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

Gino Sturla – U. Diego Portales, Chile.

Benedetto Rocchi – U. of Florence, Italy.

Eugenio Figueroa – U. of Chile, Chile.

31st International Input-Output Association Conference, Malé, Maldives.

Contents

I. Objetives

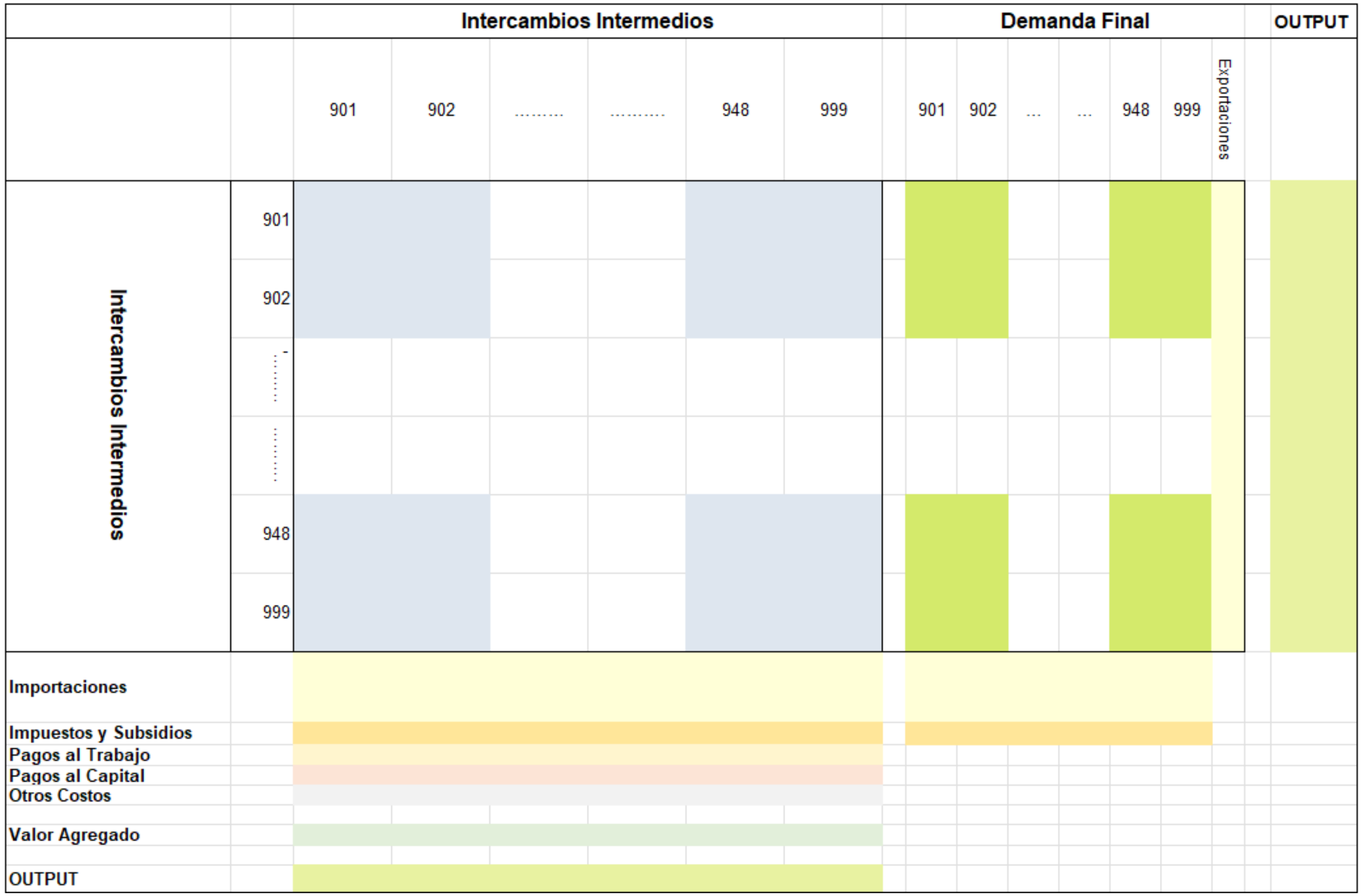
Objetivos

- Determine the demand for freshwater and the return flows (volume and quality) of water from productive sectors by region in Chile.
- Estimate, using an environmentally extended MRIO model (MRIO-EE), the virtual water flows and regional water footprint, as well as their pollution content, value added, and scarcity across regions.
- Calculate the volume of water exceeding scarcity thresholds and the hydroeconomic equilibrium cost by region.
- Determine, based on the hydroeconomic equilibrium cost (opportunity cost), the economic value of water provision, purification, and regulation services by region.

II. Data and estimations

Matriz insumo-producto multirregional

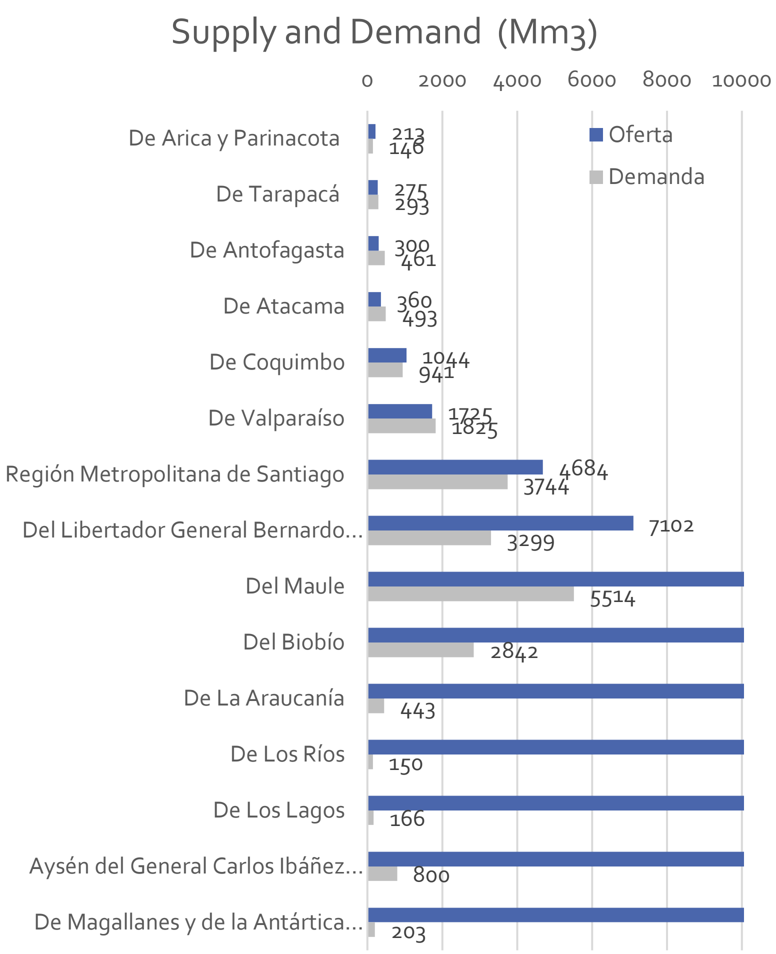
- NEREUS, 2014.
- 12 sectors, 15 regions.

