water flows from both the production and regional consumption sides. iv) It expands the concept of hydroeconomic equilibrium (HEE) introduced by Sturla and Rocchi (2022) by incorporating value added and excess of ED, and estimating the ST considering the capacity of surface water regulation. v) The contribution to value added (both regional and national) of aquifers and reservoirs is estimated using the concept of CHEE.

In the following sections, after introducing the sources of information used, we provide some descriptive statistics on Chilean the hydrological system. After describing the methodology, the main results of the analysis are then provided. A discussion of the main advances achieved as well as of the main limits of the proposed model will follow. Conclusions will figure out the further step in hydro-economic modelling suggested by the present work.

2 Data

The MRIO matrix (Haddad et al., 2018b) is used, including 15 regions and 12 economic sectors: Agriculture, forestry and fishing, Mining, Manufacturing industry, Electricity, gas and water, Construction, Trade, Restaurants and hotels, Transport, Communications, Financial and business services, Social, communal and personal services, Public administration. Figure 1 provides a schematic representation of the matrix.

Figure 1. MRIO Outline for Chile 2014



Source: own elaboration

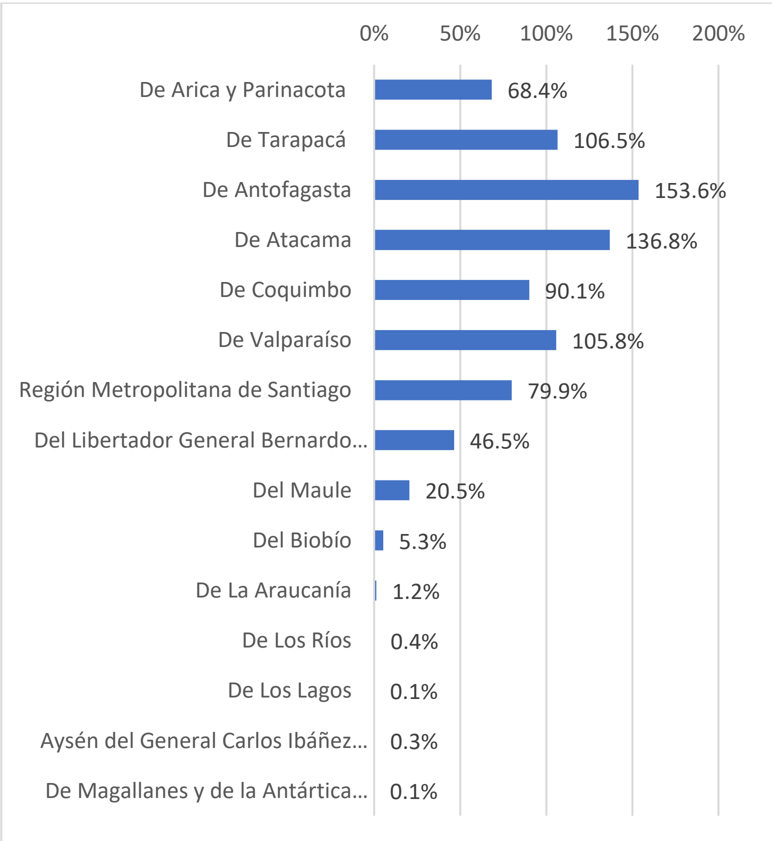
Water withdrawal coefficients (cubic meters of water per USD of output) are quantified using sector-specific data. Data concerning the water supply industry originates from sectoral records (SISS, 2023), while mining sector withdrawals are based on COCHILCO information (2021). The agricultural sector's coefficients are derived from DGA (2016), DGA (2017), and Fernández and Gironás (2021). Similarly, the manufacturing sector's coefficients rely on DGA (2016). For the electricity generation sector, water use is estimated relative to energy production (CEN, 2023), with coefficients sourced from relevant literature (Bakken et al., 2013; Macknick et al., 2012; Spang et al., 2014). Return flows are determined based on effluent data from treatment plants (SISS, 2023), while indirect estimation methodologies are applied for return flows in the manufacturing and agricultural sectors (DGA, 2016; Rocchi and Sturla, 2021). Grey water estimation relies on chemical oxygen demand (COD) data from treated water (DGA, 2016; Fernández and Gironás, 2021).

Information pertaining to water availability is sourced from DGA (2016) and DGA (2022). To assess anticipated shifts in water availability, the study draws from the national water balance report by DGA (MOP, 2018, 2019). In the calculation of the scarcity threshold (STg), the study incorporates regional storage capacity data (DGA, 2016), which encompasses both surface and groundwater management capacities.

3 Descriptive statistics

Based on information from the sources described in the previous section, the most relevant water data for the regions of Chile are presented. Figure 2 shows the relationship between water demand and supply, with the regions ordered from North to South. It can be observed that from the Metropolitan Region (Santiago, the capital) northwards, the demand/supply ratio exceeds 50%. The southern regions of Chile (from Biobío southward) show conversely very high levels of water supply.

Figure 2. Water demand and supply ratio

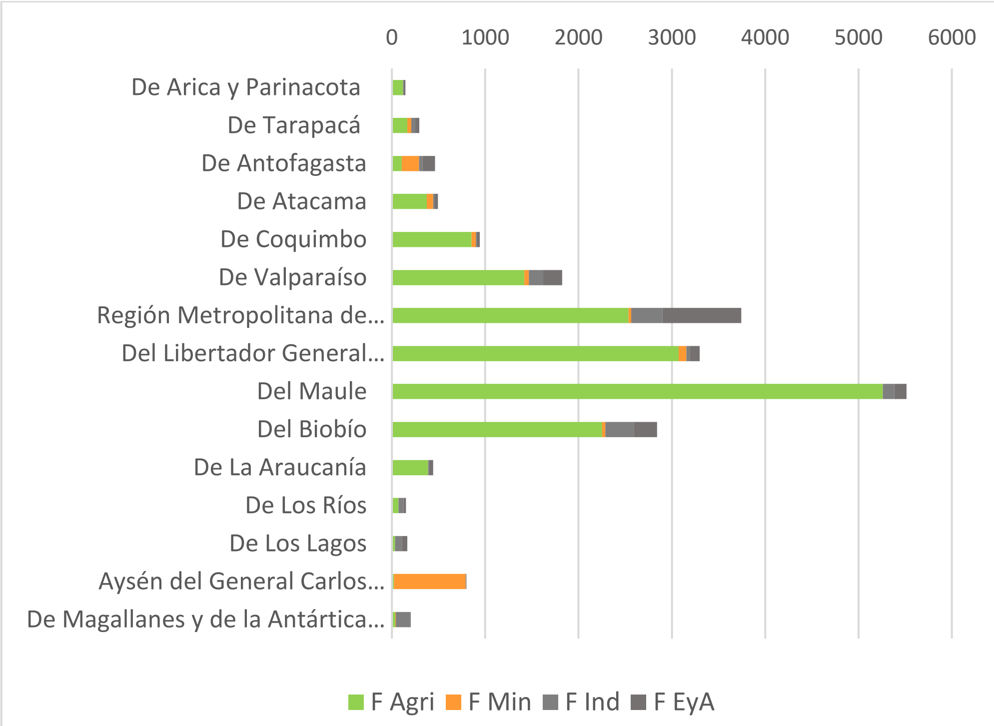


Source: own elaboration

Regarding water withdrawals from natural sources, these are carried out by the sectors Agriculture, Mining, Manufacturing, and Electricity, Gas, and Water. Figure 3 presents the composition of these withdrawals across Chilean regions. It can be observed that agriculture accounts for the largest share in almost all regions. In Northern Chile, where water availability is lower, mining plays a significant role as a fresh water extractor. Water withdrawals for domestic consumption are concentrated in the Metropolitan Region, which is home to more than 42% of the country's population.

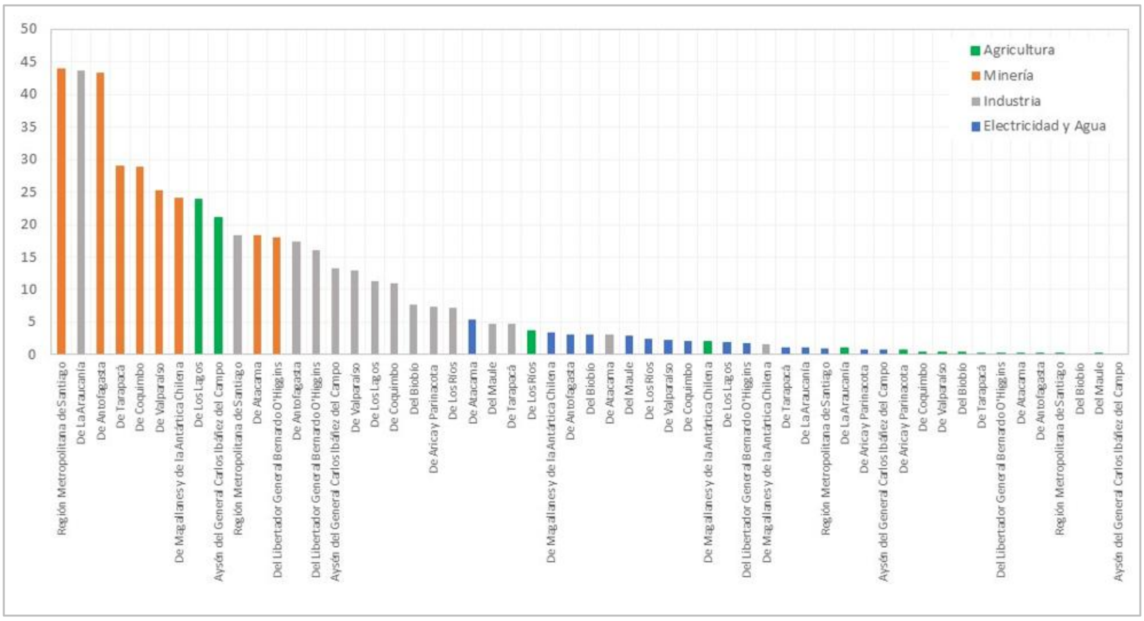
Figure 4 shows the relationship between value added and freshwater withdrawals for the sector-region combinations where this ratio is highest. Mining, from the central to the northern regions of the country (where water stress is higher), is the activity where water use is associated with the highest generation of value added.

Figure 3. Water withdrawals by economic sector



Source: own elaboration

Figure 4. Value added per volume of water withdrawals (CLP/m^3)



Source: own elaboration

The overview presented in the previous figures highlights the spatial mismatch between the Chilean economy and water resources. In regions with lower natural water availability, economic activities that generate the highest value added—such as mining and, to some extent, manufacturing—are concentrated. This makes hydroeconomic analysis particularly relevant when considering the integrated structure of the Chilean economy through the MRIO matrix. This approach allows for a better understanding of the economic pressures (consumption) exerted by key regions (such as the Metropolitan Region of Santiago) on water resources (both in quality and quantity) of other regions.

The chosen framework enables to quantify value added associated with virtual water flows, meaning it does not only identify the key regions in terms of value added produced by using water (Figure 4) but also highlights the most relevant regions demanding goods and services generated through water resource exploitation.

By applying the HEE concept, it becomes possible to quantify the value added produced overexploiting water resources. This is essential for assessing the contribution of each region to water overexploitation in the Chilean economy, while also evaluating potential alternatives to artificially increase water supply (e.g., through desalination).

