Scaling the Value of Water Regulation Services Beyond the Watershed: An Integrated InVEST–MRIO Framework

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Abstract

The economic valuation of seasonal surface water regulation (SSWR) is commonly conducted at the watershed scale using replacement or opportunity cost methods, capturing only local economic value (LEV). This approach overlooks how ecosystem service impacts propagate through intersectoral and interregional production networks, leading to systematic undervaluation by omitting regional (REV) and national economic value (NEV). This paper develops an integrated framework that scales SSWR valuation from the watershed to the national economy by combining biophysical modeling with an interregional economic approach. Specifically, estimates from the Seasonal Water Yield module of the InVEST model are linked to a multiregional input–output model for Chile, covering 16 regions and 12 sectors, allowing us to trace how water regulation affects production and trade across regions. Methodologically, the paper builds on the Hydro-Economic Equilibrium Cost (CHEE) approach—which captures the national opportunity cost of water-related ecosystem services in terms of avoided production losses—and extends it through a value-added formulation (CHEE-A). Unlike previous CHEE applications, which typically assume fixed production structures, CHEE-A incorporates substitution possibilities and sector-specific efficiency differences, enabling the model to represent how economic systems adjust to changes in water availability. This provides a more flexible and realistic valuation framework while remaining consistent with ecosystem accounting principles. Applied to the Choapa River basin in Chile—a semi-arid region where water regulation is critical for sustaining agricultural and mining activities—results show that NEV represents 0.017% of GDP under historical hydrological conditions and 0.022% under climate change. National economic value exceeds local economic value by a factor of 2.5–3, highlighting the importance of interregional production linkages and trade multipliers. Overall, the results demonstrate that water regulation services generate economic effects well beyond the watershed, functioning as macroeconomically relevant infrastructure embedded in interregional value chains.

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1.- Introduction

The economic valuation of seasonal surface water regulation (SSWR) ecosystem services is commonly conducted at the watershed scale, estimating stored water volumes and applying replacement or opportunity cost methods (Legesse et al., 2022; NCAVES and MAIA, 2022). These approaches typically quantify the economic worth of ecosystems by estimating the cost of artificial infrastructure required to replace natural regulation or by calculating foregone production under water scarcity scenarios. While such methods provide a Local Economic Value (LEV), they implicitly assume that the economic relevance of ecosystem services is geographically bounded by the watershed and sectorally limited to directly water-dependent activities.

However, modern economies are structurally interconnected through dense intersectoral and interregional production networks (Miller and Blair, 2022). Seasonal water regulation capacity in one region influences not only local agricultural output but also downstream manufacturing, agro-processing, mining, transportation, energy supply, and export-oriented activities through supply-chain linkages (Sturla and Rocchi, 202). Increased dry-season regulation capacity, for instance, enhances crop yields and mineral processing stability by smoothing intra-annual water variability, which in turn affects intermediate demand, trade flows, and value added across regions. Traditional watershed-based valuation therefore neglects the propagation of impacts through production systems, leading to systematic underestimation of ecosystem services' macroeconomic contribution (Sturla et al., 2025).

This limitation becomes particularly relevant in water-scarce and climate-exposed economies, where ecosystem regulation services function as implicit production constraints. When hydrological variability intensifies, the marginal productivity of regulated water increases, and its economic value is transmitted through backward and forward linkages within national economies.

This paper explicitly addresses this limitation by incorporating these production linkages into a valuation framework that integrates biophysical ecosystem service modeling with a hydrologically extended multiregional input–output model (HIMRIO). By embedding ecosystem service flows into an interregional production structure, we identify and quantify economy-wide propagation effects beyond the watershed of origin. The framework treats SSWR not merely as a local environmental benefit, but as a supply-side production factor whose availability shapes interregional value chains.

