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Hydro-economic equilibrium with climatic variability in interconnected local economies

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Abstract:	This study addresses the challenge of unsustainable water use in regional economies, where productive activities and water availability are unevenly distributed in space and time. The objective is to assess the economic implications of this spatial mismatch and to provide a tool for identifying feasible pathways toward sustainable water use. Focusing on the case of Tuscany, Italy, we develop an interregional input–output (IO) model extended to include hydrological variability and a detailed representation of economic interdependencies across Labor Market Areas (LMA). The model explicitly integrates hydrology and economics, enabling the estimation of subregional water scarcity thresholds and the economic cost of overexploitation. A key and novel contribution of this study is the development of an original indicator—the Cost of Hydro-Economic Equilibrium (CHEE)—which quantifies, in monetary terms, the value of production currently sustained by unsustainable water use. This allows for the identification of areas under pressure and supports the design of targeted water management strategies, including improvements in water-use efficiency and investment in infrastructure. The results confirm that Tuscany exhibits significant spatial heterogeneity in water scarcity, with several local economies operating under hydrological stress. The study offers a framework to evaluate the opportunity cost of transitioning toward sustainable water allocation and provides a foundation for future applications such as the accounting and valuation of water-related natural capital, contributing to both scientific understanding and evidence-based public policy.

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To the Editors of
Ecological Economics

Dear colleagues,

I am glad to submit to Economic Ecological, together with my coauthors Benedetto Rocchi and Renato Paniccià, the paper titled "Hydro-economic equilibrium with climatic variability in a subregional input-output framework: the case of Tuscany".

The paper presents an interregional input-output model extended to water resources. This model incorporates elements that have been scarcely studied or not yet addressed in the literature:

1. It is applied to the 49 local economies of the Tuscany region in Italy, utilizing an interregional input-output table with sufficient economic granularity to approximate the unit of hydrological analysis, namely, the basin or sub-basin.
2. It accounts for the natural supply of groundwater and surface water through a spatial stochastic hydrological model, enabling the simulation of water supply series with a spatial structure. This hydrological model also includes precipitation and evapotranspiration, which are relevant elements in the agricultural sector.
3. In addition to water supply variability, the model considers the endogenous variability of agricultural water demand and dilution water demand (gray water), both of which depend on water availability.
4. Endogenous water scarcity thresholds are estimated, taking into account intra-annual variability in water supply and demand. These thresholds are calculated by optimizing the natural regulation capacity of aquifers.

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5. The concept of hydro-economic equilibrium is proposed for local economies that are productively interconnected. This allows for the estimation of the (optimal) value of production generated through the overexploitation of water resources, considering both their quantity and quality.

I would like to highlight the last point, which, in my perspective and that of my co-authors, represents the main contribution of this study to the literature. This is because it intimately integrates the productive structure with the hydrological structure of the region, enabling an interconnected (both economic and hydrological) approach to ecological (aquatic ecosystems) and economic problems. Moreover, it allows for the spatially precise simulation of the impact and effectiveness of public policies.

Alongside the description of the economic model and the analysis of the results, the paper also provides the essential elements needed to understand the role played by the hydrological component. For interested readers, additional information on data, assumptions, and procedures followed in the empirical application to Tuscany is provided in a Supplementary Materials document.

We hope to have the opportunity to share our research we the readers of Ecological Economics.

Best regards,

Gino Sturla

Firenze, 18/03/2025

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Title Page

HYDRO-ECONOMIC EQUILIBRIUM WITH CLIMATIC VARIABILITY IN A SUBREGIONAL INPUT-OUTPUT FRAMEWORK: THE CASE OF TUSCANY

BENEDETTO ROCCHI, RENATO PANICCIÀ, GINO STURLA

Abstract

An interregional IO model of a regional economy (Tuscany, IT) extended to water resources is used to provide an economic assessment of water resources overexploitation. A comprehensive representation of the interdependencies between hydrological and productive systems, allows to define a set of endogenous thresholds of water scarcity and the conditions for the hydro-economic equilibrium of the regional economy. Despite only 24% of the annual supply of freshwater is used for production, on average about 172 Mm^3 of water are used in condition of scarcity, due to a spatial mismatch between supply and demand. The opportunity cost to reach the absence of overexploitation in all sub-regional areas would be 129 Euro for each m^3 of water used in condition of scarcity. Hydro-economic equilibrium would require a decrease of about 10% of the regional output, a value that would be increased to 14% in a climate change scenario.

Keywords

Water Scarcity, Input-output, Interregional Models, Tuscany, Climate Change

JEL Codes

D57, Q25, Q56

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Dear Editor

We are pleased to submit the revised version of our manuscript titled "Hydro-economic equilibrium with climatic variability in interconnected local economies". We greatly appreciate the valuable and insightful comments provided by the two reviewers, which have significantly enhanced the quality and clarity of our work. In response to their feedback, we have made extensive revisions to the manuscript. These changes are reflected in the tracked version of the text and detailed in the four response letters we have prepared for the reviewers. We believe the revised manuscript is conceptually and technically solid, and it is also aligned with the scientific objectives of *Ecological Economics*. We thank you for the opportunity to revise our work and hope it meets the expectations of the editorial team and reviewers.

What follows presents in detail the responses to both reviewers. The reviewers' comments are indicated in bold.

REVIEWER #1

The manuscript examines the water and economic balance in a region and uses various methods to measure the interactions. Although the paper has some interesting features, the following concerns also exist.

1- The abstract is incomplete. The study's objective and problem statement are not clearly stated.

Thank you for the comment. Indeed, the original abstract did not fully capture the essence of the study, and the research objectives and problem statement were not clearly stated. We have now revised this section accordingly.

"This study addresses the challenge of unsustainable water use in regional economies, where productive activities and water availability are unevenly distributed in space and time. The objective is to assess the economic implications of this spatial mismatch and to provide a tool for identifying feasible pathways toward sustainable water use. Focusing on the case of Tuscany, Italy, we develop an interregional input–output (IO)

model extended to include hydrological variability and a detailed representation of economic interdependencies across Labor Market Areas (LMA). The model explicitly integrates hydrology and economics, enabling the estimation of subregional water scarcity thresholds and the economic cost of overexploitation. A key and novel contribution of this study is the development of an original indicator—the Cost of Hydro-Economic Equilibrium (CHEE)—which quantifies, in monetary terms, the value of production currently sustained by unsustainable water use. This allows for the identification of areas under pressure and supports the design of targeted water management strategies, including improvements in water-use efficiency and investment in infrastructure. The results confirm that Tuscany exhibits significant spatial heterogeneity in water scarcity, with several local economies operating under hydrological stress. The study offers a framework to evaluate the opportunity cost of transitioning toward sustainable water allocation and provides a foundation for future applications such as the accounting and valuation of water-related natural capital, contributing to both scientific understanding and evidence-based public policy."

2- The proposed suggestion regarding reducing production is naturally unacceptable to policymakers. Is there no alternative suggestion?

Thank you very much for this observation. This is indeed a sensitive and important point. The purpose of the study is not to suggest a reduction in production as a policy recommendation—which, as you rightly note, would be unacceptable, unfeasible, and inefficient—but rather to estimate, in the short term, the production cost of achieving hydro-economic equilibrium. The proposed indicator is not prescriptive; instead, it aims to quantify the value of economic output currently sustained by the overexploitation of water resources. This indicator is calculated both at the regional and local economy levels.

From a public policy perspective, the indicator provides a measure of the opportunity cost of water use. In essence, it shows how much society is currently willing to overexploit one cubic meter of water in order to generate one monetary unit of output. If the societal goal is to transition toward a more sustainable production model, doing so entails a cost. That cost, in theoretical terms, would involve "artificially" reducing production and, consequently, value added. However, the indicator can be interpreted differently: instead of reducing production, technological changes can be introduced to decrease the amount of production that depends on unsustainable water use. These measures must carry a monetary cost lower than the value added currently generated by unsustainable practices.

This is the concrete contribution of the study to public policy: to provide a tangible, monetary metric (in terms of output, convertible to value added) that can inform the design of technological or institutional solutions, under the principle that such solutions must be less costly than the gains derived from transitioning to sustainable production.

We have included a paragraph in the Discussion (Section 6.2) that clearly addresses this point:

"A key contribution of this study to public policy lies in the development of an indicator that quantifies, in monetary terms, the short-term production cost of achieving hydro-economic equilibrium. It is essential to clarify that this does not represent a recommendation to reduce production. Such an approach would be not only politically unacceptable, but also economically unfeasible and inefficient. Rather, the purpose of the indicator is to estimate the current value of economic output that is sustained through the overexploitation of water resources. Calculated at both regional and local levels, the indicator provides a measure of the opportunity cost of water use—namely, how much society is implicitly willing to overexploit one cubic meter of water to produce one monetary unit of output. From a policy perspective, this metric is not prescriptive but informative: it highlights the trade-offs involved in pursuing sustainability goals and offers a benchmark for evaluating alternative measures. In particular, it can guide the design of technological or institutional interventions aimed at reducing the reliance on unsustainable water use, under the condition that their implementation cost remains lower than the value currently generated through overexploitation. In this sense, the indicator serves as a practical tool to support economically sound and environmentally responsible water management strategies."

3- The problem statement and research necessity are not convincingly demonstrated for the study area. Documentation should be provided to prove the need for research in the target region.

Thank you for the comment, as it is indeed not sufficiently clear why Tuscany is a suitable case study. We have added a paragraph in the introduction emphasizing this point:

"The selection of Tuscany as a case study is grounded in the region's unique combination of water abundance at the aggregate level and significant localized scarcity due to spatial mismatches between natural supply and economic demand. While Tuscany is typically characterized as a water-abundant region, previous studies (Rocchi et al., 2024; Sturla and Rocchi, 2024) have shown that this classification masks critical subregional imbalances. Those studies, which applied a regional-scale water exploitation index (EWEI), found no evidence of overall scarcity, even under hydrological stress scenarios. However, their analyses assumed spatial homogeneity in water supply and demand, and perfect substitutability between surface and groundwater. In contrast, when disaggregated, the EWEI for surface water alone often exceeds established scarcity thresholds, suggesting that specific subregions may indeed face persistent overexploitation. This is supported by evidence of high spatial variability in water availability (Fatichi and Caporali, 2009; Bartolini et al., 2018) and highly uneven patterns of water withdrawals and discharges across the region (Venturi et al., 2014). Additionally, the spatial distribution of productive activities frequently misaligns with hydrological units, partly due to the legacy structure of water concessions within river basins (Venturi et al., 2014). These mismatches—between the spatial pattern of water needs and that of available resources—highlight an overlooked but pressing form of water stress: localized scarcity within seemingly abundant regions. Such situations are increasingly relevant under climate variability and changing land use dynamics. Tuscany thus serves as a representative and policy-relevant case for testing methodologies aimed at identifying and managing water scarcity at high spatial resolution. By developing an interregional hydro-economic input–output model with spatiotemporal hydrological variability, this study responds directly to the need for improved tools to assess subregional water scarcity in contexts that, like Tuscany, exhibit aggregate abundance but hidden vulnerabilities."

4- A conceptual framework should be developed to clearly illustrate the relationships between the various models used in this study.

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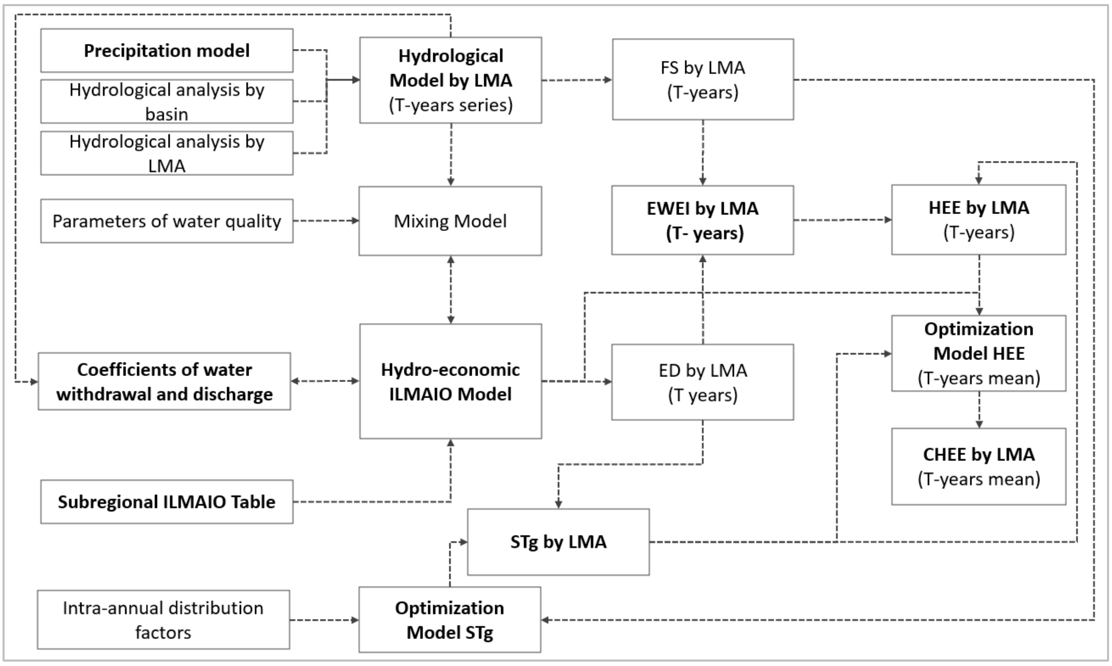
This point is very important—thank you for highlighting it. To clearly illustrate the methodological framework of the study, including the relationships between the hydrological model, the water quality model, and the economic model, we have developed a diagram. This diagram explicitly depicts the interactions among the models, which are also explained in the text. It has been incorporated into Section 4.1 "Overview." Below, we present both the diagram and its accompanying description:

Figure 1. Scheme of the methodology



Source: own elaboration

"Figure 1 presents a general overview of the methodology guiding this study. First, as detailed in the supplementary material, a spatially distributed model is developed to generate precipitation across the region based on meteorological station records. Together with a hydrological analysis at both the basin and LMA (Local Management Area) levels, this enables the construction of a hydrological model capable of producing synthetic time series of precipitation, evapotranspiration, groundwater recharge, and runoff by LMA. This model allows for the calibration of blue water use intensity coefficients (agricultural sector), estimation of grey water demand based on

water quality data and a mixing model (which depends on sectoral effluent discharges), and the determination of feasible supply (FS).

The ILMAIO hydroeconomic model is used to estimate the extended water demand (ED, including both blue and grey water), based on the region's ILMAIO table, blue water use intensity coefficients, and the mixing model outcomes for grey water. Using ED and FS, the Extended Water Exploitation Index (EWEI) is constructed for each LMA. The EWEI is then compared with the endogenous scarcity threshold for each LMA—obtained through an optimization process that accounts for annual distribution factors of surface and groundwater supply and demand, ED, and FS—thereby characterizing the hydroeconomic equilibrium (HEE) for local economies.

Finally, a macroeconomic optimization model, which maximizes production subject to the constraint that HEE is achieved in each LMA (EWEI < STg), is used to estimate the Cost of Hydroeconomic Equilibrium (CHEE), both regionally and by LMA. This cost represents the value of production sustained through water overexploitation, or equivalently, the opportunity cost of achieving the absence of overexploitation."

5- In the IO (Input-Output) model, Leontief coefficients are used, which assume linear relationships between inputs and outputs. However, many production relationships in agriculture, water, and climate sectors are nonlinear. How has this issue been addressed in the study?

Thank you for this important observation. We fully acknowledge the limitation inherent in the use of Leontief coefficients within the MRIO framework, which assume fixed input–output relationships and do not account for nonlinearities commonly observed in sectors such as agriculture, water, and climate-related systems. This is a well-known constraint of IO models and is explicitly addressed in the discussion of model limitations (section 6.3). As noted, the MRIO framework does not capture substitution effects, price adjustments, or behavioral responses—features that would require a CGE approach with flexible functional forms such as CES or nested production functions.

However, the choice of the MRIO model in this study is justified by its structural advantages for integrating economic and hydrological systems in a spatially explicit and empirically grounded manner (included in Introduction). Unlike CGE models, MRIO models allow for a more tractable incorporation of complex hydrological components (e.g., groundwater regulation, water mixing models, scarcity thresholds), which are difficult to embed in CGE frameworks due to data and structural constraints—particularly in contexts like Tuscany, where regionally disaggregated SAMs do not exist.

The following two paragraphs present, respectively, the justification for the use of the MRIO model and the limitations of this modeling approach:

"Regarding the choice of a multiregional input–output (MRIO) model over a computable general equilibrium (CGE) model, it is acknowledged, for example, that CGE models are powerful tools for simulating behavioral responses, market adjustments, and policy shocks. However, MRIO models allow for a more straightforward integration of elements that are highly complex to implement within a CGE framework—such as linkages between economic and hydrological systems, hydroeconomic optimization, and scenario simulation. For instance, Xin and Guo (2023) developed a multiregional CGE model for China with explicit constraints on water quantity and quality, which required deeply nested CES functions and custom-built social accounting matrices (SAMs) to integrate hydrological, environmental, and economic flows. While MRIO models do not capture price formation, substitution effects, or behavioral responses—as CGE models do—they offer a structurally consistent, demand-driven, empirically grounded framework, compatible with biophysical extensions and aligned with national accounts (Cazcarro et al., 2025; United Nations, 2021; Obst and Eigenraam, 2016)."

"As for the limitations of the MRIO framework, it does not simulate market behavior, price adjustments, or substitution elasticities, as CGE models do. As a demand-driven linear system with fixed technical coefficients, the MRIO model cannot capture behavioral responses to policy shocks or dynamic price interactions. Nevertheless, its structural consistency with national accounts and the transparency of its assumptions make it particularly well suited for integration with the SEEA-EA framework (United Nations, 2021). The model structure also provides a solid empirical foundation for the future development of multiregional CGE models based on SAMs and integrated with

water-related components—positioning MRIO as a complement, rather than a substitute, for behavioral modeling. This is a necessary future step, especially if the goal is to estimate the value of WES related to purification, provisioning, and regulation (e.g., groundwater) in order to operationalize the implementation of the NCA in Tuscany"

6- How is the hydrological model linked to the economic model? Are they solved together within a single model, or are they solved separately?

This is a central element of our work. In fact, the resolution of the overall framework explicitly includes the interaction between the hydrological model and the economic model. The hydrological model—including the mixing model—is essential for calibrating the intensity coefficients of blue water use in agriculture and grey water in the sectors that discharge into aquatic ecosystems. Moreover, both the hydrological and economic models, jointly, enable the calculation of scarcity thresholds. In short, the connection between hydrology and economics is quite strong. We have made this explicit in Section 4.1, specifically in the description of the overall methodological framework:

"Figure 1 presents a general overview of the methodology guiding this study. First, as detailed in the supplementary material, a spatially distributed model is developed to generate precipitation across the region based on meteorological station records. Together with a hydrological analysis at both the basin and LMA (Local Management Area) levels, this enables the construction of a hydrological model capable of producing synthetic time series of precipitation, evapotranspiration, groundwater recharge, and runoff by LMA. This model allows for the calibration of blue water use intensity coefficients (agricultural sector), estimation of grey water demand based on water quality data and a mixing model (which depends on sectoral effluent discharges), and the determination of feasible supply (FS).

