An Integrated Hydro-Economic Assessment of Water Footprint, Scarcity, and Social Vulnerability: Evidence from Tuscany, Italy

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Abstract

Freshwater scarcity and unequal exposure to water-related risks are increasingly recognised as constraints on sustainable development, yet most water footprint assessments lack the spatial and social resolution needed to inform subregional policy. This study develops an integrated hydro-economic framework that links multiregional input–output (MRIO) modelling with basin-level hydrological scarcity indicators and a demographic social vulnerability index. Applied to 48 Local Labour Systems (LLSs) in Tuscany (Italy), the approach quantifies production- and consumption-based water footprints, scarcity-weighted impacts, and socially weighted risk displacement across intra-regional supply chains. Results allow the identification of production-oriented hotspots that generate a substantial share of the regional water footprint while exhibiting significantly higher scarcity-weighted and socially weighted risks than neighbouring areas, even when volumetric water use is comparable. In contrast, consumption-oriented LLSs function as large net importers of virtual water, externalising a considerable share of their embodied demand to more hydrologically stressed and socially vulnerable locations. Overall, the findings demonstrate that volumetric indicators alone obscure pronounced inequalities in the spatial distribution of water-related risk, and they highlight the need for socio-hydrological governance strategies that jointly address efficiency, equity, and the redistribution of risk through economic linkages.

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1. Introduction

Freshwater availability is increasingly recognised as a binding constraint on socioeconomic development (Baggio et al. 2021). Global assessments estimate that nearly half of the world's population experiences at least one month of severe water scarcity per year, while roughly one quarter is exposed to extremely high baseline water stress (≥80 % withdrawal to availability ratio) according to UN WWDR, 2024. These pressures are amplified by climate induced hydrological variability, land use change, and rising demand from agriculture, industry, and urban consumption. However, scarcity is not experienced uniformly: biophysical water stress interacts with economic structures and social vulnerability, creating geographically uneven patterns of risk (Hohenthal & Minoia, 2017). In this sense, water scarcity is increasingly understood not merely as a physical imbalance between supply and demand, but as a coupled human–water phenomenon shaped by economic organisation, institutional settings, and social conditions; an understanding that lies at the core of socio-hydrological research.

A growing body of research employs the water footprint (WF, Hoekstra and Chapagain, 2007) and the concept of virtual water trade to examine how consumption in one location externalises water demand to distant regions, often those experiencing greater water stress. Water footprinting studies have demonstrated the importance of tracing both direct and indirect freshwater use along supply chains (Aldaya et al. 2012, Hoekstra, 2016). Building on this foundation, subsequent studies have applied WF accounting at global, national, and sectoral scales, revealing the central role of agricultural commodities and international trade in driving hidden water flows (D'Odorico et al., 2020; Vallino et al., 2021; Ji et al., 2022). This literature has been instrumental in reframing water scarcity as a telecoupled process, whereby economic linkages redistribute pressures across space, often disconnecting the location of water use from that of economic benefits (Cotta et al. 2022). However, much of this evidence remains anchored at highly aggregated spatial scales, limiting its ability to inform place-specific governance and equity-oriented interventions.

Going in this direction recent advances in water-footprint research have relied on input–output (IO) analysis as a powerful complement to traditional process-based WF accounting (Wang, et al. 2013; Islam et al. 2021; Sturla et al. 2024). In this approach, monetary IO tables are augmented with satellite accounts of water use by economic sector allowing to trace not just the direct water used in production, but also the indirect freshwater embedded throughout global supply chain (Stadler et al. 2021; Ingewersen et al. 2022). This enables a detailed disaggregation by origin region and economic sector, thereby highlighting "hotspots" of external water dependence that would remain invisible under a simple production-based accounting. Moreover, the IO hydro-economic approach permits the extension of WF beyond volumetric measures, by integrating impact-based indicators such as water scarcity (Zhang et al., 2023). From a socio-hydrological standpoint, IO-based hydro-economic models offer a consistent framework to link economic demand, spatially differentiated water availability, and indirect pressures transmitted through trade networks, thus bridging hydrological processes and socioeconomic dynamics.

To translate volumetric footprints into indicators of risk, several scarcity-weighting approaches have been proposed (Wang et al. 2021). However, physical scarcity alone cannot capture the differentiated capacity of communities to cope with water stress. Recent contributions therefore incorporate social components into water footprint metrics, drawing from environmental justice and social life cycle assessment frameworks (Liu et al. 2022; Rocchi et al., 2026; An et al. 2025). These approaches recognise that identical levels of biophysical scarcity may result in unequal burdens depending on income, health, institutional quality, and adaptive capacity. Such perspectives resonate with socio-hydrological research emphasising that vulnerability and risk emerge from the interaction between hydrological stressors and socially mediated adaptive capacities, rather than from exposure alone. Yet, existing applications often treat social vulnerability as an external modifier rather than embedding it within a coherent representation of economic–hydrological interactions.

Despite this progress, some limitations persist: almost all applications operate at coarse spatial scales that mask intra-regional heterogeneity, and few studies assess how consumption within a region can displace scarcity-weighted and socially weighted impacts to other sub-regions. As a result, water-abundant regions may still host persistent localised hotspots of overexploitation and social vulnerability that remain undetected by aggregate indicators.
This gap is particularly relevant for socio-hydrology, which seeks to understand how human–water interactions unfold across scales and how internal economic linkages shape the distribution of risk within coupled systems.

In particular this paper addresses these gaps by contributing three main advances: (i) it develops a hydro-economic water accounting framework at a subregional functional scale, (ii) it integrates hydrological scarcity and social vulnerability directly into the assessment of virtual water flows, and (iii) it explicitly analyses producer–consumer asymmetries within a single, internally connected regional economy. We develop an integrated framework that combines multi regional input–output (MRIO) modelling, hydrological scarcity metrics, and demographic vulnerability indices to produce a spatially explicit assessment of water use and risk. We apply the framework to Tuscany (Italy), a region characterized by heterogeneous climatic conditions, strong manufacturing clusters, and dense intra-regional supply chains.