An innovation compared to the work of Sturla and Rocchi (2022) is the inclusion of reservoirs (and their intra-annual water regulation capacity) in the HEE assessment, particularly for the calculation of scarcity thresholds. Table 1 presents the storage capacity relative to runoff for the country's main reservoirs. *Appendix A* contains the intra-annual variability of surface runoff (natural supply) and of evapotranspiration (agriculture demand).

Table 1. Reservoirs capacity by region

Region	Capacity (Mm3)	Runoff (Mm3)	Capacity/Runoff (%)
De Arica y Parinacota		173	
De Tarapacá		201	
De Antofagasta	22	28	78%
De Atacama	192	59	320%
De Coquimbo	1,324	700	189%
De Valparaíso	130	1,293	10%
Región Metropolitana de Santiago	221.7	3,248	7%
Del Libertador General Bernardo O'Higgins	932	6,464	14%
Del Maule	3,271	24,188	14%
Del Biobío	6,868	51,656	13%
De La Araucanía		32,829	
De Los Ríos		32,986	
De Los Lagos		129,581	
Aysén del General Carlos Ibáñez del Campo		319,585	
De Magallanes y de la Antártica Chilena		319,270	

Source: own elaboration

4 METHODOLOGY

4.1 The general model

Assuming the number of regions is *n*, and that in each area there are *m* industries, the mathematical structure of an interregional input–output system consists of (*m* x *n*) linear equations (Isard et al., 1960) showing the contribution of the output of each industry in each region to the intermediate and final consumption of all the sectors in all regions in the form of monetary transactions.

The environmentally extended interregional input-output model (Miller and Blair, 2009) allows to calculate the total environmental resource used by an economic system:

$$\mathbf{g} = \hat{\mathbf{c}} \cdot \mathbf{x} \tag{1}$$

where $\mathbf{g}$ is the (*mn* x *1*) vector of a given environmental resource used in regions by different industries, $\mathbf{x}$ is the (*mn* x *1*) vector of outputs and $\mathbf{c}$ is a (*mn* x *1*) vector of environmental resource use intensities. The hat symbol denotes the diagonalization of the vector.

The vector $\mathbf{x}$ can be expressed as a function of the inter-region input coefficients (*mn* x *mn*) matrix $\mathbf{A}$, a (*mn* x *1*) vector **d** of final demand (sum of the demand by region and exports).

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{d} \tag{2}$$

where,

a_{ij}^{rs}= requirement of intermediate input demanded by sector *j-nth* in area *s-th* supplied by sector *i-nth* in area *r-nth* per unit of output of sector *j-nth* in area *s-nth*

Defining $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ as the inter-region Leontief inverse (*mn* x *mn*) matrix, (1) yields:

$$\mathbf{g} = \hat{\mathbf{c}} \cdot \mathbf{L} \cdot \mathbf{d} \tag{3}$$

4.2 Virtual water flows

Suppose that the vector **c** corresponds to water use intensities (blue and/or grey water). If, instead of using the vector **d**, the (*mn x [n+1]*) matrix **Y** is used, including the vectors of final demand in the *n* regions and the vector of exports, the (*mn x [n+1]*) matrix **M** can be obtained, representing the virtual water flows from the economic sectors of each region to each of the other regions.

$$\mathbf{M} = \hat{\mathbf{c}} \cdot \mathbf{L} \cdot \mathbf{Y} \tag{4}$$

The element $m_{i,r}^{s}$ of the matrix **M** (located in the row corresponding to sector *i* of region *r* and in column *s*) represents the volume of water extracted in sector *i* of region *r* that is required to meet the final demand of region *s.*

These correspond to the virtual water flows for the purposes of this study.

4.3 Value added in virtual water flows

Regions produce (within their territory) and purchase (both within and outside their territory) virtual water associated with production of value added. The value added (monetary units per volume of water) produced in region *r*, to supply the final demand in region *s*, is defined as:

$$VA^{r,s} = \sum_{i,s} \left[\frac{va_{i,r}}{\left(\sum_{s} m_{i,r}^{s}\right)} \frac{\chi_{i,r}^{s}}{\left(\sum_{i,r} \chi_{i,r}^{s}\right)} \right] \tag{5}$$

where $va_{i,r}$ is to the value added produced in sector *i* of region *r*, $m_{i,r}^{s}$ are the elements of matrix $\mathbf{M}$, and $\chi_{i,r}^{s}$ corresponds to the output produced in sector *i* of region *r* to support the final consumption in region *s*.

4.4 Scarcity in virtual water flows

The degree of scarcity (qualitative and/or quantitative) is obtained by weighting the virtual flows associated with final consumption (volumetric footprint) in region *s* by the percentage of water used under scarcity conditions in the other region*s* *r*. The scarce water footprint (SWF) is defined as (Sturla et at., 2023):

$$SW^{s} = \sum_{i,r} m_{i,r}^{s} \cdot \xi_{r} \tag{6}$$

Where ξ_r is the share of water demand in region *r* used in conditions of scarcity, i.e. beyond a sustainable level of exploitation of available water resources.

To obtain the volume of excess demand (extended demand, section 4.5), it is necessary to perform the hydroeconomic equilibrium analysis in each region (section 4.8). Equation (15) below shows how to calculate ξ_r.

4.5 Extended demand for water

The extended water demand is defined as withdrawals of water minus discharges (blue water) plus the water requirements for dilution (grey water). The extended demand of water for region s by water body k (surface waters and groundwaters) could be expressed as:

$$ED_{\mathrm{k}}^{s} = (\mathbf{f_k^s} - \mathbf{r_k^s} + \mathbf{w_k^s}) \cdot \mathbf{L^s} \cdot \mathbf{y} \qquad (7)$$

where the $\boldsymbol{L^s}$ (m x m) matrix corresponds to the Leontief inverse matrix block associated with production in the region s, and $\mathbf{f_k^s}$, $\mathbf{r_k^s}$ and $\mathbf{w_k^s}$ correspond to the (m x 1) vectors of intensity coefficients (m^3/€) respectively for withdrawals, discharges and water for dilution by water body k in region s.

The grey water intensity coefficients are estimated based on a mixing model (Rocchi et al., 2024 and Xie, 1996), considering the following factors: the legal maximum concentration limits for pollutants in discharges, the availability and quality of water in receiving water bodies, and parameters related to the chemical degradation reactions of organic matter within these water bodies. *Appendix B* presents the model used, based on Rocchi et al. (2024).

4.6 The EWEI indicator

To study scarcity we adopt as a measure of pressures on water resources the Extended Water Exploitation Index (EWEI) (Rocchi and Sturla, 2024). The EWEI is defined as the ratio between the extended demand for blue and grey water and a feasible supply quantified considering environmental, technical and institutional constraints to the use of water. For region *s,* the EWEI is:

$$EWEI^{s} = \frac{\sum_{i=1}^{m}\sum_{k=1}^{2}(f_{k,i}^{s} - r_{k,i}^{s} + w_{k,i}^{s}) \cdot x_{i}^{s}}{z^{s,feas} + q^{s,feas}} \qquad (8)$$

where the sums consider m industries and two water bodies (groundwater and surface water). The variables $z^{s,feas}$ and $q^{s,feas}$ are the groundwater and surface water *feasible* supplies. We adopt the definition of feasible supply from Rocchi and Sturla (2024), considering average annual values.

The technical, institutional, and environmental limitations that characterize the feasible supply are different for surface and groundwater. The runoff of rivers and lakes water is not available as such for economic purposes. On one hand, the possibility to capture and accumulate water (hydraulic works) is limited; moreover, withdrawals are limited to the total amount of concessions released within the regulatory framework. Finally, a minimum "ecological" flow should be maintained to ensure that the aquatic ecosystem could continue to thrive and provide its services.

4.7 Endogenous scarcity threshold

Conditions of scarcity emerge when the demand for water exceeds the feasible supply. A critical issue is the choice of the period within which demand and supply are compared. So far, we considered the year as a reference period. Water demand and supply, however, varies also within every single year. Consequently, an average *annual* EWEI (for a given territory) lower than 1 could still hide temporary conditions of scarcity. This is the reason why in environmental studies the volumetric measures of water footprint of whole economies are weighted for scarcity through some mathematical transformations of annual pressure indicators like the EWEI (Pfister et al. 2009). In the present analysis we use the model itself to define a water scarcity threshold for the annual regional EWEI, considering the intra-annual variability of water demand and supply and the geographical differentiation in the hydro-economic system. The scheme proposed by Sturla and Rocchi (2022) is considered.

Let $FS^s = z^{s,feas} + q^{s,feas}$ the feasible supply in region *s,* including both groundwater and surface water. The regional EWEI for a generic month *i* can be expressed as:

$$EWEI_i^s = \frac{(1-\alpha^s)\cdot\frac{ED^s}{12} + \alpha^s\cdot\frac{FS^s}{12}\cdot a_i^s}{(1-\beta^s)\cdot\frac{ED^s}{12}\cdot c_i^s + \beta^s\cdot\frac{FS^s}{12}\cdot b_i^s} \tag{9}$$

Where,

$\alpha^s = \frac{ED_{Var}^s}{e^s}$	Is the share of the extended demand corresponding to industries with intra-annual variability
$\beta^s = \frac{u_{sw}^s}{u^s}$	Is the share of surface water feasible supply
$a_i^s = \frac{ED_{Var,i}^s}{ED_{Var}^s/12}$	Is the intra-annual distribution coefficient of the extended demand from industries with intra-annual variability for month *i*
$b_i^s = \frac{u_{sw,i}^s}{u_{sw}^s/12}$	Is the intra-annual distribution coefficient of surface water feasible supply for month *i*
$c_i^s = \frac{u_{gw,i}^s}{u_{gw}^s/12}$	Is the intra-annual distribution coefficient of groundwater feasible supply for month *i*

Using the definition of the annual EWEI^s from equation (10) we can rewrite the monthly indicator for region *s* as:

$$EWEI_i^s = \frac{(1-\alpha^s) + \alpha^s a_i^s}{(1-\beta^s)c_i^s + \beta^s b_i^s} EWEI^s \tag{10}$$

The sub-regional scarcity threshold corresponds to the annual $EWEI^s$ ensuring that the $EWEI_i^s$ will be equal to 1 in the critical month, i.e. the month with the smaller difference between supply and demand, and less or equal than 1 for the other months:

$$ST^s = \min_i \frac{(1-\beta^s)c_i^s + \beta^r b_i^s}{(1-\alpha^s) + \alpha^s a_i^s} \tag{11}$$

This scarcity threshold is defined for the average hydrological conditions (the average of the N simulated hydrological years) and can be compared with the annual $EWEI^s$ calculated for each simulated hydrological year.

It is important to consider also the possibility of groundwater and surface water regulation within the year. Therefore, we introduce the concept of scarcity threshold with integrated water management. In particular, the intra-annual distribution coefficients of the feasible supply (c_i^r, b_i^r) depends on the regulation capacity of groundwater and surface water. For groundwater, intra-annual regulation is intrinsic to the nature of the water body (natural impoundment). In the case of surface water, the degree of intra-annual regulation depends on the existence of regulation infrastructures (reservoirs)

The scarcity threshold (ST_{gs}^s) with integrated groundwater and surface water management will correspond to the value of the expression in equation (11) maximized by the sets of c_i^r and b_i^r values:

$$ST_{gs}^s = \max_{c_i^s, b_i^s} \left[\min_i \frac{(1-\beta^s)c_i^s + \beta^r b_i^s}{(1-\alpha^s) + \alpha^s a_i^s} \right] \tag{12}$$

This threshold is less restrictive than the threshold considering only natural scarcity conditions (ST^s).