By combining ecosystem service modeling and macroeconomic analysis, the study offers an interdisciplinary contribution to the Input–Output literature, bridging hydrology, environmental economics, and regional economic modeling within a unified analytical framework. It also advances ongoing efforts to integrate natural capital into national accounting systems under the System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA-EA) (United Nations, 2021).

2.- Methodology

2.1.- The HIMRIO Framework

This study embeds ecosystem service flows into a HIMRIO constructed upon Chile's official multiregional input–output (MRIO) table, which comprises 16 regions and 12 economic sectors. The MRIO structure captures interregional trade flows, intermediate consumption patterns, and value-added generation across the national economy.

In a standard MRIO framework, production is modeled through fixed technical coefficients that describe the input requirements per unit of output. However, conventional IO models assume perfectly elastic primary inputs and do not explicitly represent biophysical constraints. To overcome this limitation, the HIMRIO framework introduces water availability as a binding supply-side constraint affecting sectoral production.

Water-dependent sectors—such as agriculture, mining, energy generation, and selected manufacturing activities—are linked to water input coefficients calibrated to reflect hydrological availability conditions. Seasonal surface water regulation enters the model as a variation in effective water supply during the dry season, altering feasible production levels.

2.2.- Hydro-Economic Equilibrium Cost

The methodological foundation builds on the Hydro-Economic Equilibrium Cost (CHEE) concept developed by Rocchi et al. (2026). CHEE measures the opportunity cost of water within an optimization framework subject to sustainable water-use constraints. In this setting, production levels are determined through a constrained optimization problem in which water availability acts as a limiting factor.

Formally, the economy maximizes value added subject to:

- Technical production relationships,
- Water-use coefficients,
- Hydrological sustainability constraints,
- Interregional trade balances.

The dual solution of this problem yields a shadow price of water consistent with hydro-economic equilibrium conditions. This shadow price reflects the marginal contribution of water to production under scarcity.

2.3.- Extension to CHEE-A

In this study, we extend the CHEE concept by expressing it directly in value-added terms and incorporating substitution elasticities and efficiency coefficients, generating what we term CHEE-A (Hydro-Economic Equilibrium Cost – Adjusted). The inclusion of substitution elasticities allows partial adjustment between water and other production inputs, avoiding unrealistic fixed-coefficient rigidity. Efficiency coefficients reflect technological adaptation and water-use productivity.

This adjustment ensures that the resulting opportunity cost:

- Reflects real production flexibility,
- Captures structural propagation through interregional linkages,

- Remains consistent with value-added accounting principles.

Importantly, CHEE-A is aligned with SEEA-EA exchange-value principles, ensuring conceptual compatibility with national accounts (United Nations, 2021).

2.4.- Biophysical Modeling

We conduct a biophysical modeling exercise using the InVEST software (Natural Capital Project, 2023), specifically the Seasonal Water Yield (SWY) module. The SWY model estimates seasonal runoff retention and dry-season water contribution based on land cover, soil properties, precipitation, evapotranspiration, and topography.

Two hydrological scenarios are simulated:

1. Historical baseline conditions.
2. Climate change projections incorporating altered precipitation seasonality and reduced mean annual runoff.

The resulting SSWR estimates represent the volume of water retained and gradually released during dry months due to ecosystem regulation. These biophysical outputs are translated into economically meaningful supply constraints within the HIMRIO framework, affecting sectoral water availability.

For benchmarking purposes, LEV is calculated using replacement cost and traditional opportunity cost methods confined to the watershed scale.