By explicitly tracing how economic demand redistributes hydrological stress and social vulnerability within the region, this study operationalises sociohydrology as an analytical framework for examining distributive water governance at the subregional scale.
The results enable a more equitable framing of water related policy, highlighting where efficiency, demand management, and social support measures may be most effective.

2. Materials and Methods

The assessment integrates three components: (i) a multi-regional input–output (MRIO) model which we extended into a hydro-economic model by adding coefficients for water withdrawals and discharges to evaluate the water footprint across interlinked production and consumption activities, (ii) an hydrological model to account for local water availability and evaluate the scarcity to quantify the water scarcity footprint, and (iii) a social vulnerability and institution quality assessment to weight impacts by social exposure and determine the social water scarcity footprint (Figure 1 summarizes the workflow).

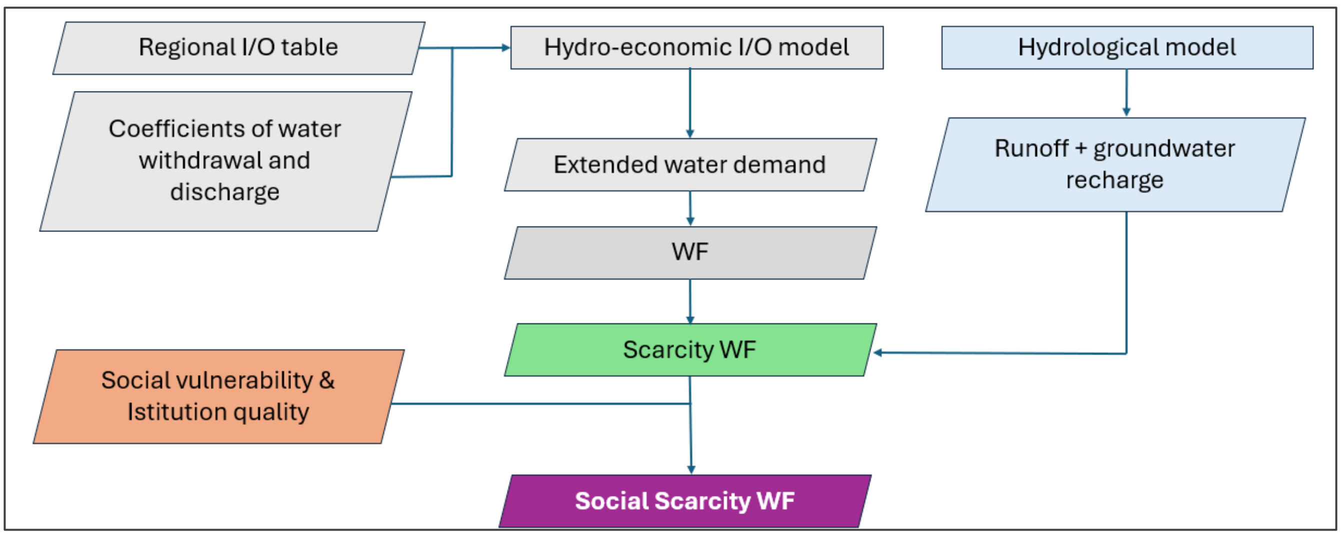

Figure 1. Methodology Overview

2.1 Hydro economic modelling and water footprint

The hydro-economic model is based on an environmentally extended multiregional input–output (EE-MRIO) framework, which has been widely applied in the literature to estimate water footprints at regional, national, and global scales (Feng et al., 2011; Wood, 2017; Arto et al., 2016; Sturla et al., 2024; Sturla et al., 2023). From a socio-hydrological perspective, the EE-MRIO framework provides a system-level representation of how economic activities generate water demands that interact with spatially heterogeneous water availability, allowing the identification of indirect and displaced pressures that cannot be observed through local water balances alone.

The model employed in this study builds upon the framework developed by Rocchi et al. (2026), which is based on the 2017 MRIO table for the Tuscany region. This matrix represents 48 Local Labour Systems (LLSs) and 53 economic sectors, and incorporates industry-specific coefficients of water use, return flows, and water requirements for dilution for each sector in each LLS. The objective of this study is not to compute the water footprint (WF) per se, but rather to derive indicators of water stress for each local economy, together with related measures of sustainable water use and pressure.

The present study therefore advances the analysis of WF by adopting both production- and consumption-based perspectives. The production-based water footprint corresponds to the extended demand for water (blue water plus grey water) generated within each LLS. In contrast, the consumption-based WF accounts for all water resources used across all LLSs to satisfy the final consumption of a specific LLS. These two perspectives can also be interpreted in terms of exported virtual water flows (namely, the production-based water footprint of an LLS embodied in goods and services supplied to other LLSs) and imported virtual water flows, defined as the water footprint embodied in goods and services produced by multiple LLSs and consumed by a given LLS.

To quantify these virtual water export and import flows, the EE-MRIO framework is particularly well suited, as the MRIO matrix explicitly captures all inter-sectoral and inter-regional flows of goods and services among the Tuscan LLSs.

Formally, consider a system composed of *n* local economies (LLS) and *m* industries. The Leontief inverse matrix is defined as:

$$\boldsymbol{L} = (\boldsymbol{I} - \boldsymbol{A})^{-\mathbf{1}} \tag{1}$$

where A is the *(nm x nm)* matrix of direct requirement coefficients for the *n* countries in the *m* industries, and I is the *(nm x nm)* identity matrix.

Starting from the Leontief inverse matrix *L* and considering a vector of water-use coefficients by LLS and industry, it is possible to construct a matrix *M* of dimension *(nm x (nm+1))*, where each row corresponds to the virtual water flows exported (WF production) to the *m* sectors of each LLS and to destinations outside Tuscany. In addition, each column represents the virtual water flows imported by a given LLS from each industry in each LLS:

$$\mathbf{H} = \hat{\mathbf{c}} \cdot \mathbf{L} \cdot \mathbf{Y} \tag{2}$$

$$\mathbf{c} = \mathbf{f} - \mathbf{r} + \mathbf{w} \tag{3}$$

where *Y* is the *(nm × (nk+1))* final demand matrix, with *k* denoting the number of final demand components for each LLS. The *(nm × 1)* vector *c* contains the coefficients of withdrawal (*f*), return flows (*r*), and grey water (*w*) volumes by sector and local economy. The hat symbol denotes the diagonal matrix.