For groundwater we consider that $c_i^s \in (1-\lambda^s, 1+\lambda^s)$, where λ^s corresponds to the percentage by which the groundwater supply in month *i* can be above or below the average monthly supply. A similar approach is adopted for surface water also. If only the groundwater management capacity is considered, the threshold will be ST_g^s, which is estimated by maximizing solely based on the variable c_i^s.

4.8 Hydro-economic equilibrium

Local hydro-economic equilibrium (LHEE) for region *s* is defined as the situation where the annual $EWEI^s$ is less than or equal to the ST_g^s calculated considering the average hydrological conditions. National hydro-economic equilibrium (RHEE) is defined as a situation where all regions satisfy the LHEE conditions. That is, there is no water stress in any subregion *s*. RHEE condition can be written as:

$$\frac{(\mathbf{v}_{\mathbf{blue}}^{\mathbf{s}} + \mathbf{v}_{\mathbf{grey}}^{\mathbf{s}})^T \cdot \mathbf{L}^{\mathbf{s}} \cdot \mathbf{y}}{FS^s} \leq ST_g^s \quad ,\forall s \tag{14}$$

Where,

$$\mathbf{v}_{\mathbf{blue}}^{\mathbf{s}} = \sum_{k=1}^{2} (\mathbf{f}_{\mathbf{k}}^{\mathbf{s}} - \mathbf{r}_{\mathbf{k}}^{\mathbf{s}})$$

$$\mathbf{v}_{\mathbf{blue}}^{\mathbf{s}} = \sum_{k=1}^{2} \mathbf{w}_{\mathbf{k}}^{\mathbf{s}}$$

The excess of extended demand (EED^s) for region *s* can be estimated as the difference between the extended demand and the demand that makes the *EWEI* equal to the scarcity threshold.

$$EED^s = ED^s - u^s \cdot ST_g^s \tag{15}$$

Then the ξ_r value in equation (6), is calculated as:

$$\xi_s = \frac{EED^r}{ED^r} \tag{16}$$

4.9 Cost of the hydroeconomic equilibrium

The original concept of the opportunity cost of the regional hydro-economic equilibrium corresponds to the minimum reduction in output that would be required to bring all subregions to the LHEE condition (Sturla and Rocchi, 2022). As an innovation compared to the work of Sturla and Rocchi (2022), instead of working with output, this study considers value added.

The optimization problem has the objective function of maximizing value added (minimum reduction) by varying the final demand in deficit subregions (where the final demand supplied by the regional economy system could be zero).

The final demand in each region is modified on the basis of the control variable ϕ^s. The (*mn x 1*) vector of value added (VA) is defined as:

$$\mathbf{VA} = \hat{\boldsymbol{\pi}} \cdot \mathbf{L} \cdot \hat{\boldsymbol{\Phi}} \cdot \mathbf{y} \tag{17}$$

Where $\hat{\boldsymbol{\pi}}$ is a diagonal matrix (mn x mn) containing the ratio between the value added and the output of each sector in each region. $\hat{\boldsymbol{\Phi}}$ is a diagonal matrix (*mn* x *mn*) containing *m* times the value of ϕ^s for each of the *n* subregions. The optimization problem is:

$$\max_{\phi} \boldsymbol{\epsilon}' \cdot \hat{\boldsymbol{\pi}} \cdot \mathbf{L} \cdot \hat{\boldsymbol{\Phi}} \cdot \mathbf{y}$$

$$s.t.$$

$$\frac{(\mathbf{v}^{\mathbf{s}}_{\mathbf{blue}} + \mathbf{v}^{\mathbf{s}}_{\mathbf{grey}})^{\mathrm{T}} \cdot \mathbf{L}^{\mathbf{s}} \cdot \hat{\boldsymbol{\Phi}} \cdot \mathrm{y}}{u^s} \leq ST^s_g \quad , \quad \forall s \tag{18}$$

$$\phi^s \in [0,1] \quad , \quad \forall s \in \Gamma$$

where $\boldsymbol{\epsilon}$ is a (*mn* x 1) vector of ones and Γ is the set of subregions with scarcity conditions.

Let $\mathbf{VA}^*$ as the value added vector after the optimization process and $\mathbf{VA^b}$ the value added vector in the base situation (the current production of the economy). The opportunity cost of the hydro-economic equilibrium is given by:

$$CHEE = \boldsymbol{\epsilon}' \cdot (\boldsymbol{VA}^* - \boldsymbol{VA}^{\mathbf{b}}) \tag{19}$$

The opportunity cost refers to the regional hydro-economic equilibrium (RHEE). When using an MRIO-EE model, any reductions in VA necessary to satisfy each local hydro-economic equilibrium (LHEE) in any region *s* will have an impact on all the other regions (with and without water scarcity). The MRIO-EE model developed in this study allows to study the reduction of value added in each of the *n* regions necessary to ensure the *national/regional* hydro-economic equilibrium.

5 RESULTS

5.1 Virtual water flows: blue and grey water

Table 2 presents the results for virtual blue water flows between the regions of Chile. Each row contains the volume of blue water used in a region to sustain the final consumption of other regions and the rest of the world (exports). The diagonal of the matrix (regions) corresponds to the water used within a region to support its own consumption. Table 3 presents the same amounts but as a percentage of the total water used in the region (the rows sum to 100%). This table highlights that the Santiago Metropolitan Region (RMS) acts as a hub for virtual water flows, especially from neighboring regions, where nearly 30% of the water used is allocated to satisfy consumption in the RMS. A similar dynamic is observed when including pollution (gray water), as shown in Table 4. On average, more than 40% of the blue and gray water in the regions supports exports, meaning the final consumption of the rest of the world.

Table 2. Virtual water flows (blue water, Mm3)

Total Agua (Mm3)	De Arica y Parinacota	De Tarapacá	De Antofagasta	De Atacama	De Coquimbo	De Valparaíso	Región Metropolitana de Santiago	Del Libertador General Bernardo O'Higgins	Del Maule	Del Biobío	De La Araucanía	De Los Ríos	De Los Lagos	Aysén del General Carlos Ibáñez del Campo	De Magallanes y de la Antártica Chilena	Resto del Mundo	
De Arica y Parinacota	25.3	7.0	9.9	1.5	2.5	4.5	21.4	1.7	1.8	3.7	1.7	0.7	2.0	0.4	0.5	61.1	145.7
De Tarapacá	2.5	72.0	10.0	1.9	3.1	4.8	24.8	1.9	2.1	4.5	2.3	0.9	2.6	0.6	0.7	157.9	292.7
De Antofagasta	2.3	6.3	41.1	2.9	5.2	7.1	38.5	2.9	3.1	6.6	3.7	1.5	4.2	0.9	0.9	333.2	460.7
De Atacama	2.1	7.3	20.7	58.3	10.3	17.2	81.0	6.5	6.4	12.6	5.9	2.3	6.5	1.2	1.5	253.2	493.0
De Coquimbo	2.9	10.4	26.9	8.5	99.6	52.8	226.4	18.8	16.1	29.0	12.2	4.6	12.8	2.4	2.8	415.2	941.5
De Valparaíso	4.0	12.4	28.0	11.5	34.4	229.9	575.2	39.6	30.1	48.6	21.5	7.7	21.5	4.6	4.3	751.3	1824.6
Región Metropolitana de Santiago	9.7	30.6	67.0	25.3	78.9	299.8	1352.2	120.8	76.9	119.6	53.3	18.5	52.7	11.1	10.9	1416.3	3743.7
Del Libertador General Bernardo O'Higgins	7.4	23.5	54.1	21.6	60.5	196.0	1065.4	157.2	72.9	107.4	44.0	15.8	43.2	8.6	8.3	1413.0	3298.9
Del Maule	14.0	46.7	104.5	38.1	101.6	295.0	1514.6	153.5	413.9	275.5	99.2	33.6	91.6	16.4	16.8	2298.7	5513.6
Del Biobío	8.6	28.5	58.4	21.2	52.9	117.2	647.2	56.4	77.2	383.0	84.8	24.4	66.3	12.1	11.1	1192.7	2842.1
De La Araucanía	1.2	4.3	9.0	3.0	7.3	17.7	89.2	8.0	9.7	27.0	71.8	5.5	13.3	1.7	1.9	172.8	443.3
De Los Ríos	0.4	1.5	2.9	1.1	2.4	4.5	25.2	2.1	2.6	7.2	6.0	28.1	7.5	0.9	0.7	57.0	149.9
De Los Lagos	0.5	1.6	3.0	1.1	2.5	4.0	24.0	1.9	2.4	6.4	5.1	2.7	52.8	1.3	0.8	55.9	166.0
Aysén del General Carlos Ibáñez del Campo	0.5	1.6	3.4	1.0	2.3	5.1	25.1	2.3	2.6	6.0	3.4	1.6	5.2	28.9	2.1	708.9	800.1
De Magallanes y de la Antártica Chilena	0.7	2.3	4.0	1.5	2.6	3.5	21.2	1.5	2.0	5.0	3.0	1.2	3.8	3.1	61.4	86.5	203.3
	82.0	256.2	443.1	198.5	466.0	1259.0	5731.5	575.3	719.9	1042.3	417.8	149.1	386.0	94.0	124.7	9373.6	21319.2

Source: own elaboration

Table 3. Virtual water flows (blue water, %)

% Agua en Region Extractora (Mm3)	De Arica y Parinacota	De Tarapacá	De Antofagasta	De Atacama	De Coquimbo	De Valparaíso	Región Metropolitana de Santiago	Del Libertador General Bernardo O'Higgins	Del Maule	Del Biobío	De La Araucanía	De Los Ríos	De Los Lagos	Aysén del General Carlos Ibáñez del Campo	De Magallanes y de la Antártica Chilena	Resto del Mundo
De Arica y Parinacota	17.4%	4.8%	6.8%	1.0%	1.7%	3.1%	14.7%	1.2%	1.2%	2.5%	1.2%	0.5%	1.4%	0.3%	0.4%	41.9%
De Tarapacá	0.9%	24.6%	3.4%	0.7%	1.1%	1.7%	8.5%	0.7%	0.7%	1.5%	0.8%	0.3%	0.9%	0.2%	0.2%	53.9%
De Antofagasta	0.5%	1.4%	8.9%	0.6%	1.1%	1.5%	8.4%	0.6%	0.7%	1.4%	0.8%	0.3%	0.9%	0.2%	0.2%	72.3%
De Atacama	0.4%	1.5%	4.2%	11.8%	2.1%	3.5%	16.4%	1.3%	1.3%	2.6%	1.2%	0.5%	1.3%	0.2%	0.3%	51.4%
De Coquimbo	0.3%	1.1%	2.9%	0.9%	10.6%	5.6%	24.0%	2.0%	1.7%	3.1%	1.3%	0.5%	1.4%	0.3%	0.3%	44.1%
De Valparaíso	0.2%	0.7%	1.5%	0.6%	1.9%	12.6%	31.5%	2.2%	1.7%	2.7%	1.2%	0.4%	1.2%	0.3%	0.2%	41.2%
Región Metropolitana de Santiago	0.3%	0.8%	1.8%	0.7%	2.1%	8.0%	36.1%	3.2%	2.1%	3.2%	1.4%	0.5%	1.4%	0.3%	0.3%	37.8%
Del Libertador General Bernardo O'Higgins	0.2%	0.7%	1.6%	0.7%	1.8%	5.9%	32.3%	4.8%	2.2%	3.3%	1.3%	0.5%	1.3%	0.3%	0.3%	42.8%
Del Maule	0.3%	0.8%	1.9%	0.7%	1.8%	5.3%	27.5%	2.8%	7.5%	5.0%	1.8%	0.6%	1.7%	0.3%	0.3%	41.7%
Del Biobío	0.3%	1.0%	2.1%	0.7%	1.9%	4.1%	22.8%	2.0%	2.7%	13.5%	3.0%	0.9%	2.3%	0.4%	0.4%	42.0%
De La Araucanía	0.3%	1.0%	2.0%	0.7%	1.6%	4.0%	20.1%	1.8%	2.2%	6.1%	16.2%	1.2%	3.0%	0.4%	0.4%	39.0%
De Los Ríos	0.3%	1.0%	1.9%	0.7%	1.6%	3.0%	16.8%	1.4%	1.7%	4.8%	4.0%	18.7%	5.0%	0.6%	0.5%	38.0%
De Los Lagos	0.3%	1.0%	1.8%	0.7%	1.5%	2.4%	14.5%	1.1%	1.4%	3.9%	3.1%	1.6%	31.8%	0.8%	0.5%	33.7%
Aysén del General Carlos Ibáñez del Campo	0.1%	0.2%	0.4%	0.1%	0.3%	0.6%	3.1%	0.3%	0.3%	0.8%	0.4%	0.2%	0.7%	3.6%	0.3%	88.6%
De Magallanes y de la Antártica Chilena	0.3%	1.1%	2.0%	0.8%	1.3%	1.7%	10.4%	0.8%	1.0%	2.5%	1.5%	0.6%	1.9%	1.5%	30.2%	42.5%