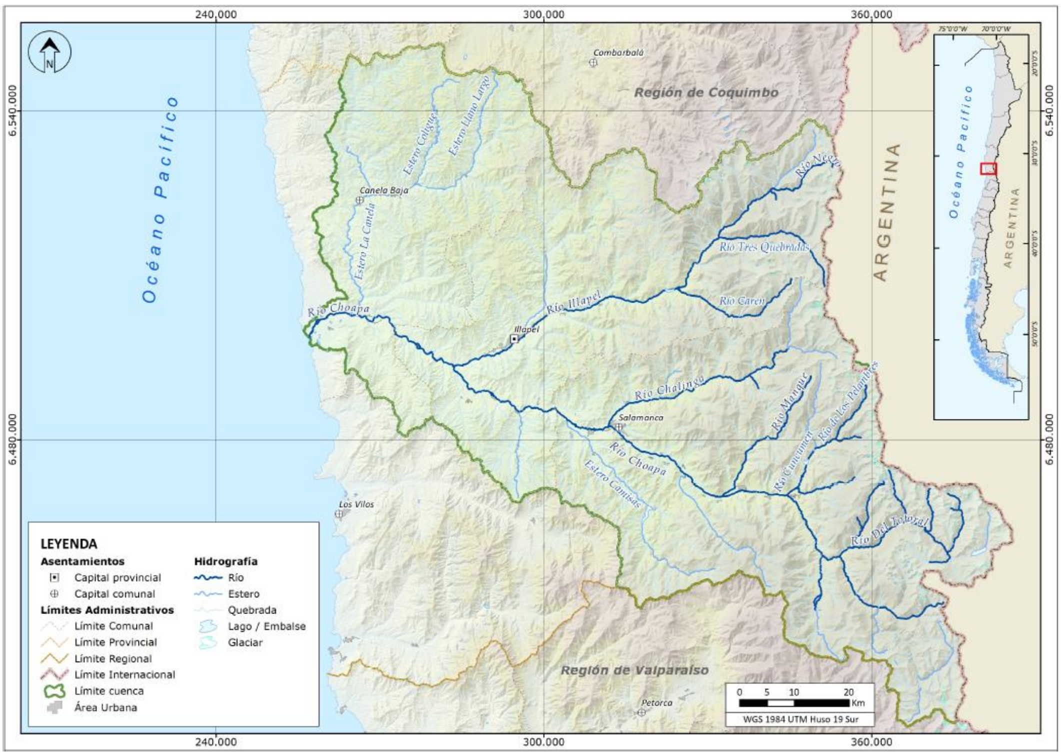
3.- Case Study

The empirical application focuses on the Choapa River basin in the Coquimbo Region (Chile), a structurally water-scarce territory exposed to recurrent droughts and projected declines in hydrological supply under climate change (DGA, 2020). Hydrological modeling indicates a reduction in surface flows for the 2020–2050 period compared to historical conditions, with lower discharges across monitoring stations for equivalent exceedance probabilities.

Hydrological modeling conducted within the Strategic Water Management Plan for the Choapa Basin indicates a projected decline in surface water availability for the 2020–2050 period compared to historical conditions (1989–2019), with lower discharges observed across monitoring stations for equivalent exceedance probabilities (DGA, 2020). Duration curves show that, for the same probability of exceedance, future flows are systematically below historical levels, reflecting reduced surface runoff under climate change scenarios. Surface water demand in the basin is dominated by irrigated agriculture, which accounts for approximately 89.5% of total registered consumption, while mining represents about 9.3%, and urban and rural drinking water together account for close to 1% (DGA, 2020). This high dependence on surface flows, combined with projected reductions in mean annual discharge and altered seasonal patterns, underscores the strategic importance of SSWR for stabilizing dry-season water supply and sustaining economic activity in the basin.

Given the strong dependence of irrigated agriculture and large-scale mining on reliable dry-season water availability, SSWR plays a critical buffering role. Because these sectors are deeply embedded in national production and export value chains, changes in SSWR capacity have implications that extend beyond the watershed, affecting interregional trade, value added, and macroeconomic performance.

Figure 1. Choapa River Basin



Source: DGA (2020)

4.- Results

Results indicate that NEV represents 0.017% of national GDP under historical hydrology and increases to 0.022% under climate change conditions.