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LMA. The EWEI is then compared with the endogenous scarcity threshold for each LMA—obtained through an optimization process that accounts for annual distribution factors of surface and groundwater supply and demand, ED, and FS—thereby characterizing the hydroeconomic equilibrium (HEE) for local economies.

Finally, a macroeconomic optimization model, which maximizes production subject to the constraint that HEE is achieved in each LMA (EWEI < STg), is used to estimate the Cost of Hydroeconomic Equilibrium (CHEE), both regionally and by LMA. This cost represents the value of production sustained through water overexploitation, or equivalently, the opportunity cost of achieving the absence of overexploitation."

7- The application of the IO model is unclear. Why were this method chosen? One of the keys uses of input-output analysis is to compare the roles of different production activities, but such results are missing in this study. It should be clarified which sectors have a larger role in water footprints or which are more responsive to economic policies.

This is a crucial point, and we appreciate the comment. We have included one paragraph in the literature review and another in the discussion (limitations) that address the choice of an IO model for calculating the cost of hydro-economic equilibrium, rather than a computable general equilibrium (CGE) model. These paragraphs acknowledge the limitations of IO models while also highlighting their advantages in terms of simplicity and transparency with respect to national accounts—especially given the complexity involved in integrating hydrological modules into a CGE framework. The two paragraphs are provided below (first from the literature review, then from the discussion).

"Regarding the choice of a multiregional input–output (MRIO) model over a computable general equilibrium (CGE) model, it is acknowledged, for example, that CGE models are powerful tools for simulating behavioral responses, market adjustments, and policy shocks. However, MRIO models allow for a more straightforward integration of elements that are highly complex to implement within a CGE framework—such as linkages between economic and hydrological systems, hydroeconomic optimization, and scenario simulation. For instance, Xin and Guo

(2023) developed a multiregional CGE model for China with explicit constraints on water quantity and quality, which required deeply nested CES functions and custom-built social accounting matrices (SAMs) to integrate hydrological, environmental, and economic flows. While MRIO models do not capture price formation, substitution effects, or behavioral responses—as CGE models do—they offer a structurally consistent, demand-driven, empirically grounded framework, compatible with biophysical extensions and aligned with national accounts (Cazcarro et al., 2025; United Nations, 2021; Obst and Eigenraam, 2016)."

"As for the limitations of the MRIO framework, it does not simulate market behavior, price adjustments, or substitution elasticities, as CGE models do. As a demand-driven linear system with fixed technical coefficients, the MRIO model cannot capture behavioral responses to policy shocks or dynamic price interactions. Nevertheless, its structural consistency with national accounts and the transparency of its assumptions make it particularly well suited for integration with the SEEA-EA framework (United Nations, 2021). The model structure also provides a solid empirical foundation for the future development of multiregional CGE models based on SAMs and integrated with water-related components—positioning MRIO as a complement, rather than a substitute, for behavioral modeling. This is a necessary future step, especially if the goal is to estimate the value of WES related to purification, provisioning, and regulation (e.g., groundwater) in order to operationalize the implementation of the NCA in Tuscany"

Regarding the estimation of the water footprint for each LMA in the region—disaggregated at the LMA level—this is an area we are currently working on, including water and social scarcity components. However, it falls outside the scope of the present study. The use of the input–output model serves two primary purposes in this work:

i. Disaggregating final demand at the LMA level.

ii. Calculating the cost of hydro-economic equilibrium while accounting for interregional and intersectoral productive linkages.

In the section (6.3), we have included a discussion of future work, which highlights, among other aspects, the importance of using this type of model to calculate and disaggregate the water footprint while incorporating scarcity and social dimensions. The paragraph is detailed below.

"A final element related to future work involves using the model to estimate the water footprint (WF) within the Tuscany region for each local economy, spatially disaggregated and accounting for both physical water scarcity (SWF) and social water scarcity (SoSWF), as demonstrated, for example, in Sturla et al. (2023). The input–output approach is particularly well suited for this type of analysis, which can contribute to a deeper understanding of hydro-socioeconomic linkages within the region and help identify those local economies that generate the greatest volumetric, scarcity-related, and socially driven water impacts."

The following is a list of the new references used, which we believe provide a much more robust theoretical and empirical foundation for the paper.

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REVIEWER #2

This study develops an integrated hydro-economic framework combining hydrological modeling and inter-regional input-output (IRIO) analysis, using Italy's Tuscany region as a case study to explore the dynamic interactions between regional economic systems and water resources. While the research holds academic merit, the following aspects require improvement:

1. The rationale for selecting the case study region needs strengthening. As Tuscany is generally water-abundant, the representativeness of choosing it as a water scarcity case study requires more systematic justification. Specific manifestations of the "spatial mismatch between supply and demand", as stated in the paper, should be strengthened. Moreover, existing research gaps in studying localized scarcity in regions with similar natural (water, weather) conditions, thereby highlighting this case's representative value.

Thank you for the comment, as it is indeed not sufficiently clear why Tuscany is a suitable case study. We have added a paragraph in the introduction emphasizing this point:

"The selection of Tuscany as a case study is grounded in the region's unique combination of water abundance at the aggregate level and significant localized scarcity due to spatial mismatches between natural supply and economic demand. While Tuscany is typically characterized as a water-abundant region, previous studies (Rocchi et al., 2024; Sturla and Rocchi, 2024) have shown that this classification masks critical subregional imbalances. Those studies, which applied a regional-scale water exploitation index (EWEI), found no evidence of overall scarcity, even under hydrological stress scenarios. However, their analyses assumed spatial homogeneity in water supply and demand, and perfect substitutability between surface and groundwater. In contrast, when disaggregated, the EWEI for surface water alone often exceeds established scarcity thresholds, suggesting that specific subregions may indeed face persistent overexploitation. This is supported by evidence of high spatial variability in water availability (Fatichi and Caporali, 2009; Bartolini et al., 2018) and highly uneven patterns of water withdrawals and discharges across the region

(Venturi et al., 2014). Additionally, the spatial distribution of productive activities frequently misaligns with hydrological units, partly due to the legacy structure of water concessions within river basins (Venturi et al., 2014). These mismatches—between the spatial pattern of water needs and that of available resources—highlight an overlooked but pressing form of water stress: localized scarcity within seemingly abundant regions. Such situations are increasingly relevant under climate variability and changing land use dynamics. Tuscany thus serves as a representative and policy-relevant case for testing methodologies aimed at identifying and managing water scarcity at high spatial resolution. By developing an interregional hydro-economic input–output model with spatiotemporal hydrological variability, this study responds directly to the need for improved tools to assess subregional water scarcity in contexts that, like Tuscany, exhibit aggregate abundance but hidden vulnerabilities."

2. The model treats groundwater and surface water as independent variables, while in reality they exhibit dynamic recharge relationships through hydrological cycles (e.g., surface water infiltration replenishing groundwater during rainy seasons). This simplification may underestimate water resource resilience in dry years, potentially overestimating scarcity risks.

This is a very important point. A first consideration is that, in Tuscany, pressure on surface water resources is significantly higher than on groundwater resources (Sturla and Rocchi, 2024). For this reason, the analysis disaggregates surface and groundwater resources; however, key indicators such as the Extended Water Exploitation Index (EWEI), the Hydro-Economic Equilibrium (HEE), and its associated cost (CHEE) are calculated by jointly considering both sources. In fact, the estimation of the endogenous scarcity threshold—explained in Section 4.5 of the methodology—explicitly incorporates the potential for intra-annual groundwater management. This reflects the resilience provided by aquifers, as water can be stored during months with lower demand and withdrawn in the critical month, thus reducing overall scarcity.

Nevertheless, as the reviewer rightly points out, the model does not capture the physical interactions between surface and groundwater—such as recharge from surface infiltration during wet periods—nor the potential for interannual storage and regulation. These hydrological feedbacks may indeed increase system resilience and reduce effective scarcity, particularly in dry years. Incorporating such dynamics, as well as the regulation capacity of surface reservoirs (present in some basins in Tuscany), would enhance the realism of the hydro-economic system's response under climate stress. This limitation has been explicitly acknowledged and discussed in Section 6.3 of the manuscript.

"An important limitation of the current model lies in its treatment of surface water and groundwater as independent sources. While this disaggregation is analytically useful—especially given the greater pressure observed on surface water in Tuscany—it overlooks key hydrological interactions between the two sources. In particular, the model does not capture dynamic recharge relationships, such as the infiltration of surface water contributing to groundwater replenishment during wet seasons, nor does it consider interannual storage dynamics. These processes can provide substantial resilience to the water system, especially in dry years, and their omission may lead to an overestimation of water scarcity risks. Although the model incorporates intra-annual groundwater management when estimating scarcity thresholds—thereby partially reflecting the buffering capacity of aquifers—future work should explore more integrated representations of the hydrological cycle. This could include explicit modeling of surface–groundwater interactions and the regulation capacity of existing reservoirs, thereby enhancing the model's realism and its policy relevance under climate variability and change."

3. The climate change scenario settings are overly simplistic. The current approach only adjusts precipitation means and variances, failing to account for frequency changes of extreme weather events and their non-linear impacts on agricultural water demand.

Indeed, we conducted only a sensitivity analysis rather than using climate change scenarios derived from global circulation models. The scope of this study does not include assessing how the Tuscan economy would respond to projected changes in runoff and groundwater recharge under climate change. The development of a hydrological model at the scale of the economy, incorporating uncertainty, has been a demanding and complex task. As detailed in the supplementary material, determining the hydrological components for each local economy required considerable effort, involving water balance estimations at the watershed level to ensure coherence between the economic and hydrological scales. While the sensitivity analysis performed addresses a concrete issue—namely, a decrease in average annual precipitation and an increase in its variability—future work (which is currently underway) will incorporate climate change projections using non-stationary time series. Below we present the paragraph included in the limitations section, where this point is clarified. Finally, regarding extreme events, we fully agree that this is a highly relevant issue for water policy in the region (and globally); however, the temporal scale of such events is typically daily or even hourly, and thus cannot be captured by a model of this type. This point has also been explicitly acknowledged as a limitation of the study.

"Regarding climate change projections, this study does not aim to represent hydrological components under future climate change scenarios using global circulation model outputs. These models provide precipitation and temperature data under different socioeconomic scenarios (IPCC, 2021), which can be used to estimate runoff and groundwater recharge through non-stationary time series, thus exposing the productive structure to more realistic future climate scenarios (Distefano et al., 2025). What has been done in this study is a sensitivity analysis based on the main expected effects of climate change on precipitation in Tuscany: a decrease in average annual precipitation and an increase in its variability. In this sense, while not within its core scope, the study partially addresses a highly relevant dimension. This is, in the authors' view, a valuable contribution that will serve as a foundation for future work involving climate data extraction, downscaling to sub-basin and LMA levels, and the estimation of runoff and groundwater recharge under climate change. Finally, it should be noted that the BIGBANG platform (ISPRA, 2024) will be highly useful for incorporating climate change into the model, as it is currently producing gridded hydrological data under climate change scenarios."

"Regarding extreme events, which may be highly relevant for water policy, the model developed does not allow for their representation. This is because such events occur at daily or even hourly scales, while the input–output model operates at an annual temporal resolution, disaggregated to monthly data only for the purpose of calculating scarcity thresholds. This limitation is difficult to overcome within the structure of this type of model and would require the use of physically based hydrological models with

high temporal resolution (e.g., hourly). Nevertheless, the model developed could offer insights into which local economies are more exposed to such extreme events—whether related to excess or scarcity. This represents a highly relevant topic for future research."

4. Policy implications lack practical relevance. Recommendations should be better grounded in Tuscany's specific policies to propose more concrete operational measures.

We have revised the section of the manuscript dedicated to policy implications, creating a new subsection titled *"Practical and policy implications"* within the Discussion. Thank you for highlighting this point, as both the work developed and future extensions based on it are intended to inform public policy in the Tuscany region. Moreover, this research was funded by the regional authorities of Tuscany with the objective of improving water management and evaluating scenarios involving technological and infrastructure-related changes. Importantly, the model developed also provides a useful basis for advancing the implementation of the Natural Capital Approach (NCA) in the region, by enabling the integration of hydrological and economic dimensions into spatially explicit decision-making.

"6.2 Practical and policy implications

When looking at the average annual value of the EWEI, Tuscany appears to be a water-abundant region. Only 24% of the annual "feasible" supply of freshwater (adjusted to account for technological and institutional constraints) is needed to meet the demand for blue and grey water. According to standard approaches to water footprint analysis in environmental studies (Pfister et al., 2009), such an average would indicate an "absence of scarcity problems." However, the natural variability of water supply can nearly double the value of the regional indicator in critical years (even more so under climate change scenarios). Moreover, the uneven spatial distribution of water resources and economic activity leads to more frequent scarcity conditions at the subregional scale. In a base hydrological scenario (reproducing the natural variability of the past 40 years), an average of 172 million m³ of blue water is used under scarcity conditions—i.e., exceeding thresholds that ensure environmental *sustainability (minimum ecological flows and non-decreasing aquifer stocks). In 5 out of 49 subregional areas, this condition is likely to be permanent. In 14 areas, water scarcity occurs at least once every four years, on average.*

The relevance of these results goes beyond the empirical application of the model to support regional water policy decisions. The case of Tuscany shows how critical the scale of analysis is when using input–output models for water footprint assessment. The more aggregated the evaluation of water pressures, the less useful volumetric water footprint measures become for management and environmental analysis. Some forms of scarcity-based weighting of water pressures are used in global water footprint analyses (Wichelns, 2017; Ridoutt et al., 2018; Sturla et al., 2023). However, the adoption of standard methods and thresholds may not be sensitive enough to account for the extreme spatial heterogeneity in the distribution of water supply and demand. Applying such methodologies (Pfister et al., 2009) to a regional economy like Tuscany would indicate an almost complete absence of water scarcity problems; even more distorted might be national-level assessments of water pressures, such as those used in the global water footprint literature. Water scarcity issues arise and must be managed at the local level. Our findings call for caution when modeling water–economy interactions globally as a basis for designing sustainability strategies.

The inter-LMA structure of the regional IO table enabled an in-depth analysis of internal water–economy interdependencies in Tuscany. Local scarcity thresholds were defined, considering natural supply variability and the specific sectoral composition of each LMA. Trade flows among LMAs redefine the map of water pressures generated by exogenous economic shocks or policy-imposed restrictions on water use. These features make the model suitable for impact assessments supporting regional water management. We extended the structural analysis to estimate what we call the CHEE: the minimum reduction in regional output consistent with the absence of water scarcity conditions—not only at the regional level but also across all LMAs—holding the sectoral mix and water technologies constant. In the base hydrological scenario, the regional CHEE amounts to €21.298 billion, about 10% of regional output; under a climate change scenario, this rises to €30.035 billion (14% of total output). This value serves as a useful benchmark for evaluating regional water policies aimed at reducing water imbalances, both in quantitative and qualitative terms, as required by the EU regulatory framework. New regulations to improve discharge quality, promote more *efficient irrigation technologies, or invest in water regulation infrastructure can all be assessed based on their ability to reduce the regional CHEE. Notably, the model's interregional structure allows for assessing local investments in terms of the regional benefits they generate.*

The model also allows for estimating the cost of hydro-economic equilibrium at the local level. The opportunity cost of reducing by one cubic meter the excess of demand over feasible supply varies across LMAs, and this variation should be considered when prioritizing investments and water management decisions under limited financial resources. Although the CHEE adopts a short-run, comparative static perspective, it can be readily extended to include choices among alternative technologies (Duchin and Levine, 2012) or to model the price impacts of regulatory measures on tariffs and concessions using Ghosh linkages (Dietzenbacher, 2002).

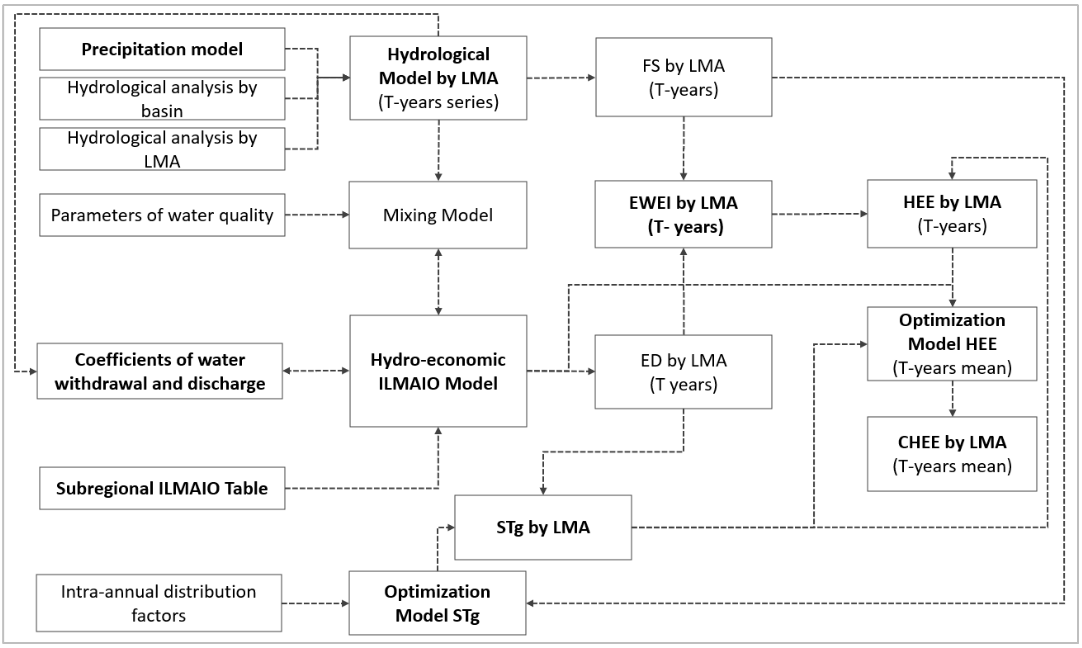
Another important policy implication relates to the implementation of the Natural Capital Approach (NCA) in Italy (NCAVES and MAIA, 2022; United Nations, 2021). Among the most essential natural resources—supporting directly or indirectly most ecosystem services (ES)—is water. Water is closely associated with provisioning, purification, and regulation services, including physical regulation, flood protection, and chemical condition (CICES: Haines-Young & Potschin, 2018), and underpins a wide array of services such as nutrient cycling, sediment retention, erosion control, recreation, and tourism (United Nations, 2021; TEEB, 2010; MEA, 2005). Implementing the NCA in the context of WES requires both their quantification and economic valuation, which this study advances, leaving for future work the implementation of monetary valuation of WES and natural water capital (NWC). The substantive contribution of an IO model lies in its capacity to capture both the direct and indirect economic contributions of WES to the national economy—a gap still largely unaddressed in the international literature and highly relevant for Tuscany (and Italy). Bridging this knowledge gap requires methodological tools that link economic structures with hydrological ecosystems."

5. Regarding paper structure optimization, I suggest adding a conceptual framework diagram illustrating data coupling processes between hydrological and economic modules, along with key interactive variables. Moreover, I also

suggest a separate discussion section be added to systematically elaborate on theoretical and practical implications

This point is very important—thank you for highlighting it. To clearly illustrate the methodological framework of the study, including the relationships between the hydrological model, the water quality model, and the economic model, we have developed a diagram. This diagram explicitly depicts the interactions among the models, which are also explained in the text. It has been incorporated into Section 4.1 "Overview." Below, we present both the diagram and its accompanying description:

Figure 1. Scheme of the methodology



Source: own elaboration

"Figure 1 presents a general overview of the methodology guiding this study. First, as detailed in the supplementary material, a spatially distributed model is developed to generate precipitation across the region based on meteorological station records. Together with a hydrological analysis at both the basin and LMA (Local Management Area) levels, this enables the construction of a hydrological model capable of producing synthetic time series of precipitation, evapotranspiration, groundwater recharge, and runoff by LMA. This model allows for the calibration of blue water use

intensity coefficients (agricultural sector), estimation of grey water demand based on water quality data and a mixing model (which depends on sectoral effluent discharges), and the determination of feasible supply (FS).