Let us define the *(n x (n+1))* matrix *M* as the aggregation by LLS of the matrix *H*, that is, each element $m_{s,r}$ of the matrix M represents the water used in LLS *s* related to the consumption of all goods in LLS *r*. This matrix has *n + 1* columns, as exports outside Tuscany are explicitly included.

In this way, based on matrix *M*, it is possible to define the WF associated with the production of each LLS (WFP_s), corresponding to the virtual water flows exported. Likewise, the WF associated with consumption (WFC_s) is defined as the virtual water flows imported (in this case, only from other LLSs and not from outside the region).

$$WFP_s = \sum_{j}^{n+1} m_{s,j} \tag{4}$$

$$WFC_s = \sum_{i}^{n} m_{i,s} \tag{5}$$

2.2 Hydrological modelling

The estimation of water availability was based on the BIGBANG model (Bilancio Idrologico GIS-Based a scala Nazionale), developed by the Italian Institute for Environmental Protection and Research (ISPRA) due to its consistency, spatial coverage, and suitability for large-scale water-resource assessment. BIGBANG is a spatially distributed, GIS-based water-balance model designed to quantify the main components of the hydrological cycle at national and macro-regional scales. The model operates on a regular grid with a spatial resolution of 1 km × 1 km and a monthly temporal resolution, ensuring spatial consistency and long-term comparability across the entire Italian territory.

The model is based on the mass-conservation equation:

$$P - E = R + G + \Delta V \tag{6}$$

where *P* is total precipitation, *E* is actual evapotranspiration, *R* is surface runoff, *G* is groundwater recharge, and *ΔV* represents the variation in soil-water and snowpack storage.

Monthly precipitation and temperature data are spatially interpolated from the national meteorological station network. Actual evapotranspiration (E) is estimated using the Thornthwaite method, which derives potential evapotranspiration from mean monthly air temperature and latitude and adjusts it based on soil-water availability conditions. Although this approach requires limited climatic input, it provides stable long-term estimates suitable for large-scale hydrological applications.

Soil-water storage and snowpack dynamics (ΔV) are computed using a soil-texture-based capacity approach. Each grid cell is assigned a maximum available water capacity derived from national soil databases. When precipitation exceeds evapotranspiration, water is temporarily stored in the soil or snowpack until the capacity threshold is reached; excess water contributes to runoff and recharge. During dry conditions, evapotranspiration is limited by the available soil moisture.

Groundwater recharge (G) is estimated as a fraction of the effective precipitation (*P* − *E*) using a potential infiltration coefficient linked to the permeability of the underlying hydrogeological complexes. This coefficient is derived from the national hydrogeological and permeability maps of Italy and allows spatial differentiation of infiltration rates based on lithological and structural properties. Recent BIGBANG implementations adopt an updated, high-resolution permeability classification to improve the representation of recharge processes.

Surface runoff (R) is computed as the residual term required to close the water-balance equation once evapotranspiration, groundwater recharge, and storage variations are accounted for. Model outputs are produced as gridded monthly and annual maps and can be aggregated at different spatial scales, including river-basin districts, administrative regions, and national level.

For this study the R and G data for the period between 2011 and 2022 have been aggregated at the LLSs level and used to evaluate the natural water availability in the different LLs. This amount has been then reduced considering the average values of the ecological flow reported by Northern Apennine District Authority (2021) in the area, i.e 5% of the mean annual flow. For each LLS the contribution of the reservoirs present in each LLS has been considered by adding to each LLS an extra water availability corresponding to the total storage volume present in the area (as reported by Giambastiani et al. 2020 and Northern Apennine District Authority, 2021). The feasible supply (Rocchi et al., 2024; Sturla & Rocchi, 2024) for each LLS results as follow:

$$FS_s = (R_s + G_s) \cdot 0.95 + VS_s \tag{7}$$

where,

R_s: total yearly surface runoff in the LLS s.

G_s: total yearly groundwater recharge in the LLS s.

VS_s : is the volume of water stored in the reservoir present in each LLS s.

2.3 Water Scarcity Footprint and Social water scarcity Footprint assessment

To capture the multidimensional nature of water scarcity, this study introduces two complementary indicators estimated at the level of each Local LLS.

First, the Extended Water Exploitation Index (EWEI), defined as the ratio between water demand (WFP) and feasible water FS.

$$EWEI_s = \frac{WFP_s}{FS_s} \quad (8)$$

Second, the Scarce Water Footprint (SWF), developed by Sturla et al. (2023), which integrates both pressure and stress dimensions of water scarcity, calculated as the product of the EWEI and the Water Stress Index (WSI) (Pfister et al., 2009).

$$SWF = WFP_s \cdot WSI_s \quad (9)$$

where,

$$WSI_s = \frac{1}{1 + e^{-6{,}4 \cdot EWEI_s} \cdot (\frac{1}{0{,}01} - 1)} \quad (10)$$

The SWF has the limitation of not taking into account any aspect related to the condition of the socioeconomic condition of the areas that supply or demand water. To take this aspect into consideration a social weighting of the WF is introduced. In particular to measure the Social Vulnerability (SV) in each LLS a new metric is proposed by combining the Social and Material Vulnerability Index (Indice di Vulnerabilità Sociale e Materiale, in Italian), as defined by ISTAT (2020) at the municipal level and the IQI is the Istitutional quality index as defined by Lasagni eta l. (2015) which is available at the LLS level. To obtain a coherent LLS-level measure, the IQI was downscaled by adjusting each LLS's value around the provincial average in proportion to the deviation of its social vulnerability score from the corresponding provincial mean. Th SV for the LLS *s* is defined as:

$$SV_s = IQI \cdot \frac{IVSM_{LLS}}{IVSM_{Prov}} \quad (11)$$

Then the Social Scarcity Water Footprint (SoSWF) associated to the LLS s, is calculated as follow:

$$SoSWF_s = SWF \cdot SV_s \quad (12)$$

Results are presented first in terms of the net virtual water flows between LLS are also computed as the difference between water embodied in exports and imports of intermediate and final goods.