Source: own elaboration

Table 4. Virtual water flows (blue and grey water, %)

% Produccion Regional	De Arica y Parinacot a	De Tarapacá	De Antofag asta	De Atacama	De Coquimbo	De Valparaíso	Región Metropolit ana de Santiago	Del Libertado r General Bernardo O'Higgins	Del Maule	Del Biobío	De La Araucanía	De Los Ríos	De Los Lagos	Aysén del General Carlos Ibáñez del Campo	De Magallan es y de la Antártica Chilena	Resto del Mundo
De Arica y Parinacota	22.6%	4.6%	6.3%	1.0%	1.6%	2.7%	13.5%	1.1%	1.1%	2.3%	1.1%	0.4%	1.3%	0.3%	0.4%	39.6%
De Tarapacá	0.9%	25.6%	3.2%	0.6%	1.0%	1.5%	7.9%	0.6%	0.7%	1.4%	0.7%	0.3%	0.9%	0.2%	0.2%	54.1%
De Antofagasta	0.5%	1.4%	9.5%	0.6%	1.2%	1.5%	8.4%	0.6%	0.7%	1.4%	0.8%	0.3%	0.9%	0.2%	0.2%	71.6%
De Atacama	0.4%	1.5%	4.1%	12.0%	2.1%	3.3%	16.1%	1.3%	1.2%	2.5%	1.2%	0.5%	1.3%	0.3%	0.3%	52.0%
De Coquimbo	0.3%	1.1%	2.7%	0.9%	12.4%	5.3%	23.1%	1.9%	1.6%	2.9%	1.3%	0.5%	1.3%	0.3%	0.3%	44.3%
De Valparaíso	0.2%	0.7%	1.5%	0.6%	1.9%	14.6%	31.5%	2.1%	1.6%	2.5%	1.2%	0.4%	1.2%	0.3%	0.2%	39.7%
Región Metropolitana de Santiago	0.3%	0.8%	1.7%	0.7%	2.1%	7.5%	40.0%	3.1%	1.9%	3.0%	1.4%	0.5%	1.4%	0.3%	0.3%	34.9%
Del Libertador General Bernardo O'Higgins	0.2%	0.7%	1.6%	0.6%	1.8%	5.8%	32.0%	5.3%	2.2%	3.2%	1.3%	0.5%	1.3%	0.3%	0.3%	42.8%
Del Maule	0.3%	0.9%	1.9%	0.7%	1.9%	5.3%	27.5%	2.8%	8.0%	4.9%	1.8%	0.6%	1.7%	0.3%	0.3%	41.2%
Del Biobío	0.3%	1.0%	2.0%	0.7%	1.9%	4.0%	22.9%	2.0%	2.7%	14.3%	3.2%	0.9%	2.4%	0.5%	0.4%	40.8%
De La Araucanía	0.3%	0.9%	1.8%	0.6%	1.5%	3.5%	18.3%	1.6%	1.9%	5.4%	25.3%	1.2%	2.9%	0.4%	0.4%	34.0%
De Los Ríos	0.3%	1.0%	1.8%	0.7%	1.5%	2.7%	15.8%	1.2%	1.6%	4.5%	4.1%	23.1%	5.1%	0.6%	0.5%	35.6%
De Los Lagos	0.3%	0.9%	1.7%	0.6%	1.4%	2.1%	13.4%	1.0%	1.3%	3.5%	3.0%	1.5%	37.5%	0.8%	0.5%	30.5%
Aysén del General Carlos Ibáñez del Campo	0.1%	0.2%	0.4%	0.1%	0.3%	0.6%	3.1%	0.3%	0.3%	0.8%	0.4%	0.2%	0.7%	4.2%	0.3%	87.9%
De Magallanes y de la Antártica Chilena	0.3%	1.1%	1.9%	0.7%	1.3%	1.6%	10.1%	0.7%	0.9%	2.4%	1.4%	0.6%	1.9%	1.5%	32.2%	41.2%

Source: own elaboration

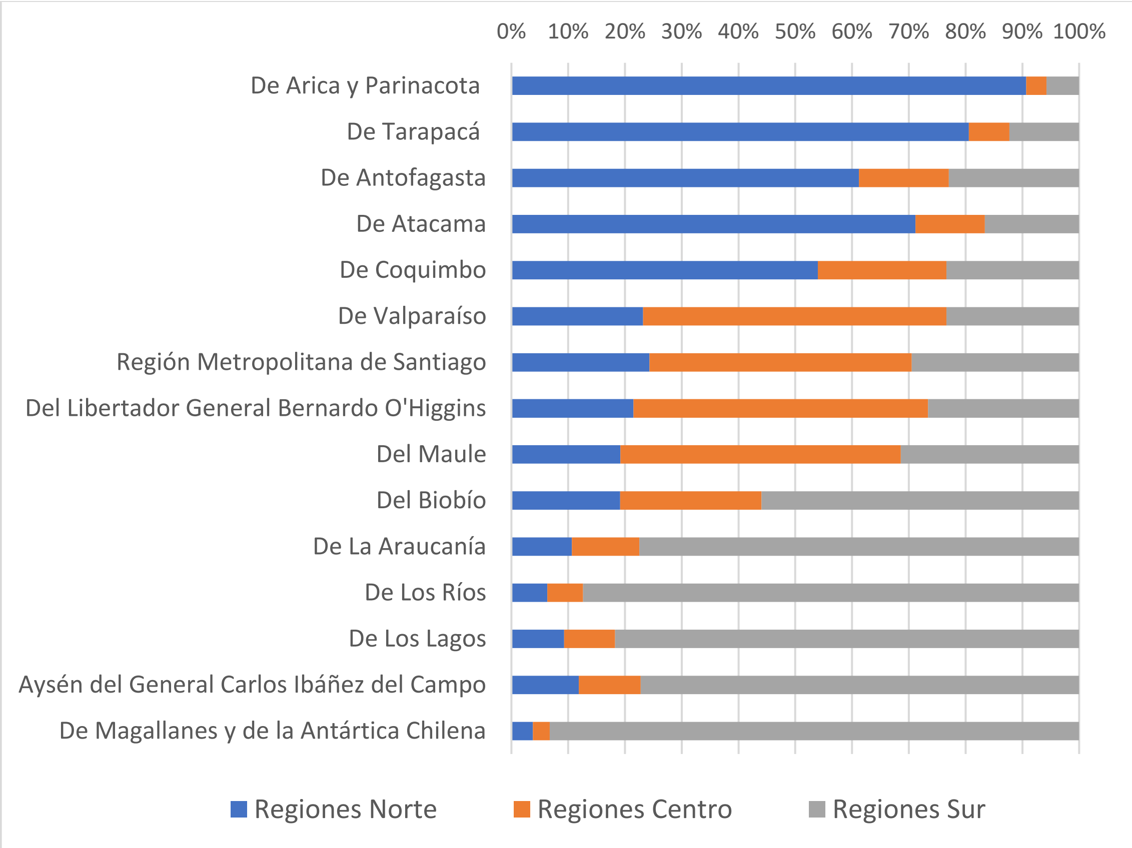
The columns in the tables above correspond to the structure of the national water footprint for each of the regions. Figure 5 illustrates the water footprint structure of the regions, distinguishing whether the pressures are generated in the Northern, Central, or Southern zones of the country. As shown, the Central regions exert significant water pressures on both the Northern and Southern regions. Of particular importance are the Valparaíso and the Santiago regions, which, in absolute terms (volume), show the highest values in the country (see Once estimated the relative excess demand the scarcity in virtual water flows was determined. This allows for the identification of the scarce water footprint (SWF) of each Chilean region and its structure. In quantitative terms, the Central and Northern regions (water-scarce areas) exert a Water Footprint (WF) of 9,479 Mm³ (75%), while the Southern regions account for 3,175 Mm³ (25%). When virtual water flows are weighted by scarcity (SWF), the share of water-scarce regions increases to 86% of the national (internal) water footprint.

Figure 12 presents both the SWF and the WF for each region. As in Figure 11, the Northern and Central regions of the country have a higher proportion of SWF relative to their WF, indicating a greater relative environmental impact of their consumption. Specifically, the SWF represents the portion of the WF that corresponds to overexploited resource (both in quantity and quality).

In quantitative terms, the Central and Northern regions (water-scarce areas) exert a Water Footprint (WF) of 9,479 Mm³ (75%), while the Southern regions account for 3,175 Mm³ (25%). When virtual water flows are weighted by scarcity (SWF), the share of water-scarce regions increases to 86% of the national (internal) water footprint.

Figure 12), generating substantial impacts on regions facing greater water scarcity (North).

