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Linking water footprint and social vulnerability: a sub-regional input–output framework for assessing multiple dimensions of water scarcity

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Freshwater scarcity and unequal exposure to water-related risks are increasingly recognised as constraints on sustainable development. However, most water footprint assessments remain primarily volumetric and spatially aggregated, limiting their ability to diagnose how hydrological pressure, environmental stress, and socially differentiated impacts are redistributed within interconnected regional economies. This diagnostic gap constrains the capacity of existing approaches to inform subregional and basin-level governance. This study develops a territorially coherent hydro-economic framework that integrates multi-regional input–output modelling with spatially explicit indicators of hydrological pressure, environmental stress, and social vulnerability. Applied to 48 Local Labour Systems in Tuscany (Italy), the approach jointly quantifies production- and consumption-based volumetric water demand, scarcity-weighted impacts, and socially differentiated exposure across intra-regional supply chains. The results reveal pronounced internal asymmetries. Production-oriented territories generate a substantial share of regional water demand while experiencing disproportionately high environmental stress and social vulnerability, even where total water use is comparable to neighbouring areas. Conversely, consumption-oriented territories act as net importers of virtual water, redistributing pressure and impact to more hydrologically constrained and socially fragile locations within the same regional economy. By explicitly tracing the internal redistribution of hydrological stress and social vulnerability through economic linkages, the framework extends conventional volumetric assessments and provides a diagnostic basis for governance strategies that address not only efficiency, but also equity and the territorial distribution of water-related risk.

KEYWORDS
footprint, hydro-economic analysis, nexus, sociohydrology, Tuscany (Italy), water management

1 Introduction

Freshwater availability is increasingly recognised as a binding constraint on socioeconomic development (Baggio et al., 2021). Global assessments indicate that nearly half of the world's population experiences at least 1 month of severe water scarcity each year, while approximately one quarter is exposed to extremely high baseline water stress, defined as annual total freshwater withdrawals divided by total renewable freshwater availability equal to or exceeding 80% (UN WWDR, 2024). These conditions are further intensified by climate-induced hydrological variability, land-use change, and rising water demand from agriculture, industry, and urban consumption. However, water scarcity is not uniformly experienced. Hydrological constraints interact with economic structures, institutional arrangements, and social vulnerability, generating spatially uneven patterns of exposure (Hohenthal and Minoia, 2017; Rhouma et al., 2025). These interactions between hydrological processes and social systems have motivated the development of sociohydrology as a framework for understanding the co-evolution of human–water dynamics. Within this perspective, scarcity emerges not solely from physical imbalance, but from the behaviour and feedbacks of coupled human–water systems.

Within this broader effort to understand the interconnectedness of water and socio-economic systems, we synthesise the literature on water scarcity within economic systems into three main research strands.

The first strand is represented by the Water Footprint (WF) framework and the concept of virtual water trade (Hoekstra and Chapagain, 2007), which have been central to revealing how consumption in one location externalises volumetric water demand to distant regions. WF studies across multiple spatial scales have traced direct and indirect freshwater use along supply chains, highlighting the role of agricultural production and international trade in redistributing volumetric water demand across territories (Aldaya et al., 2012; Hoekstra, 2016; D'Odorico et al., 2020; Vallino et al., 2021; Ji et al., 2022). This literature reframed water scarcity as a telecoupled phenomenon, often disconnecting the location of volumetric water demand from that of economic benefits (Cotta et al., 2022). However, most assessments remain primarily volumetric and highly aggregated, which constrains their capacity to explicitly represent how volumetric water demand translates into territorially differentiated pressure, hydrological stress, and impact within internally connected economic systems.

The second research strand consists of hydro-economic approaches based on Input–Output (IO) and Multi-Regional Input–Output (MRIO) modelling, which extend water footprint analysis by integrating economic interdependencies into water accounting (Wang et al., 2013; Islam et al., 2021; Stadler et al., 2018; Ingwersen et al., 2022). By incorporating water-use satellite accounts into monetary IO tables, these models trace both direct and indirect freshwater embodied in production and trade, enabling a more explicit representation of intersectoral and interregional economic linkages. MRIO-based water accounting has been applied at national (Distefano et al., 2025), regional (Cámara and Llop, 2020; Rocchi et al., 2024), subregional (Rocchi et al., 2026; García-Hernández and Brouwer, 2021), and global–regional scales linking regional economies to global production networks (Sturla et al., 2024), significantly strengthening the analysis of spatially distributed volumetric water demand within interconnected economic systems. However, the explicit transformation of volumetric demand into pressure (EWEI-type ratios), hydrological stress (WSI-based constraints), and scarcity-weighted impacts remains unevenly implemented across scales.

The third strand focuses on the development of scarcity-weighted indicators that move beyond purely volumetric accounting by incorporating hydrological constraints into water footprint metrics (Wang et al., 2021). In response to criticisms that volumetric WF reflects water demand without accounting for hydrological conditions, the concept of the Scarce Water Footprint (SWF), developed by White et al. (2015), was introduced to transform volumetric demand into impact-based metrics through stress coefficients such as the Water Stress Index (WSI) (Pfister et al., 2009; Ridoutt and Pfister et al., 2010; Pfister and Hellweg, 2009). By weighting water volumes according to locally modelled hydrological stress, the SWF marked a shift from inventory-based measures of volumetric water demand to impact-based assessments that incorporate nonlinear ecosystem responses to increasing pressure. The SWF concept has since been widely applied across multiple sectors and spatial scales, including agricultural production, basin-level assessments, national accounts, and global MRIO analyses (Pfister et al., 2011; Lenzen et al., 2013; Feng et al., 2014; Wang et al., 2015; Zhang et al., 2018; Sturla et al., 2023; Zhang et al., 2023).

More recently, this third research strand has been extended to incorporate social dimensions by integrating proxies of socio-institutional capacity into scarcity-weighted metrics (Liu and Zhang, 2022; Sturla et al., 2023; An et al., 2025). Specifically, Sturla et al. (2023) adjusted national water availability using the Human Development Index (HDI) to approximate differences in adaptive capacity. In this context, they introduced the Social Scarce Water Footprint (SoSWF) to represent impact-based water use occurring under conditions of both hydrological stress and socio-institutional vulnerability. By extending impact weighting to include social capacity constraints, this approach represents an important step toward integrating hydrological stress and vulnerability within global production networks.

However, current implementations remain structurally constrained by spatial aggregation. Hydrological availability is typically represented through national averages, and vulnerability is proxied by broad composite indicators, masking substantial intra-regional heterogeneity in hydrological stress, pressure intensity, and institutional performance. Despite these advances, existing implementations have not yet fully integrated the SoSWF within a territorially coherent subregional hydro-economic system capable of simultaneously representing detailed hydrological variability and spatially differentiated socio-institutional processes within an internally connected regional economy. As a result, the internal redistribution of impact-based water risk within a single region remains insufficiently understood.