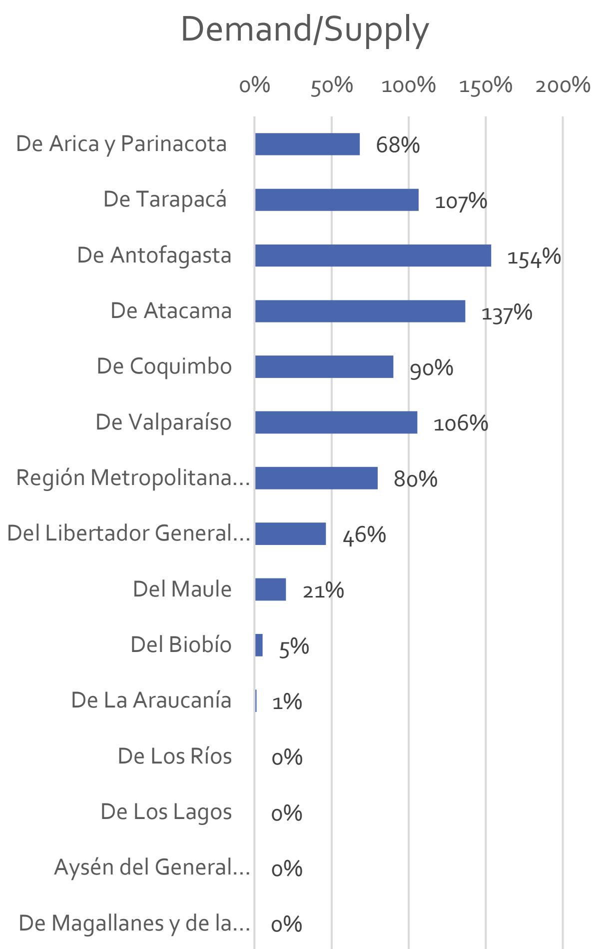


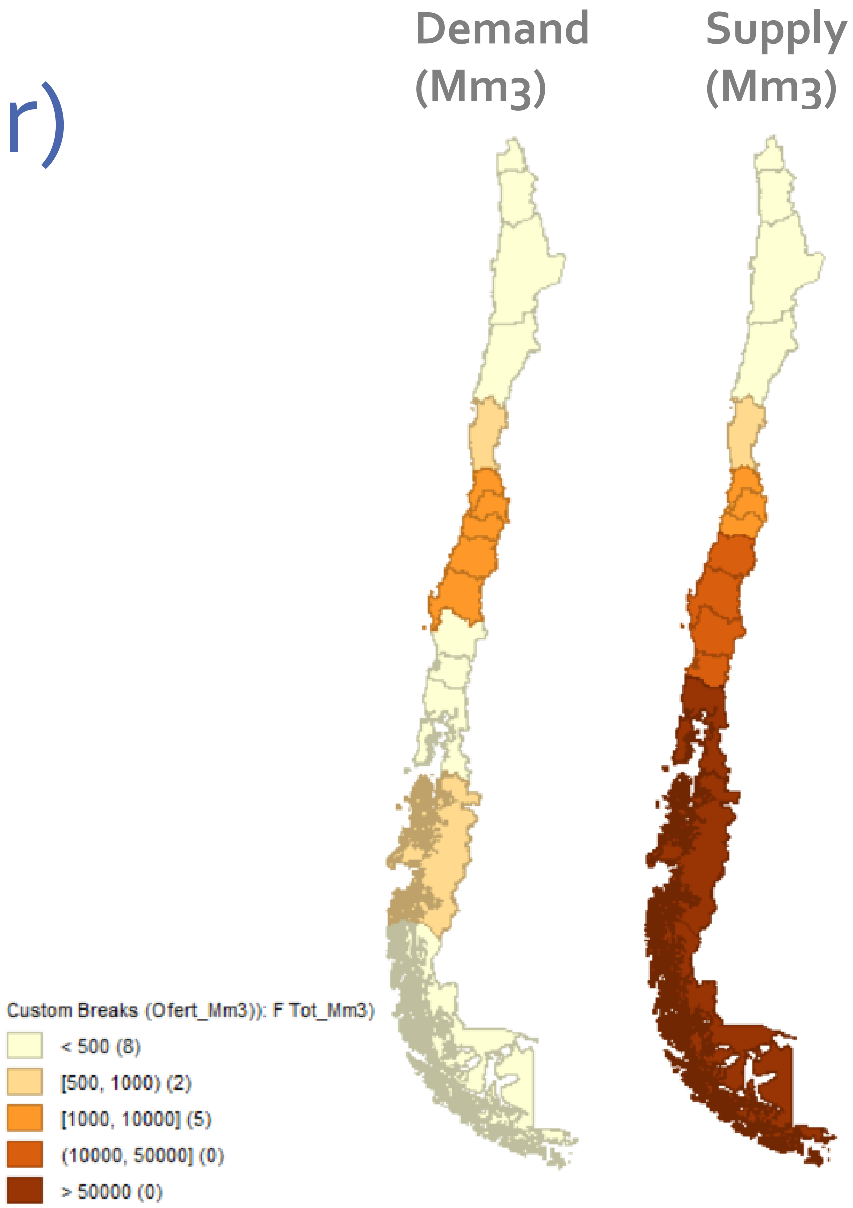
Data sources

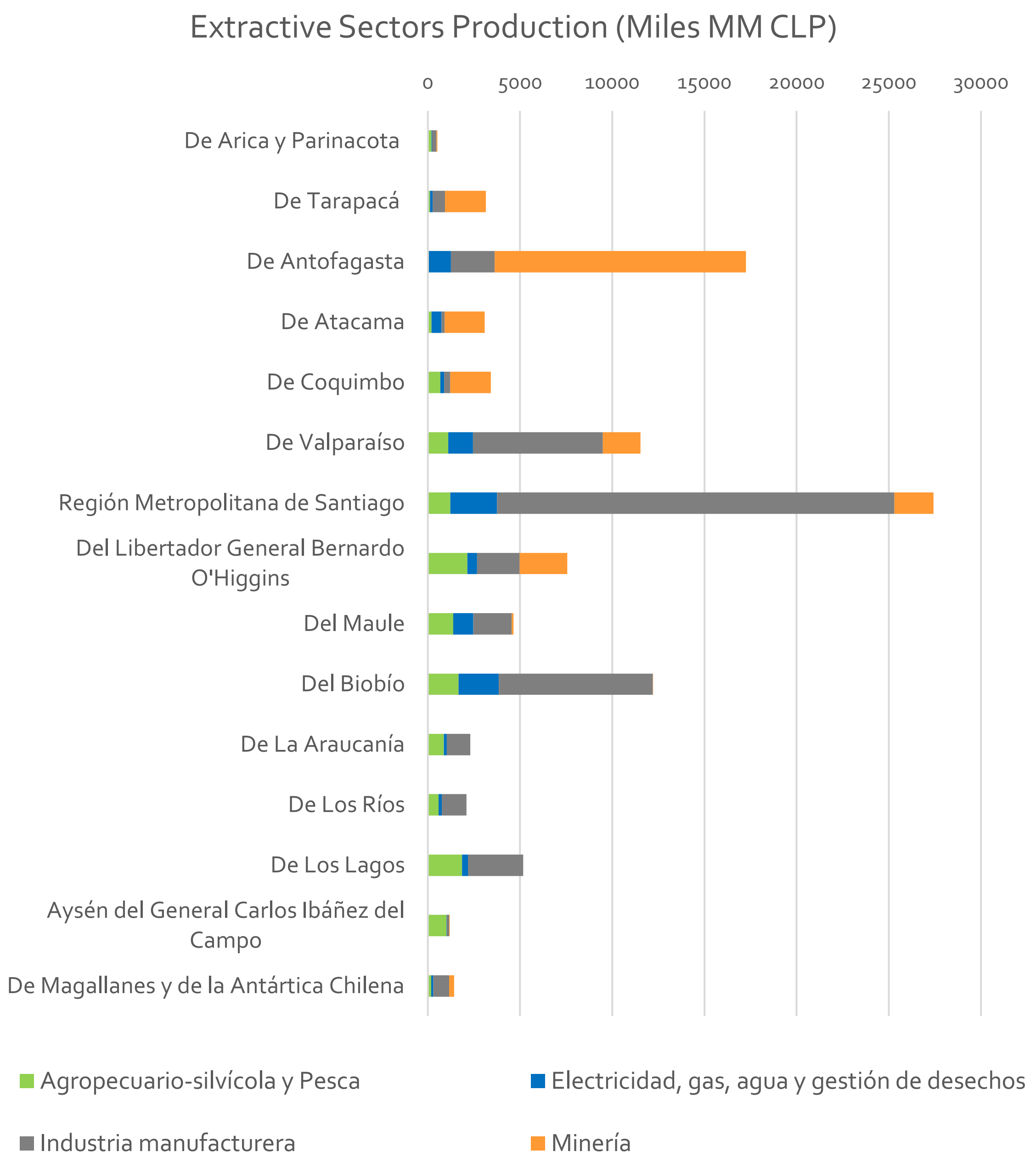
- **Matriz IRIO** NEREUS 2014 (15 regiones, 12 sectores)
- **Extracciones sectoriales**
  - Atlas del Agua (DGA, 2016)
  - Actualización del Balance Hídrico Nacional (DGA, 2017)
  - Aplicación de la Metodología de Actualización del Balance Hídrico Nacional en las Cuencas de la Macrozonas Norte y Centro (MOP, 2018)
  - Coordinador Eléctrico Nacional (CEN, 2023)
  - Anuario Cochilco (Cochilco, 2021)
  - Supertintendencia de Servicios Sanitarios (SISS, 2023)
  - Water Resources of Chile (Fernández y Gironás , 2021)
- **Restituciones sectoriales**
  - Supertintendencia de Servicios Sanitarios (SISS, 2023)
  - Water Resources of Chile (Fernández y Gironás , 2021)
  - Base de datos estadísticos DGA (DGA, 2023)
- **Agua gris por sectores**
  - Supertintendencia de Servicios Sanitarios (SISS, 2023)
  - En base a la concentrición COD (Sturla y Rocchi, 2022)
  - Proyecto CAMELS (CR2, 2023)
- **Oferta de agua regional**
  - Atlas del Agua (DGA, 2016)
  - Actualización del Balance Hídrico Nacional (DGA, 2017)
  - Base de datos estadísticos DGA (DGA, 2023)
- **Variabilidad intra-annual**
  - Proyecto CAMELS (CR2, 2023)
  - Base de datos estadísticos DGA (DGA, 2023)

Demand and supply (blue water)