Scarcity is therefore assessed from two complementary perspectives, as formally defined in Section 2.1: (i) a production-based accounting that allocates footprints to the LLS where production takes place (WFP), and (ii) a consumption-based accounting that reallocates footprints to the final demand of each LLS (WFC).

2.4 Case study description

Tuscany, located in central Italy, cover an area of roughly 23,000 km^2 with a a territory characterised by high diversity of landscape typologies. Despite pressures from urban sprawl and changes in land use, including agricultural simplification and reforestation, Tuscany still maintains a varied mosaic of landscapes, from woodlands and mixed agricultural-forest patterns to peri-urban zones, with mixed landscapes showing particularly high structural complexity (Venturi et al., 2021). At the end of 2022, the resident population of Tuscany was 3,661,981 people with nearly half of the region's inhabitants concentrated in the provinces of Firenze, Pisa and Lucca. The demographic trend is shaped by a negative natural balance partially offset by positive internal and international migration. The region's median age is high (47.8 years) and reflects population aging, with comparatively older populations in provinces such as Massa-Carrara and Grosseto, and relatively younger profiles in Prato and Pisa (ISTAT, 2024).

Tuscany's climate is strongly influenced by its Mediterranean setting and complex topography, shifting from humid regimes in the northern mountain areas to semiarid conditions along the southern coastal zones. Annual total precipitation exceed 2000 mm near the Apuan Alps and the Apennines, while parts of the Maremma and southern inland areas receive less than 600 mm. Rainfall is seasonally concentrated, with autumn and spring as the wettest periods and a marked summer dry phase, especially along the coast and in lowland areas. From a water management perspective the region shows a high spatial variability in water availability and highly uneven patterns of water withdrawals and discharges across the region (Fatichi and Caporali, 2009; Venturi et al., 2014; Nigro et al., 2024).

At the subregional level, Tuscany exhibits a highly heterogeneous economic structure whose spatial organization is closely intertwined with water resource availability and use. LLS specialize in markedly different production activities (ranging from water-intensive agriculture and agri-food processing in rural and peri-urban areas, to manufacturing clusters, tourism-related services, and urban activities concentrated around major cities) generating uneven patterns of water demand across the region. Previous studies have shown that, while aggregate indicators suggest no overall water scarcity, this apparent balance conceals significant subregional pressures

(Rocchi et al., 2024; Sturla and Rocchi, 2024; Rocchi et al., 2026). In particular, areas characterized by dense productive activity and limited surface water availability often rely heavily on groundwater abstraction, leading to localized overexploitation. These pressures are further amplified by the spatial misalignment between economic systems and hydrological units, a legacy of historical water concessions and infrastructure development that does not necessarily follow basin boundaries (Venturi et al., 2014). As a result, subregional water stress in Tuscany emerges not from absolute scarcity, but from the interaction between economic specialization, spatial concentration of demand, and the high natural variability of water supply (Bartolini et al., 2018). This makes Tuscany a paradigmatic case of a water-abundant region where localized economic–hydrological mismatches generate persistent and policy-relevant water scarcity challenges.

The region is divided into 48 LLSs (Figure 2), defined as functional economic zones based on daily commuting patterns. This territorial provide a policy-relevant resolution at which both production and consumption dynamics can be observed.

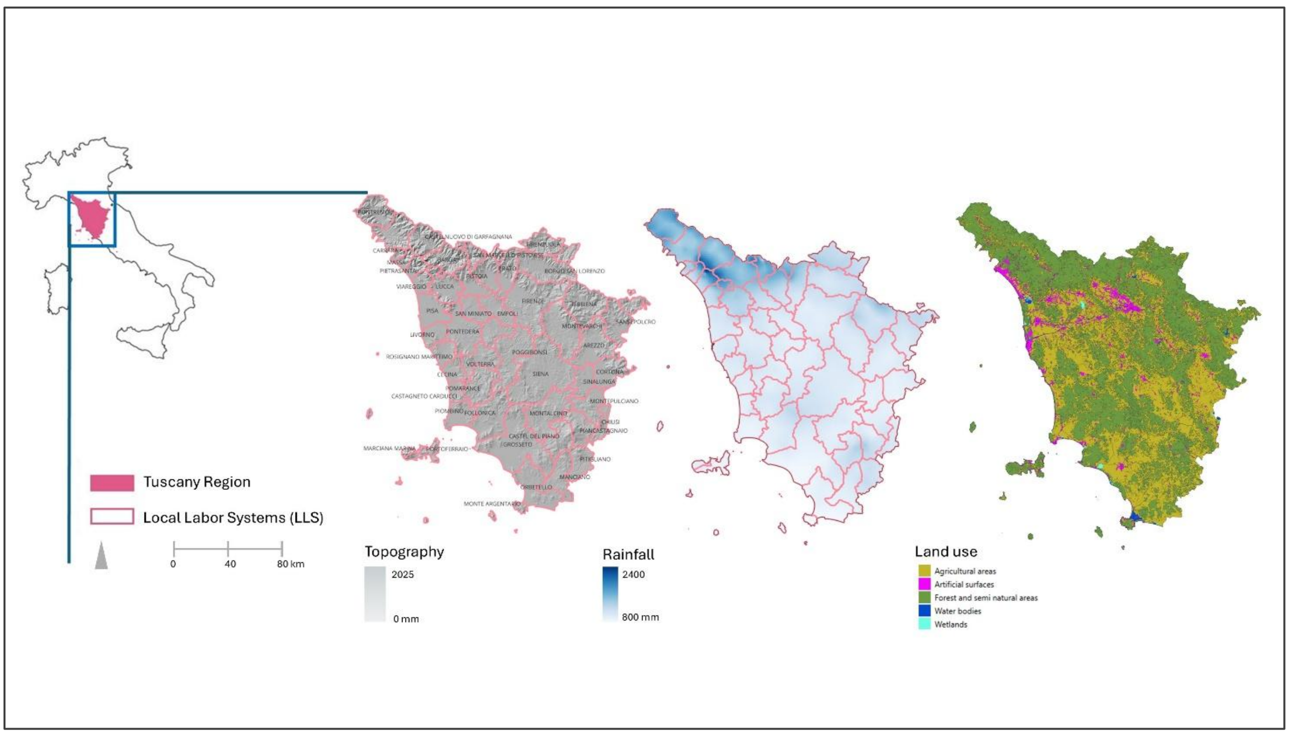

Figure 2. Study area with Tuscany region divided in its 48 Local Labor Systems including topography, mean precipitation and land use