This limitation is particularly critical because hydrological constraints are inherently territorial (Pfister et al., 2009). Hydrological processes unfold at basin and subregional scales, economic interdependencies redistribute volumetric water demand across regional economies, and vulnerability and institutional capacity vary markedly across local contexts. Even regions characterised by relatively high renewable availability may therefore contain localized areas of intensified pressure (high demand-to-supply ratios) and elevated hydrological stress that remain hidden within aggregate indicators, especially where internal producer–consumer linkages redistribute scarcity-weighted impacts across interconnected subregions.

Building on these limitations, this study contributes to the literature by embedding the SoSWF within a territorially coherent subregional hydro-economic framework that integrates volumetric water demand, pressure (EWEI), hydrological stress (WSI), and socio-institutional vulnerability within a unified analytical system. The analysis is conducted at the level of Local Labour Systems (LLS), clusters of municipalities representing functionally integrated local economic areas. Throughout this study, water demand refers to the volumetric water footprint (WF), representing the total volume of freshwater directly and indirectly required to satisfy final consumption. The scarcity-weighted extensions of this volumetric indicator are the Scarce Water Footprint (SWF) and the Social Scarce Water Footprint (SoSWF), which incorporate hydrological stress and socio-institutional vulnerability, respectively.

By aligning the analytical scale with territorially meaningful socio-economic units, the study complements national-level assessments by revealing intra-regional redistribution patterns of pressure, stress, and socially differentiated impact that remain structurally aggregated in broader-scale analyses. The model combines high-resolution hydrological data derived from the GIS-based BIGBANG water balance model (Braca et al., 2021) with spatially differentiated indicators of social vulnerability and institutional capacity. Social vulnerability is operationalised through a composite metric that integrates the municipal-level Social and Material Vulnerability Index (ISTAT, 2020) with the Institutional Quality Index at the provincial level (Lasagni et al., 2015), thereby capturing both social fragility and governance performance across interconnected subregional economic systems.

Importantly, as demonstrated by Sturla and Rocchi (2024a), LLS units can be coherently aggregated to sub-basin and river basin levels. These basin scales represent the fundamental territorial units for water management and policy, as widely recognised in the hydrological governance literature (D'Oria et al., 2019; Fatichi and Caporali, 2009). The LLS framework therefore enables the analysis of water-related challenges at economically functional scales while remaining consistent with basin-based governance structures, bridging socio-economic dynamics and hydrological management within nested territorial systems.

The novelty of this study lies in embedding scarcity-weighted water footprint indicators within a territorially coherent subregional MRIO system that reveals internally redistributed and socially differentiated impact-based water risk that remains invisible at national scales. Operationally, this approach advances the field in three ways:

i. By developing a hydro-economic water accounting model at a subregional functional scale;
ii. By integrating pressure, hydrological stress, and spatially differentiated social vulnerability into virtual water flow analysis; and
iii. By identifying producer–consumer asymmetries within a single, internally connected regional economy.

Accordingly, the objective of this study is to apply this framework to Tuscany (Italy), a region characterised by heterogeneous climatic conditions, strong manufacturing clusters, and dense intra-regional supply chains. By tracing how internal economic volumetric water demand redistributes both hydrological stress and socially mediated impact across subregional territories, the study contributes to a more spatially differentiated and equity-oriented understanding of water risk in interconnected regional economies.

2 Materials and methods

To ensure conceptual clarity, key analytical terms are used in this study with the following operational meanings. Water demand refers to the volumetric water footprint (WF), expressed either as production-based (WFP) or consumption-based (WFC) accounts. These represent inventory measures of water use and do not incorporate scarcity or stress adjustments. Pressure refers to the intensity of water demand (i.e., volumetric WF) relative to locally available renewable supply and is quantified through EWEI-type ratios. Stress denotes hydrological constraints transformed through the Water Stress Index (WSI), capturing the nonlinear response of ecosystems to increasing pressure. Impact refers to impact-based indicators (SWF and SoSWF), in which volumetric water demand (WF) is adjusted by hydrological stress and, where applicable, social vulnerability. In this framework, water scarcity is operationalised as the interaction between pressure (EWEI) and stress (WSI) and is expressed through these impact-based indicators. Vulnerability refers exclusively to the Social Vulnerability (SV) indicator used in this study. In conceptual terms, vulnerability denotes territorially differentiated socio-institutional conditions that may limit the capacity of a local system to cope with hydrological stress. It reflects relative exposure and sensitivity to water-related constraints, rather than a direct measure of adaptive capacity specific to water governance (Adger, 2006; Turner et al., 2003). Finally, risk is used descriptively to denote compounded exposure to hydrological stress and social vulnerability and does not represent a formally modelled probabilistic metric. The assessment integrates three main components.

First, an MRIO model extended into a hydro-economic framework, incorporating sectoral coefficients for water withdrawals, water restitutions to water bodies (blue water defined as withdrawals minus restitutions), and water required for pollutant dilution (grey water), together with the expressions used to calculate production- and consumption-based water footprints (WF) across interlinked economic activities.

Second, a spatially distributed hydrological model is employed to estimate renewable local water availability under natural regime conditions and to compute the feasible supply used to derive pressure (EWEI) and stress (WSI) indicators at the territorial scale.

Third, scarcity-weighted indicators are computed through the integration of pressure (EWEI), hydrological stress (WSI), and social vulnerability (SV), resulting in the SWF and the SoSWF. The case study design and territorial aggregation procedures are described subsequently.

Figure 1 summarises the analytical workflow.

2.1 Hydro-economic modelling

The hydro-economic model is based on an Environmentally Extended Multi-Regional Input–Output (EE-MRIO) framework, widely applied 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 approach provides a system-level representation of how economic activities generate volumetric water demand (WF) that interacts with spatially heterogeneous water availability, enabling the identification of indirect and displaced pressures that cannot be observed through local water balances alone.

The economic backbone of the model is the 2017 inter-LLS MRIO table developed by the Tuscan Regional Institute for Economic Planning (IRPET, 2021) and subsequently refined in Rocchi et al. (2026). The matrix represents 48 Local Labour Systems (LLSs) and 53 productive sectors, together with five components of domestic final

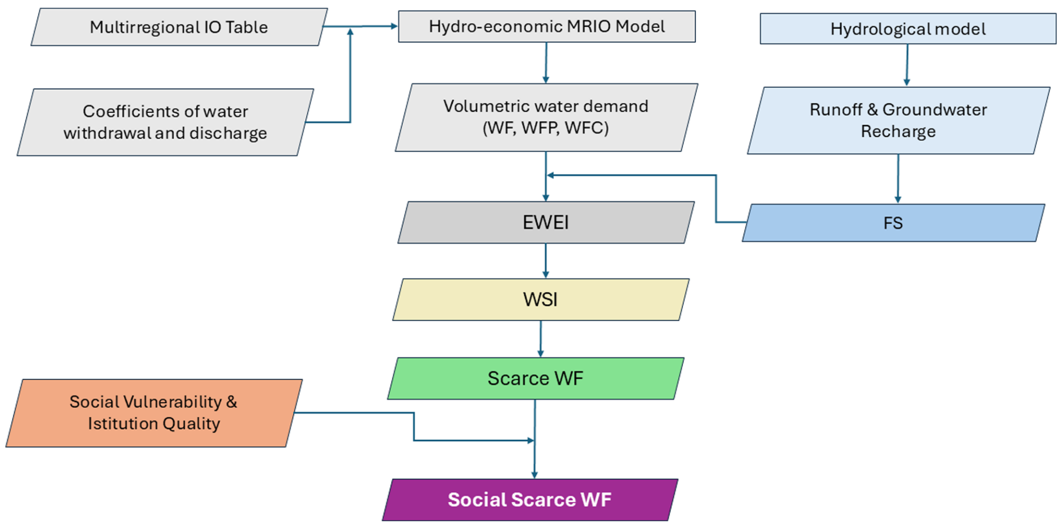

FIGURE 1
Methodology overview.