The ILMAIO hydroeconomic model is used to estimate the extended water demand (ED, including both blue and grey water), based on the region's ILMAIO table, blue water use intensity coefficients, and the mixing model outcomes for grey water. Using ED and FS, the Extended Water Exploitation Index (EWEI) is constructed for each LMA. The EWEI is then compared with the endogenous scarcity threshold for each LMA—obtained through an optimization process that accounts for annual distribution factors of surface and groundwater supply and demand, ED, and FS—thereby characterizing the hydroeconomic equilibrium (HEE) for local economies.

Finally, a macroeconomic optimization model, which maximizes production subject to the constraint that HEE is achieved in each LMA (EWEI < STg), is used to estimate the Cost of Hydroeconomic Equilibrium (CHEE), both regionally and by LMA. This cost represents the value of production sustained through water overexploitation, or equivalently, the opportunity cost of achieving the absence of overexploitation."

As you rightly suggested, we have also developed a separate discussion, outlining the theoretical and practical implications of the study. Section 6 "Discussion" has been added and is structured into four subsections: theoretical implications, practical and policy implications, and limitations and future work. The full section is presented below:

"6. Discussion

6.1 Theoretical implications

The study developed here, unlike previous water-extended IO models (Rocchi et al., 2024; Sturla and Rocchi, 2024), incorporates theoretical and methodological innovations, notably the concept of hydro-economic equilibrium (HEE) with endogenous scarcity thresholds and the cost of hydro-economic equilibrium (CHEE).

HEE allows characterizing water scarcity in each local economy based on the EWEI and STm. This characterization considers hydrological dynamics, enabling a more realistic modeling of the replacement of green water with blue water in agriculture, *as well as the grey water requirements of sectors that discharge into aquatic ecosystems. EWEI values and their variations are assessed against endogenous scarcity thresholds. Previously, such models only considered thresholds from the literature, which do not allow for a localized characterization of water scarcity (Raskin et al., 1997; Alcamo et al., 2000; Pfister et al., 2009; CIRCABC, 2012). By incorporating intra-annual variability of supply and demand, together with optimal groundwater management, these thresholds offer a more realistic reflection of when a local economy is in hydro-economic equilibrium, taking into account its specific characteristics. This theoretical approach represents an evolution in environmentally extended water IO models, which—by tightly combining economic, hydrological, and water quality components—pave the way for a new generation of models we may call hydrologically extended IO models.*

As for the CHEE, this concept is entirely new in the literature. Theoretically, it corresponds to an optimization problem in which production is maximized under the constraint that all local economies must be in HEE. The control variable is the vector of final demand, consistent with the demand-driven nature of the IO model. The use of a multiregional water-extended (or hydrologically extended) IO model is key, as it captures interregional and intersectoral productive relationships. Conceptually, the CHEE represents a short-run measure of the optimal level of production that depends on the overexploitation—both in quantity and quality—of water resources; in other words, it measures the cost in terms of forgone optimal output required to eliminate water scarcity. This concept provides a metric of the trade-off between production and sustainability in water use. While MRIO models do not capture price formation, substitution effects, or behavioral responses (as CGE models do, see section 6.4), they offer a structurally consistent, demand-driven, empirically grounded framework, compatible with biophysical extensions and aligned with national accounts (Cazcarro et al., 2025; United Nations, 2021; Obst and Eigenraam, 2016).

CHEE can also serve as a first step toward a more comprehensive environmental analysis of water use. Each cubic meter of water used beyond the local endogenous scarcity threshold is likely to generate adverse environmental impacts within and beyond the hydrological system. Temporary or permanent variations in ecosystem services (ES) in response to unsustainable water use could be compared with the CHEE, which represents the economic return from overexploitation. Moreover, this *proposed opportunity cost could be used to economically value water ecosystem services (WES) using the opportunity cost method (Legesse et al., 2022; NCAVES and MAIA, 2022), for the first time within an IO modeling framework. Specifically, by maximizing the economy's value added instead of total output (in the optimization problem) and assuming that this value added represents the best alternative use of water, the value of provisioning and purification WES (provided by natural surface and groundwater sources) could be estimated. Regarding regulation services, the difference between the opportunity cost with and without optimal groundwater management could serve as a proxy for the value of groundwater-related regulation services.*

6.2 Practical and policy implications

When looking at the average annual value of the EWEI, Tuscany appears to be a water-abundant region. Only 24% of the annual "feasible" supply of freshwater (adjusted to account for technological and institutional constraints) is needed to meet the demand for blue and grey water. According to standard approaches to water footprint analysis in environmental studies (Pfister et al., 2009), such an average would indicate an "absence of scarcity problems." However, the natural variability of water supply can nearly double the value of the regional indicator in critical years (even more so under climate change scenarios). Moreover, the uneven spatial distribution of water resources and economic activity leads to more frequent scarcity conditions at the subregional scale. In a base hydrological scenario (reproducing the natural variability of the past 40 years), an average of 172 million m³ of blue water is used under scarcity conditions—i.e., exceeding thresholds that ensure environmental sustainability (minimum ecological flows and non-decreasing aquifer stocks). In 5 out of 49 subregional areas, this condition is likely to be permanent. In 14 areas, water scarcity occurs at least once every four years, on average.

The relevance of these results goes beyond the empirical application of the model to support regional water policy decisions. The case of Tuscany shows how critical the scale of analysis is when using input–output models for water footprint assessment. The more aggregated the evaluation of water pressures, the less useful volumetric water footprint measures become for management and environmental analysis. Some forms of scarcity-based weighting of water pressures are used in global water footprint *analyses (Wichelns, 2017; Ridoutt et al., 2018; Sturla et al., 2023). However, the adoption of standard methods and thresholds may not be sensitive enough to account for the extreme spatial heterogeneity in the distribution of water supply and demand. Applying such methodologies (Pfister et al., 2009) to a regional economy like Tuscany would indicate an almost complete absence of water scarcity problems; even more distorted might be national-level assessments of water pressures, such as those used in the global water footprint literature. Water scarcity issues arise and must be managed at the local level. Our findings call for caution when modeling water–economy interactions globally as a basis for designing sustainability strategies.*

The inter-LMA structure of the regional IO table enabled an in-depth analysis of internal water–economy interdependencies in Tuscany. Local scarcity thresholds were defined, considering natural supply variability and the specific sectoral composition of each LMA. Trade flows among LMAs redefine the map of water pressures generated by exogenous economic shocks or policy-imposed restrictions on water use. These features make the model suitable for impact assessments supporting regional water management. We extended the structural analysis to estimate what we call the CHEE: the minimum reduction in regional output consistent with the absence of water scarcity conditions—not only at the regional level but also across all LMAs—holding the sectoral mix and water technologies constant. In the base hydrological scenario, the regional CHEE amounts to €21.298 billion, about 10% of regional output; under a climate change scenario, this rises to €30.035 billion (14% of total output). This value serves as a useful benchmark for evaluating regional water policies aimed at reducing water imbalances, both in quantitative and qualitative terms, as required by the EU regulatory framework. New regulations to improve discharge quality, promote more efficient irrigation technologies, or invest in water regulation infrastructure can all be assessed based on their ability to reduce the regional CHEE. Notably, the model's interregional structure allows for assessing local investments in terms of the regional benefits they generate.

The model also allows for estimating the cost of hydro-economic equilibrium at the local level. The opportunity cost of reducing by one cubic meter the excess of demand over feasible supply varies across LMAs, and this variation should be considered when prioritizing investments and water management decisions under limited financial resources. Although the CHEE adopts a short-run, comparative static perspective, it *can be readily extended to include choices among alternative technologies (Duchin and Levine, 2012) or to model the price impacts of regulatory measures on tariffs and concessions using Ghosh linkages (Dietzenbacher, 2002).*

A key contribution of this study to public policy lies in the development of an indicator that quantifies, in monetary terms, the short-term production cost of achieving hydro-economic equilibrium. It is essential to clarify that this does not represent a recommendation to reduce production. Such an approach would be not only politically unacceptable, but also economically unfeasible and inefficient. Rather, the purpose of the indicator is to estimate the current value of economic output that is sustained through the overexploitation of water resources. Calculated at both regional and local levels, the indicator provides a measure of the opportunity cost of water use—namely, how much society is implicitly willing to overexploit one cubic meter of water to produce one monetary unit of output. From a policy perspective, this metric is not prescriptive but informative: it highlights the trade-offs involved in pursuing sustainability goals and offers a benchmark for evaluating alternative measures. In particular, it can guide the design of technological or institutional interventions aimed at reducing the reliance on unsustainable water use, under the condition that their implementation cost remains lower than the value currently generated through overexploitation. In this sense, the indicator serves as a practical tool to support economically sound and environmentally responsible water management strategies.

Another important policy implication relates to the implementation of the Natural Capital Approach (NCA) in Italy (NCAVES and MAIA, 2022; United Nations, 2021). Among the most essential natural resources—supporting directly or indirectly most ecosystem services (ES)—is water. Water is closely associated with provisioning, purification, and regulation services, including physical regulation, flood protection, and chemical condition (CICES: Haines-Young & Potschin, 2018), and underpins a wide array of services such as nutrient cycling, sediment retention, erosion control, recreation, and tourism (United Nations, 2021; TEEB, 2010; MEA, 2005). Implementing the NCA in the context of WES requires both their quantification and economic valuation, which this study advances, leaving for future work the implementation of monetary valuation of WES and natural water capital (NWC). The substantive contribution of an IO model lies in its capacity to capture both the direct and indirect economic contributions of WES to the national economy—a gap still *largely unaddressed in the international literature and highly relevant for Italy. Bridging this knowledge gap requires methodological tools that link economic structures with hydrological ecosystems.*

6.3 Limitations and future work

"The model developed in this study has five main limitations: (i) the use of a stochastic rather than a physically based hydrological model; (ii) the absence of climate change projections; (iii) the inability to capture extreme events occurring at short temporal scales; (iv) the simplified treatment of surface and groundwater as independent sources, overlooking their dynamic interactions; and (v) the inherent limitations of the input–output framework in estimating the CHEE, including its linearity and lack of behavioral responses.

Regarding the hydrological model, although it represents a significant effort to estimate hydrological components at the LMA level through detailed analysis (supplementary material) consistent with watershed-scale hydrological processes, it could be improved by adopting a physically based hydrological model (e.g., SWAT, WEAP, InVEST), which would represent a substantial advancement. The main limitation lies in the fact that a physically based model could better simulate the substitution of green water with blue water in agriculture based on green water scarcity (i.e., soil moisture), whereas the current model uses precipitation as a proxy. However, developing such a model for the entire region at the sub-basin scale (to later aggregate at the LMA level) would be extremely complex, costly, and time-consuming. An additional aspect concerns the ecological flow threshold used to define feasible supply, which in this study is considered as a fixed proportion of runoff; moving toward a model capable of more accurately reproducing ecological flows would enhance both hydrological and institutional realism (Sturla and Figueroa, 2025). Despite these limitations, the developed hydrological model—which incorporates precipitation variability (uncertainty)—represents a fundamental step forward.

Regarding climate change projections, this study does not aim to represent hydrological components under future climate change scenarios using global circulation model outputs. These models provide precipitation and temperature data under different socioeconomic scenarios (IPCC, 2021), which can be used to estimate runoff and groundwater recharge through non-stationary time series, thus exposing *the productive structure to more realistic future climate scenarios (Distefano et al., 2025). What has been done in this study is a sensitivity analysis based on the main expected effects of climate change on precipitation in Tuscany: a decrease in average annual precipitation and an increase in its variability. In this sense, while not within its core scope, the study partially addresses a highly relevant dimension. This is, in the authors' view, a valuable contribution that will serve as a foundation for future work involving climate data extraction, downscaling to sub-basin and LMA levels, and the estimation of runoff and groundwater recharge under climate change. Finally, it should be noted that the BIGBANG platform (ISPRA, 2024) will be highly useful for incorporating climate change into the model, as it is currently producing gridded hydrological data under climate change scenarios.*

Regarding extreme events, which may be highly relevant for water policy, the model developed does not allow for their representation. This is because such events occur at daily or even hourly scales, while the input–output model operates at an annual temporal resolution, disaggregated to monthly data only for the purpose of calculating scarcity thresholds. This limitation is difficult to overcome within the structure of this type of model and would require the use of physically based hydrological models with high temporal resolution (e.g., hourly). Nevertheless, the model developed could offer insights into which local economies are more exposed to such extreme events—whether related to excess or scarcity. This represents a highly relevant topic for future research.

As for the limitations of the MRIO framework, it does not simulate market behavior, price adjustments, or substitution elasticities, as CGE models do. As a demand-driven linear system with fixed technical coefficients, the MRIO model cannot capture behavioral responses to policy shocks or dynamic price interactions. Nevertheless, its structural consistency with national accounts and the transparency of its assumptions make it particularly well suited for integration with the SEEA-EA framework (United Nations, 2021). The model structure also provides a solid empirical foundation for the future development of multiregional CGE models based on SAMs and integrated with water-related components—positioning MRIO as a complement, rather than a substitute, for behavioral modeling. This is a necessary future step, especially if the goal is to estimate the value of WES related to purification, provisioning, and *regulation (e.g., groundwater) in order to operationalize the implementation of the NCA in Tuscany.*

An important limitation of the current model lies in its treatment of surface water and groundwater as independent sources. While this disaggregation is analytically useful—especially given the greater pressure observed on surface water in Tuscany—it overlooks key hydrological interactions between the two sources. In particular, the model does not capture dynamic recharge relationships, such as the infiltration of surface water contributing to groundwater replenishment during wet seasons, nor does it consider interannual storage dynamics. These processes can provide substantial resilience to the water system, especially in dry years, and their omission may lead to an overestimation of water scarcity risks. Although the model incorporates intra-annual groundwater management when estimating scarcity thresholds—thereby partially reflecting the buffering capacity of aquifers—future work should explore more integrated representations of the hydrological cycle. This could include explicit modeling of surface–groundwater interactions and the regulation capacity of existing reservoirs, thereby enhancing the model's realism and its policy relevance under climate variability and change.

A final element related to future work involves using the model to estimate the water footprint (WF) within the Tuscany region for each local economy, spatially disaggregated and accounting for both physical water scarcity (SWF) and social water scarcity (SoSWF), as demonstrated, for example, in Sturla et al. (2023). The input–output approach is particularly well suited for this type of analysis, which can contribute to a deeper understanding of hydro-socioeconomic linkages within the region and help identify those local economies that generate the greatest volumetric, scarcity-related, and socially driven water impacts."

This study examines water scarcity in the regional economy of Tuscany using an ILMAIO model extended to capture the interactions between the economic system and hydrological variability. A key feature of the model is the strong integration between hydrology and economics, which allows for a detailed analysis of how fluctuations in water availability affect local production systems. Unlike traditional approaches, this model incorporates both the average and stochastic variability of water supply and

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demand—considering their volume and composition by source—at a spatially disaggregated level.

Finally, the conclusion has been separated and simplified, highlighting the main findings, the novelty of the study, and its contribution to public policies:

"The results reveal a high degree of heterogeneity in water scarcity across the region, confirming insights from previous studies. One of the main methodological contributions of this work is the endogenous estimation of water scarcity thresholds and the calculation of the Cost of Hydro-Economic Equilibrium (CHEE). These tools offer an innovative alternative to the fixed thresholds commonly used in the literature, enabling a context-specific understanding of scarcity and overexploitation. The CHEE provides a monetary estimate of how much current economic output depends on unsustainable water use—both in terms of quantity and quality—and how much society would need to "spend" (through technological or institutional means) to transition toward a sustainable water economy.

In its current form, the model already provides valuable support for water policy in Tuscany. It enables regional authorities to identify local economies most exposed to scarcity, assess trade-offs between production and sustainability, and design targeted interventions such as water-use efficiency improvements, technological upgrades, or expansion of water storage infrastructure.

Finally, the model offers a robust foundation for quantifying and valuing natural water capital (NCA) in the region. By linking hydrological limits, economic structures, and the consequences of overexploitation, it contributes directly to the integration of water-related ecosystem services into public policy, environmental planning, and ecosystem accounting frameworks."

The following is a list of the new references used, which we believe provide a much more robust theoretical and empirical foundation for the paper.

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Sincerely,

Gino Sturla

Florence, 14 July 2025

HYDRO-ECONOMIC EQUILIBRIUM WITH CLIMATIC VARIABILITY IN INTERCONNECTED LOCAL ECONOMIES

Abstract

An interregional IO model of a regional economy (Tuscany, IT) extended to water resources is used to provide an economic assessment of water resources overexploitation. A comprehensive representation of the interdependencies between hydrological and productive systems, allows to define a set of endogenous thresholds of water scarcity and the conditions for the hydro-economic equilibrium of the regional economy. Despite only 24% of the annual supply of freshwater is used for production, on average about 172 Mm^3 of water are used in condition of scarcity, due to a spatial mismatch between supply and demand. The opportunity cost to reach the absence of overexploitation in all sub-regional areas would be 129 Euro for each m^3 of water used in condition of scarcity. Hydro-economic equilibrium would require a decrease of about 10% of the regional output, a value that would be increased to 14% in a climate change scenario.

Keywords

Water Scarcity, Input-output, Interregional Models, Tuscany, Climate Change

JEL Codes

D57, Q25, Q56

1. Introduction

A renewed emphasis on the state of water resources recently emerged in the international debate on sustainable development. On March 2023, the UN Conference on the Midterm review of the Decade for action "Water for sustainable development" (2018-2028) was held in New York. During the general debate, among other topics, was stressed the strategic importance of reliable data for the analysis of water systems, to support a science-based approach to water management (United Nations, 2023: 12). Beside the lack of systematic sharing of data and efforts to design a global information system on water, delegates recalled also the need to adopt a "whole system" perspective in monitoring and modeling water systems for management purpose. Interlinkages among water use, energy supply and production activities have to be taken into account for an effective water management, both at the regional and global level (UNESCO and UN Water, 2020). A "nexus" approach in water management, however, can be adopted only in presence of proper information and adequate modelling tools. According to the UN Water Meteorological Organization (WMO, 2022) together with indirect satellite observations, hydrological models are still fundamental in monitoring the state of water resources, due to the lack of timely, verified and accessible hydrological data.