3. Results

Figure 3 illustrates the spatial distribution of net internal virtual water flows across the 48 LLSs in Tuscany. The total internal regional water footprint attributable to production and consumption amounts to approximately 450 million $m^3\ yr^{-1}$, and is strongly concentrated in the most productive and industrialised areas of the region. The map reveals a clear spatial polarisation between net importing and net exporting LLSs, reflecting the uneven geography of economic activity and water use.

Firenze emerges as the main net virtual water importer, with inflows of approximately 31 million $m^3\ yr^{-1}$, primarily sourced from neighbouring and economically connected production hubs such as Prato, Pontedera, and Livorno. This pattern highlights the role of Firenze as a consumption-oriented centre that externalises a substantial share of its water demand to surrounding industrial LLSs. In contrast, Rosignano Marittimo stands out as the dominant net exporter, contributing roughly 10 million $m^3\ yr^{-1}$ of embodied water to the regional system, reflecting its highly water-intensive industrial base.

More generally, the network of internal virtual water exchanges is markedly asymmetric. A small group of LLSs (five in total) accounts for more than 60 % of all internally exported virtual water, indicating a strong concentration of water-intensive production activities. Conversely, consumption-oriented LLSs rely on imports for approximately 30 % of their embodied water demand, underscoring the extent to which water-related pressures are redistributed through intra-regional economic linkages. This asymmetric structure reveals how internal trade within a single region can generate significant displacement of water use and associated risks, even in the absence of interregional or international exchanges.

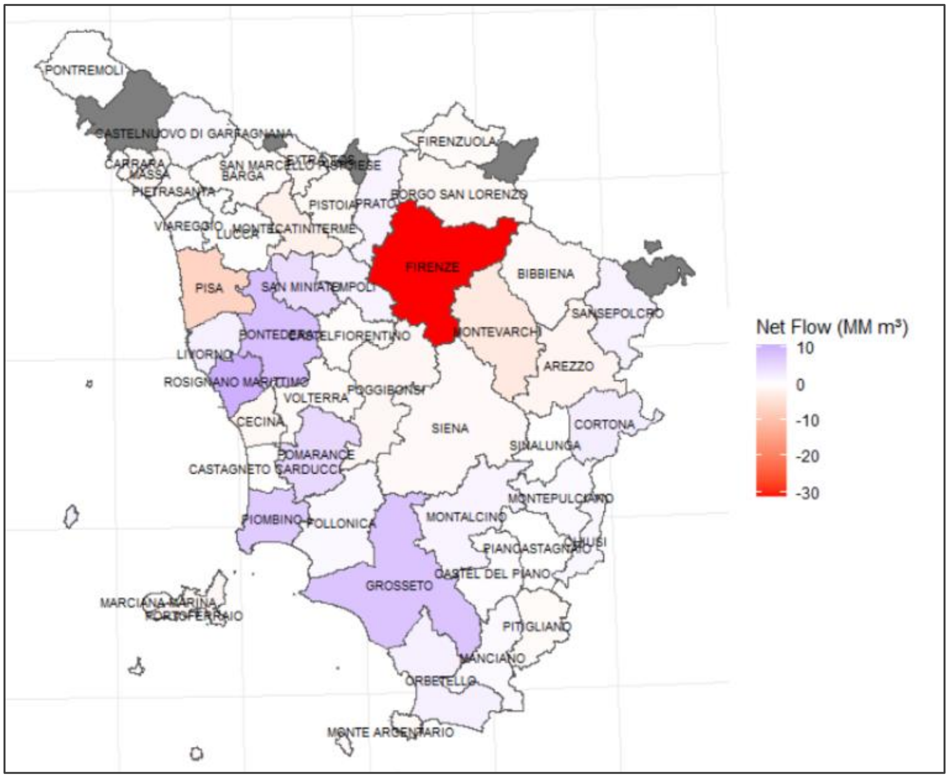

Figure 3. Net flow of virtual water in Tuscany LLSs

Figure 4 compares volumetric water demand, scarcity-weighted water footprints (SWF), and socially weighted water scarcity footprints (SoSWF) across the 48 LLSs, highlighting how successive layers of weighting reshape the spatial distribution of impacts. Applying the Water Stress Index (WSI) substantially amplifies differences between LLSs by accounting for local hydrological constraints. In particular, while Prato's absolute volumetric water demand associated with production is approximately half that of Firenze, its SWF is about 1.8 times higher, reflecting its location within a basin characterised by significantly higher withdrawal-to-availability ratios.

When social vulnerability is further incorporated, these contrasts become even more pronounced. Prato's SoSWF is approximately 2.4 times higher than that of Firenze, indicating that identical or even lower levels of water use can translate into substantially higher socio-environmental risk when scarcity and vulnerability are jointly considered. This divergence illustrates how volumetric indicators alone may underestimate critical hotspots of risk, particularly in production-oriented LLSs located in hydrologically stressed and socially vulnerable contexts.

More generally, the figure shows that the combined application of scarcity and social weighting reshapes the ranking of LLSs, shifting attention away from large consumption centres toward areas where water use coincides with constrained hydrological conditions and limited adaptive capacity. This reinforces the importance of integrating biophysical and socio-economic dimensions when assessing water-related impacts at the subregional scale.