demand and four components of external demand (Rest of Italy and Rest of the World). The table is fully consistent with official regional accounts and preserves accounting balance across intermediate consumption, value added, and total output. As part of the refinement process, agriculture was disaggregated into eight sub-sectors according to the EU Farm Type classification using georeferenced crop and irrigation data and FADN-based value-added ratios, improving the representation of water-intensive activities and increasing the sensitivity of sectoral volumetric water demand to hydrological variability (Rocchi et al., 2026).

Environmental extensions were developed by Rocchi et al. (2026) and integrated as sector- and LLS-specific water coefficients (m^3/€), fully aligned with the 2017 reference year of the economic accounts. Blue water coefficients represent net water abstraction, calculated as gross withdrawals from surface and groundwater bodies minus return flows. Green water coefficients reflect soil moisture use in agricultural production.

Gross withdrawal data were derived from regional water accounts and sectoral statistics consistent with the 2017 economic structure. Return flows were estimated using sector-specific discharge ratios obtained from regional water management data, distinguishing between water incorporated into products and water returned to surface or groundwater bodies. Net abstraction therefore captures the effective pressure exerted on water bodies per unit of economic output.

Grey water coefficients were calculated using a mixing-model approach (Guan and Hubacek, 2008; Rocchi et al., 2024), estimating the freshwater volume required to dilute sectoral pollutant loads to environmentally acceptable concentration thresholds. Pollutant loads were derived from sectoral emission data consistent with the 2017 accounts, ensuring full temporal alignment between economic activity and hydrological pressures.

The environmental coefficients are consistent with official regional water accounts and sectoral statistics, ensuring full coverage of productive sectors included in the MRIO system. Where direct measurements were not available at the subregional level, water use and discharge data were harmonised using sector-specific allocation ratios to preserve accounting consistency across LLSs. While some uncertainty may arise from the spatial allocation of aggregated water statistics, the strict alignment with the 2017 economic accounts ensures structural coherence between economic flows and hydrological pressures.

While Rocchi et al. (2026) developed the inter-LLS hydro-economic accounting framework and constructed the associated sector- and territory-specific water coefficients, their contribution focused primarily on the structural integration of water extensions within the regional MRIO system. The present study advances this framework by explicitly applying it to estimate and interpret volumetric water demand (WF), scarcity-weighted impact (SWF), and socially weighted impact (SoSWF) within a territorially differentiated context. In addition, it integrates high-resolution hydrological variability and spatially differentiated socio-institutional indicators into the operationalisation of water scarcity, understood as the interaction between pressure (EWEI) and hydrological stress (WSI). The contribution therefore lies not in the construction of the MRIO database itself, but in its analytical deployment to examine internally redistributed and socially differentiated water risk at subregional scale.

These extensions transform the MRIO structure into a hydro-economic accounting framework capable of tracing direct and indirect volumetric water demand (blue plus grey water) across interlinked production networks and subregional economies. The model supports both production- and consumption-based perspectives. The production-based WF (WFP) measures volumetric water demand generated within each LLS, while the consumption-based WF (WFC) accounts for volumetric water demand across all LLSs required to satisfy the final demand of a given LLS. This dual perspective enables the identification of virtual water exchanges, producer–consumer asymmetries, and the internal redistribution of pressure (demand relative to supply) within the regional economy.

This dual perspective is particularly relevant because economic footprint analyses typically emphasise consumption-based accounting, whereas hydrological assessments are generally grounded in production-based measures linked to basin-scale water balances (Sturla et al., 2024). Integrating both approaches within a unified subregional MRIO framework enables water scarcity to be analysed simultaneously as an outcome of economic volumetric water demand

and as a territorially embedded interaction between pressure and hydrological stress.

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 and m industries. The Leontief inverse matrix is defined as:

$$\boldsymbol{L} = \left(\boldsymbol{I} - \boldsymbol{A}\right)^{-1}$$

Where A is the $(nm \times nm)$ matrix of direct requirement coefficients for the n local economies in the m industries, and I is the $(nm \times nm)$ 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 $[nm \times (nm+1)]$, 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:

$$\mathrm{H} = \hat{\mathrm{c}} \cdot \mathrm{L} \cdot \mathrm{Y}$$

$$\mathrm{c} = \mathrm{f} - \mathrm{r} + \mathrm{w}$$

Where Y is the $[nm \times (nk+1)]$ final demand matrix, with k denoting the number of final demand components for each LLS. The $(nm \times 1)$ 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.

The $[n \times (n + 1)]$ matrix M is defined 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).

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

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

2.2 Hydrological modelling

The estimation of water availability was based on the BIGBANG model, developed by the Italian Institute for Environmental Protection and Research (ISPRA) (Braca et al., 2021). BIGBANG is a spatially distributed, GIS-based water balance model grounded in the mass-conservation principle of the hydrological cycle. It quantifies the main components of the water balance at national and macro-regional scales by solving the continuity equation at a monthly time step over a regular 1 km grid. This structure ensures spatial consistency, internal water-balance closure at the cell level, and long-term comparability across the entire Italian territory. Beyond its original development, outputs from the BIGBANG framework have been widely used in recent studies to support hydrological modelling, drought assessment, and analyses of key water-balance components across Italy (e.g., El Jeitany et al., 2024; Mariani et al., 2025; Amaranto et al., 2025; Di Nunno and Granata, 2026).

Importantly, BIGBANG reproduces hydrological conditions under natural regime, simulating runoff and groundwater recharge independently of anthropogenic abstractions and flow regulation. This allows the derivation of renewable water availability indicators without the bias inherent in measurements taken at gauging stations, which typically reflect regulated flows and post-withdrawal conditions. The model is widely used in Italy for national water accounting and basin planning purposes, and was therefore selected as a calibrated and nationally validated framework for this study.

The empirical performance of BIGBANG has been documented in Braca et al. (2021). Model outputs have been evaluated against independent datasets, including: (i) comparison of actual evapotranspiration with MODIS16A2 satellite-derived estimates; (ii) validation of aquifer recharge against local-scale groundwater balance modelling; and (iii) calibration and validation of monthly streamflow using monitored river sections (e.g., the Fiora basin), with performance metrics reported in the ISPRA technical report. These evaluations support the robustness of the model for large-scale hydrological assessment and for deriving spatially explicit water availability indicators.