Further, managing problems of quantity and quality decline in water resources, asks to integrate hydrological with economic data, to model interactions between human activities and water systems. Environmentally extended input-output (EEIO) models are a natural answer to this problem. A wide literature has been developed using IO hydro-economic models to quantify the water footprint of economic systems, to study the so called 'water-food-energy nexus' or to support water management decisions at different geographical levels. In this paper we contribute to this stream of literature studying the balance between water resources and economic activities at the regional level. We use an interregional IO (IRIO) model of a regional economy extended to water resources to study the structural drivers of water scarcity problems and to provide an economic assessment of water resources overexploitation. A peculiar feature of our model is the full integration of a hydrological module, reproducing the natural variability of water supply, with the usual multi-sector representation of the economy. This allows us to consider both temporal and spatial variability of the balance between water supply and demand, and to generate results in the form of probability distributions of exploitation indicators. Furthermore, a comprehensive representation of the interdependencies between natural supply variability, industry composition of the economy and variability of water demand, allows us to define a system of endogenous thresholds of water scarcity to identify the overexploitation of water resources. The model is then used to define the conditions for the hydro-economic equilibrium of the regional economy (absence of overexploitation) and to assess its opportunity cost (optimal output reduction to achieve the equilibrium). The case study is Tuscany (IT), a region in the temperate zone despite an overall sufficient natural availability of water, scarcity problems emerge due to a relevant spatial mismatch between supply and demand.

The paper is organized as follows. The next section provides a review of input-output models extended to water resources, to position our study within the relevant literature and highlight the advances of our analysis compared to the current state of the art. Section 3 outlines the empirical characteristics of the IRIO table and the associated hydrological module, while section 4 describes the solution of the model and the methodology adopted in quantifying water pressures, the endogenous scarcity thresholds at the subregional level and the cost of the regional hydro-economic equilibrium. Section 5 summarizes the main results of the analysis. The final section propose some concluding remarks, discussing the relevance of results and future research perspectives.

2. Literature Review

Regional and interregional input–output models have been implemented to study the interactions between the economy and the environment since the 1960's (Duarte and Yang, 2011). In 1970 Leontief itself proposed a first description of an input-output model generalized to include material flows between economic activities and the environment. Among other resources also water was early considered in input-output analysis applied to the environmental management (Lofting and Mcgauhey, 1968).

Since then, IO models have been widely used to study water use in economic systems, both as an accounting framework to quantify direct and indirect water consumed by industries to supply the final demand (Velazquez, 2006; Lenzen et al., 2013; Ridoutt et al., 2018; Camara and Llop, 2020; Rocchi et al., 2023; Sturla et al., 2024) and for the estimation of virtual water flows and water footprint at the regional, national and global scale (Feng et al., 2011, 2014; Zhuoying et al., 2011; White et al., 2015; Duarte et al., 2016; Arto et al., 2016; Deng et al., 2020; Sturla et al., 2023; Sturla et al., 2024).

A relevant part of recent literature on input-output modelling extended to water resources has been oriented to the structural analysis of the so-called water-energy-food (WEF) nexus within economic systems. This is a natural use of the input-output approach, well suited to show how technical interdependencies between production activities as well as trade flows among regions affect the exploitation of limited natural resources. Guan and Hubacek (2008) study virtual water flows among China regions using a hydro-economic model. Xiao and colleagues (2019) use an input-output model to identify supply chains that directly and indirectly mostly affect the use of water and energy. A specific focus on tourism as a key industry in determining the pressure on water resources characterizes the study of Lee et al. (2021). A regional disaggregation of the IO table is exploited by Liu et al. (2017) to highlight how internal trade flows could affect the sustainability in the use of water resources in different regions of China. Following a similar approach White and colleagues study the structure of the WEF nexus in South East Asia finding "a mismatch between regional resource availability and resource flows destinations, and a lack of consideration for environmental impacts of trade policies … in resource scarce countries" (White et al., 2018: 564).

The studies cited above rely on a "volumetric" concept of water footprint, i.e. quantify the total amount of water used to produce a given basket of goods or necessary to support a given pattern of final consumptions. Such an approach has been contested to be not environmentally relevant, as water is a renewable resource that can be used without adverse effects within some limits. In the field of environmental studies, an interesting debate has been developed about the opportunity to weight water footprint measures according to some criteria of scarcity relevance (Hoekstra, 2016; Wichelns, 2017).

The availability of an IRIO table extended to water resources is the first step to support water management according to some optimization criteria. The inclusion of a water endowment measure is needed to use a water IRIO type model extended to water resources not only as an "hydroeconomic-accounting framework" (Guan and Hubacek, 2008) but as a tool for water management decisions. This type of models has been used to estimate the water *balance* of economic systems, comparing the water demand based on the economic model with the water supply based on water availability estimations. An IRIO hydro-economic model has been recently used to simulate the impact of exogenous shocks in the final demand and their effect on the water balance in Spain (Cámara and Llop, 2020). Based on a structural path analysis of a water-extended IRIO model of China, Deng and colleagues (2020) suggest strategies to save water, energy and waste production in China by adjusting final consumption and the output of critical supply chains. Duchin and López-Morales (2012) study the comparative advantage of different Mexican regions in producing food using a global IRIO model extended to water resources endowments, where the choice between rainfed and irrigated agriculture is based on a rectangular choice-of-technology rule. In a recent paper, Garcia-Hernandez and Brouwer (2021) study how the impact of water supply constraints could affect the output level and the water balance in the regions of an IRIO model. They include water restrictions in solving the model, leaving final consumption components unmet as some exogenous constraints to water supply (water endowments) at the local level are reached. An optimization procedure allows to map spatially localized water disruptions in the area of Great Lakes Basin in Canada.

In all these models blue water supply, i.e. water available for withdrawals from water bodies (Hoekstra et al., 2011), is assumed to be constant, depending on an estimate of water endowments that is exogenous to the model. Water availability for productive uses depends on the average natural supply (annual surface runoff and aquifer recharge generated by precipitations) and on the presence of waterworks to support the withdrawals (Duchin and Lopez-Morales, 2012). Water supply, whatever the concept used to define it, works as a constraint in production that can alternatively generate reductions in the produced output (Duchin and López-Morales, 2012) and/or overexploitation of water resources (Cámara and Llop, 2020; Garcia-Hernandez and Bower, 2021). Furthermore, also the technology is static: water use is linear in the level of output for each industry, depending on a fixed water coefficient. This is also the case of the model with optimal choice of technology proposed by Duchin and López-Morales, where the solution simply defines the optimal mix of rain fed and irrigated agriculture under different scenarios of water availability. Water supply and water demand, however, are both *variable* and *interdependent*. The annual average water endowments as well as the average water intensity coefficients hide an intrinsic variability of the water balance that should be considered in studying water scarcity.

In the short-run water scarcity of economic systems depends on different sources of variation. First of all, with a given structure of the economy (industry mix, average technologies and output level) the water balance is affected by the variability of the natural supply. Years with wet hydrology could reduce scarcity problems while years of dry hydrology can exacerbate them. Second, water demand co-varies with water supply depending itself on the hydrological characteristics of each year. Consider for example blue water withdrawals to irrigate crops: they are likely to be variable depending of the variation of green water availability, depending in turn on variability in precipitations. It is reasonable to expect an increase in average blue water coefficients of agriculture in years with low precipitations. Further, temporal variation could generate scarcity also *within* a given period: typically, IO models refers to a single year period, but the water balance can show a strong *within-year* variation. Finally, a third source of variation is of spatial nature. On one side, the spatial distribution of water resources is typically uneven, given the characteristics of the hydrological system. On the other side, also the spatial pattern of water demand is variable, depending on how the structural economic dynamics shaped the spatial distribution of production activities and population. As a consequence, within a region showing an overall balance between water supply and demand, several critical situations in terms of water scarcity could exists and generate different sources of endogenous variability in the water balance.

In this paper we use an IRIO type model fully integrated with a hydrological module reproducing the natural variability of the hydrological balance at the sub-regional level, to analyse the structural problems of water scarcity within a regional economy (Tuscany, Italy). To our knowledge this is the first attempt to integrate hydrological modelling in an IRIO type framework. The characteristics of the model allow us to answer to research question like the following: what is the variability of the water balance of the regional economy? What is the average (yearly) level of pressure on water resources beyond which critical situations of water scarcity are likely to emerge? What are the conditions for a hydro-economic equilibrium in the region, given the structure of the economy and the endowment of water resources? What is the opportunity cost of such conditions? In the following section we provide a description of the empirical implementation of the hydro-economic accounting framework, before to move to the formal description of the model.

3. The empirical framework

The IRIO table used to build the model was developed by the Tuscan Regional Institute for Economic Planning[1]. The accounting framework provides a very detailed representation of the Tuscan economy, with production activities classified into 46 industries and 49 sub-regional areas corresponding to the Labour Market Areas (LMA), as defined by Eurostat[2].

A first release of the InterLMA IO table (henceforth ILMAIO) included agriculture as a single industry. To better represent the role of agriculture in determining the overall water demand and its variability, the agriculture sector of that table was disaggregated into 8 sub-sectors, according to the Farm Types (FT) classification used in economic analyses to support EU sector policies (Common Agricultural Policy). The disaggregation of agriculture's output in the ILMAIO table was based on georeferenced information on cultivated crops and irrigated areas at a single-field geographic scale, reporting administrative data generated by the implementation of agricultural policy. Other information on agriculture (livestock inventories) available at the sub-regional level were also used. The value added produced by each subsector of the regional agriculture was estimated applying an average value added/output ratio by Farm Type based on the sample of farms surveyed in Italy by the National Research Council Center for Agriculture (CREA) under the European Farm Accounting Data Network (FADN)[3].

The final ILMAIO matrix is referred to year 2017 and contains 53 economic sectors, 49 LMAs, 5 components of the domestic final demand and 4 components of external final demand (Rest of Italy and Rest of the World).

The ILMAIO table has been extended to represent the water exchange flows between the economic and the hydrological systems, following the approach proposed by Guan and Hubacek (2008). To each production activity in each LMA was assigned a water intensity coefficient (m^3/€) to link the value of output with withdrawals of green and blue water[4] from the hydrological system. Withdrawals have been classified by water body (surface and groundwater for blue water, soil moisture for green water withdrawals). A similar coefficient was defined to represent discharges of water non-incorporated in products. Not all the industries actually withdraw and discharge water from/to water bodies: service sectors for example purchase water from Water Supply and discharge water through the Sewerage Service, both separately represented in the table. The difference between withdrawal and discharge coefficients expresses the *net* demand for water for each Euro of output. Also, the demand for *grey* water demand was considered. Grey water is the amount of freshwater required to dilute pollution of discharged water bringing back water bodies to their qualitative equilibrium. The mixing model used by Guan and Hubacek (2008) have been developed to assign a specific grey water coefficient to each production activity in each LMA. Summing the grey water requirement coefficients to the unitary net demand allows to quantify the *extended* demand for water generated by one Euro of output[5].

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[1] See for description of the IRPET interLMA I-O model : https://www.irpet.it/archives/57005

[2] According to Eurostat a LMA statistically defined as an economically integrated territory, where the majority of people both live and work. See https://ec.europa.eu/eurostat/documents/3888793/10992115/KS-TC-20-002-EN-N.pdf/5a6258be-6c53-64fa-971c-2b19908ab442?t=1591968072000 for an update of Eurostat LMA definition. Regarding the ISTAT methodology for grouping municipalities through a clustering process based on the analysis of commuting patterns see: https://www.istat.it/en/labour-market-areas.

[3] The FADN Public Database (http://ec.europa.eu/agriculture/rica/index.cfm) provides data on the average composition of farms' output and production costs at the national and regional levels, with a breakdown by FT and by economic size of the farm.

[4] We follow the standard definitions of different typologies of water used in studies on water footprint of human activities (Hoekstra et al. 2011).

[5] The quantification of water requirement and discharge coefficients relied on a wide set of data from different sources. For a detailed description of data used and assumptions made see section A in Supplementary materials.

The ILMAIO table extended with water coefficients allows for an analysis of the *average* annual balance in water resources use when a reliable estimate of natural water supply was available. This is the standard approach of environmental studies to detect water scarcity conditions of countries and regions. However, a crucial issue in integrated water management is the natural *variability* of hydrology. A region showing an overall balance between *average* annual demand and supply of water could face scarcity conditions in dry years, both for the decrease of water supply and for the consequent variation in water demand for human activities.

The empirical model used in this study includes also an explicit representation of variability in the natural supply of water. A spatial stochastic model was calibrated to generate synthetic series of the components of the hydrological balance by LMA. The model was built following the approach suggested by (Rencher and Christensen, 2002) and (Maity, 2018). A spatial stochastic model is the representation of a spatial and temporal random variable. It reproduces the main characteristics of the variable, in particular the mean, the standard deviation and the spatial correlation. The model was built based on the analysis of a spatially disaggregated time series of precipitations.

The estimated model allowed us to add a spatial structure and a temporal variability to the mean components of the regional hydrological balance. We generated 42 LMA series of N=100 years of precipitation, reproducing the mean and variance of the original series, and derived the corresponding series for the other components of the hydrological balance: evapotranspiration, surface runoff, groundwater recharge. The model was also used to generate a climate change hydrological scenario, by varying the mean and standard deviation associated with each meteorological station, so generating a change in the simulated annual volume of precipitation for each LMA[6].

The natural variability of supply represents an exogenous source of variation of the regional water balance. Its effect, however, is not limited to changes (across time and space) in the supply of water but also includes an induced variation in water *demand*. Some economic activities are likely to require different amounts of water depending on the hydrological conditions. This is mainly the case of agriculture, where the output of crops strictly depends on the water balance: in dry years we expect a shift of water demand from the green (soil moisture) to the blue component of supply (surface and groundwater used for irrigation). A further component of water demand strictly depending on hydrological conditions is grey water. Freshwater volumes required to dilute pollutant discharged in water bodies by economic activities depends on the relative concentration of discharging and receiving waters, with the latter depending on natural supply: in wet years grey water demand is likely to decrease, due to the lower concentration in receiving bodies (higher annual run-off).

The variation of water demand depending on hydrological conditions can be represented in the model as a change of water coefficients of economic activities. We included this endogenous variation of water demand. In our simulations water withdrawal and discharge coefficients vary with hydrological conditions. As a consequence, the variability of water demand in each LMA depends on the industry mix of the local economy[7].

The full integration of hydrological and economic modelling allows us to associate a probability distribution to the average results. We fully exploit this feature of the empirical framework to study water scarcity conditions in Tuscany. In the following section we detail how we use of the hydro-economic empirical model

[6] A detailed description of data and methods used to build the spatial stochastic model of the regional hydrology and the climate change scenario is available in section B of Supplementary Materials.

[7] A detailed description of how this endogenous variation of water demand has been modelled can be found in section C of Supplementary Materials.

to define a set of endogenous thresholds of water scarcity and to estimate the opportunity cost of a genuine hydro-economic equilibrium in the Tuscan economy.

4. Methodology

4.1 The general model

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

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

$$\mathbf{g} = \hat{\mathbf{c}} \cdot \mathbf{x} \qquad (1)$$

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

The vector $\mathbf{x}$ can be expressed as a function of the inter-LMA input coefficients (*mn* x *mn*) matrix $\mathbf{A}$, a (*mn* x *1*) vector **d** of domestic final demand, ;and the external exogenous components,foreign and regional exports, the (mnx1) vectors $\mathbf{h_f}$ and $\mathbf{h_r}$.Hereafter the structural form:

$$\mathbf{x} = \mathbf{A} \cdot \mathbf{x} + \mathbf{d} + \mathbf{h_f} + \mathbf{h_r} \qquad (2a).$$

Which leads to the following reduced form:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot (\mathbf{d} + \mathbf{h_f} + \mathbf{h_r}) \qquad (2b).$$

Where:

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

Defining:

i) $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ as the interLMA Leontief inverse (*mn* x *mn*) matrix
ii) $\mathbf{y} = \mathbf{d} + \mathbf{h_r} + \mathbf{h_w}$ as the LMA final production

yields:

$$\mathbf{g} = \hat{\mathbf{c}} \cdot \mathbf{L} \cdot \mathbf{y} \qquad (3)$$

4.2 Extended demand for water

For the purposes of this study, the environmental resource is water. The extended water demand is defined as withdrawals of blue water[8] from surface and groundwater bodies minus discharges plus the water

[8] The blue component of water demand is the object of water management policy, despite also the green component contributes to the water balance of the economy. In our empirical framework the green component is considered in modelling the endogenous variation of blue water demand for agriculture.

requirements for dilution (grey water). The extended demand of water (*n* x *1*) vector for each subregion $(\mathbf{e}_\mathbf{k}^\mathbf{s})$ could be expressed as:

$$\mathbf{e}_\mathbf{k}^\mathbf{s} = (\widehat{\mathbf{f}_\mathbf{k}^\mathbf{s}} - \widehat{\mathbf{r}_\mathbf{k}^\mathbf{s}} + \widehat{\mathbf{w}_\mathbf{k}^\mathbf{s}}) \cdot \mathbf{L}^\mathbf{s} \cdot \mathbf{y} \tag{4}$$

where the $\boldsymbol{L}^s$ (*m* x *mn*) matrix corresponds to the Leontief inverse matrix block associated with production in the subregion *s*, and $\mathbf{f}_\mathbf{k}^\mathbf{s}$, $\mathbf{r}_\mathbf{k}^\mathbf{s}$ and $\mathbf{w}_\mathbf{k}^\mathbf{s}$ correspond to the (*m x 1*) vectors of intensity coefficients (m^3/€) for withdrawals, discharges and water for dilution, respectively, by water body k (groundwater, surface water and soil moisture) in subregion s.

When temporal hydrological variability is considered, the water intensity coefficients change with the variation in the components of the hydrologic cycle. Let us first define the extended demand for water in the subregion *s* associated with water body *k*, industry *i* and year *t* (for notation simplicity we use $\mathbf{x}^\mathbf{s}$ instead of $\mathbf{L}^s\mathbf{y}$):

$$e_{k,i,t}^s = (f_{k,i,t}^s - r_{k,i,t}^s + w_{k,i,t}^s) \cdot x_i^s \tag{5}$$

Withdrawal coefficients vary in agricultural sub-sectors, due to variations in soil moisture availability, which implies higher withdrawals from surface and groundwater bodies when the demand for water exceeds the natural supply of green water. Discharge coefficients also change because withdrawing water from surface and groundwater bodies involves losses in the use of water for irrigation. The dilution water requirement coefficients change in all industries directly discharging polluted water into water bodies, depending on runoff and groundwater recharge, which affect the concentration of pollutant in the receiving bodies.

Equations (6), 7) and (8) present the water intensity coefficients as a function of a deterministic average value plus a time-varying term, which depends on the hydrological conditions:

$$f_{k,i,t}^s = f_{k,i}^s + \mathcal{F}_{\mathrm{k,i,t}}^{\mathrm{s}}(p_{\mathrm{t}}^{\mathrm{s}}, v_{\mathrm{t}}^{\mathrm{s}}) \tag{6}$$

$$r_{k,i,t}^s = r_{k,i}^s + \mathcal{R}_{\mathrm{k,i,t}}^{\mathrm{s}}\,(p_{\mathrm{t}}^{\mathrm{s}}, v_{\mathrm{t}}^{\mathrm{s}}) \tag{7}$$

$$w_{k,i,t}^s = w_{k,i}^s + \mathcal{H}_{\mathrm{k,i,t}}^{\mathrm{s}}[z_{\mathrm{t}}^{\mathrm{s}}, q_{\mathrm{t}}^{\mathrm{s}}, \mathcal{R}_{\mathrm{k,i,t}}^{\mathrm{s}}(p_{\mathrm{t}}^{\mathrm{s}}, v_{\mathrm{t}}^{\mathrm{s}})] \tag{8}$$

where p_t^s, v_t^s, z_t^s *and* q_t^s are respectively precipitations, evapotranspiration, groundwater recharge and surface water runoff in subregion *s* for year *t*, obtained with the hydrological model.