Figure 5. National structure of the regional water footprint (ED)



Source: own elaboration

5.2 Value added in virtual water flows

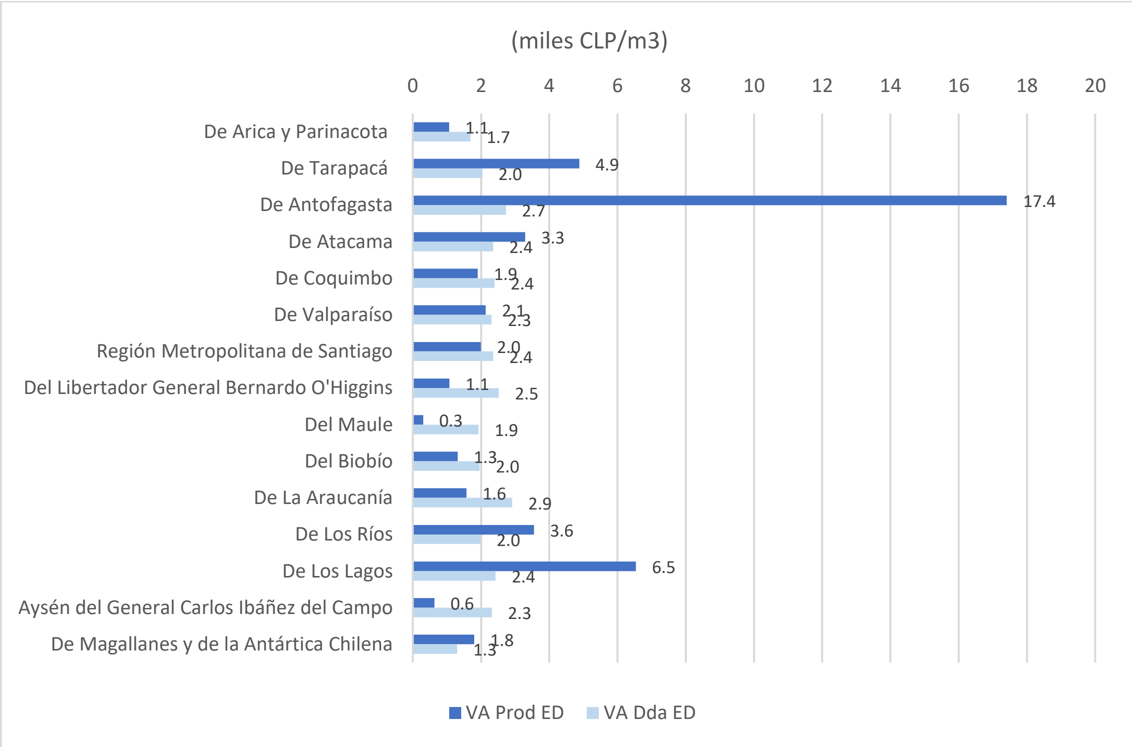
When the value added associated with the virtual flows of blue and grey water (extended demand) is considered, each region can be characterized based on the production and consumption of value added (monetary unit/volume).

Figure 6 presents the obtained values.

Regarding production, the Antofagasta region stands out above the rest due to mining activities that are able to generate a higher value added for each cubic meter of water used in production. In terms of consumption, the Araucanía region exhibits the highest unitary value. Greater variability among regions is observed in production compared to the consumption of value added per unit volume of blue and grey water.

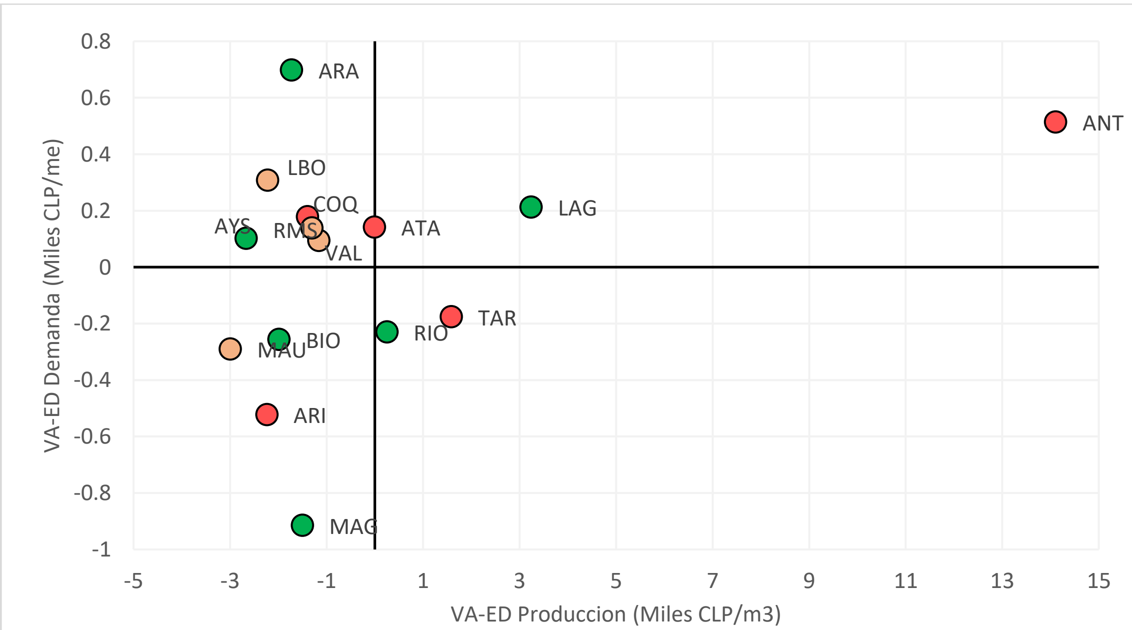
Figure 7 presents a classification of Chilean regions based on their production and consumption indicators of value added associated with water use. The graph shows the deviations of regional values from the national mean, highlighting the importance of Antofagasta and Los Lagos, which are major producers of value added generated with water (mining and manufacturing, respectively) and also significant consumers of value added embedded in virtual water flows.

Figure 6. Added value by volume of blue and grey water used (production and consumption)



Source: own elaboration

Figure 7. Value added in production and consumption (deviations from the mean). In green, the Northern regions; in orange, the Central regions; and in red, the Southern regions.



Source: own elaboration

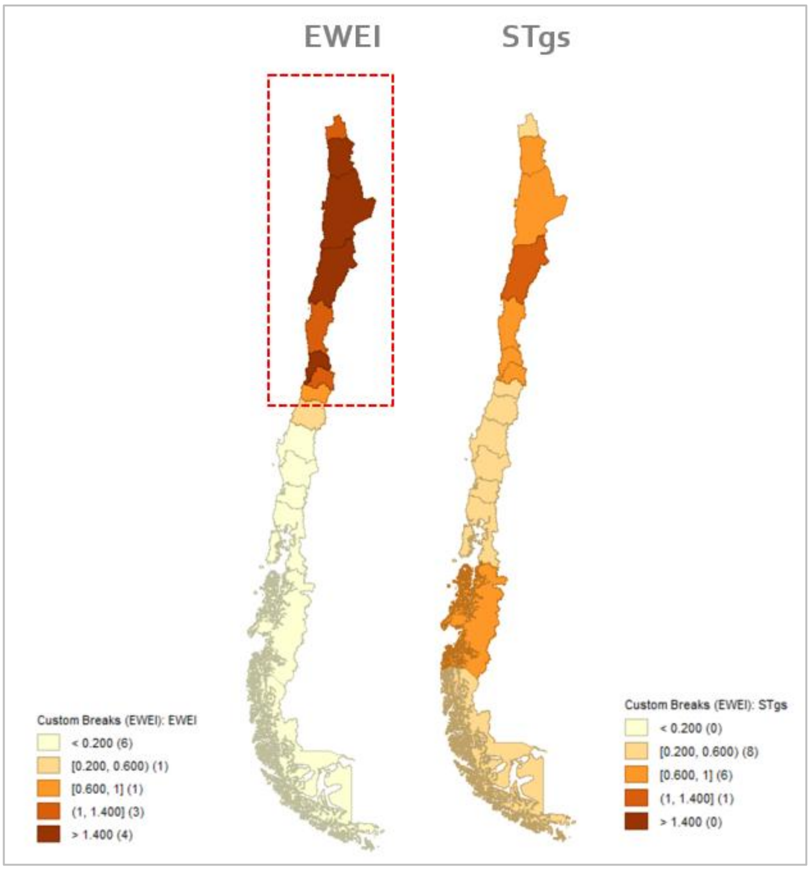
5.3 Hydroeconomic equilibrium

By incorporating the feasible supply (FS) per region into the analysis, it is possible to construct the EWEI indicator. This is then compared to the scarcity threshold (ST_{gs}) calculated considering optimal groundwater and reservoir management. Based on ST_{gs}, FS, and ED by region, the excess ED is estimated for regions that are not in equilibrium. Figure 10 shows the absolute values, with the Santiago region (1,789 Mm³) standing out, followed by the Valparaíso region and the O’Higgins region, all located in Central Chile. The total value for the country is 4,488 Mm³. When analyzing the relative excess demand (as a percentage of regional ED), high values are observed in the central zone and in the three northernmost regions (Figure 11).

Figure 8 presents a map of Chile displaying these two indicators. High EWEI values are observed in the central and, primarily, northern regions. Regarding ST_{gs}, since it depends on the intra-annual variability of water demand in the agricultural sector, it tends to be lower in the Central-Southern and Southern regions of the country. In the Central regions, despite a significant presence of agricultural activity, there is also a substantial regulation capacity (groundwater and irrigation reservoirs), which increases the scarcity threshold. Figure 9 presents a chart with EWEI and ST_{gs} values by region. The regions that are not in hydroeconomic equilibrium (EWEI > ST_{gs}) are those from Arica and Parinacota (North) to O'Higgins (Central-South), totaling eight regions.

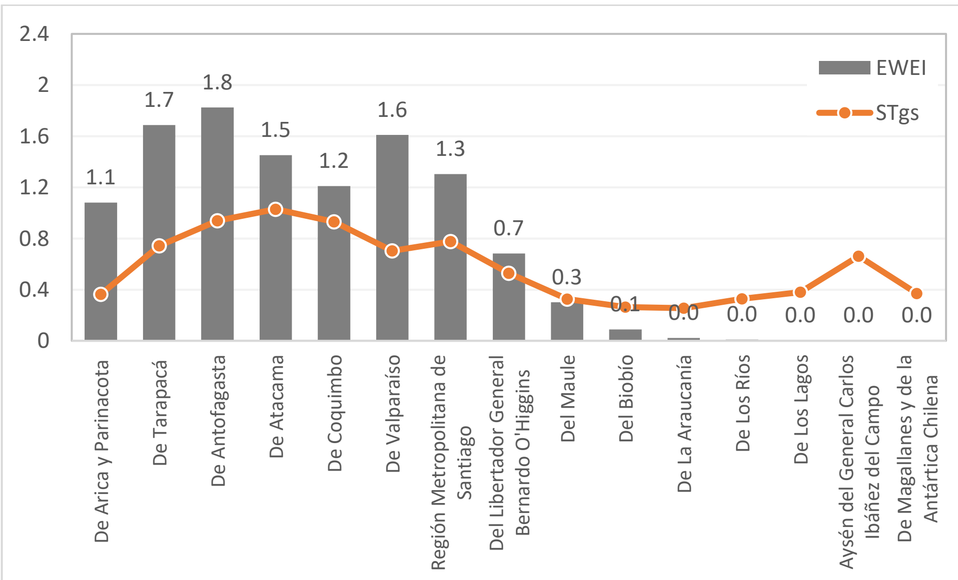
Based on ST_{gs}, FS, and ED by region, the excess ED is estimated for regions that are not in equilibrium. Figure 10 shows the absolute values, with the Santiago region (1,789 Mm³) standing out, followed by the Valparaíso region and the O’Higgins region, all located in Central Chile. The total value for the country is 4,488 Mm³. When analyzing the relative excess demand (as a percentage of regional ED), high values are observed in the central zone and in the three northernmost regions (Figure 11).