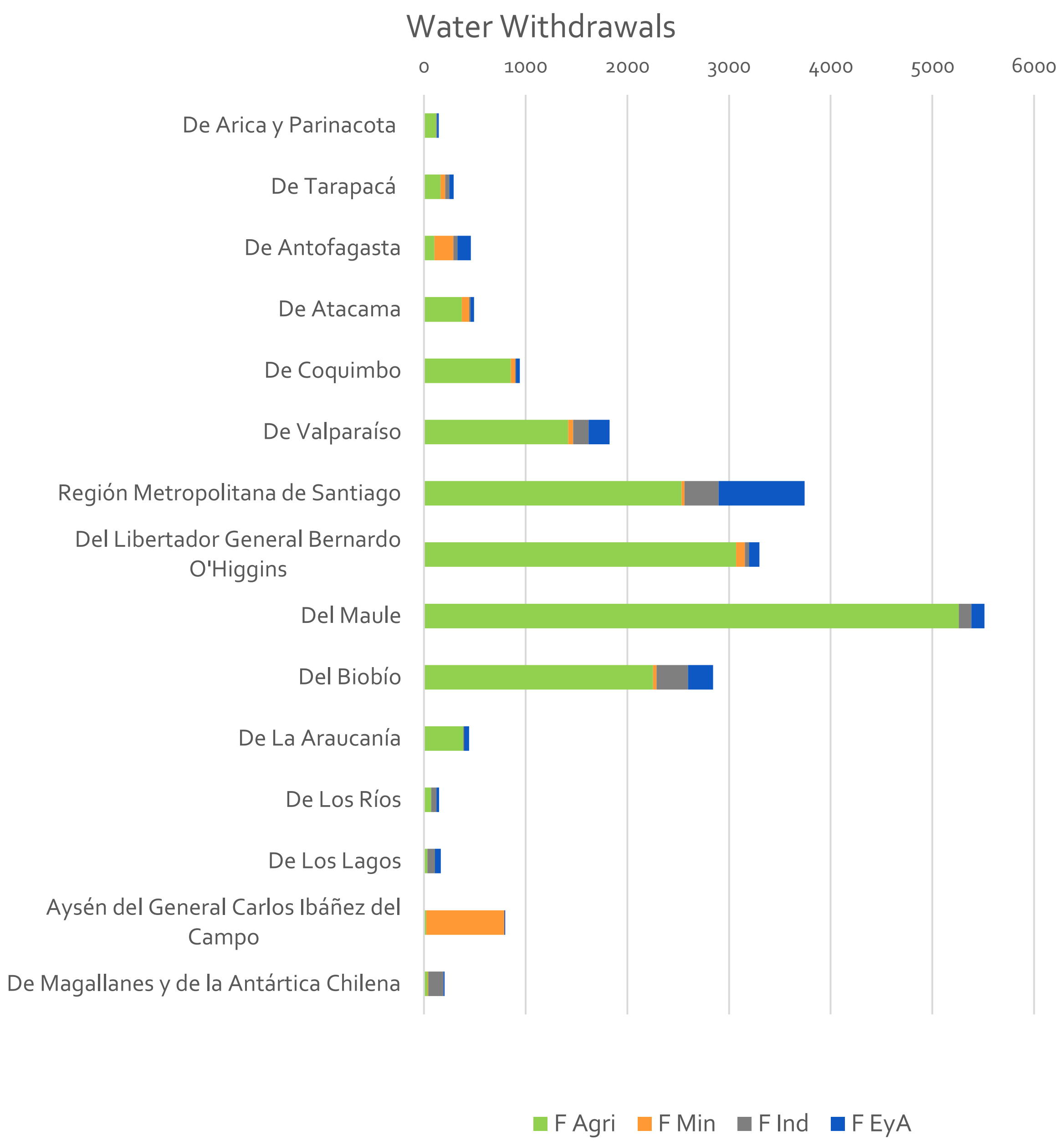






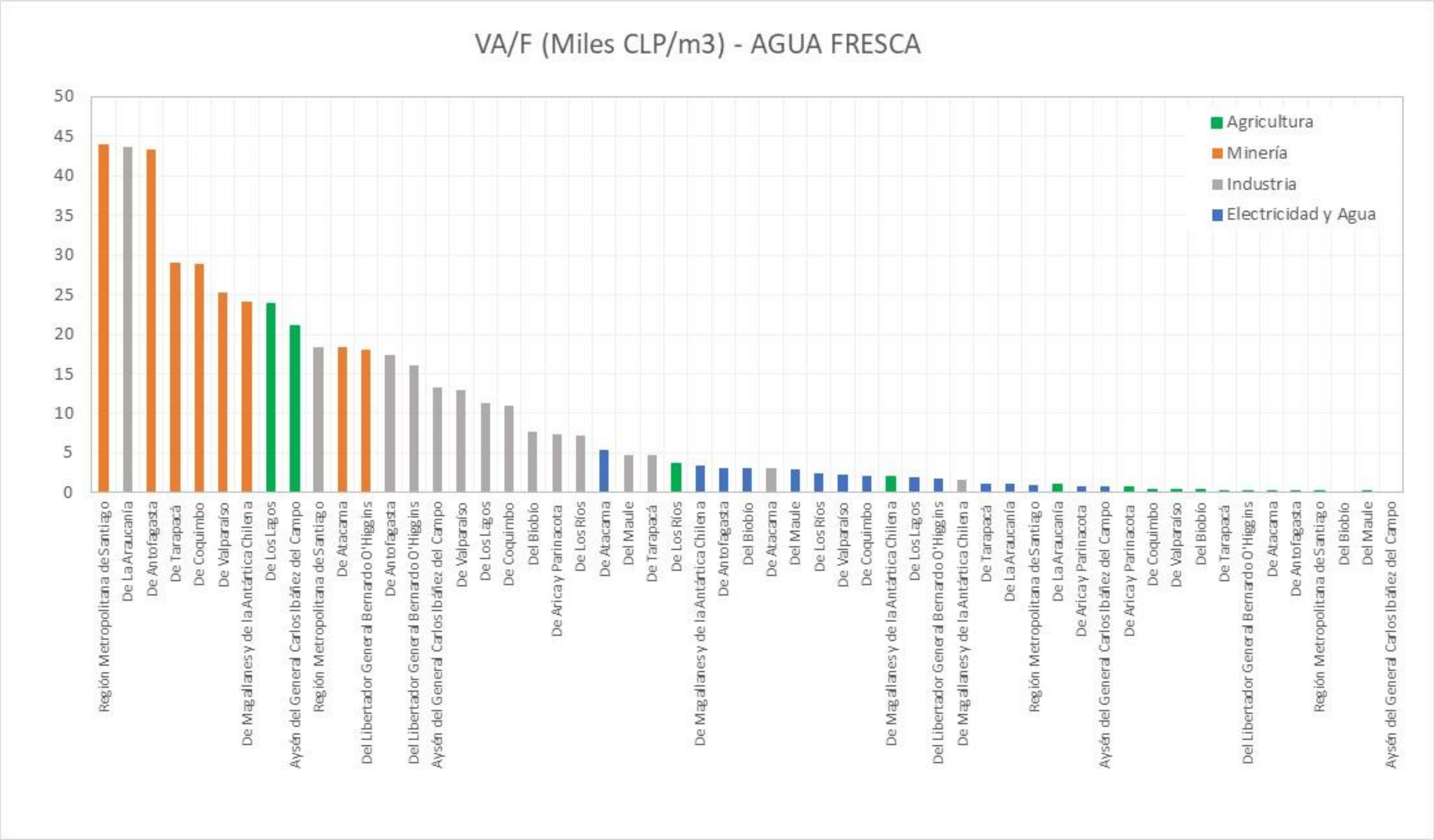


Extractive Sectors Production (Miles MM CLP)
0
5000
10000
15000
20000
25000
30000
De Arica y Parinacota
De Tarapacá
De Antofagasta
De Atacama
De Coquimbo
De Valparaíso
Región Metropolitana de Santiago
Del Libertador General Bernardo O'Higgins
Del Maule
Del Biobío
De La Araucanía
De Los Ríos
De Los Lagos
Aysén del General Carlos Ibáñez del Campo
De Magallanes y de la Antártica Chilena
Agropecuario-silvícola y Pesca
Electricidad, gas, agua y gestión de desechos
Industria manufacturera
Minería