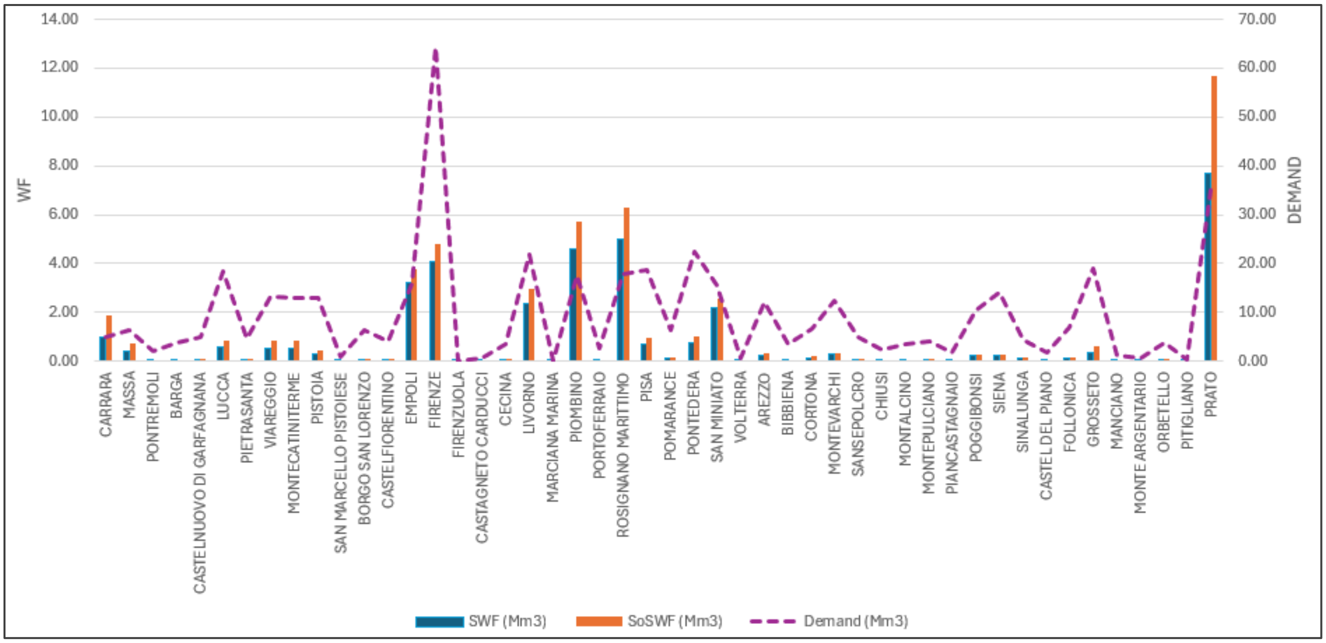

Figure 4. Net flow of virtual water in Tuscany LLSs

Figure 5 depicts the spatial structure of consumption-driven virtual water exports originating from the Prato LLS, providing a detailed view of how water-intensive production in this local economy supports final demand across the wider Tuscan region. The map reveals a highly articulated and radially structured network of outbound virtual water flows, with Prato clearly functioning as a central production hub within the regional system. Export flows extend toward almost all other LLSs, encompassing both nearby urban centres and more distant peripheral areas, which underscores the deep integration of Prato's productive activities into intra-regional supply chains.

The magnitude and spatial dispersion of these flows indicate that Prato's water footprint is sustained by a broad and geographically distributed demand base, rather than by local consumption. This visual evidence is consistent with the quantitative finding that less than 10 % of Prato's production-related water footprint is absorbed within the LLS itself, implying that most of the water use and associated pressures are induced by extra-local demand. This pattern reflects Prato's strategic productive role within the Tuscan economy, largely attributable to the concentration of textile manufacturing activities that serve regional and supra-regional markets. The figure therefore highlights a pronounced producer–consumer imbalance, whereby water withdrawals and pollution loads are spatially concentrated in Prato, while the economic benefits associated with final consumption are distributed across the wider Region.

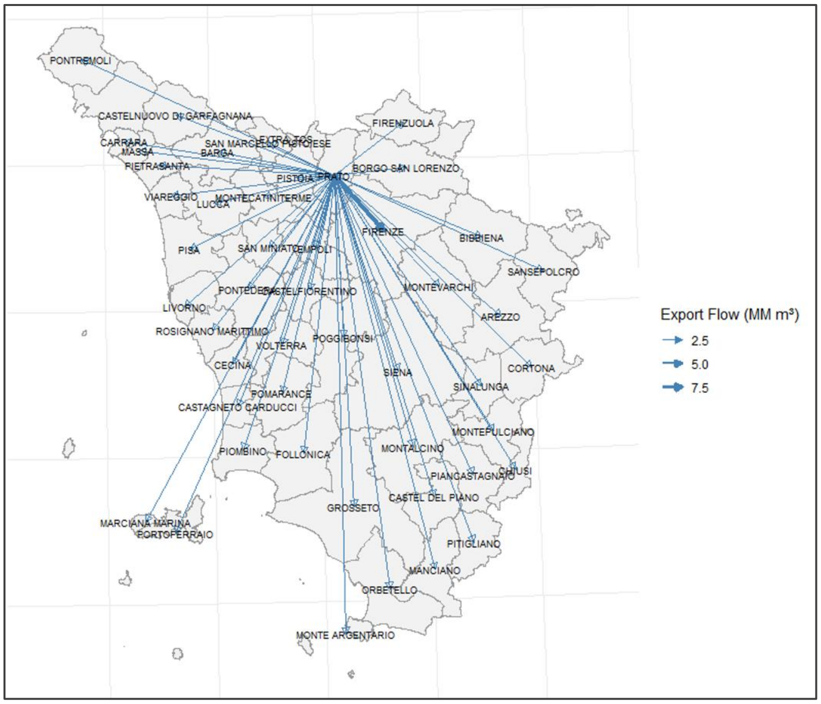

Figure 5. Prato LLS water export flows

The consumption-based analysis reveals that Firenze exhibits one of the highest water footprints in the region (Figure 6), with its consumption-based WF exceeding the production-based WF by approximately 50 %, confirming its role as a net importer of virtual water. The distribution shown in Figure 6 indicates that a substantial share of Firenze's embodied water demand originates from LLSs characterised by more constrained hydrological and social conditions. In particular, around 30 % of Firenze's consumption-based WF is sourced from LLSs with higher Water Stress Index (WSI) and Social Vulnerability (SV) scores than Firenze itself, as indicated by the relative position of these LLSs above Firenze's reference thresholds in the figure.