Although climate change reduces regulatory effectiveness by altering precipitation timing and decreasing total runoff, increasing nationwide water scarcity raises the shadow value of regulated water. These two mechanisms operate simultaneously:

1. Biophysical decline effect: Reduced ecosystem regulation lowers dry-season water smoothing capacity.
2. Scarcity amplification effect: Higher scarcity increases marginal productivity and shadow pricing of regulated water.

The second effect dominates, leading to higher macroeconomic valuation despite reduced ecological performance.

The interaction between these two mechanisms is crucial for policy and accounting purposes. The biophysical decline effect highlights the vulnerability of ecosystem functions under climate change and underscores the need for conservation and restoration strategies to maintain regulatory capacity. At the same time, the scarcity amplification effect reveals that the economic importance of ecosystem regulation increases precisely when hydrological stress intensifies. Together, these mechanisms demonstrate that ecosystem services should not be valued solely based on physical volumes delivered, but rather within an integrated hydro-economic framework that captures how scarcity conditions reshape marginal productivity and economy-wide value added.

In both scenarios, NEV exceeds LEV by a factor of 2.5–3. This gap arises because LEV captures only direct local production effects, whereas NEV incorporates:

- Backward linkages (input supply chains),
- Forward linkages (downstream processing),
- Interregional trade multipliers,
- Value-added propagation.

The results demonstrate that ignoring production networks leads to systematic undervaluation of ecosystem services. Water regulation functions as macroeconomically relevant infrastructure whose contribution is embedded in interlinked economic systems. Unlike conventional infrastructure, however, its role is often implicit and unpriced, despite shaping production possibilities across multiple sectors and regions. By stabilizing dry-season water availability, SSWR supports not only primary extraction activities but also the continuity of value chains, export competitiveness, and fiscal revenues. Recognizing this embedded contribution is therefore essential for accurate natural capital accounting and for designing climate adaptation strategies that reflect the full economy-wide significance of ecosystem regulation services.

5.- Discussion

The results highlight several important structural implications. First, ecosystem regulation services generate economic value that extends beyond their geographic origin. When embedded within interregional production networks, SSWR operates as a supply-side constraint affecting value added, trade flows, and sectoral output across regions, rather than as a purely local environmental benefit.

Second, the analysis reveals that increasing water scarcity can raise the marginal economic value of regulated water even when biophysical performance declines. As hydrological variability intensifies, the shadow price of water increases within the hydro-economic equilibrium framework, amplifying the macroeconomic relevance of ecosystem regulation.

Third, the findings underscore the amplifying role of production linkages. Intersectoral and interregional connections transmit hydrological constraints beyond directly water-intensive sectors, leading to systematic undervaluation when economy-wide effects are excluded.

Methodologically, the integration of InVEST with HIMRIO demonstrates a feasible pathway for linking biophysical ecosystem modeling with macroeconomic accounting in a manner consistent with SEEA-EA principles. Although developed for SSWR, the framework can be extended to other regulating services where biophysical outputs can be translated into binding economic constraints.

6.- Conclusion

By integrating biophysical ecosystem service modeling through InVEST with a hydrologically integrated MRIO framework, this study demonstrates that seasonal surface water regulation generates economy-wide value added that substantially exceeds watershed-level estimates. Linking InVEST-derived outputs with interregional production networks allows ecosystem services to be treated as supply-side constraints embedded in value chains.

The CHEE-A approach expresses the opportunity cost of water in value-added terms consistent with macroeconomic accounting and aligned with the SEEA-EA framework. Results show that ignoring production linkages leads to systematic undervaluation, particularly under increasing water scarcity.

Overall, the integration of InVEST and HIMRIO provides an operational pathway to scale ecosystem service valuation from the watershed to the national economy. This constitutes a fundamental contribution to the advancement of natural capital accounting in Chile and demonstrates how ecosystem regulation services can be incorporated into macroeconomic decision-making, climate adaptation strategies, and sustainability-oriented public policy.

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