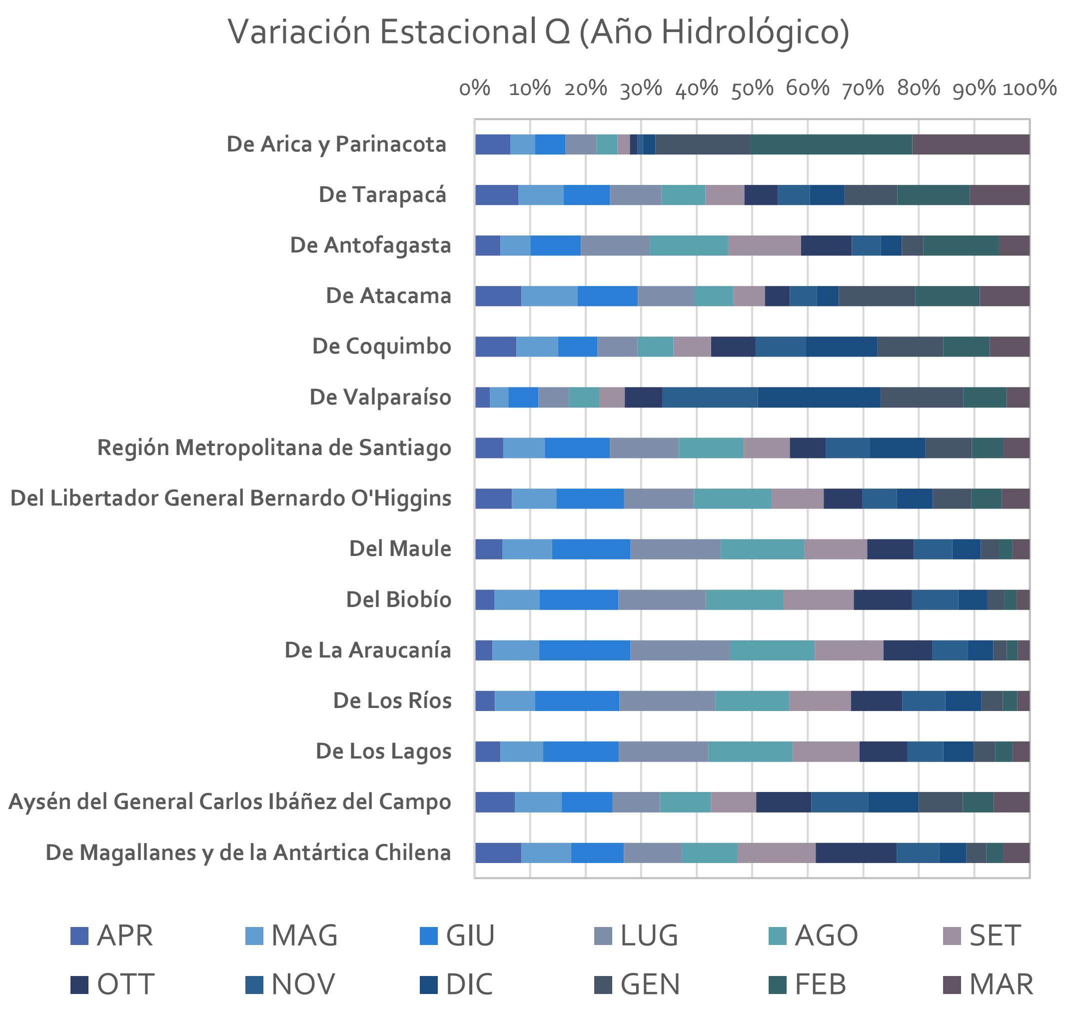


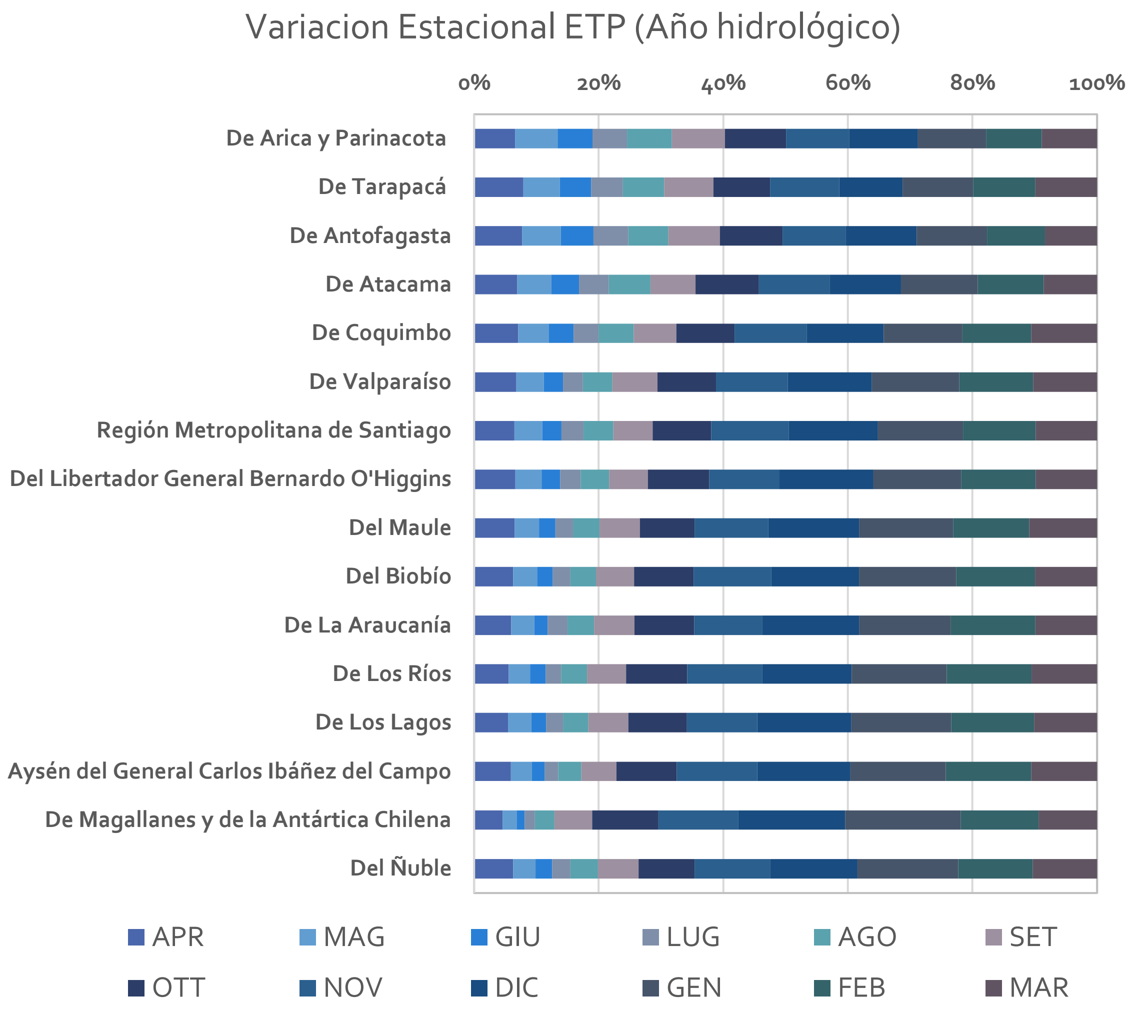
Water Withdrawals
0
1000
2000
3000
4000
5000
6000
De Arica y Parinacota
De Tarapacá
De Antofagasta
De Atacama
De Coquimbo
De Valparaíso
Región Metropolitana de Santiago
Del Libertador General Bernardo O'Higgins
Del Maule
Del Biobío
De La Araucanía
De Los Ríos
De Los Lagos
Aysén del General Carlos Ibáñez del Campo
De Magallanes y de la Antártica Chilena
F Agri
F Min
F Ind
F EyA

Added value in water withdrawals



Seasonal variability: supply and demand





Regulation capacity reservoirs

Región	Cod_Region	**Capacidad (Mm3)**	Escorrentía Superficial (Mm3)	Cap/Disp (%)
Arica y Parinacota	r1		173.4	
Tarapacá	r2		201.8	
Antofagasta	r3	**22.0**	28.4	**78%**
Atacama	r4	**192.0**	59.9	**320%**
Coquimbo	r5	**1,324.0**	700.1	**189%**
Valparaíso	r6	**130.0**	1,293.0	**10%**
Metropolitana de Santiago	r7	**221.7**	3,248.2	**7%**
Libertador General Bernardo O'Higgins	r8	**932.0**	6,464.9	**14%**
Maule	r9	**3,271.0**	24,188.1	**14%**
Biobío	r10	**6,868.0**	51,656.0	**13%**
La Araucanía	r11		32,829.0	
Los Ríos	r12		32,986.7	
Los Lagos	r13		129,581.4	
Aysén del General Carlos Ibáñez del Campo	r14		319,585.8	
Magallanes y de la Antártica Chilena	r15		319,270.5	

III. Methodology

Virtual water

- Matrix **W** (180x16): virtual water embedded in the production of each sector/region, required to satisfy final consumption.
- Matrix **Y** (180x16): final demand.
- Matrix $\boldsymbol{L}$ (180x180): Leontief.
- Matrix $\boldsymbol{\hat{v}}$ (180x180): water use Intensity coeff.
- Extended demand (ED): **agua azul + agua gris.**
- Virtual flows, water footprint.

$$W = \hat{v} \cdot L \cdot Y$$

By region

	r1	r2	r3	r4	RW
r1	w11	w12	w13	w14	w15
r2	w21	w22	w23	w24	w25
r3	w31	w32	w33	w34	w35
r4	w41	w42	w43	w44	w45

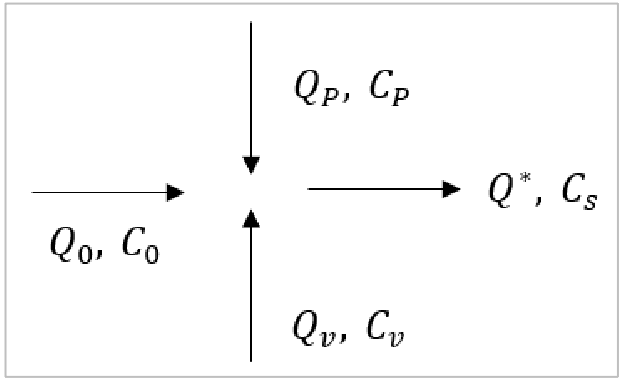
Consumption-based

Production-based

Grey water

- Chemical oxigen demand (COD)
- Water for dilution cames from the natural system $(C_v = C_0)$
- We considere the worst scenario $(Q_0 = 0)$.

$$Q_v = \frac{1}{k_1\ C_s - C_0}\left[Q_p \cdot (k_2\ \ C_p - C_s)\right]$$



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
k_1	:	Total reaction rate of pollutants after entering the water bodies
k_2	:	Pollution purification rate before entering the water bodies

Valor agregado y escasez

- Value added in production in region r:

$$VAP^r = \sum_i \frac{va_{ir}}{w_{ir}}$$

- Value added in consumption in region r:

$$VAC^s = \sum_{ir} \frac{va_{ir}}{w_{ir}} \frac{x_{i,r}^s}{\sum_{i,r} x_{i,r}^s}$$

- Scarcity embodied in WF of region s:

$$SW^s = \sum_{i,r} w_{i,r}^s \cdot \xi_r$$

Agua gris

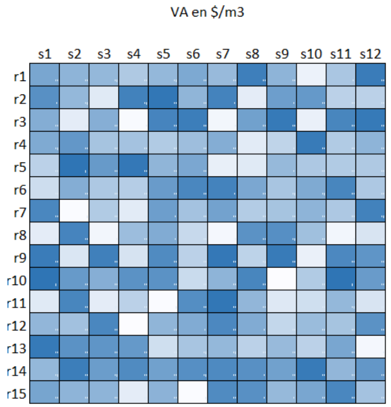
Elementos contaminantes

$ $ $ $

$ $ $ $

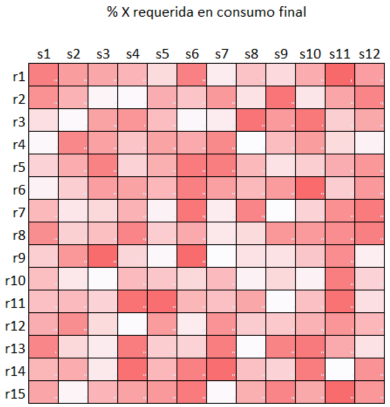
$ $ $ $

$ $ $ $



X

Multiplicação elemento por elemento



Equilibrio hidroeconómico (HEE)

To estimate ξ_r (excess of ED), we need to characterize the hydroeconomic equilibrium, incorporating Feasible Supply (FS) and the intra-annual variability of both supply (and regulation) and demand.

$$EWEI^r = \frac{\sum_{i=1}^{N}\sum_{k=1}^{2}\left[\left(f_{k,i}^r - r_{k,i}^r + w_{k,i}^r\right)\cdot\left(\sum_{r=1}^{M}\sum_{j=1}^{N} l_{i,j}^{r,s}\; y_j^s\right)\right]}{I^{r,feas} + R^{r,feas}}$$