This pattern provides clear evidence of risk externalisation, whereby final demand in a comparatively low-stress urban centre is sustained by production activities located in more hydrologically stressed and socially vulnerable areas. The cumulative distribution further shows that a limited number of high-risk LLSs account for a disproportionate share of Firenze's embodied water demand, highlighting again the asymmetric structure of intra-regional supply chains.

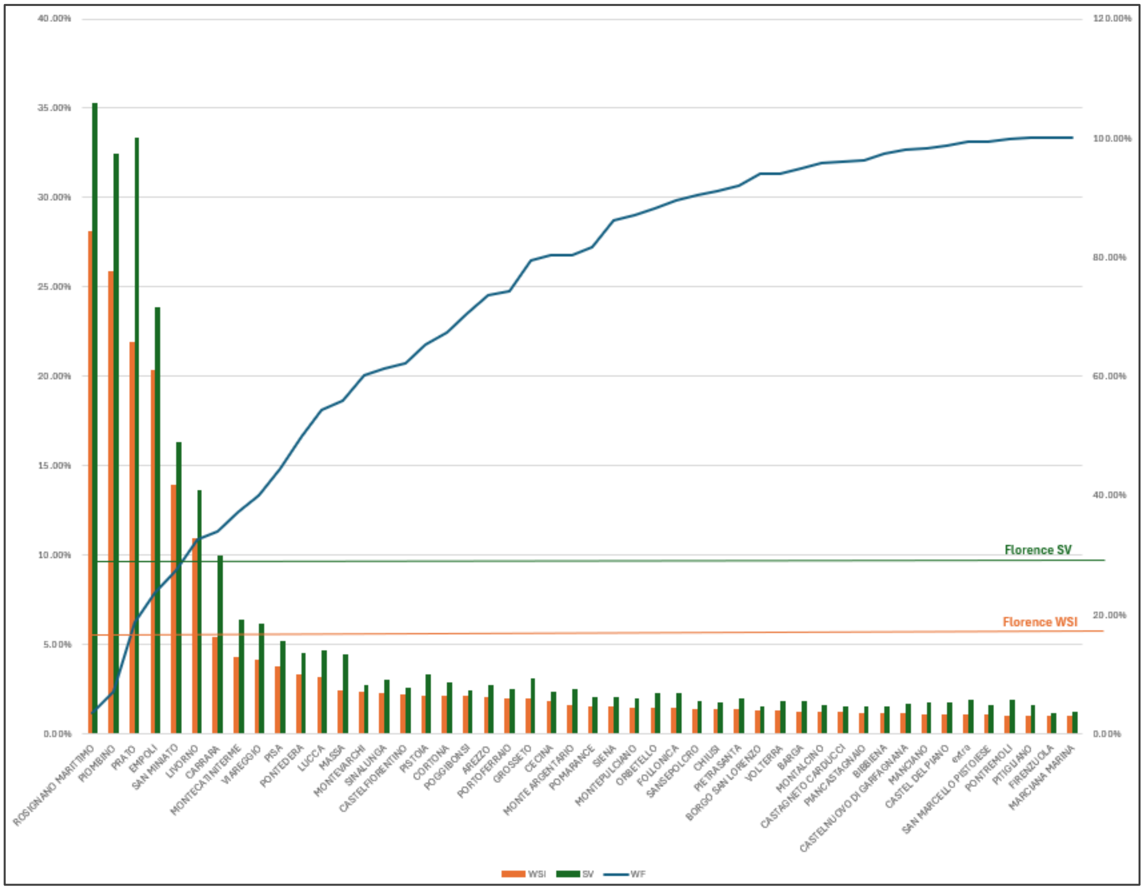

Figure 6.Firenze LLS water import and WSI and SV of the LLS of origin of the water consumed in Firenze

The largest single inflow (amounting to approximately 9 million $m^3\ yr^{-1}$) originates from Prato, underscoring the strong interdependence between Firenze’s consumption patterns and water-intensive production in neighbouring territories. This magnitude confirms that a significant share of Firenze’s final demand is directly supported by production activities located in an LLS characterised by higher levels of hydrological stress and social vulnerability. As a result, water-related pressures are spatially displaced from the main consumption centre toward adjacent production-oriented areas, reinforcing the asymmetric structure of intra-regional virtual water flows. This pattern highlights how consumption-driven demand within a single region can act as a key driver of localized water scarcity and risk beyond administrative and functional boundaries.

4. Discussion

4.1 Theoretical contributions

The results highlight pronounced spatial imbalance in how water use, scarcity, and social vulnerability are distributed across Tuscany's economic system. Although the total regional water footprint is driven by a limited number of industrial centers (with Firenze, Prato, Pontedera, and Livorno accounting for nearly one third of the total WF), the associated risk exposure does not align with economic benefit. Prato illustrates a case of concentrated production externalities: it generates a large share of regional water-intensive output while simultaneously exhibiting above-average scarcity and heightened social vulnerability. By contrast, Firenze, despite its sizeable economic role and final demand, carries comparatively low physical and social water risk because it imports embodied water from more stressed LLS.

These findings are consistent with broader evidence showing that urban consumption hubs systematically outsource resource pressures to peri-urban or industrial hinterlands. However, the subregional granularity adopted here demonstrates that this pattern can occur even within a single administrative region, a feature typically masked in national- or higher-level studies. The results therefore contribute conceptually by showing that water scarcity and vulnerability are not only multi-scalar phenomena but also emerge endogenously from intra-regional economic and hydrological heterogeneity.

The high divergence between volumetric WF and SoSWF further suggest the importance of incorporating socio-economic dimensions into water risk metrics. A purely biophysical perspective would rank Firenze and Prato as comparable contributors, whereas the socially weighted indicator reveals a more than twofold difference in risk burden. Overall, this evidence underscores that robust subregional water assessments must move beyond volumetric metrics and explicitly integrate biophysical scarcity with socio-economic vulnerability, as only their joint consideration can reliably identify priority hotspots and inform effective, equity-sensitive water management strategies. This finding aligns with emerging environmental justice literature showing that physical exposure alone is insufficient to predict vulnerability (Chakraborty et al., 2020).