Using equations (6) to (8) it is possible to write a general expression for the extend demand from water body *k*, in year *t* associated with industry *i* in LMA *s*:

$$e_{k,i,t}^s = e_{k,i}^s + \left[\mathcal{F}_{\mathrm{k,i,t}}^{\mathrm{s}}(p_t^s, v_t^s) + \mathcal{R}_{\mathrm{k,i,t}}^{\mathrm{s}}\,(p_t^s, v_t^s) + \mathcal{H}_{\mathrm{k,i,t}}\left[z_t^s, q_t^s, \mathcal{R}_{\mathrm{k,i,t}}(p_t^s, v_t^s)\right]\right] \cdot x_i^s \tag{9}$$

Note that $\mathcal{F}_{k,i,t}^s(p_t^s, v_t^s) = 0$ and $\mathcal{R}_{k,i,t}^s\,(p_t^s, v_t^s) = 0$ for non-agricultural sectors, and $\mathcal{H}_{k,i,t}[q_t^s, z_t^s, \mathcal{R}_{k,i,t}(p_t^s, v_t^s)] = 0$ for non-discharging sectors. Section C in the Supplementary Material details how the stochastic components of the extended demand have been modelled.

4.3 The EWEI Indicator

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

$$EWEI_t^S = \frac{\sum_{i=1}^{m} \sum_{k=1}^{2} (f_{k,i,t}^s - r_{k,i,t}^s + w_{k,i,t}^s) \cdot x_i^s}{z_t^{s,feas} + q_t^{s,feas}} \quad (10)$$

where the sums considers *m* industries and two water bodies (groundwater and surface water). The variables $z_t^{s,feas}$ and $q_t^{s,feas}$ are the groundwater and surface water *feasible* supplies.

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

The limitations to the use of groundwater are different. Groundwater is a stock that varies according to the annual recharge. Consequently, the annual extraction depends more on the long-term average recharge than that of a single year. Unlike surface water, if the recharge in a given year is low, it is still possible to extract a larger quantity (reservoir effect); conversely, when the recharge is high, there are technical and institutional limitations to extraction (withdrawals capacity, concession). To be sustainable the average feasible supply should be equal to the average recharge (non-decreasing groundwater stock condition). The annual withdrawals will vary around the average recharge and will be a little lower than the actual recharge in a rainy year and higher in a dry year. This is the reason why concessions are usually awarded for a slightly higher value than the annual sustainable recharge.

In equation (10) $z_t^{s,feas}$ and $q_t^{s,feas}$ are defined as follows:

$$z_t^{s,feas} = \left\{ \begin{array}{ll} \bar{z}^s(1-\varepsilon^s) & if \;\; z_t^s < \bar{z}^s(1-\varepsilon^s) \\ \bar{z}^s(1+\varepsilon^s) & if \;\; z_t^s > \bar{z}^s(1+\varepsilon^s) \\ z_t^s & if \;\; z_t^s \in [\bar{z}^s(1-\varepsilon^s), \bar{z}^s(1+\varepsilon^s)] \end{array} \right\} \quad (11)$$

$$q_t^{s,feas} = \left\{ \begin{array}{ll} q_t^s - \delta^s \bar{q}^s & if \;\; \delta\bar{q}^s \le q_t^s \le \theta^s q^s + \delta\bar{q}^s \\ \theta^s \bar{q}^s & if \;\; q_t^s > \theta^s \bar{q}^s + \delta\bar{q}^s \\ 0 & if \;\; q_t^s < \delta\bar{q}^s \end{array} \right\} \quad (12)$$

where

z_t^s	:	Groundwater recharge volume in year t in subregion *s*
$\bar{z}^s$	:	Long-term groundwater recharge volume in subregion *s*
ε^s	:	Parameter defining the range of groundwater feasible availability in subregion *s*
q_t^s	:	Runoff volume in year t (multivariate model)
$\bar{q}^s$	:	Long-term runoff volume in subregion *s*
δ^s	:	Minimum ecological flow as proportion of mean runoff in subregion *s*
θ^s	:	Maximum volume of concessions as proportion of mean runoff in subregion *s*

We use a value of $\varepsilon^s = 13\%$ and $\delta^s = 20\%$ for all subregions. The value of θ^s depends on the concessions active in each subregion, estimated based on information from regional Hydro-geological Service (SIR)[9] according with the with methodology proposed by Venturi et al. (2014).

[9] https://www.sir.toscana.it/strati-gis.

4.4 Endogenous scarcity threshold

Conditions of scarcity emerge when the demand for water exceeds the feasible supply. A critical issue is the choice of the period within which demand and supply are compared. So far, we considered the year as a reference period. Water demand and supply, however, varies also within every single year. Consequently, an average *annual* EWEI (for a given territory) lower than 1 could still hide temporary conditions of scarcity. This is the reason why in environmental studies the volumetric measures of water footprint of whole economies are weighted for scarcity through some mathematical transformations of annual pressure indicators like the EWEI. This is, for instance, the case of the Water Stress Index (WSI) proposed by Pfister and colleagues (2009), a logistic transformation of the ratio of total annual freshwater withdrawals to hydrological availability[10]. WSI varies between 0.01 to 1; usually a value of 0.2 is considered as a threshold for moderate scarcity, while 0.4 delimits situations of severe scarcity.

In the present analysis we use the model itself to define a water scarcity threshold for the annual regional EWEI, considering the intra-annual variability of water demand and supply and the geographical differentiation in the hydro-economic system. Different form the approach of (Pfister et al., 2009) our threshold is endogenous, depending on the economic structure and the hydrological conditions of each subregion *s*.

Let e^s and u^s the annual extended demand and the feasible supply in region *s,* including both groundwater and surface water. The sub-regional EWEI for a generic month *i* can be expressed as:

$$EWEI_i^s = \frac{(1-\alpha^s)\cdot\frac{e^s}{12} + \alpha^s\cdot\frac{u^s}{12}\cdot a_i^s}{(1-\beta^s)\cdot\frac{e^s}{12}\cdot c_i^s + \beta^s\cdot\frac{u^s}{12}\cdot b_i^s} \tag{13}$$

where

$\alpha^s = \frac{e_{Var}^s}{e^s}$ is the share of the extended demand corresponding to industries with intra-annual variability

$\beta^s = \frac{u_{sw}^s}{u^s}$ is the share of surface water feasible supply

$a_i^s = \frac{e_{Var,i}^s}{e_{Var}^s/12}$ is the intra-annual distribution coefficient of the extended demand from industries with intra-annual variability for month *i*

$b_i^s = \frac{u_{sw,i}^s}{u_{sw}^s/12}$ is the intra-annual distribution coefficient of surface water feasible supply for month *i*

$c_i^s = \frac{u_{gw,i}^s}{u_{gw}^s/12}$ is the intra-annual distribution coefficient of groundwater feasible supply for month *i*

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

$$EWEI_i^s = \frac{(1-\alpha^s)+\alpha^s a_i^s}{(1-\beta^s)c_i^s + \beta^s b_i^s} EWEI^s \tag{14}$$

[10] The ratio corresponds to the Water to Availability (WTA) index and is calculated correcting natural water supply according to the presence of storage capacities available in different watersheds (Pfister et al., 2009)

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

$$ST^s = \min_i \frac{(1-\beta^s)c_i^s + \beta^r b_i^s}{(1-\alpha^s) + \alpha^s a_i^s} \qquad (15)$$

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

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

The scarcity threshold (ST_m^s) with integrated groundwater and surface water management will correspond to the value of the expression in equation (15) maximized by the sets of c_i^r and b_i^r values:

$$ST_m^s = \max_{c_i^s, b_i^s} \left[\min_i \frac{(1-\beta^s)c_i^s + \beta^r b_i^s}{(1-\alpha^s) + \alpha^s a_i^s} \right] \qquad (16)$$

Of course, this threshold is less restrictive than the threshold considering only natural scarcity conditions (ST^s).

For groundwater, management is always possible. We consider that $c_i^r \in (1-\lambda^s, 1+\lambda^s)$, where λ^s corresponds to the percentage by which the groundwater supply in month *i* can be above or below the average monthly supply. A similar approach could be adopted for surface water also. However, due to the lack of complete and reliable information on regulation infrastructures in our analysis we consider only the groundwater regulation, defining the scarcity threshold with groundwater optimal management (ST_g^s) as follows:

$$ST_g^s = \max_{c_i^s} \left[\min_i \frac{(1-\beta^s)c_i^s + \beta^r b_i^s}{(1-\alpha^s) + \alpha^s a_i^s} \right] \qquad (17)$$

4.4 Hydro-economic equilibrium

Local hydro-economic equilibrium (LHEE) for subregion *s* is defined as the situation where the annual $EWEI^s$ is less than or equal to the ST_g^s calculated considering the average hydrological conditions. Regional Hydro-Economic Equilibrium (RHEE) is defined as a situation where all LMA satisfy the LHEE conditions. That is, there is no water stress in any subregion *s*. Using equation (4) the RHEE condition can be written as:

$$\frac{(\mathbf{v}_{\mathbf{blue}}^{\mathbf{s}} + \mathbf{v}_{\mathbf{grey}}^{\mathbf{s}})^T \cdot \mathbf{L}^{\mathbf{s}} \cdot \mathbf{y}}{u^s} \leq ST_g^s \quad , \forall s \qquad (18)$$

where $\mathbf{v}_{\mathbf{blue}}^{\mathbf{s}}$ and $\mathbf{v}_{\mathbf{grey}}^{\mathbf{s}}$ corresponds to the (*m* x *1*) vectors of blue (groundwater and surface water) and grey (water for dilution) water use intensity coefficients by industry in subregion *s*, considering average hydrological conditions. The feasible supply u^s is also considered for the average hydrological conditions.

The opportunity cost of the regional hydro-economic equilibrium is the minimum reduction in output that would be required to bring all subregions to the LHEE condition. The optimization problem has the objective function of maximizing production (minimum reduction) by varying the final demand without restrictions in deficit subregions (where the final demand supplied by the LMA economy system could be zero).

The final demand in each subregion is modified on the basis of the control variable ϕ^s. The production vector x is redefined as:

$$x = \mathbf{L} \cdot \widehat{\boldsymbol{\phi}} \cdot \mathbf{y} \tag{19}$$

where $\widehat{\boldsymbol{\phi}}$ is a diagonal matrix (*mn* x *mn*) containing *m* times the value of ϕ^s for each of the *n* subregions. The optimization problem is:

$$\begin{gathered} \max_{\phi} \boldsymbol{\epsilon}' \cdot \mathbf{L} \cdot \widehat{\boldsymbol{\phi}} \cdot \mathbf{y} \\ s.t. \\ \frac{(\mathbf{v}^{\mathbf{s}}_{\mathbf{blue}} + \mathbf{v}^{\mathbf{s}}_{\mathbf{grey}})^{\mathrm{T}} \cdot \mathbf{L}^{\mathbf{s}} \cdot \widehat{\boldsymbol{\phi}} \cdot \mathrm{y}}{u^s} \leq ST_g^s \quad , \quad \forall s \\ \phi^s \in [0,1] \quad , \quad \forall s \in \Gamma \end{gathered} \tag{20}$$

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

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

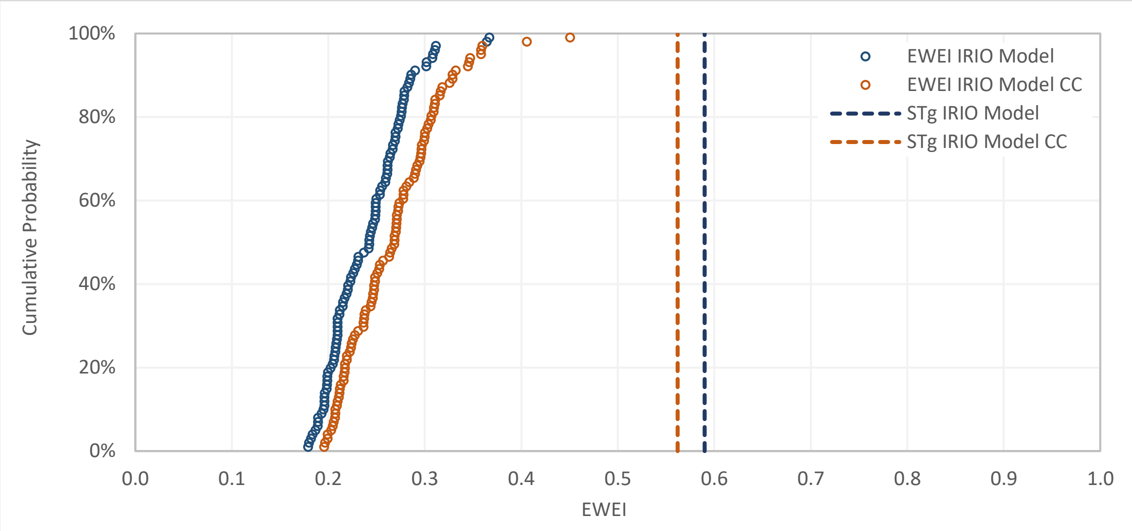
$$HEEC = \boldsymbol{\epsilon}' \cdot (\mathbf{x}^* - \mathbf{x}^{\mathbf{b}}) \tag{21}$$

The opportunity cost refers to the regional hydro-economic equilibrium (RHEE). When using an ILMAIO model, any reductions in production necessary to satisfy each local hydro-economic equilibrium (LHEE) in any subregion *s* will have an impact on all the other sub-regions (with and without deficit). The ILMAIO model developed in this study allows to study the reduction of production in each of the *n* subregions necessary to ensure the *regional/LMA* hydro-economic equilibrium. The HEEC strictly depends on the hydrologic *and* the economic structure of the region.

5. Results

The average EWEI for the whole region under the base (historical) hydrological scenario is equal to 0.24. The cumulative probability distribution of the regional EWEI is represented in Figure 1, for the base and climate change (CC) scenarios. In the latter, the EWEI increases from 0.24 to 0.27, the variance increases by 24% and the skewness increases by 24%.

Figure 1. EWEI cumulative probability distribution and Scarcity threshold
Whole Tuscany - Base and Climate Change scenario



Source: own elaborations

Nonetheless, although the maximum EWEI increases up to 0.45, it still remains largely below the scarcity threshold (0.562). However, the situation changes dramatically when considering the spatial heterogeneity of the hydro-economic conditions within the region.

Table 1 shows the spatial statistics considering the average hydrology conditions (the mean of 100 simulations) for the extended demand (blue and grey water) for surface and ground water, the component water required for dilution (grey water) and the total feasible supply. Grey water represents 66% of the extended demand, which in turn corresponds to 24% of the feasible supply (a regional EWEI of 0.24). Regarding the first order spatial autocorrelation, water for dilution has the highest value of the Moran Index (0.369)[11].

Table1. Spatial statistics for demand and supply of water

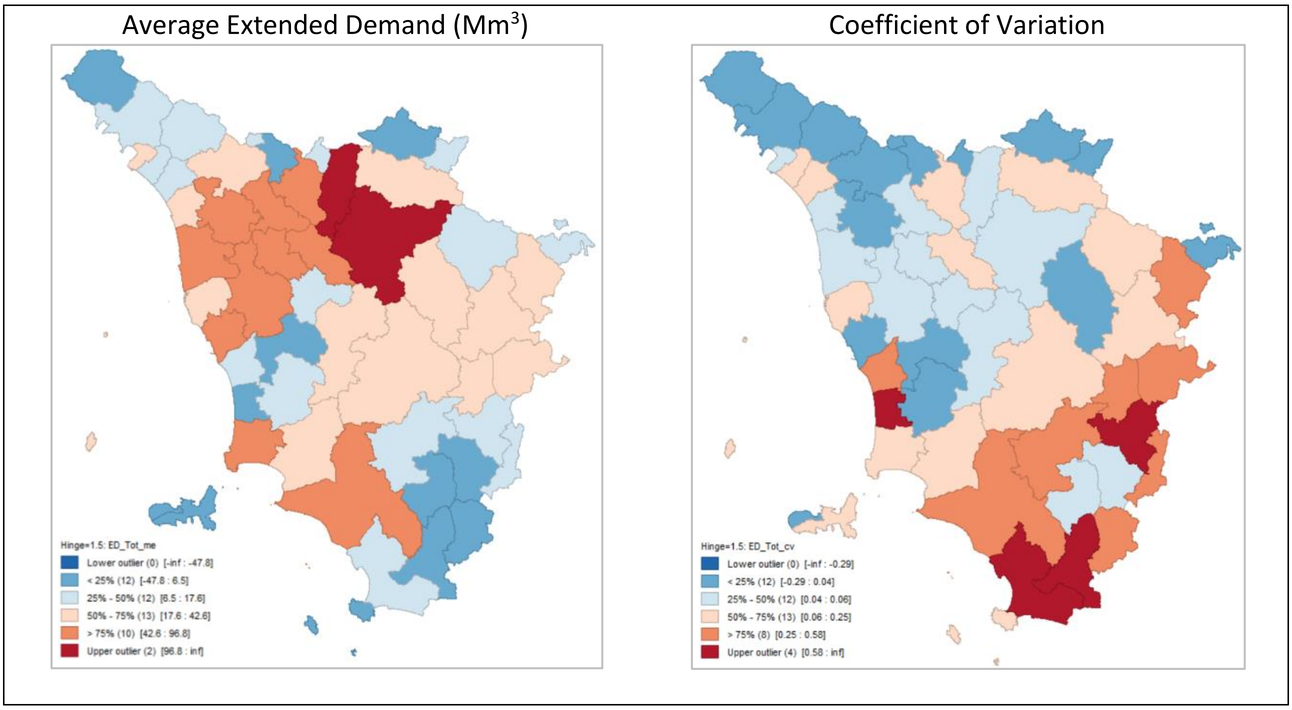
Spatial Statistics	Extended demand (gw+sw)	Water for dilution	Feasible supply
Mean (Mm^3)	28.0	18.4	118.8
SD (Mm^3)	32.7	23.6	133.2
CV	117%	129%	112%
Skewness	2.5	2.4	1.9
Min (Mm^3)	0.0	0.0	3.3
Max (Mm^3)	159.3	113.0	514.6
Moran Index (1st ord.)	0.270	0.369	0.294

Source: own elaborations

The maps in figure 1 analyses the extended demand across the LMA. The spatial distribution of water demand is uneven. The highest values are present, as expected, in LMA corresponding to the metropolitan area of Firenze (Florence) and Prato (upper outliers in the regional distribution), along the basin of the Arno River, as well as in some LMA along the shoreline of the region. The interannual variability of water demand also shows a clear geographic pattern. Southern Tuscany presents a higher variability, due to the replacement of green water by blue water in agriculture and the changes in the demand for grey water due to a stronger variation in the natural supply.