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

$$EWEI^r \leq ST_{gs}^r$$

Costo del equilibrio hidroeconómico

- Minimum value-added reduction required for all regions to meet $EWEI^r \leq STgs^r$. With $\hat{\pi}$ as a diagonal matrix of the VA/Output ratio, and $\hat{\phi}$ as a diagonal matrix with m times ϕ^r (regional demand reduction).

$$\max_{\phi} e^T \cdot \hat{\pi} \cdot L \cdot \hat{\phi} \cdot y$$

$$s.t.$$

$$EWEI^r = \frac{(v_{blue}^r + v_{grey}^r)^T \cdot L^r \cdot \hat{\phi} \cdot y}{FS^r} \leq ST_g^r, \qquad \forall r$$

$$\phi^r \in [0,1]$$

- *If* VA^* is the optimized VA vector and VA^b the original one. The cost of the HEE is:

$$CHEE = e^T \cdot (VA^* - VA^b)$$

IV. Results

Virtual water flows (blue water)

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

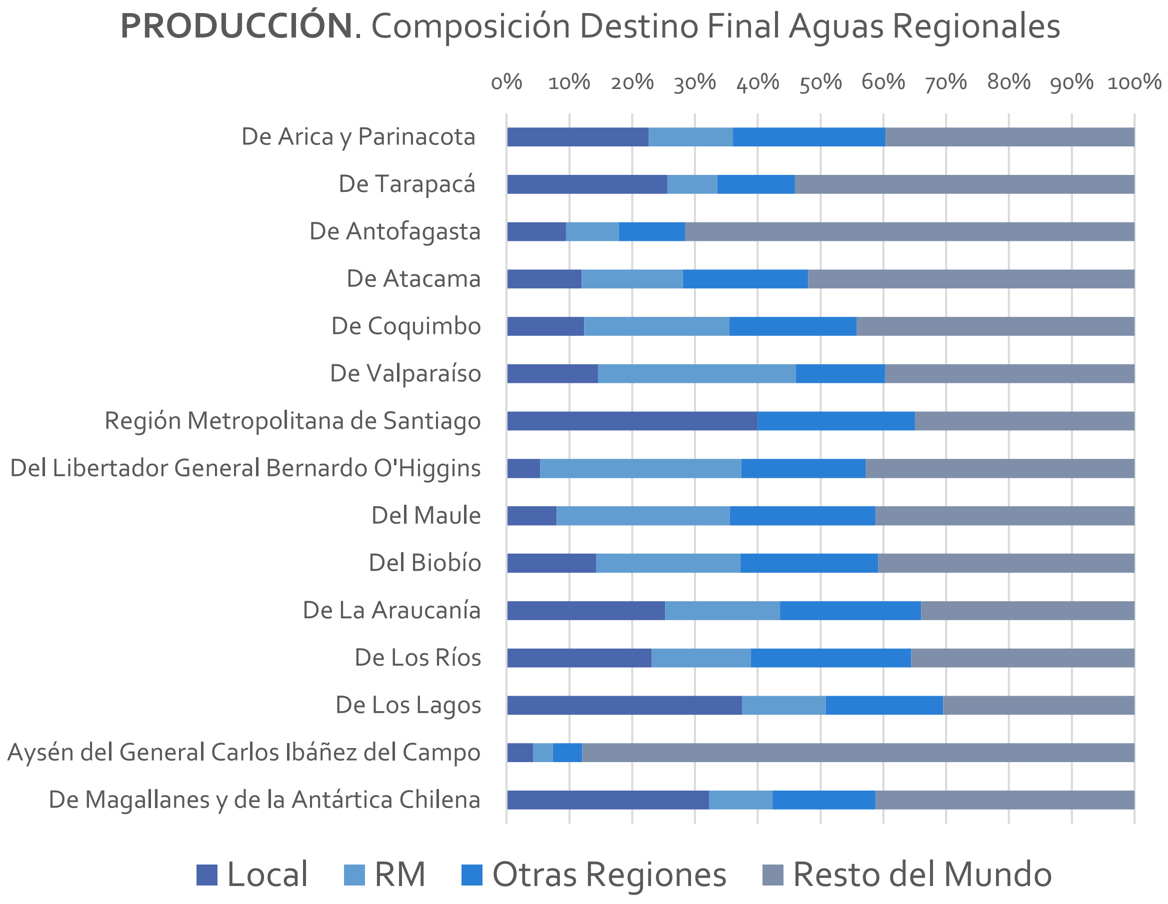
Huella hídrica (azul)
nacional RM

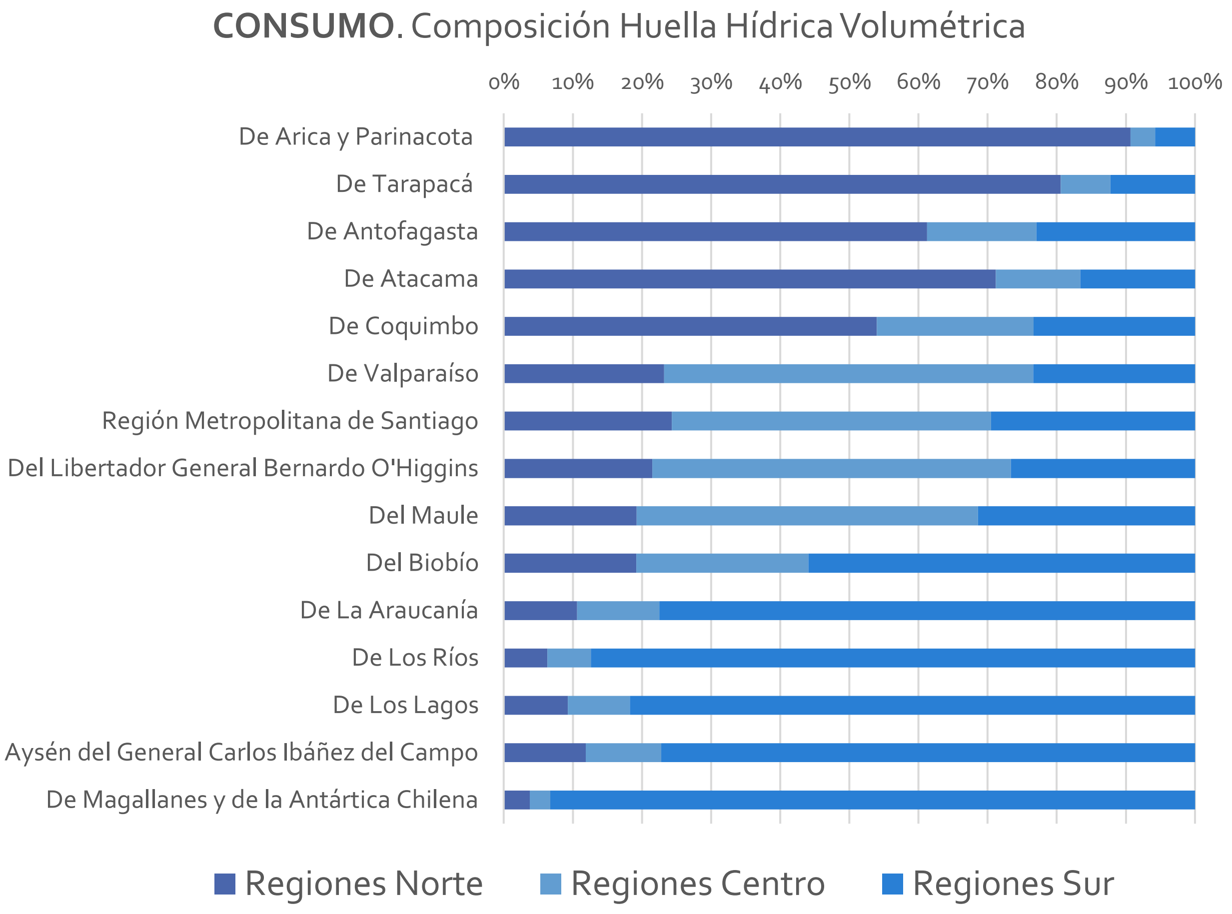
Pollution in virtual water flows (blue and gre water)

% Produccion Regional	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	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%

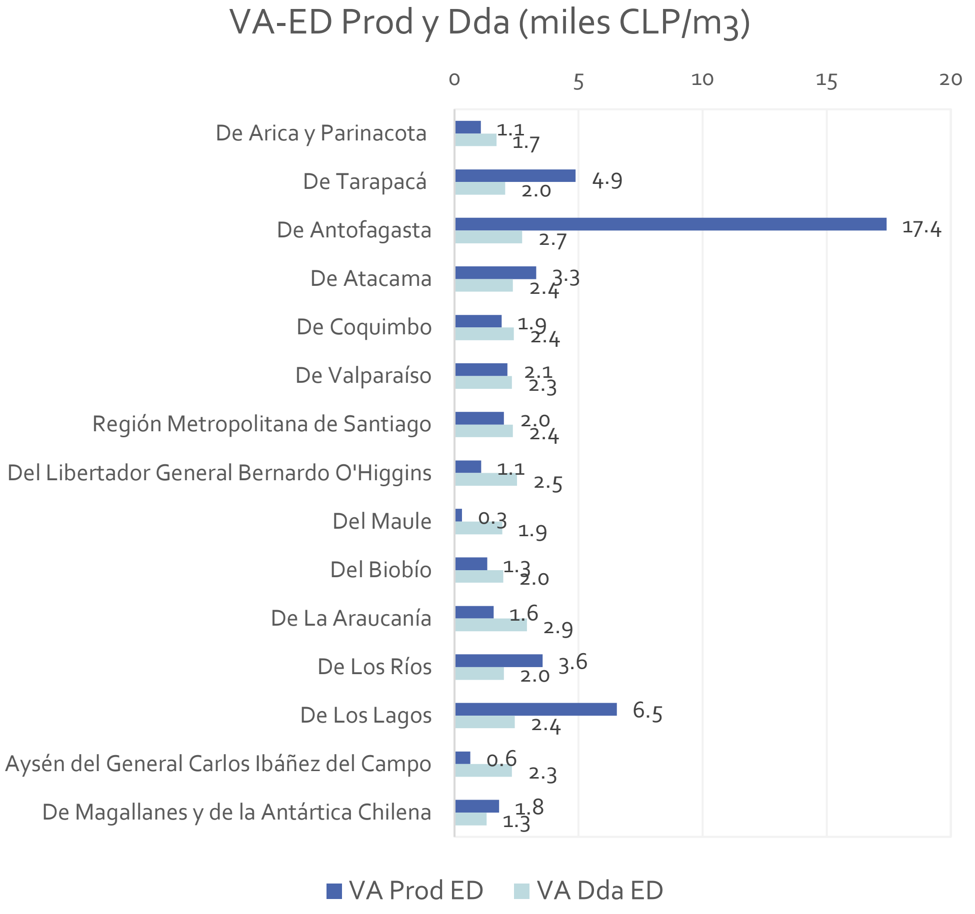
Huella hídrica (azul y gris) nacional RM