Although originally developed for national-scale assessments, the model's gridded architecture allows spatial aggregation and disaggregation to different territorial units. In this study, grid-level hydrological outputs were spatially overlaid with the boundaries of Local Labour Systems (LLSs), and water availability indicators were computed through area-weighted aggregation. This procedure preserves the spatial heterogeneity captured at 1 km resolution while ensuring full methodological consistency between the hydrological modelling framework and the territorial units adopted in the MRIO analysis.

The model is based on the mass-conservation equation:

$$P - E = R + G + \text{Ä}V$$

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.

Precipitation (P) and temperature inputs are spatially interpolated within the BIGBANG modelling framework to generate continuous climatic fields at 1 km resolution consistent with the model grid. Actual evapotranspiration (E) is estimated using the Thornthwaite method and adjusted according to soil-water availability conditions. Soil-water storage and snowpack dynamics (ΔV) are represented through a soil-capacity approach derived from national soil databases, which regulates the partitioning of water between storage, surface runoff, and groundwater recharge. Groundwater recharge (G) is estimated as a fraction of effective precipitation (P − E) based on the permeability of the underlying hydrogeological complexes, while surface runoff (R) is computed as the residual term required to close the water-balance equation. A detailed description of the model structure, algorithms, and parameterization is provided in Braca et al. (2021).

For this study, runoff (R) and groundwater recharge (G) for the period 2011–2022 were spatially aggregated to the LLS level through area-weighted overlay procedures and used to estimate renewable natural water availability for each LLS. To account for environmental constraints, the available volume was adjusted by subtracting ecological flow requirements, defined as 5% of the mean annual flow, following the guidelines of the Northern Apennine District Authority (2021).

In addition, the contribution of existing reservoirs within each LLS was incorporated by adding a storage-based availability component corresponding to the total reservoir capacity located in the territory (Giambastiani et al., 2020; Northern Apennine District Authority, 2021). This adjustment allows the availability indicator to reflect both natural renewable resources and regulated storage capacity within each local system.

While alternative water scarcity indicators exist—such as the Withdrawal-to-Availability ratio (WTA), the Water Exploitation Index (WEI), defined as the ratio between blue water withdrawals and long-term natural availability net of ecological flow (European Environment Agency, 2005; OECD, 2015), and the WEI (Faergemann, 2012; European Environment Agency, 2020), which incorporates return flows and thus reflects net volumetric water demand—these indicators primarily focus on blue water withdrawals relative to physical availability. In this study, we adopt the Extended Water Exploitation Index (EWEI) proposed by Rocchi et al. (2024), as it integrates both blue and grey water components and accounts for feasible water supply constraints. This approach provides a more comprehensive representation of water scarcity, particularly at subregional scales where both consumptive use and dilution requirements can be quantified with greater precision.

2.3 Scarce water footprint and social scarce water scarce footprint assessment

To capture the multidimensional nature of water scarcity, this study introduces two complementary impact-based indicators estimated at the level of each Local Labour System (LLS). As illustrated in Figure 1, the computation follows a sequential structure consistent with the conceptual definitions introduced above. Hydrological availability is first estimated and used to derive pressure (EWEI), defined as the ratio between volumetric water demand and feasible renewable supply. Pressure is subsequently transformed into hydrological stress through the WSI, which captures the nonlinear ecological response to increasing demand-to-supply ratios. Finally, stress is used to weight volumetric water demand, generating impact-based indicators (SWF and SoSWF), with the latter further adjusted to account for social vulnerability. The following steps detail the calculation procedure.

Step 1 – Hydrological availability and feasible supply at LLS level.

Renewable natural water availability is derived from the BIGBANG hydrological model, whose gridded outputs (1 km resolution) are spatially aggregated to LLS boundaries using area-weighted overlay procedures. For each LLS s, annual surface runoff (R_s) and groundwater recharge (G_s) are computed and represent renewable water resources under natural regime conditions.

To account for environmental constraints, ecological flow requirements (5% of mean annual flow) are subtracted. In addition, reservoir storage volumes (VS_s) located within each LLS are incorporated to reflect regulated supply capacity.

The feasible supply (Rocchi et al., 2024; Sturla and Rocchi, 2024b) for each LLS results as follow:

$$FS_s = \left(R_s + G_s\right) \cdot 0.95 + VS_s$$

This step explicitly links basin-level hydrological modelling outputs to the territorial units adopted in the MRIO framework.

Step 2 – Extended water exploitation index.

Water scarcity pressure is first expressed through the Extended Water Exploitation Index (EWEI), defined as the ratio between production-based water footprint (WFP) and feasible supply:

$$EWEI_s = \frac{WFP_s}{FS_s}$$

The EWEI integrates both blue and grey water components and relates total volumetric water demand to locally available renewable resources, providing a pressure-based measure of water scarcity.

Step 3 – Scarce water footprint.

To account for the nonlinear ecological response associated with increasing demand-to-supply ratios, the SWF is computed following Sturla et al. (2023). This indicator transforms WF into an impact-based metric by weighting it with hydrological stress, as quantified through the WSI proposed by Pfister et al. (2009).

$$SWF_s = WFP_s \cdot WSI_s$$

Where,

$$WSI_s = \frac{1}{1 + e^{-6.4 \cdot EWEI_s} \cdot \left(\frac{1}{0.01} - 1\right)}$$

In this formulation, the impact-based indicator adjusts WF using WSI as a stress coefficient derived from EWEI. The WSI transforms EWEI into a bounded coefficient between 0 and 1, capturing the nonlinear increase in ecological sensitivity as pressure intensifies.

Step 4 – Social vulnerability and social scarce water footprint.

While SWF captures impact derived from hydrological stress, it does not account for differences in socio-institutional capacity to manage water-related challenges. To incorporate this dimension, a Social Vulnerability (SV) indicator is introduced as an additional weighting factor.

The conceptual foundation of SV builds on the notion of "social scarcity" proposed by Ohlsson (2000), according to which water-related constraints are not determined solely by physical availability but also by society's capacity to manage and adapt to them. Sturla et al. (2023) operationalised this concept at national scale using the Human Development Index (HDI) as a proxy for adaptive capacity. In the present study, this approach is extended to the subregional level by explicitly integrating territorially differentiated vulnerability into the impact-based framework.

The SV indicator combines:

- The Social and Material Vulnerability Index (IVSM) at municipal level (ISTAT, 2020), aggregated to LLS. This index captures structural socio-economic conditions that may increase exposure and sensitivity to environmental stressors, including demographic fragility, labour market conditions, housing quality, and access to essential services. In the context of water scarcity, these factors influence the capacity of households and local communities to cope with water-related constraints and economic disruptions.

- The Institutional Quality Index (IQI) at provincial level (Lasagni et al., 2015), downscaled to LLS by adjusting each LLS's value proportionally to deviations in its social vulnerability score from the provincial mean. Institutional quality reflects governance effectiveness, administrative capacity, and the ability of local institutions to implement policies and coordinate responses to environmental pressures. In water management contexts, stronger institutions are associated with greater capacity to regulate water use, implement adaptive policies, and mitigate the socio-economic impacts of hydrological stress.