4.2 Practical contributions

The integration of MRIO modelling with basin- and subregional-level hydrology provides a scalable analytical template for regions where subregional trade and environmental heterogeneity coexist. From a socio-hydrological perspective, this integration enables the explicit representation of feedbacks between economic organisation, hydrological constraints, and socially differentiated exposure to water stress. By jointly accounting for virtual water flows, scarcity weighting, and social vulnerability, the framework allows for a more operational identification of local hotspots of risk, capturing how human activities redistribute hydrological pressures across space in ways that are not observable through purely physical or aggregate economic indicators.

The subregional resolution achieved here enables practitioners to distinguish between locations where water-intensive production and associated environmental burdens are concentrated and those where consumption-driven demand effectively displaces water-related risk to other areas. In socio-hydrological terms, this distinction is critical for understanding the spatial decoupling between water use, economic benefit, and social exposure, and for identifying the mechanisms through which internal trade sustains persistent localised stress within seemingly water-abundant regions. In this sense, the framework complements existing national assessments by revealing fine-scale inequities and offering diagnostics that are directly usable for regional planning, industrial targeting, and equity-oriented adaptation strategies.

More broadly, the approach responds to recent calls within the socio-hydrology literature for analytical tools capable of linking hydrological variability, economic drivers, and social vulnerability within a unified framework. By providing spatially and temporally resolved hydro-economic accounting at the subregional level, the proposed framework contributes to the development of place-specific water governance strategies that acknowledge water scarcity as a coupled human–water phenomenon (Ortiz-Partida et al., 2023).

4.3 Policy implications

The spatial and distributional patterns identified in this study suggest several implications for regional water governance. First, water-efficiency measures are likely to yield the greatest marginal benefit when targeted at a limited number of production-intensive LLS, particularly those with high scarcity-weighted and socially weighted footprints. In Tuscany, this implies prioritising industrial retrofits, process-water recycling, and stricter discharge permits in Prato and selected neighbouring LLS, as well as in major industrial centers such as Firenze and Pontedera.

Second, demand-side interventions in major consumption centres may complement production-oriented measures. LLS that account for a substantial share of high-risk water use through their consumption profiles could contribute to a more equitable redistribution of responsibility along supply chains, for instance through procurement standards, product labelling, or consumer awareness initiatives.

Third, the explicit integration of social vulnerability into water accounting highlights the need for cross-sectoral coordination between water authorities, labour agencies, and social services. Areas with high SoSWF may require not only technical water-saving investments but also social support mechanisms to buffer households and workers from compounded environmental and socio-economic risks. Finally, the findings suggest that regional planning instruments, such as river basin management plans and industrial policy frameworks, would benefit from embedding virtual water and risk displacement metrics, rather than focusing solely on territorial withdrawals.

4.4. Limitations

Some sources of uncertainty merit attention. First, water withdrawal coefficients inevitably simplify process variability, particularly in sectors characterised by heterogeneous technologies, such as textiles. Second, WSI values are based on long-term climatic normals rather than dynamic hydrological states; recalculations under drought-year conditions would likely intensify hotspot signals.

In addition, while the framework integrates subregional hydrology with economic structure, future extensions could incorporate dynamic water availability, include additional components such as green water, or extend the analysis to account explicitly for virtual water fluxes beyond regional boundaries, thereby linking local and global assessments.

In addition, the social weighting adopted in this study entails further limitations. The social vulnerability indicator is partly based on information available at the provincial level, which may mask intra-provincial heterogeneity when translated to the LLS scale, despite the downscaling procedure applied. Moreover, while the combined use of social and material vulnerability and institutional quality indicators provides a coherent proxy for social exposure, it may not fully reflect the socio-institutional adaptive capacity specifically related to water management. Dimensions such as water governance effectiveness, local adaptive policies, emergency response capacity, and investment in water infrastructure are not explicitly captured. As a result, the socially weighted indicators should be interpreted as measures of relative vulnerability and risk exposure rather than as direct estimates of adaptive capacity.

5 . Conclusions

This study demonstrates that integrating subregional input–output modelling with hydrological scarcity and social vulnerability metrics provides a more nuanced and policy-relevant understanding of how water-related risks are generated, concentrated, and displaced within a single regional economy. From a socio-hydrological perspective, the proposed framework explicitly captures the interactions between economic organisation, spatially heterogeneous water availability, and socially differentiated exposure to water stress. Applied to Tuscany, the analysis reveals pronounced intra-regional asymmetries: production-oriented LLS such as Prato bear disproportionately high scarcity-weighted and socially weighted water footprints, while major consumption centres such as Firenze externalise a substantial share of water-related risk through virtual water inflows from more stressed areas. These results show that aggregate indicators of water availability or efficiency can obscure critical distributional dynamics, leading to an incomplete assessment of both environmental pressure and social exposure.

By jointly accounting for economic structure, hydrological constraints, and social vulnerability, this study contributes to the socio-hydrological literature by moving beyond purely volumetric or biophysical representations of water systems. By explicitly tracing how economic demand redistributes hydrological stress and social vulnerability within a region, this study operationalises sociohydrology as an analytical framework for distributive water governance. The findings underscore the need for water governance strategies that explicitly consider where water-related risks materialise, who bears them, and how such risks are transmitted through economic linkages. Subregional resolution thus emerges as a key requirement for designing equitable and targeted interventions, particularly in regions where overall water availability coexists with persistent localised scarcity, an increasingly common situation under climate variability and changing economic patterns.

Future research could extend this framework in several directions. Dynamic representations of water availability and demand, including explicit treatment of drought years and climate change scenarios, would allow for a more forward-looking socio-hydrological assessment of risk. Incorporating additional components such as green water, as well as extending the analysis to interregional and global virtual water flows, would further enhance the ability of the model to capture multi-scale human–water interactions. More broadly, applying this integrated hydro–economic–social approach across different regional contexts would help build a comparative evidence base to support water governance policies that are both environmentally sustainable and socially just.

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