Figure 8. EWEI and ST_{gs} indicators by region (map)



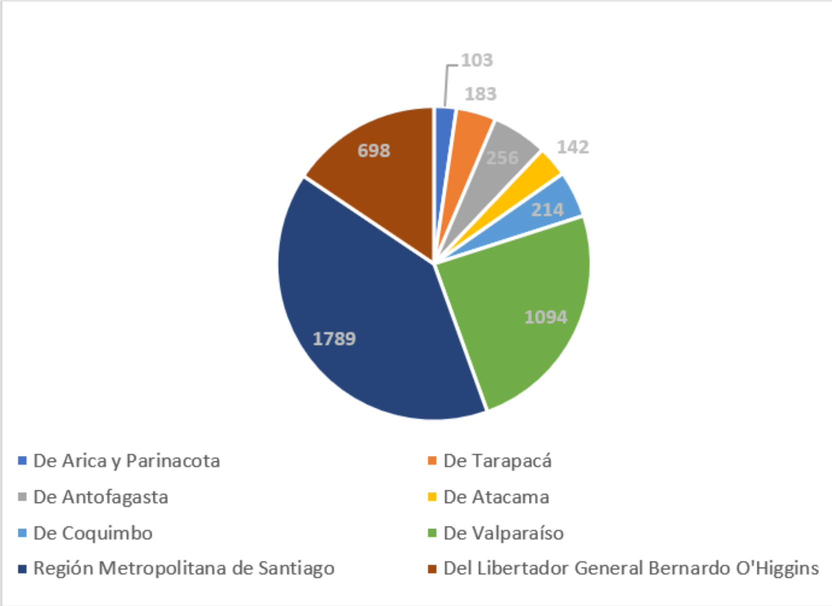
Source: own elaboration

Figure 9. EWI and ST_{gs} indicators by region (graph)



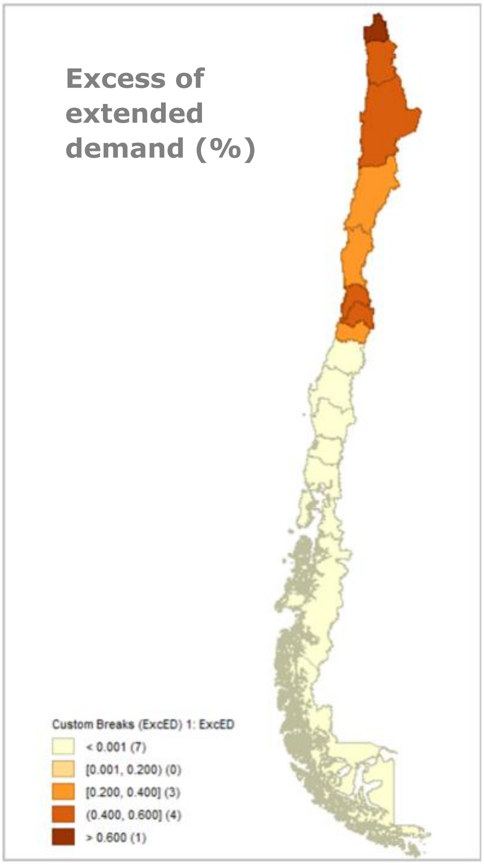
Source: own elaboration

Figure 10. Excess of extended demand (Mm^3)



Source: own elaboration

Figure 11. Excess of extended demand (% of extended demand by region)



Source: own elaboration

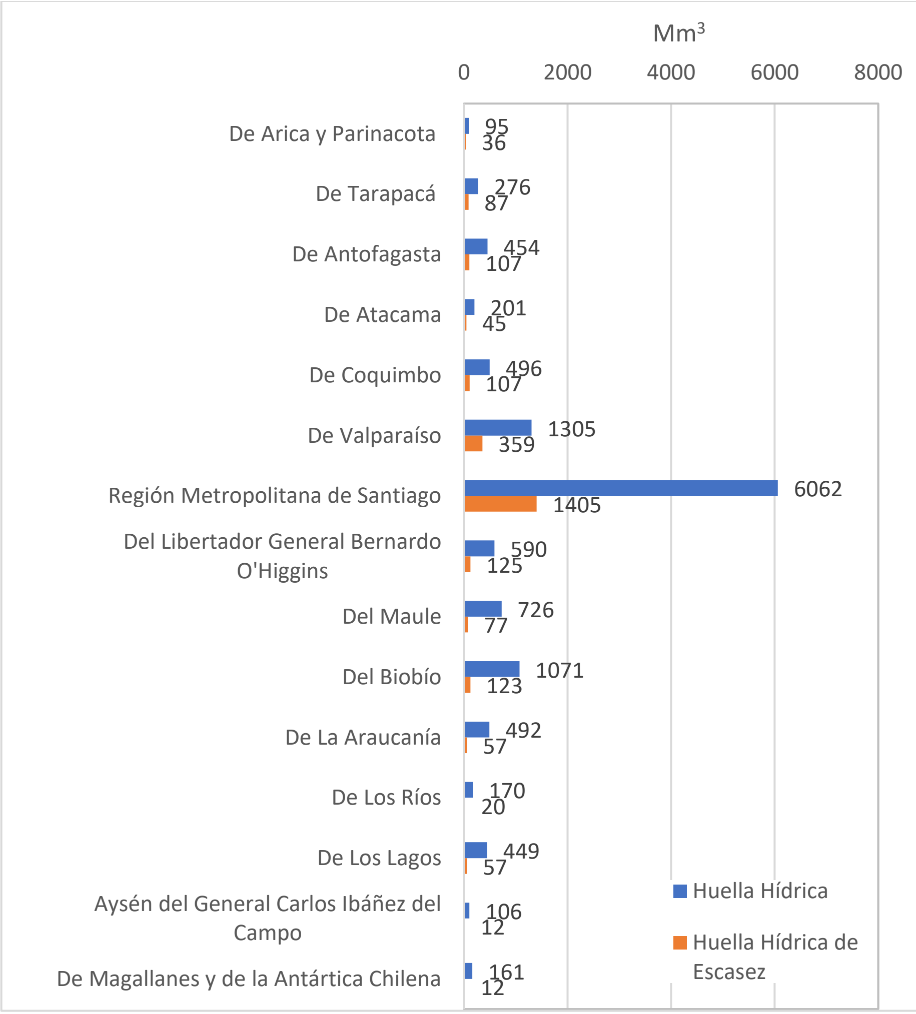
5.4 Scarcity in virtual water flows

Once estimated the relative excess demand the scarcity in virtual water flows was determined. This allows for the identification of the scarce water footprint (SWF) of each Chilean region and its structure. In quantitative terms, the Central and Northern regions (water-scarce areas) exert a Water Footprint (WF) of 9,479 Mm^3 (75%), while the Southern regions account for 3,175 Mm^3 (25%). When virtual water flows are weighted by scarcity (SWF), the share of water-scarce regions increases to 86% of the national (internal) water footprint.

Figure 12 presents both the SWF and the WF for each region. As in Figure 11, the Northern and Central regions of the country have a higher proportion of SWF relative to their WF, indicating a greater relative environmental impact of their consumption. Specifically, the SWF represents the portion of the WF that corresponds to overexploited resource (both in quantity and quality).

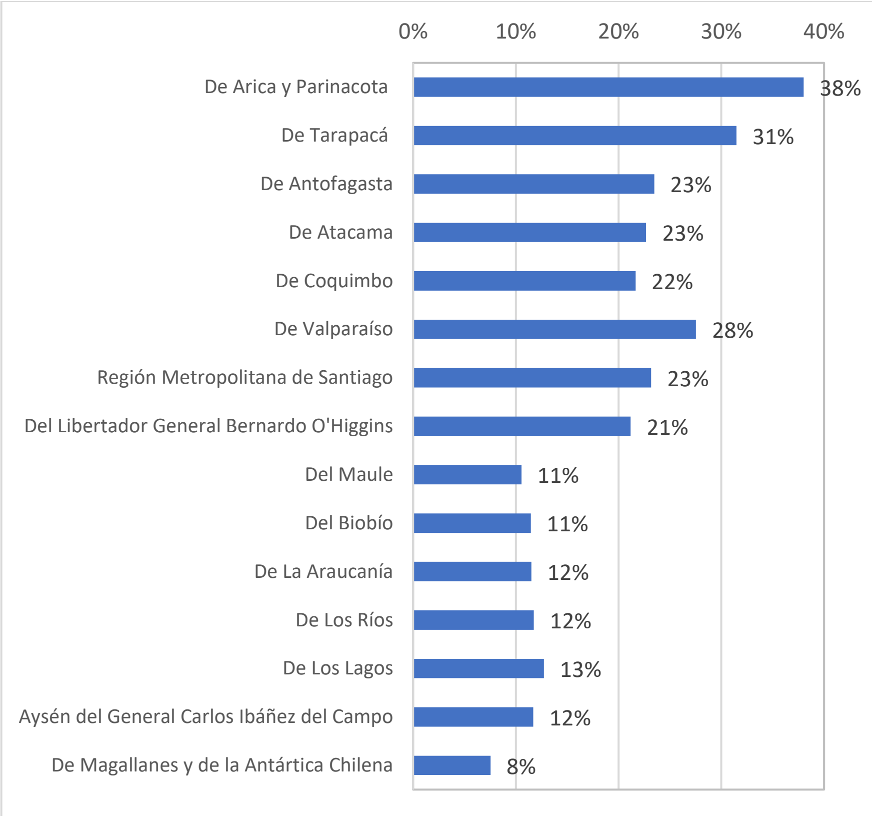
In quantitative terms, the Central and Northern regions (water-scarce areas) exert a Water Footprint (WF) of 9,479 Mm^3 (75%), while the Southern regions account for 3,175 Mm^3 (25%). When virtual water flows are weighted by scarcity (SWF), the share of water-scarce regions increases to 86% of the national (internal) water footprint.

Figure 12. Scarce water footprint (SWF) and volumetric water footprint (WF)



Source: own elaboration

Figure 13. Scarce water footprint as a percentage of volumetric water footprint



Source: own elaboration

5.5 Cost of the hydroeconomic equilibrium

The CHEE corresponds to the value added produced with overexploitation of water resources both in terms of quantity and quality (excess ED). The optimization problem maximizes the nation-wide value added (taking into account economic interdependencies among regions) conditional to the achievement of the hydroeconomic equilibrium (HEE). This is obtained by adjusting the final demand (IO models are demand-driven), which results in a decrease in value added (Table 5). Due to economic interregional economic linkages, the reduction is not limited to regions showing an excess ED. The magnitude of the reduction in each region primarily depends on the regional degree of scarcity (excess ED) and on the value added per unit of (virtual) water used to support final consumption. For example, while Antofagasta shows a higher degree of water scarcity than Santiago, its final consumption scarcity weighted footprint decreases in a lower extent because the region consumes goods from regions with a higher value added per unit of extracted water, as previously analyzed.

Table 6 presents the total CHEE per region, the excess demand (previously calculated), and the unit cost of HEE (for regions experiencing scarcity). As shown in

Figure 8, the unit cost of HEE is highest in Antofagasta (49.7 USD/m³) and Metropolitana (23.4 USD/m³). This cost represents the opportunity cost of conserving one cubic meter of water to maintain hydroeconomic equilibrium. The best alternative use (opportunity cost) is the generation of value added.

At the national level, the CHEE represents 34% of the total value added in the economy. This reflects the cost of eliminating the virtual water flows of scarce water.