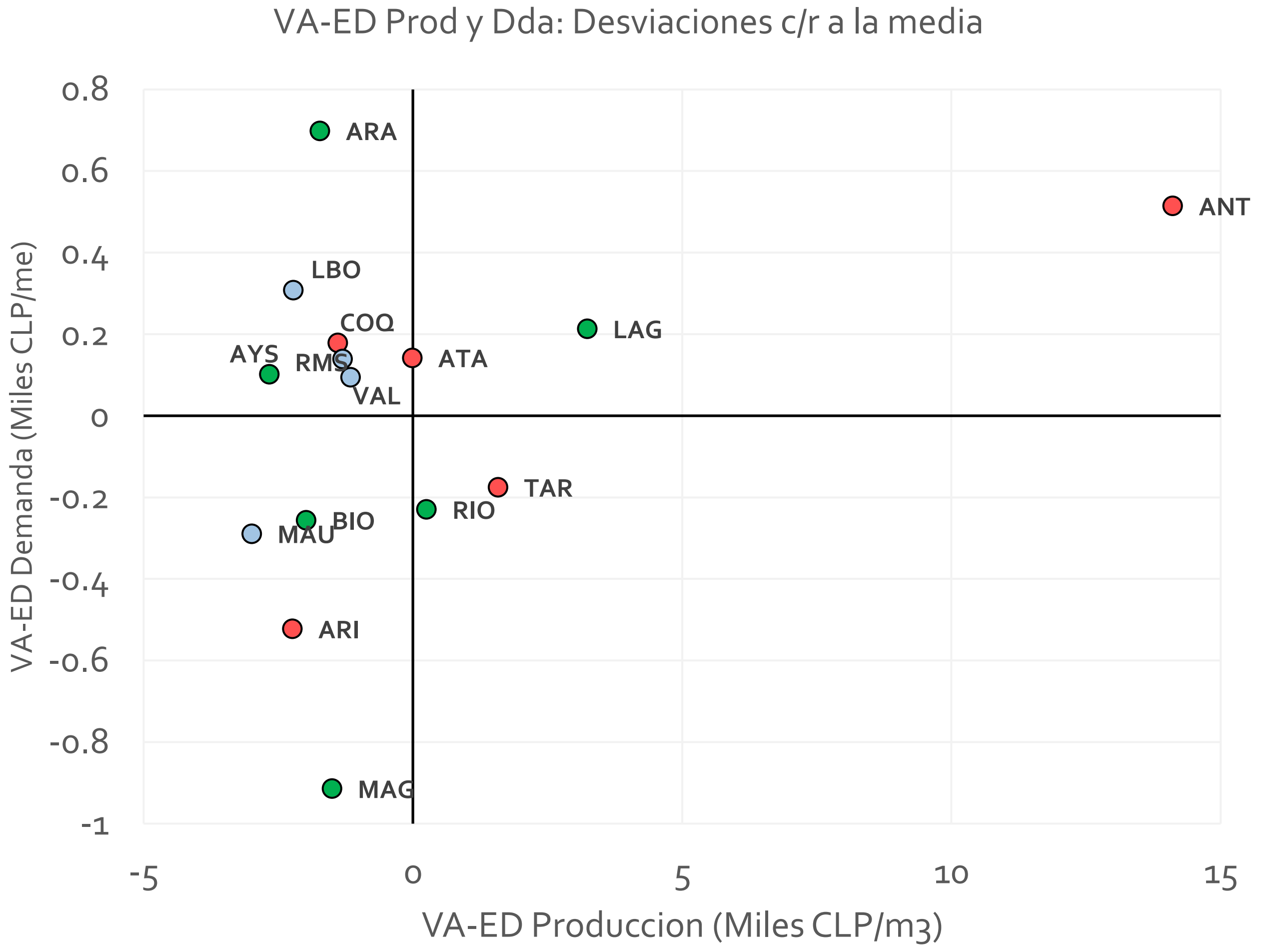
Destination of the water embedded in the water footprint (blue and grey, extended demand)