By combining socio-economic fragility with institutional capacity, the SV indicator provides a territorially differentiated proxy for the social conditions that shape exposure and response to water scarcity within interconnected regional economies.

The SV for each LLS is defined as:

$$SV_s = IQI_{Prov} \cdot \frac{IVSM_s}{IVSM_{Prov}}$$

This formulation approximates territorially differentiated adaptive capacity by combining socioeconomic fragility and institutional strength.

The Social Scarce Water Footprint (SoSWF) is then computed as:

$$SoSWF_s = WFP_s \cdot WSI_s \cdot SV_s = SWF_s \cdot SV_s$$

This final step integrates three analytical dimensions:

o Pressure (EWEI),
o Hydrological stress (WSI),
o Socio-institutional vulnerability (SV).

By sequentially combining these components, water scarcity is operationalised as the interaction between pressure and stress, while the socially weighted impact (SoSWF) further reflects territorially differentiated vulnerability. In this way, the framework captures not only hydrological constraints, but also socially differentiated exposure within interconnected subregional economies.

Scarcity-weighted impact is assessed from two complementary accounting perspectives, as formally defined in Section 2.1:

i production-based accounting (WFP), and
ii consumption-based accounting (WFC).

Results are subsequently presented in terms of net virtual water flows between LLSs, computed as the difference between water embodied in exports and imports of intermediate and final goods.

2.4 Case study description

Tuscany, located in central Italy, covers approximately 23,000 km^2 and is characterised by a high diversity of landscapes, ranging from mountain systems to coastal plains and peri-urban areas (Venturi et al., 2021). The region hosts about 3.7 million inhabitants (ISTAT, 2024) and exhibits significant spatial heterogeneity in both demographic distribution and economic structure.

Climatically, Tuscany is influenced by its Mediterranean setting and complex topography, with marked spatial variability in precipitation and renewable water availability. Annual rainfall ranges from over 2000 mm in mountainous areas to <600 mm in parts of the southern coastal zones. This variability, combined with seasonal concentration of precipitation, generates uneven hydrological conditions across the territory (Fatichi and Caporali, 2009; Venturi et al., 2014; Nigro et al., 2024).

At the subregional scale, Tuscany displays a heterogeneous economic structure organised into specialised LLSs. These range from water-intensive agricultural and agri-food districts to manufacturing clusters, tourism-oriented economies, and urban service centres. Such differentiation produces uneven patterns of volumetric water demand across the region. Previous studies show that, although Tuscany does not exhibit high pressure at the aggregate regional level (i.e., low demand-to-supply ratios), significant subregional pressure emerges due to spatial mismatches between economic volumetric water demand and renewable availability (Rocchi et al., 2024; Sturla and Rocchi, 2024b; Rocchi et al., 2026). In particular, areas with concentrated productive activities and limited surface water resources often rely heavily on groundwater abstraction, leading to locally intensified pressure and hydrological stress (Venturi et al., 2014; Bartolini et al., 2018).

The region is divided into 48 LLSs (Figure 2), defined as functional economic zones based on commuting patterns. This territorial structure provides the analytical scale at which water demand, pressure, hydrological stress, and socio-institutional vulnerability are jointly assessed within the proposed framework.

3 Results

The spatial distribution of net internal virtual water flows across the 48 LLSs in Tuscany is illustrated in Figure 3. 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.

Florence 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 Florence as a consumption-oriented centre that externalises a substantial share of its volumetric 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.

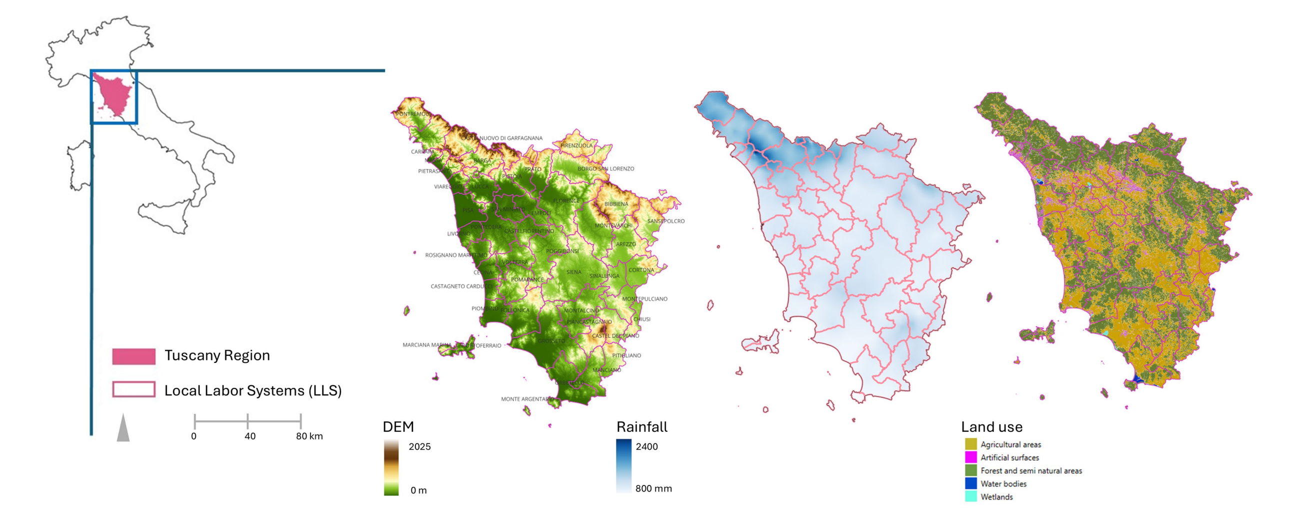

FIGURE 2
Study area with Tuscany region divided in its 48 local labor systems including topography, mean precipitation, and land use.