Table 5. Reduction in final demand and value added (CHEE)

Region	Reduction Y	Reduction VA
De Arica y Parinita	88%	80%
De Tarapacá	61%	59%
De Antofagasta	52%	49%
De Atacama	21%	24%
De Coquimbo	4%	9%
De Valparaíso	74%	66%
Región Metropolitana de Santiago	42%	40%
Del Libertador General Bernardo O'Higgins	0%	9%
Del Maule	0%	8%
Del Biobío	0%	6%
De La Araucanía	0%	4%
De Los Ríos	0%	5%
De Los Lagos	0%	6%
Aysén del General Carlos Ibáñez del Campo	0%	12%
De Magallanes y de la Antártica Chilena	0%	3%

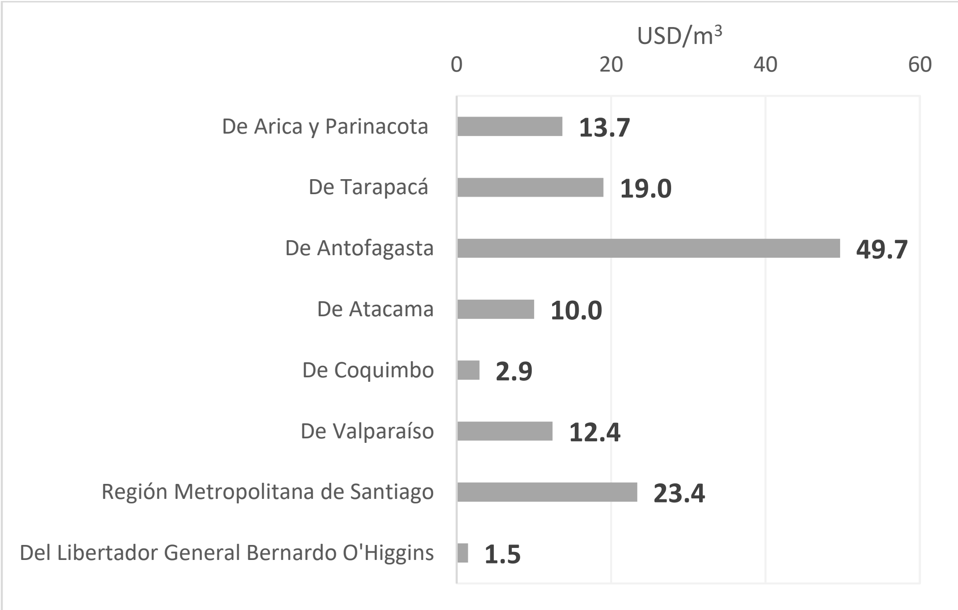
Source: own elaboration

Table 6. CHEE: total cost, excess of demand and unitary cost

Region	CHEE STgs (USD MM)	Excess of ED (m3)	CHEE STgs (USD/m3)
De Arica y Parinacota	1,414.6	103.2	13.7
De Tarapacá	3,488.8	183.4	19.0
De Antofagasta	12,706.0	261.1	49.7
De Atacama	1,425.5	184.7	10.0
De Coquimbo	628.5	278.5	2.9
De Valparaíso	13,604.9	1127.0	12.4
Región Metropolitana de Santiago	41,836.9	1840.7	23.4
Del Libertador General Bernardo O'Higgins	1,017.2	874.1	1.5
Del Maule	618.2	0.0	-
Del Biobío	1,169.8	0.0	-
De La Araucanía	241.9	0.0	-
De Los Ríos	166.9	0.0	-
De Los Lagos	482.5	0.0	-
Aysén del General Carlos Ibáñez del Campo	206.0	0.0	-
De Magallanes y de la Antártica Chilena	74.9	0.0	-
Total	79,082.7	0.0	-

Source: own elaboration

Figure 14. Unitary cost of HEE by region (USD/m^3)



Source: own elaboration

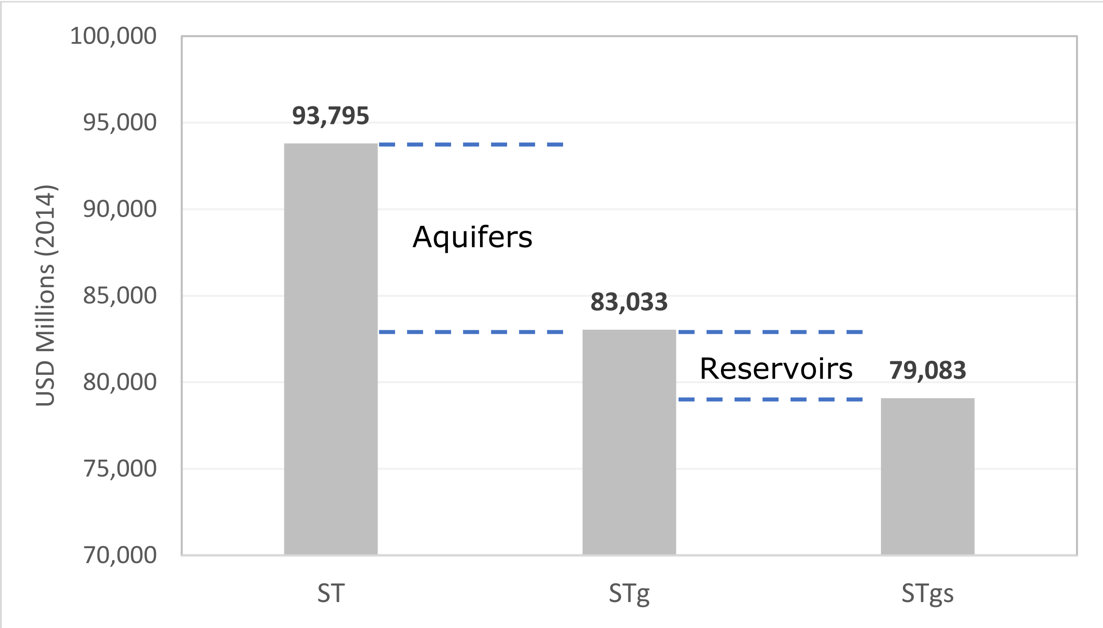
5.6 Value added by aquifers and reservoirs

Previously, the CHEE was calculated assuming an optimal use of groundwater and surface water collected in reservoirs and other waterworks (ST_{gs} as a threshold for scarcity in water use). An additional exercise was carried out, incorporating as an environmental constraint ST_g and ST into the optimization problem. This approach allows for the estimation of the additional value added that can be produced without overexploiting water resources using aquifers and reservoirs to regulate the seasonal variation of water supply—naturally through aquifers and artificially through reservoirs. Figure 15 illustrates the national-level values. The value added guaranteed by the regulatory function of aquifers amounts to 10,762 million USD, while the additional value added guaranteed by the artificial regulatory function of reservoirs is 3,951 million USD.

This calculation can also be performed at the regional level, as shown in Table 7. However, the interpretation differs: these amounts represent the total value added produced within each region that is supported by the regulatory function of aquifers and reservoirs in the whole country. This provides insights into the potential impact of projects aimed at improving seasonal water management, such as artificial aquifer recharge or reservoir construction.

To evaluate the value of the regulatory function of a specific aquifer in a particular region, the optimization problem should be solved by considering the natural ST for that region and ST_g in the others.

Figure 15. CHEE with three different thresholds



Source: own elaboration

Table 7. Value added by all chilean aquifers and reservoirs in each region

Region	CHEE ST	CHEE STg	CHEE STgs	VA Aquifers	VA Reservoirs
De Arica y Parinacota	1,500.0	1,402.7	1,414.6	97.3	-11.9
De Tarapacá	3,611.1	3,472.2	3,488.8	138.9	-16.7
De Antofagasta	13,017.4	12,942.9	12,706.0	74.5	236.9
De Atacama	2,973.9	2,167.2	1,425.5	806.7	741.7
De Coquimbo	2,201.0	1,493.3	628.5	707.7	864.8
De Valparaíso	15,043.0	13,995.4	13,604.9	1,047.6	390.5
Región Metropolitana de Santiago	49,980.4	42,627.5	41,836.9	7,352.9	790.7
Del Libertador General Bernardo O'Higgins	1,971.3	1,836.7	1,017.2	134.6	819.5
Del Maule	735.4	646.4	618.2	89.0	28.1
Del Biobío	1,387.0	1,226.1	1,169.8	160.8	56.3
De La Araucanía	285.3	252.7	241.9	32.6	10.8
De Los Ríos	196.6	174.4	166.9	22.2	7.6
De Los Lagos	566.7	503.7	482.5	63.0	21.1
Aysén del General Carlos Ibáñez del Campo	238.9	213.8	206.0	25.2	7.8
De Magallanes y de la Antártica Chilena	87.5	78.5	74.9	9.0	3.6
Total	93,795.4	83,033.4	79,082.7	10,762.0	3,950.7

Source: own elaboration

6 DISCUSSION

The estimation of the virtual water flows, considering water demand both in quantity and quality and the link between value added production water use and water scarcity, allowed to produce highly relevant results both at the national and the regional scale. These results are entirely novel, not only because this is the first study to address these issues for Chile, but also because the analysis incorporates a series of methodological innovations. This is particularly significant for a country characterized by substantial heterogeneity in both natural water availability and economic structure.

The Metropolitan Region of Santiago stands out as a significant hub for virtual water flows, a role that becomes even more pronounced when water quality is considered. This finding underscores the region's central role in national water resource dynamics and highlights the importance of sustainable management to address the growing demand for high-quality water.

By associating value added with virtual water flows, the regions of Antofagasta and Los Lagos exhibit high values in both production and final demand. This is primarily explained by Antofagasta's strong dependence on mining and Los Lagos' reliance on the aquaculture industry. Analyzing value added in virtual water flows helps to identify the differences among regions in terms of efficiency in generating value added while utilizing regional water resources and in value added intensity in consuming virtual water. When taking into account water scarcity, the Central and Northern regions of Chile significantly increase their share of the national water footprint, particularly through their consumption-related virtual water inflows. These regions, which do not comply with the Environmental Water Requirement (EWR), account for 75% of the national (internal) WF and increase their share to 86% when the SWF is considered.

The opportunity cost of a complete elimination of water overexploitation is equivalent to 34% of the total national added value. This would represents a considerable economic burden, with the Antofagasta region experiencing disproportionately higher unit costs, due to its dependence on water-intensive mining activities. The reduction in regional value added, resulting from an environmentally constrained optimization process, has a smaller impact on regions that produce and consume a higher amount of value added in virtual water. This analysis could support the targeting of public policy interventions, which should primarily focus on these regions.

The regulation function of aquifers and reservoirs on an intra-annual basis proves to be a crucial tool for promoting water sustainability. They support a substantial reduction of the cost of hydro-economic equilibrium estimated between USD 3.9 billion and USD 10.7 billion, emphasizing they effectiveness as a long-term strategy for resource management. The avoidance of these costs demonstrates the economic value of investing in infrastructure and governance systems that enhance water security. These results have been disaggregated by region.

These results underscore the critical need for integrated water resource management policies able to balance environmental sustainability with production and consumption. Priority should be given to strategies that address water scarcity, improve efficiency in water use, and incorporate ecological and social externalities into decision-making frameworks. Only through comprehensive and forward-looking measures can Chile ensure the sustainable management of its water resources, securing their availability for future generations while maintaining economic competitiveness.

One of the study's limitations of this study, is the year of the estimates (2014), which is due to the fact that, to date, only one multiregional input-output matrix (MRIO) is available for Chile. Additionally, the sectoral disaggregation into 12 sectors may introduce an aggregation bias in the results, with the most evident case being the Electricity and Water sector. Ideally, it would be beneficial to separate from the water supply industry one or two additional economic sectors (extraction, distribution, treatment, sewage). Another limitation concerns the accuracy of grey water estimates, which have been calculated based on legal thresholds and only for organic pollutants. However, previous studies have followed the same approach due to data limitations regarding water quality at industrial discharge points (Rocchi et al., 2023; Sturla and Rocchi, 2024). A final limitation is the scale of analysis. While the regional level represents a significant advancement in hydro-economic modeling, water is usually managed at the basin level, meaning that some of the estimated indicators (e.g., ED excess) may not fully capture the hydrological heterogeneity within regional basins.