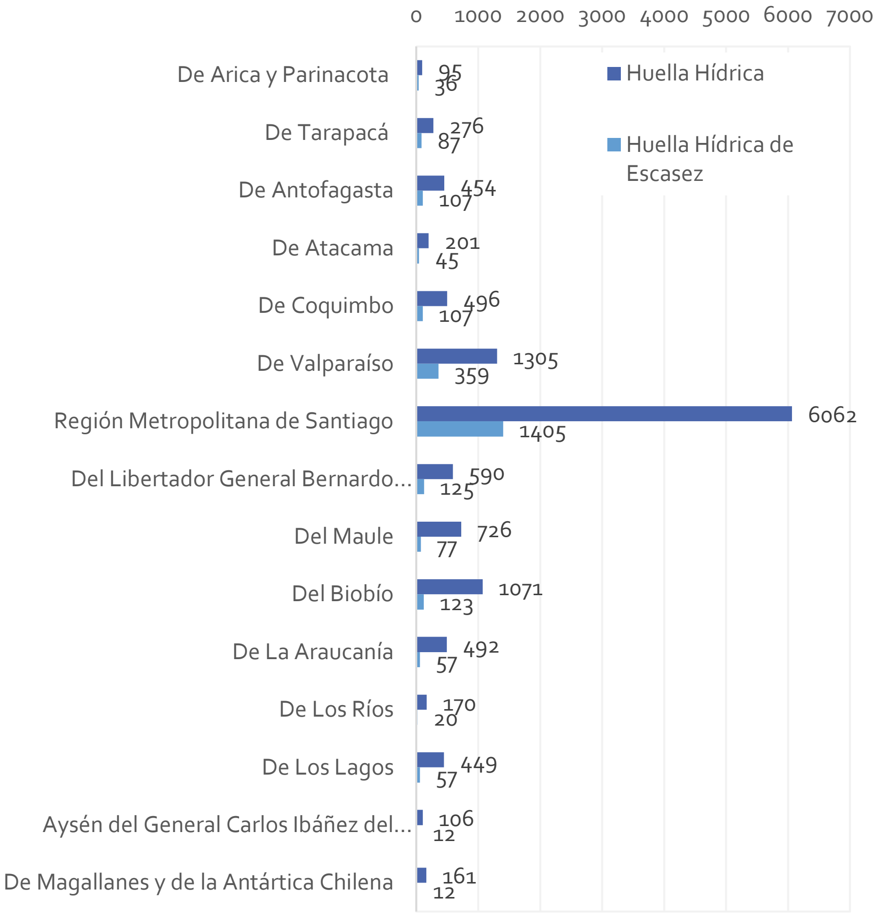


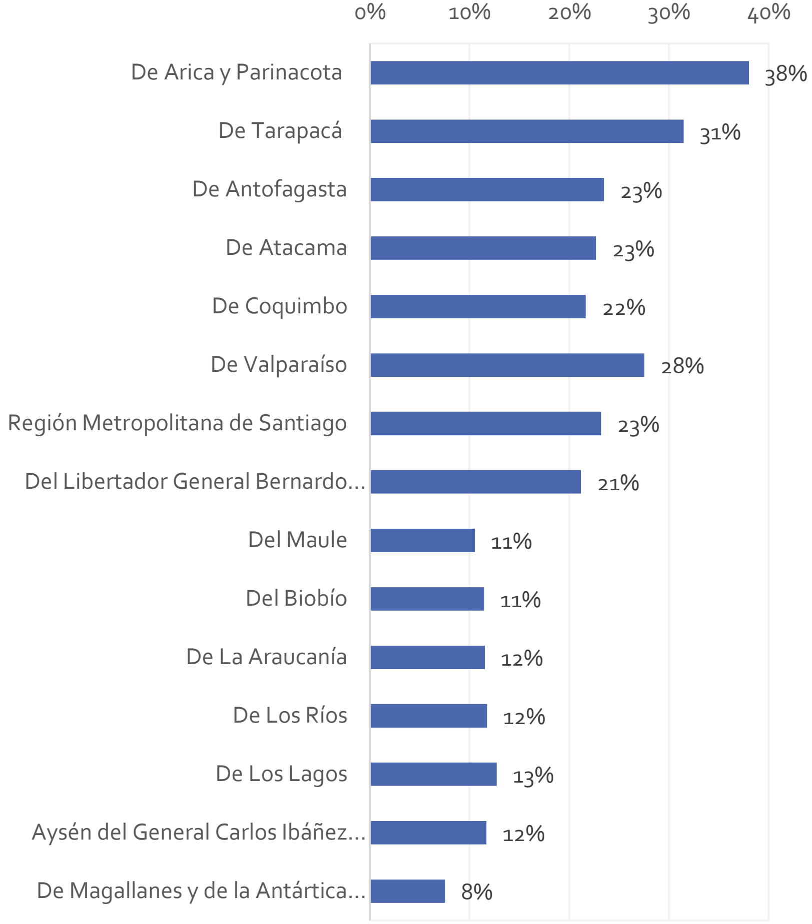
Added value in virtual water flows





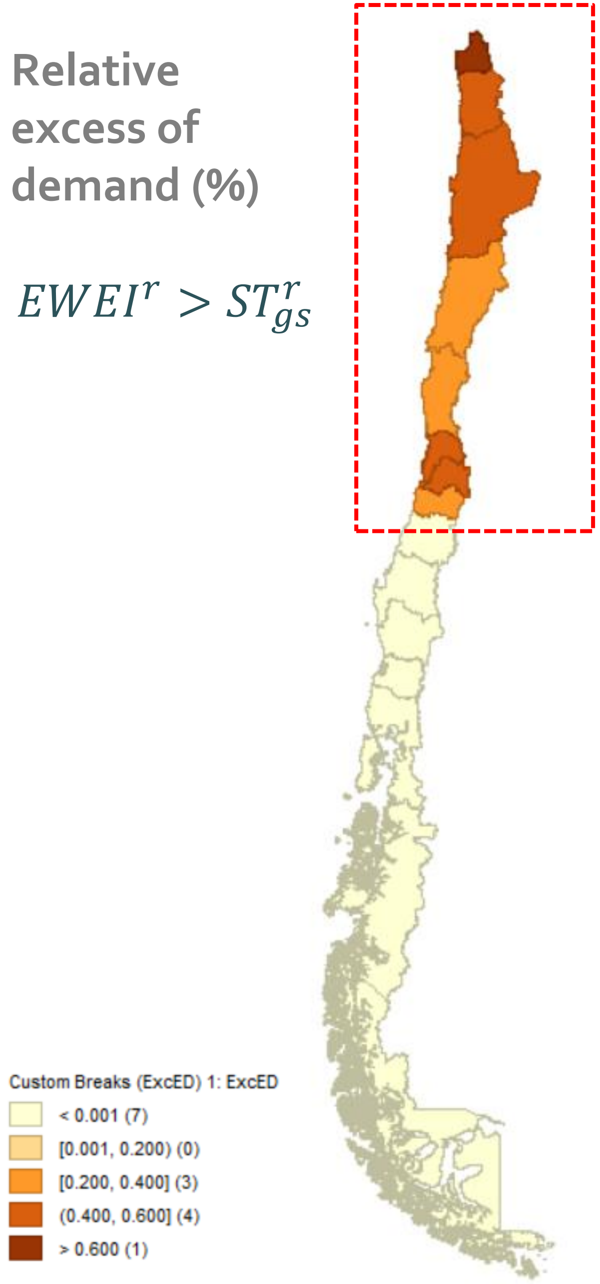
Scarcity in virtual water flows





Relative excess of demand (%)

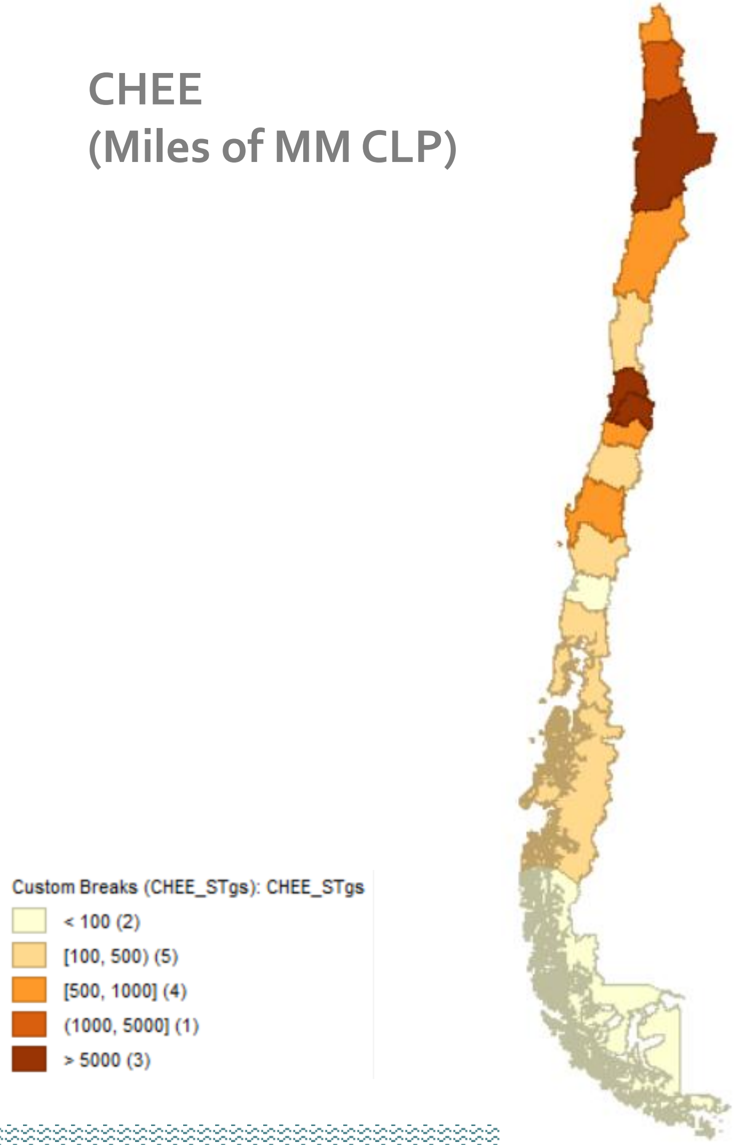
$$EWEI^r > ST^r_{gs}$$



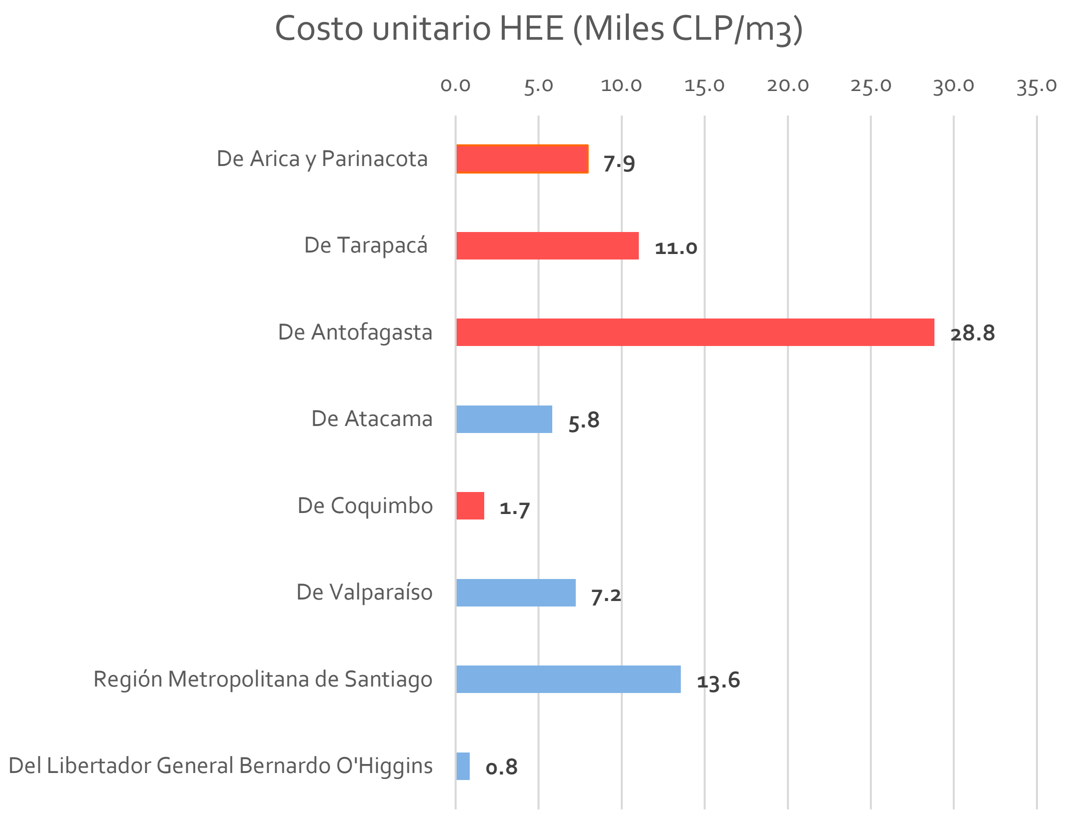
Economic cost of reducing water scarcity footprint to zero

CHEE
(Miles of MM CLP)