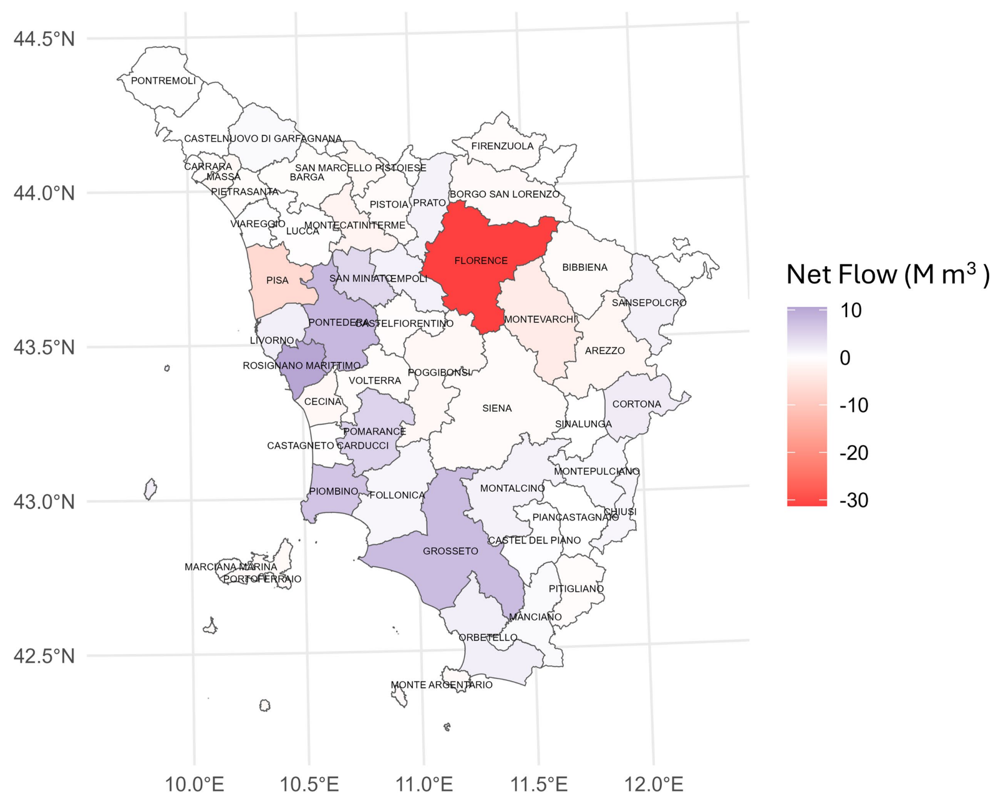

FIGURE 3
Net flow of virtual water in Tuscany LLSs (red = net importers; blue = net exporters).

Conversely, consumption-oriented LLSs rely on imports for approximately 30% of their embodied volumetric 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 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 Florence, its SWF is about 1.8 times higher, reflecting its location within a basin characterised by significantly higher withdrawal-to-availability ratios.

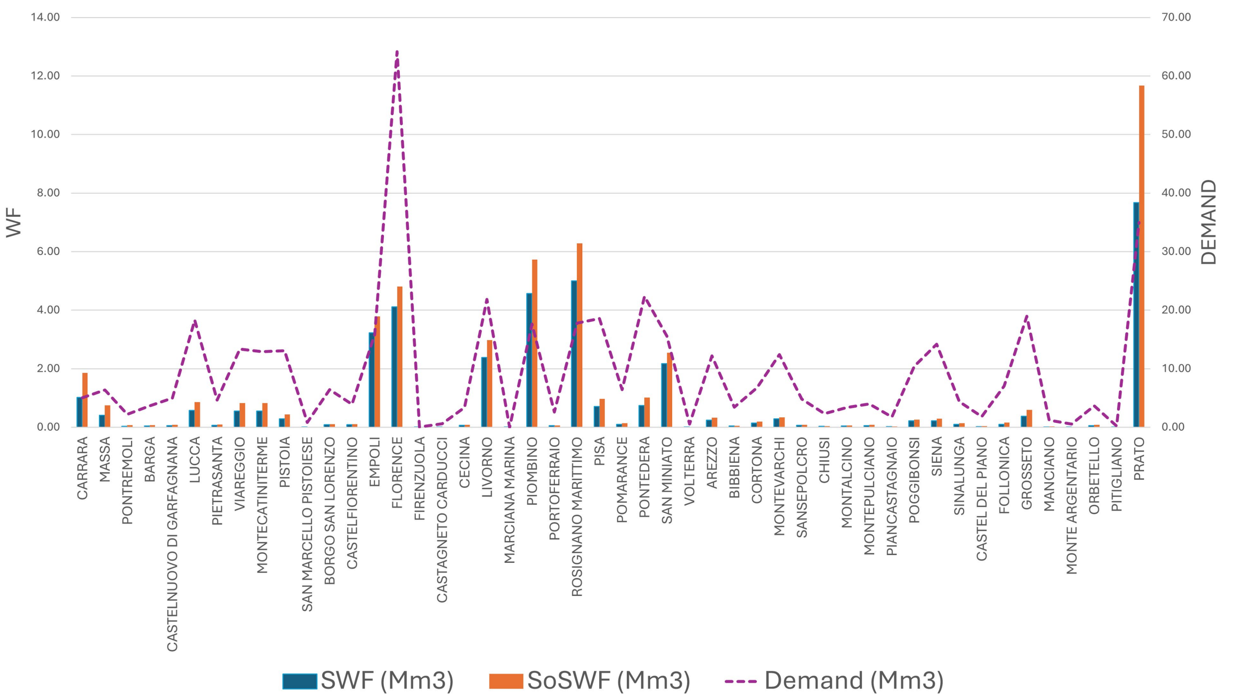

FIGURE 4
Volumetric water demand (right axis), scarcity-weighted water footprints (SWF), and socially weighted water scarcity footprints (SoSWF) (left axis) across the 48 LLSs.

When social vulnerability is further incorporated, these contrasts become even more pronounced. Prato's SoSWF is approximately 2.4 times higher than that of Florence, 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 5 illustrates the spatial structure of consumption-driven virtual water exports originating from the Prato LLS, highlighting 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 <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.

The consumption-based analysis reveals that Florence 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 Florence's embodied volumetric water demand originates from LLSs characterised by more constrained hydrological and social conditions. In particular, around 30% of Florence's consumption-based WF is sourced from LLSs with higher Water Stress Index (WSI) and Social Vulnerability (SV) scores than Florence itself, as indicated by the relative position of these LLSs above Florence's reference thresholds.

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 Florence's embodied volumetric water demand, highlighting again the asymmetric structure of intra-regional supply chains.

The largest single inflow (amounting to approximately 9 million m^3 $yr.^{-1}$) originates from Prato, underscoring the strong interdependence between Florence's consumption patterns and water-intensive production in neighbouring territories. This magnitude confirms that