[11] Section D of Supplementary Materials provides the average results for the 42 LMA

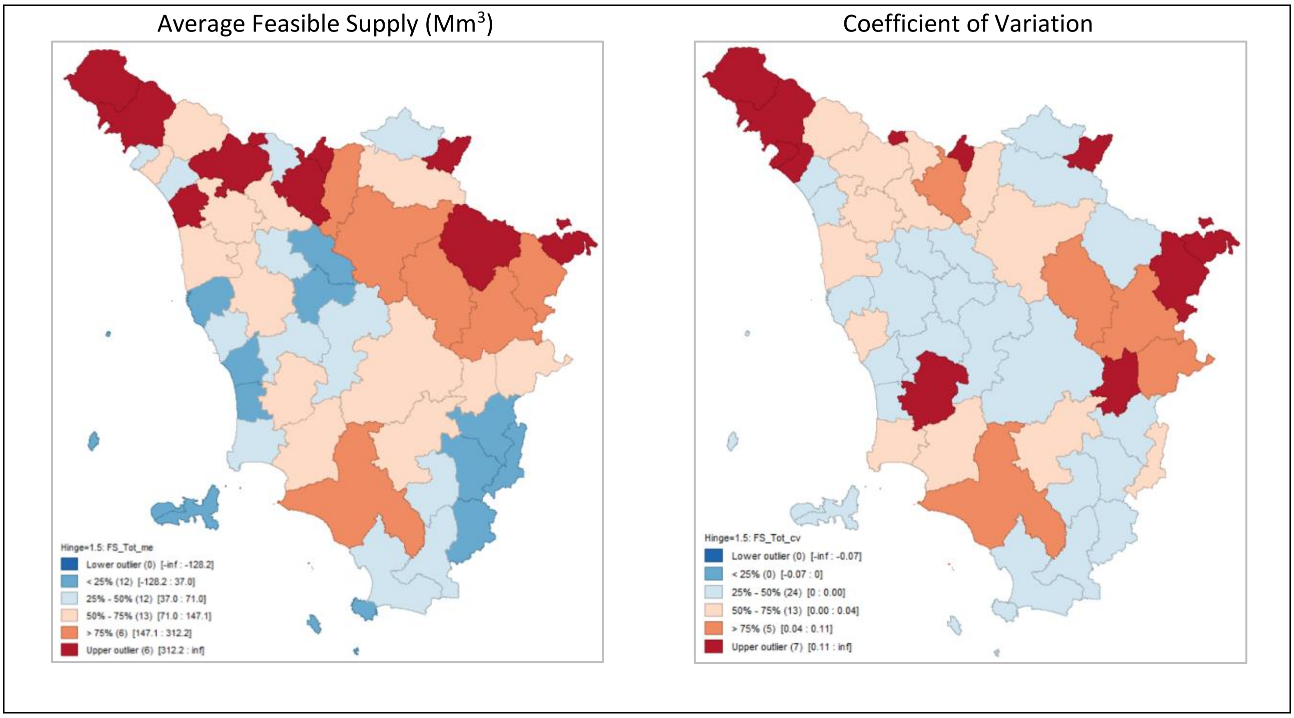
Figure 1. Average Extended demand (blue and grey water) in LMA
Volumes (Mm3) and Coefficient of Variation



Source: own elaborations

As for the feasible supply, Figure 2 presents the average value and the coefficient of variation by LMA. A higher feasible supply can be found in the Northern part of the region and in the upper areas of Tuscany (Appennine mountains). A similar spatial pattern of variability can be observed, mainly linked to the higher variability of precipitations. Another relevant factor affecting the spatial distribution of the feasible supply are water concessions, limiting the use of surface water. There is a high heterogeneity among LMA in the Ms parameter (ratio between concessions and surface runoff), showing an average of 38.5% and a coefficient of variation of 124%. In 19 out of 49 LMA the Ms parameter is lower than 9 % of the surface runoff, while in 13 LMA is over 50%. All these conditions generate the spatial distribution of the feasible supply, making it quite different from the natural availability.

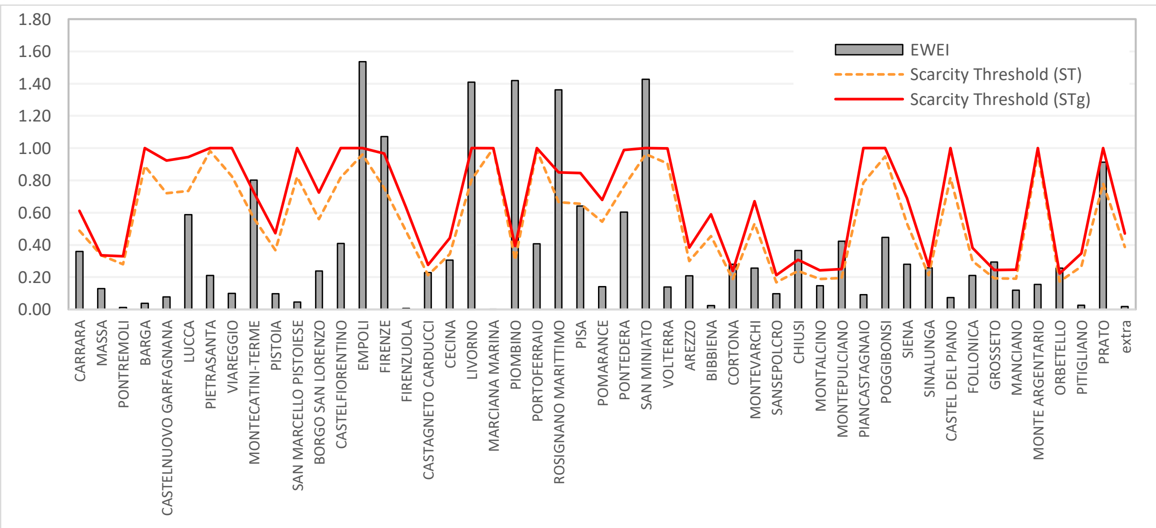
Figure 2 Feasible supply (Groundwater and surface water) Volumes (Mm3) and Coefficient of Variation



Source: own elaborations

The different geographic patterns of demand and supply generate the spatial distribution of pressures on water resources in Tuscany. Figure 3 graphically shows the average annual EWEI by LMA, comparing it with the scarcity thresholds (with and without optimal management of groundwater resources). In 12 out of 49 LMA the EWEI is higher than 0.4 and in five of them it is higher than 0.9. Scarcity conditions are present despite the region, on average, shows a modest EWEI (0.24) and would be classified in conditions of non-scarcity by indirect, aggregate measures of water stress[12].

Figure 3. Average EWEI, ST and STg by LMA



Source: own elaborations

Interestingly, scarcity at the sub-regional level is not simply an occasional condition due to the natural variability in the hydrological variables (table 2). In 14 out 49 LMA the EWEI exceeds the local scarcity

[12] The logaritmic transformation proposed by (Pfister et al., 2009) applied to the regional EWEI yields a WSI equal to 0.04, largely below the conventional threshold for moderate scarcity.

threshold (STg) on average every 4 years (25%). In 5 LMA the overexploitation of water resources is a permanent condition.

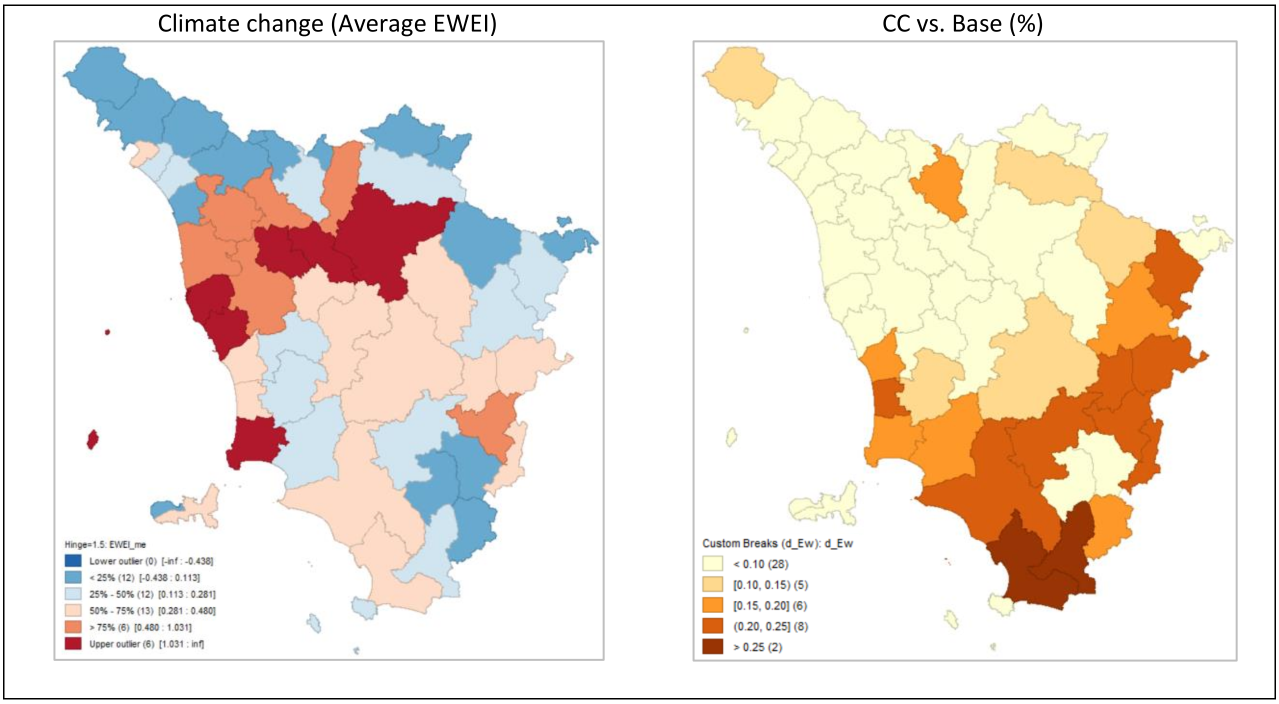
Table 2 Frequency EWEI greater than STg

Frequency in 100 years	Number of LMA
0	27
1-24	8
25-49	6
50-74	2
75-99	1
100	5

Source: own elaborations

The water balance of the region would be worsened under a climate change scenario. The EWEI would present an increase in all LMA, but with a heterogeneous spatial effect. Figure 4 shows the EWEI recalculated for the climate change scenario and (right panel) its percentage change compared with the base scenario. A greater effect can be observed in Southern Tuscany, mainly due to the higher presence of agriculture, a sector that has to replace more intensively green water with blue water. For 10 LMA the change is greater than 20% and for 2 LMA it is greater than 25% (Table 3).

Figure 4. Average EWEI in a climate change scenario
(Climate change and % change from Base scenario)



Source: own elaboration

Table 3. Increase in EWEI with climate change

EWEI increase	Number of LMA
0-9%	28
10-14%	5
15-19%	6
20-25%	8
>25%	2

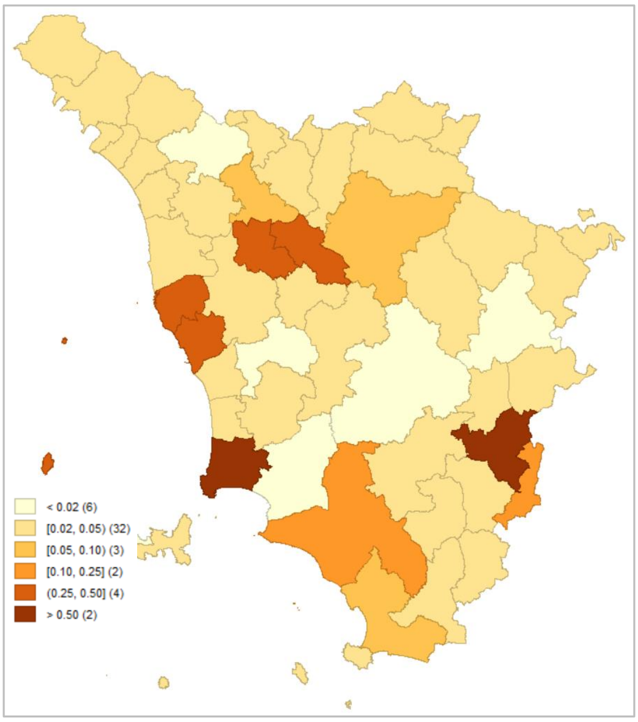
Source: own elaborations

The opportunity cost of the hydro-economic equilibrium has been defined in this study as the minimum reduction of the regional output compatible with the balance between demand and supply of water in all

LMA. The estimated cost for the regional hydro-economic equilibrium in Tuscany is 21,298 Million of Euro, corresponding to the 9.94% of the total production in Tuscany in the reference year (2017).

Since the whole ILMAIO model is used in calculating the regional HEEC, output necessarily falls in all LMA and the inter-industry linkages within and among LMA affect the spatial distribution of the cost. Figure 5 provides a map representing the output reduction. It can be seen that in 43 out 49 LMA the reduction of production is greater than 2%, in 11 LMA is greater than 5%, in 8 LMA is greater than 10% and in 6 of them it is greater than 25% (Table 3).

Figure 5. Opportunity Cost of the regional Hydro-economic Equilibrium.
Base scenario - Value of Output decrease (%)



Source: own elaborations

With climate change the regional HEEC would increase to 30,035 million euros (14% of total output), 8,737 M€ more than in the baseline scenario. For 11 LMA the percentage increase of the cost compared to the baseline scenario would be higher than 2.5% (Figure 6). Table 4 compares the two scenarios. To reach the regional hydro-economic equilibrium with climate change, all LMA would need to reduce their output more than 2% (only 43 in the base case) and for 10 LMA the output decrease would be larger than 25% (only 6 in the base case).

Figure 6
Impact of climate change on HEEC
% variation

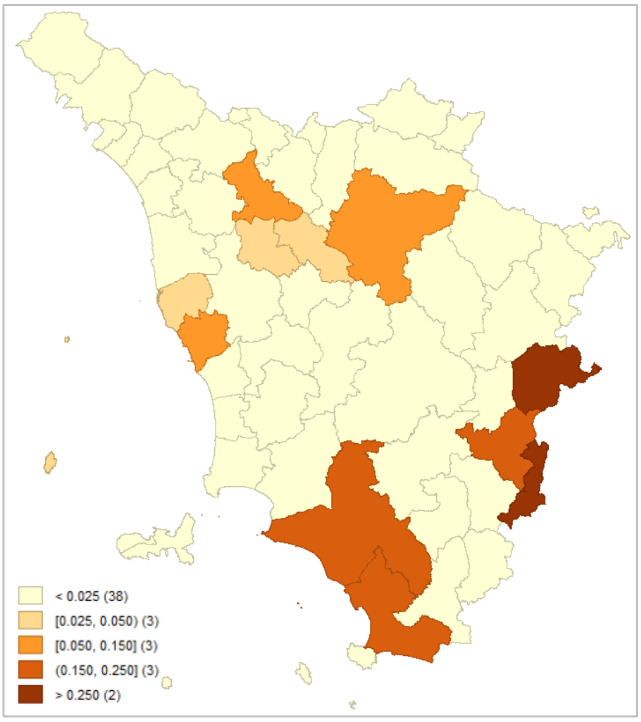


Table 4. Output decrease in LMA with hydroeconomic equilibrium
Climate change vs. Base scenario, % values

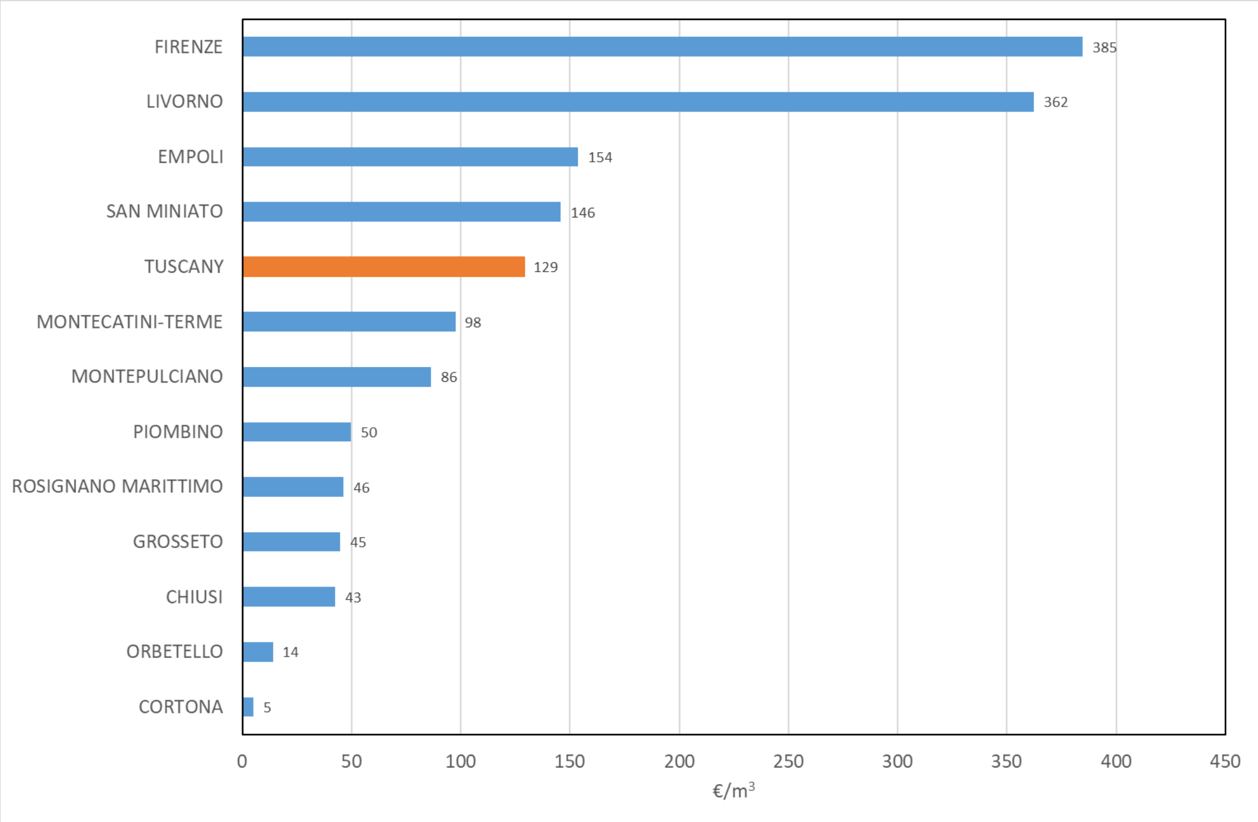
Reduction of Prod.	Number of LMA	
	Base scenario	Climate change
<2%	6	0
2-5%	32	36
5-9%	3	1
10-24%	2	2
25-49%	4	8
>50%	2	2

Source: own elaborations

It is interesting to look also at the unitary cost of HEE, i.e. the cost necessary to reduce by one cubic meter the extended demand exceeding the feasible supply. The average excess of water demand in the base hydrological scenario is equal to 172 Mm^3, corresponding to an overall RHEE cost 21,298 M€. Different LMA show different unbalances in water exploitation and, due to their mix of industries, contribute in a different extent to the regional output. Consequently, the unitary cost varies across LMA, showing how worth is for the regional economy to overexploit water resources in different sub-regional areas.

The graph in figure 7 compares the unitary cost of the 12 LMA where the average annual EWEI exceeds the STg. Water over-exploitation in these sub-regional areas is 96% of total.