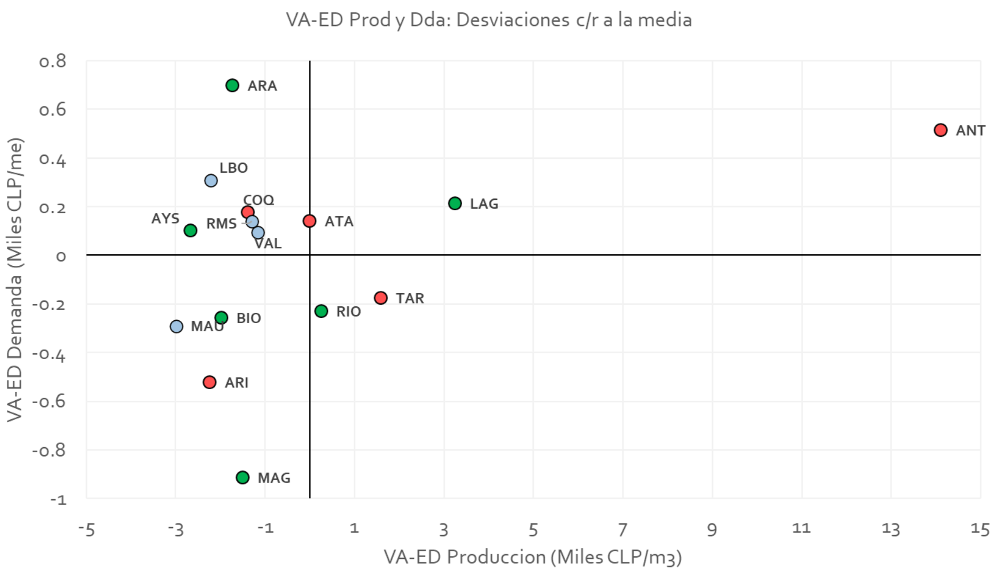
	Reducción Y	Reducción VA	Exceso ED
De Arica y Parinacota	88%	80%	66%
De Tarapacá	61%	59%	56%
De Antofagasta	52%	49%	49%
De Atacama	21%	24%	29%
De Coquimbo	4%	9%	23%
De Valparaíso	74%	66%	56%
Región Metropolitana de Santiago	42%	40%	41%
Del Libertador General Bernardo O'Higgins	0%	9%	23%
Del Maule	0%	8%	0%
Del Biobío	0%	6%	0%
De La Araucanía	0%	4%	0%
De Los Ríos	0%	5%	0%
De Los Lagos	0%	6%	0%
Aysén del General Carlos Ibáñez del Campo	0%	12%	0%
De Magallanes y de la Antártica Chilena	0%	3%	0%



Economic cost of reducing water scarcity footprint to zero



- As a reference, the value of desalinated water at sea level is between 0.7 and 1.5 USD/m³. With pumping in mining areas: 4–5 USD/m³.



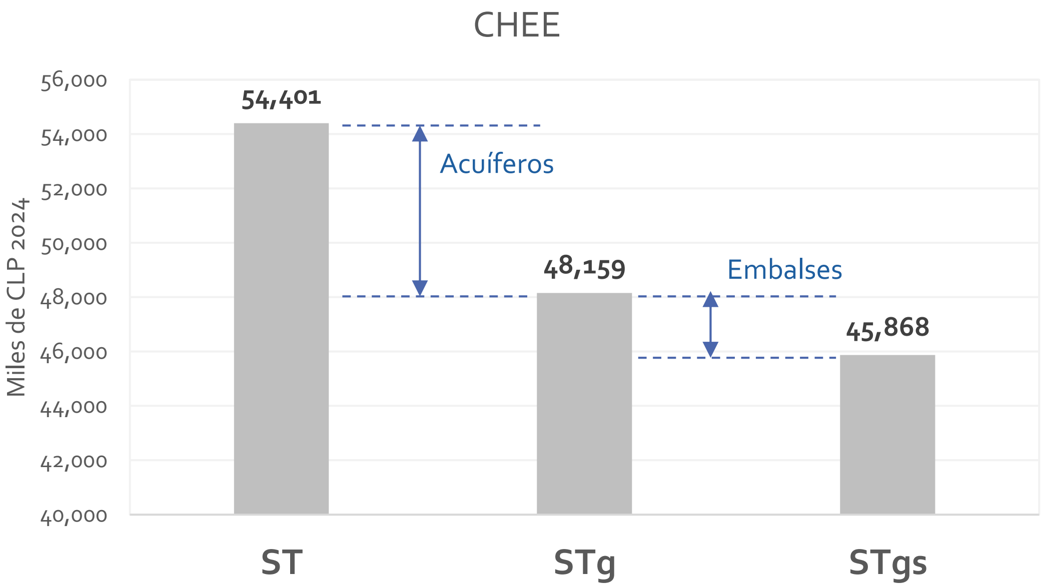
Added value by Reservoirs and Aquifers

The CHEE is estimated for:

- ST (no regulation)
- STg (no surface water regulation)

Avoided costs:

- Aquifers: USD 10,700 million (2014)
- Reservoirs: USD 3,900 million (2014)



Economic value of WES

- The calculations correspond to estimating the value of the water-related ecosystem services (provision, purification, and regulation) based on the opportunity cost method.
- It is assumed that under economic equilibrium, the value of water provision is zero.
- The same assumption applies to water purification, which is measured by the amount of freshwater required to dilute pollutants in discharges (gray water).
- The best alternative use of the resource corresponds to the added value generated by the marginal addition of one cubic meter of water to production (overexploitation), in the case of provision and purification services.
- For water regulation, the added value generated by aquifers (seasonal regulation of supply) is used.

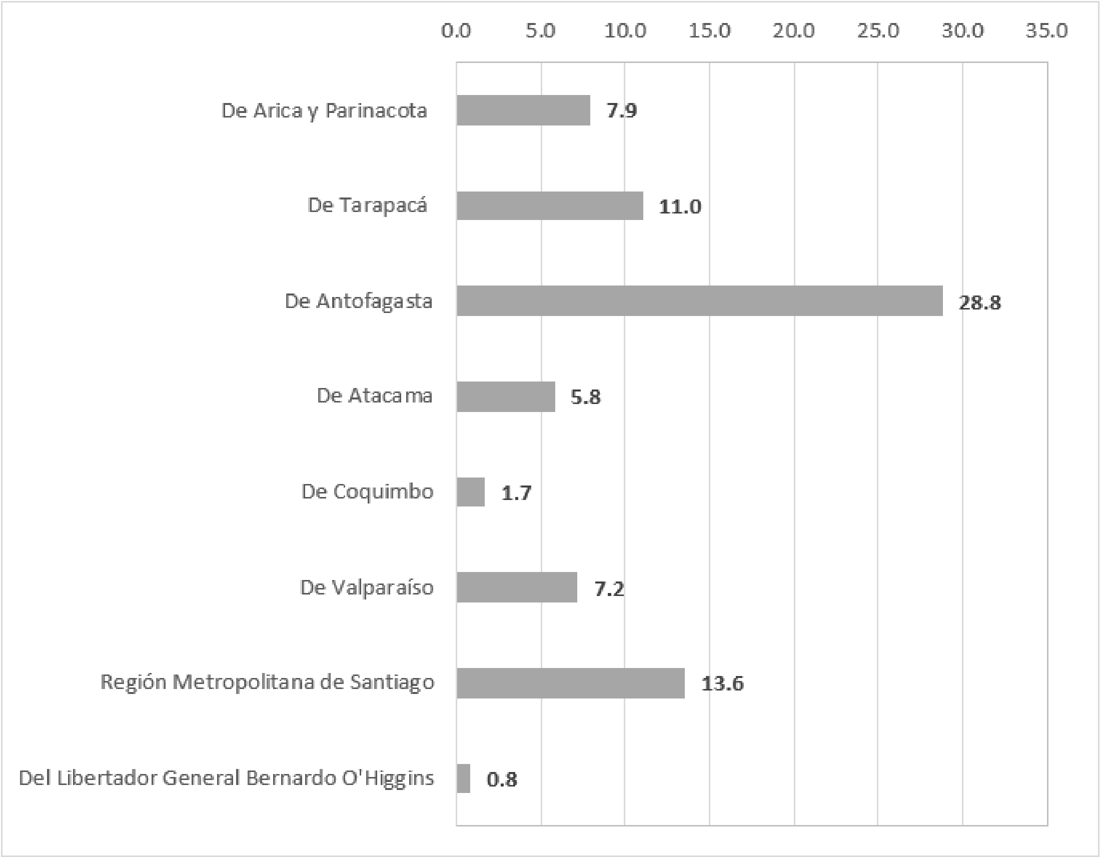
Economic value of WES

Provision:
- o 540 CLP/m^3 to 20.100 CLP/m^3
- o MM USD 57.700 total country.

Purification (surface and groundwater):
- o 260 CLP/m^3 to 7.900 CLP/m^3
- o MM USD 20.900 total country.

o **Regulation** (aquifers):
- o MM USD 10.700 total country.

Valor económico unitario de los SSEE de provisión y purificación del agua (Miles de CLP, 2014)



Some considerations

- The estimated values per cubic meter for provision and purification services are high, as the model only considers water volumes exceeding feasible supply.
- The regional scale cannot detect basins or sub-basins that may be out of hydroeconomic equilibrium. The value of provision and purification services would then be greater than zero.
- Purification services from forests, grasslands, wetlands, etc., are not considered.
- The opportunity cost approach assumes that without sufficient water, industries would cease production. However, cost-efficient alternatives such as water reuse or desalination may exist.

Future work

- Compare results with ecosystem service valuation studies conducted in Chile.
- Update the model for 2018 (currently in development with NEREUS, University of São Paulo) and incorporate the interregional input–output matrices under construction by the Central Bank.
- Include a factor associated with intra-regional imbalances, ensuring the overexploited volume reflects heterogeneity at the basin scale.
- Incorporate the regulation capacity of surface water by region, based on land use and geomorphology.
- Map pressures on natural capital (e.g., from the Metropolitan Region to others) and evaluate policies affecting final consumption.

V. Conclusions

Conclusions

- The Metropolitan Region represents a hub for attracting virtual water flows, which increases when water quality is considered.
- The regions of Antofagasta and Los Lagos show high added value embedded in virtual flows of production and consumption.
- When adjusted for scarcity, the central and northern regions increase their share in the national water footprint (virtual consumption flows). The local footprint effect (without HEE) predominates.
- The cost of eliminating virtual water scarcity amounts to 34% of total added value.

Conclusions

- The water-extended environmentally MRIO model enables a broad estimation of the value of water ecosystem services (WES) related to provision, purification (surface water and aquifers), and regulation (groundwater).
- The estimated national economic value for the WES of water provision is USD 57,700 million.
- The estimated national economic value for the WES of water purification (streams and aquifers) is USD 20,900 million.
- The estimated economic value for the WES of water regulation (aquifers) is USD 10,700 million.
- This study corresponds to the first estimation of the value of these services for all regions of Chile, although it remains partial.


MUCHAS GRACIAS