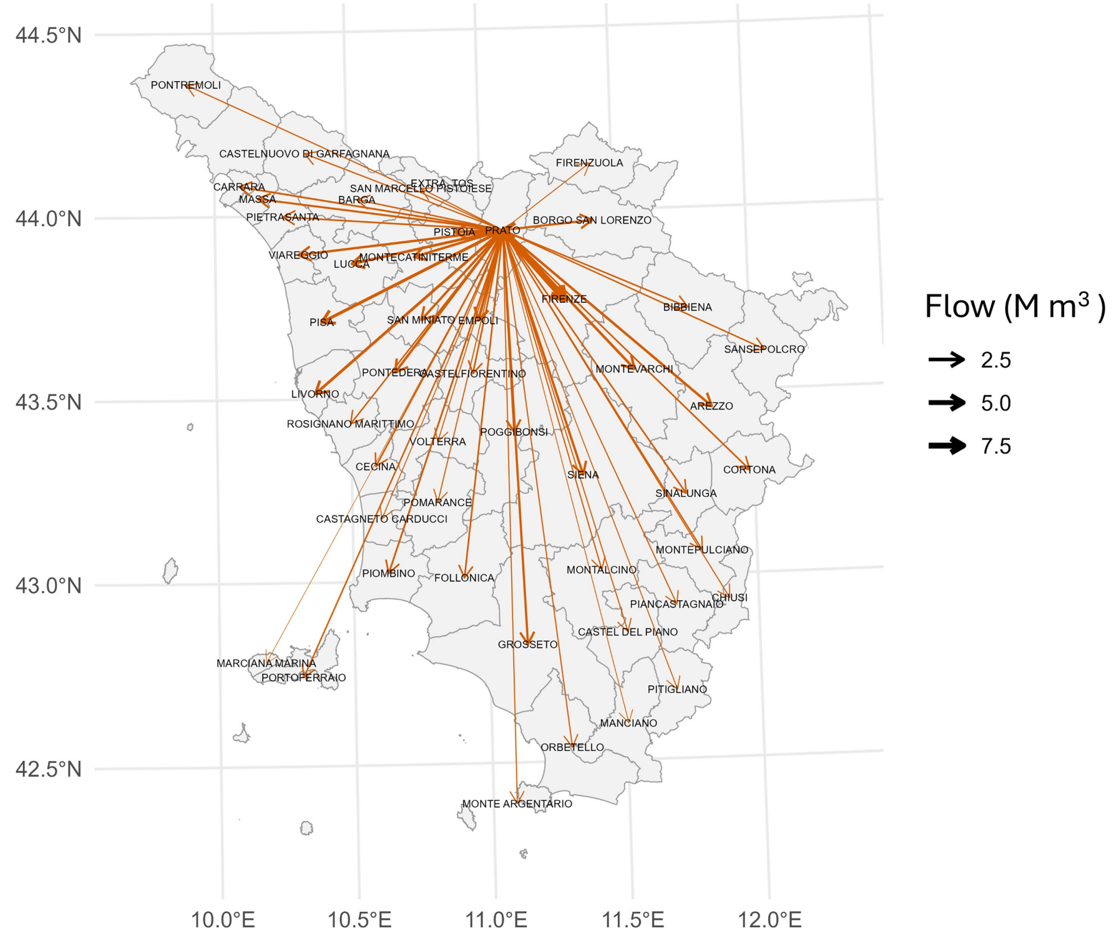

FIGURE 5
Prato LLS consumption-driven virtual water exports.

a significant share of Florence's final demand is directly supported by production activities located in each 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 volumetric water demand, scarcity, and social vulnerability are distributed across Tuscany's economic system. Although the total regional WF is driven by a limited number of LLS with a high incidence of manufacturing activities (with Florence, Prato, Pontedera, and Livorno accounting for nearly one third of total WF), the associated impact-based risk exposure does not align with the distribution of economic benefits. Prato illustrates a case of concentrated production externalities: it generates a large share of regional water-intensive output while simultaneously exhibiting above-average pressure (EWEI), elevated hydrological stress (WSI), and heightened social vulnerability (SV). By contrast, Florence, despite its sizeable economic role and final demand, exhibits comparatively lower impact-based water risk because it imports embodied volumetric water demand from LLS characterised by higher pressure and stress.

These findings are consistent with broader evidence showing that urban consumption hubs systematically externalise volumetric water demand 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 analyses. The results therefore contribute conceptually by showing that scarcity—operationalised as the interaction between pressure and hydrological stress—and vulnerability are not only multi-scalar phenomena, but also emerge endogenously from intra-regional economic and hydrological heterogeneity.

The divergence observed between volumetric WF and SoSWF does not invalidate volumetric assessments, which remain essential for quantifying absolute volumetric water demand. Rather, it illustrates how integrating pressure (EWEI), hydrological stress (WSI), and socio-institutional vulnerability (SV) modifies the interpretation of where impact-based risk is concentrated and how it is distributed. Territories with comparable volumetric footprints may differ substantially in their impact-based exposure when stress and vulnerability are

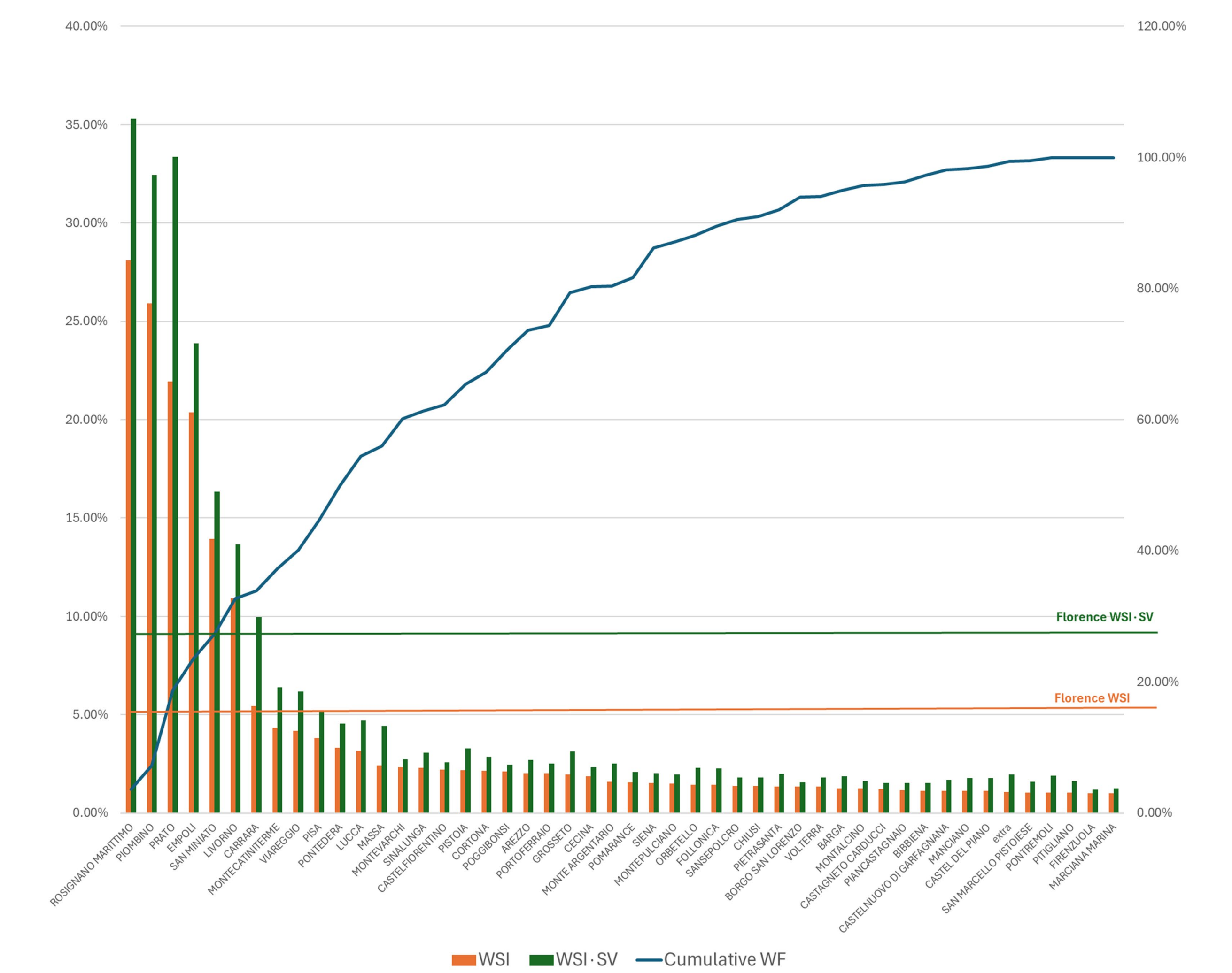

FIGURE 6
Analysis of the WSI and SV in the LLS of origin of the water consumed in Florence. The right vertical axis shows the cumulative WFC of Florence, while the left vertical axis reports the WSI and SV·WSI levels. The graph also shows the WSI and SV·WSI levels of Florence, used as threshold values.

incorporated. By making these differences explicit within an internally connected regional economy, the framework contributes to informing water management not by prescribing specific interventions, but by providing a diagnostic lens that highlights where high pressure and social fragility co-locate. This enables regional and basin-level decision-makers to better evaluate trade-offs, prioritise interventions, and consider distributive implications within existing governance structures.