Figure 7
Unitary cost of hydroeconomic equilibrium
€/m³ – Different LMA and regional Average



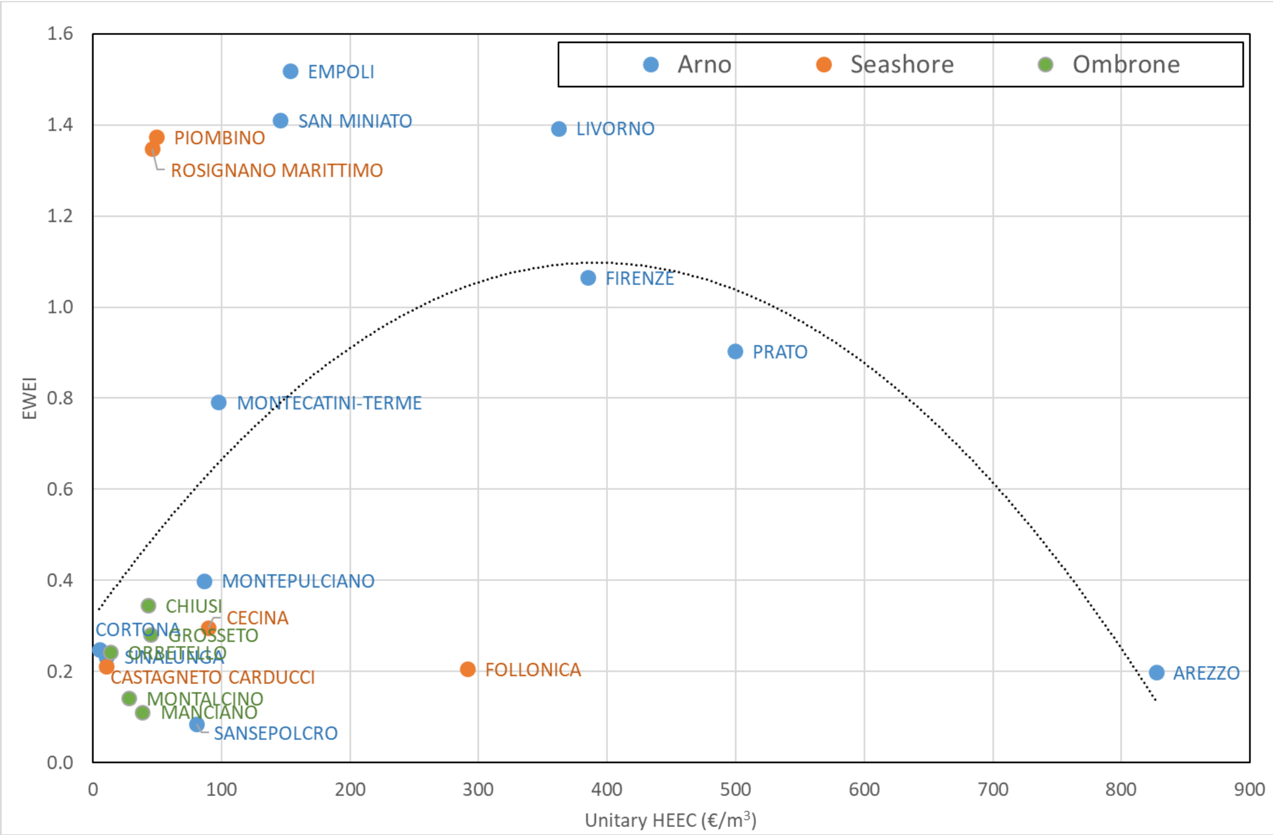
Source: own elaborations

The average unitary cost for the whole region is 129 €/m^3. Four LMA contribute the most to this average level, with a unitary cost beyond the regional mean, in two cases (Firenze and Livorno – Leghorn -, two major urban areas) more than doubling it. While also Empoli and San Miniato are areas with a relevant concentration of manufacture, the LMA showing a unitary cost below the regional average have different characteristics, including both important industrial districts (Piombino, Rosignano Marittimo) and areas where agriculture and services play a more relevant role in the industry mix (Montecatini, Montepulciano, Grosseto). A useful benchmark for comparison is the average tariff paid for water supplied by the Water Supply industry, that in the reference year (2017) was equal to 3 €/m^3. Only Cortona shows a unitary cost of the same magnitude (5 €/m^3). According to the European regulation the tariff is inclusive of a cost recovery component as well as of a "resource and environmental cost" component. Figure 7 suggests that the adverse environmental consequences of water resources over-exploitation could be more than compensated by the economic use of water. Or, conversely, that the current regulation of tariffs is unable to correctly represent the environmental costs of an unsustainable use of water resources.

The scatterplot in figure 8 provides a further insight on how the Tuscan economy uses its water resources. The graph represents all the LMA where the demand exceeds the feasible supply in years with critical hydrological conditions, despite on average their EWEI could remain within the sustainability limits[13]. The coordinates representing LMAs are the local unitary cost of hydro-economic equilibrium (€/m^3) and the average EWEI. The dots' colour allows distinguishing the hydrological basin each LMA belongs to.

[13] The LMA of Pisa is the only case non included in the graph, showing a disproportionate unitary cost (>40.000€/m3) and an almost negligible excess of water demand beyond STg.

Figure 8
Water exploitation at the subregional level
Average unitary HEEC (€/m3) and EWEI by LMA and hydrological basin



Source: own elaborations

In LMA on the left side of the graph a positive relation between the average exploitation level of water resources and the unitary cost seems to emerge. This is somehow an expected result, showing that the structural economic dynamics followed a path suitable to maximise the economic rent of water use as scarcity conditions progressively impose narrower constraints to production. The average EWEI increases moving from LMA where a major role is played by agriculture and tourism (in the Ombrone basin, in part of LMA in the seashore basin and in the higher segment of the Arno basin like Sansepolcro, Sinalunga, Cortona and Montepulciano) to LMA where manufacture is a fundamental component of the production system (Montecatini, Empoli, San Miniato, Rosignano Marittimo and Piombino). An inverse relation, however, is shown by LMA on the right side of the graph. These LMA (Livorno, Firenze, Prato and Arezzo) are all metropolitan and urban areas, where a relatively high value of the local HEEC is associated with a small average excess (m^3 of water) of the extended demand beyond the feasible supply, whatever the average level of the EWEI (decreasing moving from the left to the right of the graph). A possible interpretation of this pattern of data could rely on the urban nature of these local economies. On one side, major urban centers tend to develop where water availability doesn't represent a major environmental constraint. Moreover, beyond a given level of geographical concentration, economic activities develop regardless of environmental constraints, following agglomeration economies that favour a shift of the industry mix towards high value added production activities (such as advanced services).

6. Conclusions

The paper investigates the problem of water scarcity in a regional economy (Tuscany) using an ILMAIO model extended to water exchanges between production activities and the hydrological system. Different from previous studies we account not only for *average* flows of water resources generated by human activities but also consider the *natural variability* of water supply and the consequent variability of water demand (both in terms of quantities and in terms of composition by water sources). The full integration of a spatial stochastic hydrological model generates results going well beyond a global sensitivity and uncertainty analysis (Pianosi et al., 2016), that could be carried out to attach a probability distribution to average point estimates of water exploitation in Tuscany. The structure (industry mix and geographic pattern) of the regional economy emerges as a fundamental driver of water scarcity. The model has been used to *endogenously* determine the thresholds beyond which the exploitation of water resources faces problems of scarcity and is likely to generate adverse environmental consequences.

When looking to the average annual value of the Extended Water Exploitation Index, Tuscany appears to be a water abundant region. Only 24% of the annual "feasible" supply of freshwater from water bodies (adjusted to consider both technological and institutional constraints to water exploitation) is needed to satisfy the demand for blue and grey water. Such an average value would indicate "absence of scarcity problems" according to standard approaches to water footprint analysis in environmental studies (Pfister et al., 2009). However, the variability of natural water supply could almost double the value of the whole-region indicator in critical years (even more so in a climate change scenario). Moreover, the uneven spatial pattern of water resources and economic activities generates more frequent scarcity conditions at the sub-regional level. In a base hydrological scenario (reproducing the natural variability of the last 40 years) on average about 172 Mm^3 of blue water are used in condition of scarcity, namely beyond the threshold ensuring environmental sustainability (minimum ecological flow for surface bodies, non-decreasing stock of groundwater). In 5 out of 49 subregional areas (local labour systems) this is likely to be a *permanent* condition. In 14 LMA, water scarcity is present at least every four years, on average.

The interest of these results goes beyond the empirical application of the model to support decisions in regional water policies. The case of Tuscany shows how much the scale of analysis matters when using input-output models for water footprint analysis. The more the assessment of water pressure is carried out at an aggregate level, the more volumetric measures of water footprint are likely to lose their utility for water management and environmental analysis. Some forms of scarcity-based weighting of water pressures are used in global analysis of water footprint (Wichelns, 2017; Ridoutt et al., 2018; Sturla et al., 2023). However, the adoption of standard methods and thresholds could not be sensitive enough to account for the extreme diversity in the spatial distribution of water supply and demand. The application of these methodologies (Pfister et al. 2009) to a regional economy like Tuscany would detect an almost complete absence of water scarcity problems; all the more distorted are likely to be state/nation level assessments of water pressures, such as those used in global water footprint literature. Water scarcity problems emerge and have to be managed at the *local* level. Our results suggest a word of caution in modelling water exchanges between the economy and the environment at the global level, to support the design of strategies to target sustainability goals.

The interLMA structure of the regional IO table supported an in-depth analysis of *internal* water-economy interdependencies in Tuscany. We defined local scarcity thresholds, considering the natural variability of supply and the specific industry mix in each LMA. Trade flows among LMA re-define the map of water pressures generated by the exogenous shocks on the economy or by policy-driven constraints to water use. These features make the model suitable for impact assessments to support water management at the regional level. We extended the structural analysis to calculate what we called the *opportunity cost of hydro-economic equilibrium*, corresponding to the minimum decrease of the regional output compatible with the absence of scarcity conditions not only at the regional level but also in all LMA, holding constant the industry mix and the water technology of the regional economy. In the base hydrological scenario, the regional cost amounts to 21,298 M€, about 10% of the regional output, a value that would be increased to 30,035 M€ (14% of total output) in a climate change scenario. This value is a useful benchmark for assessing regional water policy aiming at reducing the water imbalance, both in quantitative and qualitative terms, as required by the EU regulatory framework. A new regulation to improve the quality of water discharges, the support to more efficient irrigation technologies, investments in water regulation works: all these actions could be valued according to the decrease they are able to generate in the regional HEEC. Noticeably, the interregional structure of the model allows to assess *local* actions or investments, according to the *regional* benefits they could produce.

The model also allows to calculate the cost of hydro-economic equilibrium at the local level. The opportunity cost to reduce by one cubic meter the excess of demand over the feasible supply varies among LMA and this variation should be considered in prioritising investments and other water management decisions with limited financial resources. Despite the HEEC concept adopts a short-run, comparative statics perspective, it could be easily extended to include the choice among alternative technologies (Duchin and Levine, 2012) or using Gosh linkages (Dietzenbacher, 2002) to model the price impact of regulatory actions on tariffs and concessions.

The opportunity cost of hydro-economic equilibrium quantifies in monetary terms how worth is to overexploit water resources for economic activities. As such, it could also represent a first step of a more complete environmental analysis of water uses. Each cubic meter of water used beyond the endogenous, local scarcity threshold, is likely to generate some environmental adverse effects within and outside the hydrological system. The temporary or permanent variation of ecosystem services (ES) in response to an unsustainable use of water resources could be compared with the HEEC, representing the economic return of overexploitation.

Natural resources generate a flow of ecosystem services supporting in different ways human activities, beyond their service as an input in production activities. An obvious direction for future research would aim at incorporating a comprehensive monetary evaluation of the flows of ecosystem services into the accounting framework. The extension of the analysis to ecosystem services would face several methodological challenges, both from the accounting and the modelling point of view. In the case of water, for example, the compatibility of area-based monetary estimates (such as those used in ecosystem services accounting) with values based on physical flows accounting (as in water extended input-output models) should be carefully considered. Moreover, a move towards a stock and flows accounting would be required to model the relationship between the quantity of water used beyond the scarcity thresholds and the changes in the natural capital generating the stream of ES. The UN handbook for including Ecosystem Accounting within the Environmental-Economic Accounting framework (SEEA – EA: United Nations et al., 2021) represents a starting point for these advances. Input-output models like the one presented in this study, with a strong focus on local impacts and an extensive integration of economic and environmental components, are a natural candidate for moving from environmental accounting to economic analysis and modelling.

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Declaration of interests

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HYDRO-ECONOMIC EQUILIBRIUM WITH CLIMATIC VARIABILITY IN INTERCONNECTED LOCAL ECONOMIES

Abstract

This study addresses the challenge of unsustainable water use in regional economies, where productive activities and water availability are unevenly distributed in space and time. The objective is to assess the economic implications of this spatial mismatch and to provide a tool for identifying feasible pathways toward sustainable water use. Focusing on the case of Tuscany, Italy, we develop an interregional input–output (IO) model extended to include hydrological variability and a detailed representation of economic interdependencies across Labor Market Areas (LMA). The model explicitly integrates hydrology and economics, enabling the estimation of subregional water scarcity thresholds and the economic cost of overexploitation. A key and novel contribution of this study is the development of an original indicator—the Cost of Hydro-Economic Equilibrium (CHEE)—which quantifies, in monetary terms, the value of production currently sustained by unsustainable water use. This allows for the identification of areas under pressure and supports the design of targeted water management strategies, including improvements in water-use efficiency and investment in infrastructure. The results confirm that Tuscany exhibits significant spatial heterogeneity in water scarcity, with several local economies operating under hydrological stress. The study offers a framework to evaluate the opportunity cost of transitioning toward sustainable water allocation and provides a foundation for future applications such as the accounting and valuation of water-related natural capital, contributing to both scientific understanding and evidence-based public policy.

Keywords

Water Scarcity, Input-output, Interregional Models, Tuscany.

JEL Codes

D57, Q25, Q56

1. Introduction

A renewed emphasis on the state of water resources recently emerged in the international debate on sustainable development. On March 2023, the UN Conference on the Midterm review of the Decade for action "Water for sustainable development" (2018-2028) was held in New York. During the general debate, among other topics, was stressed the strategic importance of reliable data for the analysis of water systems, to support a science-based approach to water management (United Nations, 2023: 12). Beside the lack of systematic sharing of data and efforts to design a global information system on water, delegates recalled also the need to adopt a "whole system" perspective in monitoring and modeling water systems for management purpose. Interlinkages among water use, energy supply and production activities have to be taken into account for an effective water management, both at the regional and global level (UNESCO and UN Water, 2020). A "nexus" approach in water management, however, can be adopted only in presence of proper information and adequate modelling tools. According to the UN Water Meteorological Organization (WMO, 2022) together with indirect satellite observations, hydrological models are still fundamental in monitoring the state of water resources, due to the lack of timely, verified and accessible hydrological data.

Further, managing problems of quantity and quality decline in water resources, asks to integrate hydrological with economic data, to model interactions between human activities and water systems. Environmentally extended input-output (EEIO) models are a natural answer to this problem. A wide literature has been developed using IO hydro-economic models to quantify the water footprint of economic systems, to study the so called 'water-food-energy nexus' or to support water management decisions at different geographical levels. In this paper we contribute to this stream of literature studying the balance between water resources and economic activities at the regional level. We use an interregional IO (IRIO) model of a regional economy extended to water resources to study the structural drivers of water scarcity problems and to provide an economic assessment of water resources overexploitation. A peculiar feature of our model is the full integration of a hydrological module, reproducing the natural variability of water supply, with the usual multi-sector representation of the economy. This allows us to consider both temporal and spatial variability of the balance between water supply and demand, and to generate results in the form of probability distributions of exploitation indicators. Furthermore, a comprehensive representation of the interdependencies between natural supply variability, industry composition of the economy and variability of water demand, allows us to define a system of endogenous thresholds of water scarcity to identify the overexploitation of water resources. The model is then used to define the conditions for the hydro-economic equilibrium of the regional economy (absence of overexploitation) and to assess its opportunity cost (optimal output reduction to achieve the equilibrium). The case study is Tuscany (IT), a region in the temperate zone despite an overall sufficient natural availability of water, scarcity problems emerge due to a relevant spatial mismatch between supply and demand.

The selection of Tuscany as a case study is grounded in the region's unique combination of water abundance at the aggregate level and significant localized scarcity due to spatial mismatches between natural supply and economic demand. While Tuscany is typically characterized as a water-abundant region, previous studies (Rocchi et al., 2024; Sturla and Rocchi, 2024) have shown that this classification masks critical subregional imbalances. Those studies, which applied a regional-scale water exploitation index (EWEI), found no evidence of overall scarcity, even under hydrological stress scenarios. However, their analyses assumed spatial homogeneity in water supply and demand, and perfect substitutability between surface and groundwater. In contrast, when disaggregated, the EWEI for surface water alone often exceeds established scarcity thresholds, suggesting that specific subregions may indeed face persistent overexploitation. This is supported by evidence of high spatial variability in water availability (Fatichi and Caporali, 2009; Bartolini et al., 2018) and highly uneven patterns of water withdrawals and discharges across the region (Venturi et al., 2014). Additionally, the spatial distribution of productive activities frequently misaligns with hydrological units, partly due to the legacy structure of water concessions within river basins (Venturi et al., 2014). These mismatches—between the spatial pattern of water needs and that of available resources—highlight an overlooked but pressing form of water stress: localized scarcity within seemingly abundant regions. Such situations are increasingly relevant under climate variability and changing land use dynamics. Tuscany thus serves as a representative and policy-relevant case for testing methodologies aimed at identifying and managing water scarcity at high spatial resolution. By developing an interregional hydro-economic input–output model with spatiotemporal hydrological variability, this study responds directly to the need for improved tools to assess subregional water scarcity in contexts that, like Tuscany, exhibit aggregate abundance but hidden vulnerabilities.The paper is organized as follows. The next section provides a review of input-output models extended to water resources, to position our study within the relevant literature and highlight the advances of our analysis compared to the current state of the art. Section 3 outlines the empirical characteristics of the IRIO table and the associated hydrological module, while section 4 describes the solution of the model and the methodology adopted in quantifying water pressures, the endogenous scarcity thresholds at the subregional level and the cost of the regional hydro-economic equilibrium. Section 5 summarizes the main results of the analysis. The final section propose some concluding remarks, discussing the relevance of results and future research perspectives.

2. Literature Review

Regional and interregional input–output models have been implemented to study the interactions between the economy and the environment since the 1960's (Duarte and Yang, 2011). In 1970 Leontief itself proposed a first description of an input-output model generalized to include material flows between economic activities and the environment. Among other resources also water was early considered in input-output analysis applied to the environmental management (Lofting and Mcgauhey, 1968).

Since then, IO models have been widely used to study water use in economic systems, both as an accounting framework to quantify direct and indirect water consumed by industries to supply the final demand (Velazquez, 2006; Lenzen et al., 2013; Ridoutt et al., 2018; Camara and Llop, 2020; Rocchi et al., 2023; Sturla et al., 2024) and for the estimation of virtual water flows and water footprint at the regional, national and global scale (Feng et al., 2011, 2014; Zhuoying et al., 2011; White et al., 2015; Duarte et al., 2016; Arto et al., 2016; Deng et al., 2020; Sturla et al., 2023; Sturla et al., 2024).

A relevant part of recent literature on input-output modelling extended to water resources has been oriented to the structural analysis of the so-called water-energy-food (WEF) nexus within economic systems. This is a natural use of the input-output approach, well suited to show how technical interdependencies between production activities as well as trade flows among regions affect the exploitation of limited natural resources. Guan and Hubacek (2008) study virtual water flows among China regions using a hydro-economic model. Xiao and colleagues (2019) use an input-output model to identify supply chains that directly and indirectly mostly affect the use of water and energy. A specific focus on tourism as a key industry in determining the pressure on water resources characterizes the study of Lee et al. (2021). A regional disaggregation of the IO table is exploited by Liu et al. (2017) to highlight how internal trade flows could affect the sustainability in the use of water resources in different regions of China. Following a similar approach White and colleagues study the structure of the WEF nexus in South East Asia finding "a mismatch between regional resource availability and resource flows destinations, and a lack of consideration for environmental impacts of trade policies … in resource scarce countries" (White et al., 2018: 564).