Two key research avenues emerge from this study. The first relates to updating the economic data (MRIO), separating the Water supply industry, and incorporating regional factors to address scale-related issues. Currently, efforts are underway to update the MRIO to 2018 and to develop regional indicators that allow for recalculating HEE and CHEE, considering water scarcity issues at a smaller scale. This could lead to findings indicating that regions in Central-Southern and Southern Chile may too experience some degrees of scarcity. The second research avenue is methodological and has emerged from the analysis of value added by aquifers and reservoirs. The constructed model allows for recalculating the CHEE while modifying ST for each region separately, enabling the estimation of the economic value of the groundwater ecosystem service of water regulation. Additionally, it may be possible to determine the value of ecosystem services related to water provision and purification, interpreting the results as opportunity costs (economic valuation based on the opportunity cost method). Exploring this potential of MRIO-EE models could provide a significant contribution to natural capital accounting in Chile and other countries, producing coarse but low-cost estimates. Moreover, these estimates would account not only for the direct value of ecosystem services within a region but also for their indirect value, which is transmitted through national production chains.

7 CONCLUSIONS

The present study provided an unprecedented analysis of the relations between the economy and the hydrological system in Chile. The virtual water flows estimated using the MRIO-EE model allow for the assessment of traditional indicators such as the water footprint (considering blue and grey water used both for production and consumption), as well as novel contributions to the existing literature, such as the scarcity-weighted water footprint—where scarcity is estimated endogenously—and the value added embedded in virtual water flows from both a production and final consumption perspective for each region.

The application of the concept of HEE and the estimation of CHEE, incorporating methodological innovations compared to previous studies (thresholds with surface water regulation and value-added optimization), has enabled the estimation of the opportunity cost of eliminating scarcity in virtual water flows in Chile—equivalent to one-third of the total value added. Additionally, this approach has allowed for the calculation of the opportunity cost of each cubic meter of overexploited water, which is significantly higher in the Antofagasta region, followed by the Metropolitan Region of Santiago. These results provide valuable insights for the design of public policies aiming at balancing environmental protection and economic efficiency, identifying priority economic sectors and regions for addressing water scarcity through solutions such as desalination or nature-based approaches.

Another significant and methodologically novel contribution to the literature is the estimation of the value added supported by the intra-annual water regulation capacity of aquifers and reservoirs, using the MRIO-EE model. The national value has been disaggregated by region, identifying the contribution of national water regulation to the water balance in each region. This finding has practical implications for public policy, as the constructed model enables the assessment of regional and interregional economic impacts (in terms of value added) resulting from projects aimed at improving water regulation capacity (e.g., artificial aquifer recharge, reservoir construction, and land use changes).

An intriguing extension of this model has emerged from this research. By eliminating the water regulation capacity in a given region and recalculating the CHEE, it is possible to approximate the economic value of the ecosystem service of water regulation provided by groundwater ecosystems. This future research direction represents an innovative application of environmentally extended input-output analysis, potentially transforming into a valuable tool within the natural capital framework of environmental analysis, particularly for natural capital accounting and its subsequent integration into national accounts.

In conclusion, this study has successfully generated new and policy-relevant estimations for Chile, while also providing methodological contributions to the literature at the intersection of economics and water use. Furthermore, it has revealed new potential applications of input-output models in the valuation of natural capital.

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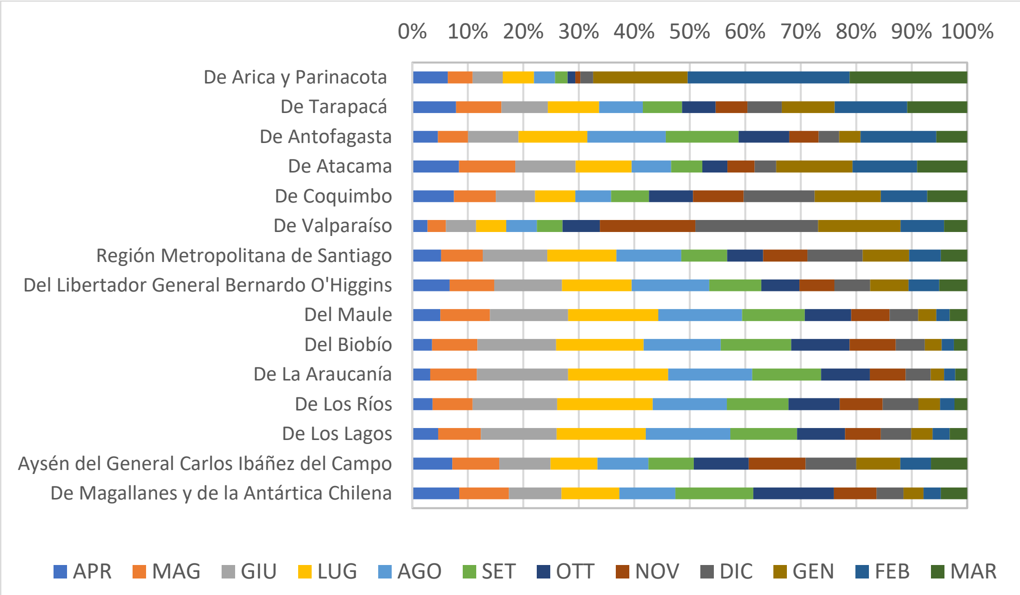
9 APPENDIX

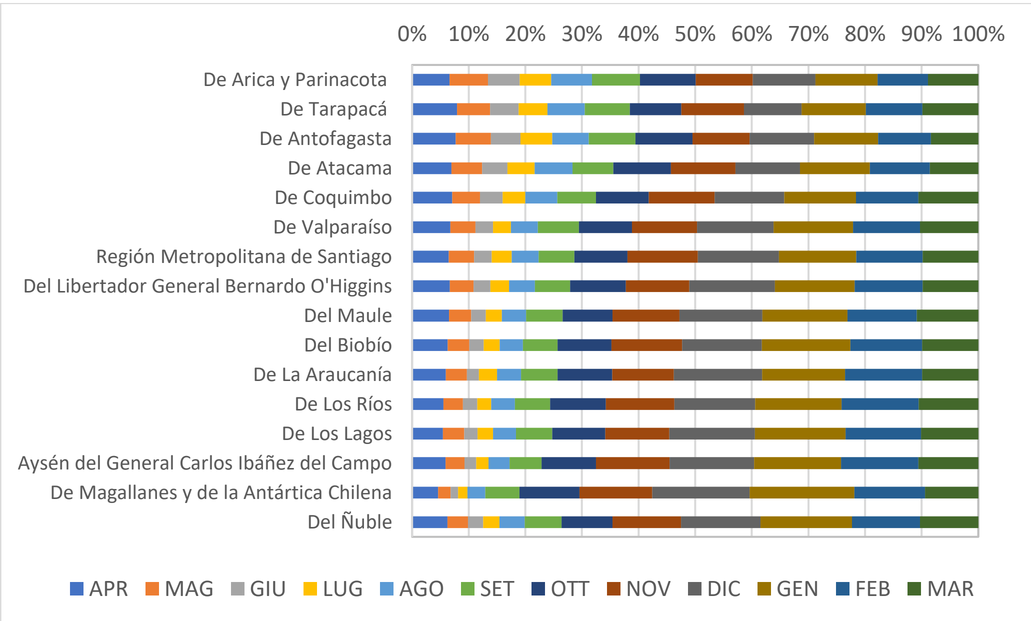
9.1 Appendix A

Figure A1. Seasonal variability of runoff by region



Source: own elaboration

Figure A2. Seasonal variability of evapotranspiration by region

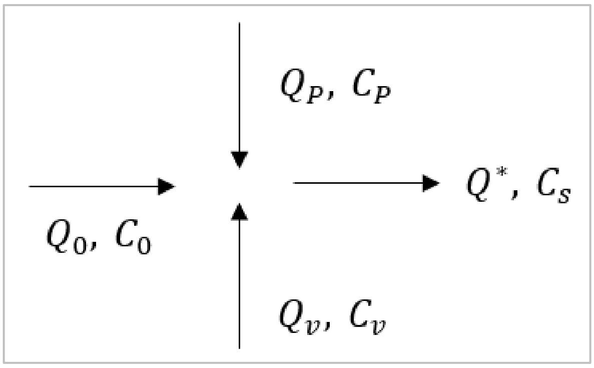


Source: own elaboration

9.2 Appendix B

Consider a mixing model in which the inputs correspond to the water present in the water body, the water discharged by an industry and the water required for dilution (each represented by a volume and a pollution concentration); and the output corresponds to the total volume of water with a standard concentration (a good water quality level for the hydrological system).

Figure A1. Scheme with inputs and outputs of the mixing model



Source: Own elaboration

where,

Q_0	:	Volume of water in the water body before discharge
C_0	:	COD concentration in the water body before discharge
Q_P	:	Volume of water of the industrial discharge
C_P	:	COD concentration in the industrial discharge
Q_v	:	Volume of water for dilution
C_v	:	COD concentration in the dilution water
Q^*	:	Total volume of water after mixing
C_s	:	COD standard concentration after mixing

Applying conservation of mass law (without intermediate chemical reactions), the mass balance can be represented as follows:

$$Q_0\, C_0 + Q_p\, C_p + Q_v\, C_v = Q\, C_s + Q_v\, C_s \quad \text{(B1)}$$

where,

$$Q = Q_0 + Q_p \quad \text{(B2)}$$

Xie (1996) and Guan and Hubacek (2008) model (Xie-Model) considers chemical reactions, introducing two parameters representing the decay of the pollutant mass (COD):

k_1 : total reaction rate of pollutants after entering the water bodies
k_2 : pollution purification rate before entering the water bodies

Considering these parameters, the mass balance equation (B1) becomes:

$$Q_0\, C_0 + K_2\, Q_p\, C_p + Q_v\, C_v = Q\, C_s + K_1\, Q_v\, C_s \quad \text{(B3)}$$

Thus, the volume of water required for dilution in is:

$$Q_v = \frac{1}{K_1\, C_s - C_v}\left[Q_0\, C_0 + K_2\, Q_p\, C_p - Q\, C_s\right] \quad \text{(B4)}$$

The Xie-Model assumes that the water for dilution does not have pollutants $(C_v = 0)$, then the volume of water required for dilution can be written as:

$$Q_v^{Xie-Model} = \frac{1}{k_1\, C_s}\left[Q_0\, C_0 + k_2\, Q_p\, C_p - Q\, C_s\right] \quad \text{(B5)}$$

As explained in the methodology, in this study, two modifications of the Xie-Model are considered:

i. The dilution water comes from the hydrological system $(C_v = C_0)$
ii. The unfavorable case is considered, i.e., when the available water in the water body is equal to the dilution water requirement $(Q_0 = 0)$

Imposing conditions (i) and (ii) on the equation (B4), the volume of water dilution requirements in our model can be expressed as:

$$Q_v^{RS} = \frac{1}{k_1\, C_s - C_0}\left[Q_p \cdot (k_2\, C_p - C_s)\right] \quad \text{(A6)}$$

This equation for dilution water has three relevant consequences to our estimates. Firstly, it corresponds to a more realistic representation of the COD concentration in the dilution water. Secondly, the worst case hypothesis is conservative rule in reserving a volume for dilution within the hydrological system. Finally, it is possible to calculate dilution requirements for each industry, not just for the whole economy, as in the case of Guan and Hubacek (2008) model.