Importantly, the analytical choice of LLS as the unit of analysis does not imply that governance occurs at this scale. LLS represent territorially meaningful socio-economic systems defined by functional economic integration, enabling the identification of intra-regional redistribution patterns and producer–consumer asymmetries that remain structurally aggregated in broader-scale analyses. By aligning the analytical scale with economically functional units, the study complements national-level assessments by revealing socially differentiated impact exposure that would otherwise remain concealed.

Moreover, as demonstrated by Sturla and Rocchi (2024a), LLS units can be coherently aggregated to sub-basin and river basin levels. These basin scales constitute the fundamental territorial units for water management and policy, as widely recognised in the hydrological governance literature (D'Oria et al., 2019; Fatichi and Caporali, 2009). The LLS framework therefore bridges socio-economic dynamics and hydrological management within nested territorial systems: it enables fine-scale diagnostic analysis while remaining fully consistent with basin-based governance structures.

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 characterised by high pressure (EWEI), elevated hydrological stress (WSI), and high impact-based footprints (SWF and SoSWF). 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 centres such as Florence and Pontedera.

Second, demand-side interventions in major consumption centres may complement production-oriented measures. LLS that account for a substantial share of impact-based exposure through their consumption profiles (WFC) 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 SV into impact-based 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 hydrological stress and socio-institutional vulnerability.

These implications should be interpreted in light of the analytical scale adopted. Although LLS are not formal governance units, their coherent aggregation to sub-basin and basin levels (Sturla and Rocchi, 2024a) enables direct translation into river basin management plans and regional industrial policy instruments (Fatichi and Caporali, 2009; D'Oria et al., 2019; Rossi and Benedini, 2020). The contribution of the framework lies not in redefining governance boundaries, but in providing granular evidence on intra-regional redistribution of pressure, stress, and impact-based risk that can be incorporated into existing planning and regulatory processes.

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, meaning that the present estimates reflect structural hydrological stress conditions rather than event-specific drought responses.

However, recent applications of the inter-LLS hydro-economic framework have explicitly explored climatic uncertainty. Rocchi et al. (2026) and Sturla and Rocchi (2024b) simulated water availability and sectoral responses under 100 alternative climatic scenarios. Their results show that climate variability affects not only renewable water availability but also sectoral water-use coefficients. In particular, agricultural sectors—which constitute the largest blue water consumers—require increased irrigation withdrawals in dry years. At the same time, sectors generating pollutant discharges exhibit higher grey water requirements under reduced dilution capacity conditions, as lower flows decrease assimilative capacity. Drought scenarios therefore simultaneously intensify blue volumetric water demand and grey water requirements, amplifying hydrological stress and impact-based indicators in already stressed territories.

These findings suggest that while the present study relies on long-term averages, the relative spatial patterns of pressure, stress, and impact redistribution identified here are structurally robust, even if their absolute magnitude would intensify under severe drought conditions.

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

The social weighting adopted in this study entails further limitations. The social vulnerability indicator partly relies on provincial-level data (ISTAT, 2020; Lasagni et al., 2015), 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 does not fully capture adaptive capacity specifically related to water governance, such as local policy effectiveness, emergency response capacity, or infrastructure investment.

These uncertainties are particularly relevant when interpreting the distributive governance implications of the analysis. Variability in withdrawal coefficients, climatic conditions, and social indicators may influence the precise ranking of hotspots. Consequently, the results should be understood as indicative of relative patterns of pressure, hydrological stress, and socially differentiated impact, rather than as prescriptive allocations of regulatory responsibility. The framework is therefore best conceived as a decision-support diagnostic tool that complements, rather than substitutes for, formal basin-level governance processes operating under climatic uncertainty.

5 Conclusion

This study develops and applies a territorially coherent subregional hydro-economic framework to analyse the redistribution of volumetric water demand (WF), pressure, hydrological stress, and socially differentiated impact within an internally connected regional economy. By integrating MRIO-based volumetric water demand accounts (WFP and WFC) with pressure (EWEI), hydrological stress (WSI), and social vulnerability (SV), the framework operationalises water scarcity as an outcome of the interaction between economic demand, local renewable availability, and socio-institutional conditions.

The results show that volumetric water demand alone does not fully capture the spatial configuration of hydrological stress and socially differentiated impact. Territories with comparable levels of volumetric water demand may exhibit substantially different impact-based indicators (SWF and SoSWF) once hydrological constraints and vulnerability are considered. This demonstrates that the internal redistribution of pressure and stress through interlinked production and consumption networks generates differentiated exposure patterns within a single region.

Importantly, the analytical scale of LLS enables the identification of producer–consumer asymmetries and intra-regional redistribution processes that remain structurally aggregated in national-level assessments. At the same time, the coherent aggregation of LLS to sub-basin and river basin levels ensures consistency with existing governance structures. In this sense, the framework does not redefine institutional boundaries but provides a diagnostic layer that can inform basin-based planning and regional policy instruments.

The contribution of this study lies not in replacing volumetric or national-scale indicators, but in extending them. By explicitly linking volumetric water demand, pressure, hydrological stress, and social vulnerability within a unified territorial accounting system, the framework supports a more differentiated understanding of impact-based water risk. Rather than prescribing specific interventions, it provides structured evidence on where hydrological stress and social fragility co-locate, thereby assisting decision-makers in evaluating trade-offs, prioritising measures, and considering distributive implications under climatic uncertainty.

Future research may extend this approach by incorporating dynamic hydrological scenarios, additional water components, and interregional virtual water exchanges beyond the regional boundary. Nonetheless, the present analysis demonstrates that integrating hydro-economic accounting with spatially differentiated vulnerability metrics enhances the capacity to interpret water scarcity as a coupled human–water phenomenon and to support more informed, territorially grounded water governance.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

TP: Writing – original draft, Formal analysis, Visualization, Data curation, Writing – review & editing, Investigation, Conceptualization, Methodology. GS: Writing – original draft, Investigation, Visualization, Data curation, Conceptualization, Writing – review & editing, Formal analysis, Methodology. JE: Writing – original draft, Writing – review & editing, Investigation, Formal analysis, Visualization, Methodology, Data curation, Conceptualization. BR: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. CB: Writing – review & editing. EC: Writing – review & editing.

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Conflict of interest

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