The studies cited above rely on a "volumetric" concept of water footprint, i.e. quantify the total amount of water used to produce a given basket of goods or necessary to support a given pattern of final consumptions. Such an approach has been contested to be not environmentally relevant, as water is a renewable resource that can be used without adverse effects within some limits. In the field of environmental studies, an interesting debate has been developed about the opportunity to weight water footprint measures according to some criteria of scarcity relevance (Hoekstra, 2016; Wichelns, 2017).

The availability of an IRIO table extended to water resources is the first step to support water management according to some optimization criteria. The inclusion of a water endowment measure is needed to use a water IRIO type model extended to water resources not only as an "hydroeconomic-accounting framework" (Guan and Hubacek, 2008) but as a tool for water management decisions. This type of models has been used to estimate the water *balance* of economic systems, comparing the water demand based on the economic model with the water supply based on water availability estimations. An IRIO hydro-economic model has been recently used to simulate the impact of exogenous shocks in the final demand and their effect on the water balance in Spain (Cámara and Llop, 2020). Based on a structural path analysis of a water-extended IRIO model of China, Deng and colleagues (2020) suggest strategies to save water, energy and waste production in China by adjusting final consumption and the output of critical supply chains. Duchin and López-Morales (2012) study the comparative advantage of different Mexican regions in producing food using a global IRIO model extended to water resources endowments, where the choice between rainfed and irrigated agriculture is based on a rectangular choice-of-technology rule. In a recent paper, Garcia-Hernandez and Brouwer (2021) study how the impact of water supply constraints could affect the output level and the water balance in the regions of an IRIO model. They include water restrictions in solving the model, leaving final consumption components unmet as some exogenous constraints to water supply (water endowments) at the local level are reached. An optimization procedure allows to map spatially localized water disruptions in the area of Great Lakes Basin in Canada.

In all these models blue water supply, i.e. water available for withdrawals from water bodies (Hoekstra et al., 2011), is assumed to be constant, depending on an estimate of water endowments that is exogenous to the model. Water availability for productive uses depends on the average natural supply (annual surface runoff and aquifer recharge generated by precipitations) and on the presence of waterworks to support the withdrawals (Duchin and Lopez-Morales, 2012). Water supply, whatever the concept used to define it, works as a constraint in production that can alternatively generate reductions in the produced output (Duchin and López-Morales, 2012) and/or overexploitation of water resources (Cámara and Llop, 2020; Garcia-Hernandez and Bower, 2021). Furthermore, also the technology is static: water use is linear in the level of output for each industry, depending on a fixed water coefficient. This is also the case of the model with optimal choice of technology proposed by Duchin and López-Morales, where the solution simply defines the optimal mix of rain fed and irrigated agriculture under different scenarios of water availability. Water supply and water demand, however, are both *variable* and *interdependent*. The annual average water endowments as well as the average water intensity coefficients hide an intrinsic variability of the water balance that should be considered in studying water scarcity.

In the short-run water scarcity of economic systems depends on different sources of variation. First of all, with a given structure of the economy (industry mix, average technologies and output level) the water balance is affected by the variability of the natural supply. Years with wet hydrology could reduce scarcity problems while years of dry hydrology can exacerbate them. Second, water demand co-varies with water supply depending itself on the hydrological characteristics of each year. Consider for example blue water withdrawals to irrigate crops: they are likely to be variable depending of the variation of green water availability, depending in turn on variability in precipitations. It is reasonable to expect an increase in average blue water coefficients of agriculture in years with low precipitations. Further, temporal variation could generate scarcity also *within* a given period: typically, IO models refers to a single year period, but the water balance can show a strong *within-year* variation. Finally, a third source of variation is of spatial nature. On one side, the spatial distribution of water resources is typically uneven, given the characteristics of the hydrological system. On the other side, also the spatial pattern of water demand is variable, depending on how the structural economic dynamics shaped the spatial distribution of production activities and population. As a consequence, within a region showing an overall balance between water supply and demand, several critical situations in terms of water scarcity could exists and generate different sources of endogenous variability in the water balance.

Regarding the choice of a multiregional input–output (MRIO) model over a computable general equilibrium (CGE) model, it is acknowledged, for example, that CGE models are powerful tools for simulating behavioral responses, market adjustments, and policy shocks. However, MRIO models allow for a more straightforward integration of elements that are highly complex to implement within a CGE framework—such as linkages between economic and hydrological systems, hydroeconomic optimization, and scenario simulation. For instance, Xin and Guo (2023) developed a multiregional CGE model for China with explicit constraints on water quantity and quality, which required deeply nested CES functions and custom-built social accounting matrices (SAMs) to integrate hydrological, environmental, and economic flows. While MRIO models do not capture price formation, substitution effects, or behavioral responses—as CGE models do—they offer a structurally consistent, demand-driven, empirically grounded framework, compatible with biophysical extensions and aligned with national accounts (Cazcarro et al., 2025; United Nations, 2021; Obst and Eigenraam, 2016).In this paper we use an IRIO type model fully integrated with a hydrological module reproducing the natural variability of the hydrological balance at the sub-regional level, to analyse the structural problems of water scarcity within a regional economy (Tuscany, Italy). To our knowledge this is the first attempt to integrate hydrological modelling in an IRIO type framework. The characteristics of the model allow us to answer to research question like the following: what is the variability of the water balance of the regional economy? What is the average (yearly) level of pressure on water resources beyond which critical situations of water scarcity are likely to emerge? What are the conditions for a hydro-economic equilibrium in the region, given the structure of the economy and the endowment of water resources? What is the opportunity cost of such conditions? In the following section we provide a description of the empirical implementation of the hydro-economic accounting framework, before to move to the formal description of the model.

3. The empirical framework

The IRIO table used to build the model was developed by the Tuscan Regional Institute for Economic Planning[1]. The accounting framework provides a very detailed representation of the Tuscan economy, with production activities classified into 46 industries and 49 sub-regional areas corresponding to the Labour Market Areas (LMA), as defined by Eurostat[2].

A first release of the InterLMA IO table (henceforth ILMAIO) included agriculture as a single industry. To better represent the role of agriculture in determining the overall water demand and its variability, the agriculture sector of that table was disaggregated into 8 sub-sectors, according to the Farm Types (FT) classification used in economic analyses to support EU sector policies (Common Agricultural Policy). The disaggregation of agriculture's output in the ILMAIO table was based on georeferenced information on cultivated crops and irrigated areas at a single-field geographic scale, reporting administrative data generated by the implementation of agricultural policy. Other information on agriculture (livestock inventories) available at the sub-regional level were also used. The value added produced by each subsector of the regional agriculture was estimated applying an average value added/output ratio by Farm Type based on the

[1] See for description of the IRPET interLMA I-O model : https://www.irpet.it/archives/57005

[2] According to Eurostat a LMA statistically defined as an economically integrated territory, where the majority of people both live and work. See https://ec.europa.eu/eurostat/documents/3888793/10992115/KS-TC-20-002-EN-N.pdf/5a6258be-6c53-64fa-971c-2b19908ab442?t=1591968072000 for an update of Eurostat LMA definition. Regarding the ISTAT methodology for grouping municipalities through a clustering process based on the analysis of commuting patterns see: https://www.istat.it/en/labour-market-areas.

sample of farms surveyed in Italy by the National Research Council Center for Agriculture (CREA) under the European Farm Accounting Data Network (FADN)[3].

The final ILMAIO matrix is referred to year 2017 and contains 53 economic sectors, 49 LMAs, 5 components of the domestic final demand and 4 components of external final demand (Rest of Italy and Rest of the World).

The ILMAIO table has been extended to represent the water exchange flows between the economic and the hydrological systems, following the approach proposed by Guan and Hubacek (2008) and Rocchi et al (2024). To each production activity in each LMA was assigned a water intensity coefficient (m^3/€) to link the value of output with withdrawals of green and blue water[4] from the hydrological system. Withdrawals have been classified by water body (surface and groundwater for blue water, soil moisture for green water withdrawals). A similar coefficient was defined to represent discharges of water non-incorporated in products. Not all the industries actually withdraw and discharge water from/to water bodies: service sectors for example purchase water from Water Supply and discharge water through the Sewerage Service, both separately represented in the table. The difference between withdrawal and discharge coefficients expresses the *net* demand for water for each Euro of output. Also, the demand for *grey* water demand was considered. Grey water is the amount of freshwater required to dilute pollution of discharged water bringing back water bodies to their qualitative equilibrium. The mixing model used by Guan and Hubacek (2008) and adapted by Rocchi et al (2024) have been developed to assign a specific grey water coefficient to each production activity in each LMA. Summing the grey water requirement coefficients to the unitary net demand allows to quantify the *extended* demand for water generated by one Euro of output[5].

The ILMAIO table extended with water coefficients allows for an analysis of the *average* annual balance in water resources use when a reliable estimate of natural water supply was available. This is the standard approach of environmental studies to detect water scarcity conditions of countries and regions. However, a crucial issue in integrated water management is the natural *variability* of hydrology. A region showing an overall balance between *average* annual demand and supply of water could face scarcity conditions in dry years, both for the decrease of water supply and for the consequent variation in water demand for human activities.

The empirical model used in this study includes also an explicit representation of variability in the natural supply of water. A spatial stochastic model was calibrated to generate synthetic series of the components of the hydrological balance by LMA. The model was built following the approach suggested by (Rencher and Christensen, 2002) and (Maity, 2018). A spatial stochastic model is the representation of a spatial and temporal random variable. It reproduces the main characteristics of the variable, in particular the mean, the standard deviation and the spatial correlation. The model was built based on the analysis of a spatially disaggregated time series of precipitations.

The estimated model allowed us to add a spatial structure and a temporal variability to the mean components of the regional hydrological balance. We generated 42 LMA series of N=100 years of precipitation, reproducing the mean and variance of the original series, and derived the corresponding series for the other components of the hydrological balance: evapotranspiration, surface runoff, groundwater recharge. The model was also used to generate a climate change hydrological scenario, by varying the mean and standard

[3] The FADN Public Database (http://ec.europa.eu/agriculture/rica/index.cfm) provides data on the average composition of farms' output and production costs at the national and regional levels, with a breakdown by FT and by economic size of the farm.

[4] We follow the standard definitions of different typologies of water used in studies on water footprint of human activities (Hoekstra et al. 2011).

[5] The quantification of water requirement and discharge coefficients relied on a wide set of data from different sources. For a detailed description of data used and assumptions made see section A in Supplementary materials.

deviation associated with each meteorological station, so generating a change in the simulated annual volume of precipitation for each LMA[6].

The natural variability of supply represents an exogenous source of variation of the regional water balance. Its effect, however, is not limited to changes (across time and space) in the supply of water but also includes an induced variation in water *demand*. Some economic activities are likely to require different amounts of water depending on the hydrological conditions. This is mainly the case of agriculture, where the output of crops strictly depends on the water balance: in dry years we expect a shift of water demand from the green (soil moisture) to the blue component of supply (surface and groundwater used for irrigation). A further component of water demand strictly depending on hydrological conditions is grey water. Freshwater volumes required to dilute pollutant discharged in water bodies by economic activities depends on the relative concentration of discharging and receiving waters, with the latter depending on natural supply: in wet years grey water demand is likely to decrease, due to the lower concentration in receiving bodies (higher annual run-off).

The variation of water demand depending on hydrological conditions can be represented in the model as a change of water coefficients of economic activities. We included this endogenous variation of water demand. In our simulations water withdrawal and discharge coefficients vary with hydrological conditions. As a consequence, the variability of water demand in each LMA depends on the industry mix of the local economy[7].

The full integration of hydrological and economic modelling allows us to associate a probability distribution to the average results. We fully exploit this feature of the empirical framework to study water scarcity conditions in Tuscany. In the following section we detail how we use of the hydro-economic empirical model to define a set of endogenous thresholds of water scarcity and to estimate the opportunity cost of a genuine hydro-economic equilibrium in the Tuscan economy.

4. Methodology

4.1 Overview

Figure 1 presents a general overview of the methodology guiding this study. First, as detailed in the supplementary material, a spatially distributed model is developed to generate precipitation across the region based on meteorological station records. Together with a hydrological analysis at both the basin and LMA (Local Management Area) levels, this enables the construction of a hydrological model capable of producing synthetic time series of precipitation, evapotranspiration, groundwater recharge, and runoff by LMA. This model allows for the calibration of blue water use intensity coefficients (agricultural sector), estimation of grey water demand based on water quality data and a mixing model (which depends on sectoral effluent discharges), and the determination of feasible supply (FS).

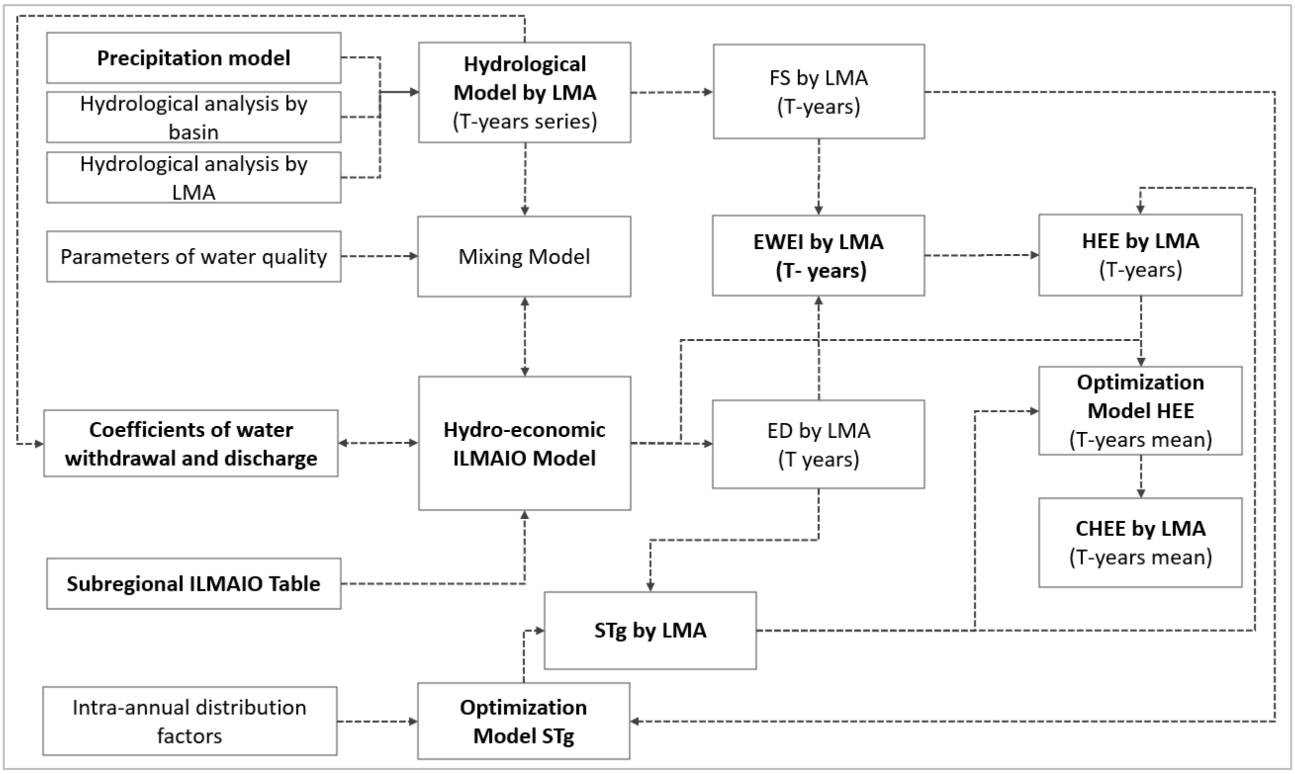
The ILMAIO hydroeconomic model is used to estimate the extended water demand (ED, including both blue and grey water), based on the region's ILMAIO table, blue water use intensity coefficients, and the mixing model outcomes for grey water. Using ED and FS, the Extended Water Exploitation Index (EWEI) is constructed for each LMA. The EWEI is then compared with the endogenous scarcity threshold for each LMA—obtained through an optimization process that accounts for annual distribution factors of surface and

[6] A detailed description of data and methods used to build the spatial stochastic model of the regional hydrology and the climate change scenario is available in section B of Supplementary Materials.
[7] A detailed description of how this endogenous variation of water demand has been modelled can be found in section C of Supplementary Materials.

groundwater supply and demand, ED, and FS—thereby characterizing the hydroeconomic equilibrium (HEE) for local economies.

Finally, a macroeconomic optimization model, which maximizes production subject to the constraint that HEE is achieved in each LMA (EWEI < STg), is used to estimate the Cost of Hydroeconomic Equilibrium (CHEE), both regionally and by LMA. This cost represents the value of production sustained through water overexploitation, or equivalently, the opportunity cost of achieving the absence of overexploitation.

Figure 1. Scheme of the methodology



Source: own elaboration

4.2 The general model

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

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

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

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

The vector $\mathbf{x}$ can be expressed as a function of the inter-LMA input coefficients (*mn* x *mn*) matrix $\mathbf{A}$, a (*mn* x *1*) vector $\mathbf{d}$ of domestic final demand, ;and the external exogenous components, foreign and regional exports, the (mnx1) vectors $\mathbf{h_f}$ and $\mathbf{h_r}$.Hereafter the structural form:

$$\mathbf{x} = \mathbf{A} \cdot \mathbf{x} + \mathbf{d} + \mathbf{h_f} + \mathbf{h_r} \quad (2a).$$

Which leads to the following reduced form:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot (\mathbf{d} + \mathbf{h_f} + \mathbf{h_r}) \quad (2b).$$

Where:

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

Defining:

i) $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ as the interLMA Leontief inverse (*mn* x *mn*) matrix
ii) $\mathbf{y} = \mathbf{d} + \mathbf{h_r} + \mathbf{h_w}$ as the LMA final production

yields:

$$\mathbf{g} = \hat{\mathbf{c}} \cdot \mathbf{L} \cdot \mathbf{y} \quad (3)$$

4.3 Extended demand for water

For the purposes of this study, the environmental resource is water. The extended water demand is defined as withdrawals of blue water[8] from surface and groundwater bodies minus discharges plus the water requirements for dilution (grey water). The extended demand of water (*n* x *1*) vector for each subregion $(\mathbf{e_k^s})$ could be expressed as:

$$\mathbf{e_k^s} = (\widehat{\mathbf{f_k^s}} - \widehat{\mathbf{r_k^s}} + \widehat{\mathbf{w_k^s}}) \cdot \mathbf{L^s} \cdot \mathbf{y} \quad (4)$$

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

When temporal hydrological variability is considered, the water intensity coefficients change with the variation in the components of the hydrologic cycle. Let us first define the extended demand for water in the subregion *s* associated with water body *k*, industry *i* and year *t* (for notation simplicity we use $\mathbf{x^s}$ instead of $\mathbf{L^s y}$)*:*

$$e_{k,i,t}^s = (f_{k,i,t}^s - r_{k,i,t}^s + w_{k,i,t}^s) \cdot x_i^s \quad (5)$$

Withdrawal coefficients vary in agricultural sub-sectors, due to variations in soil moisture availability, which implies higher withdrawals from surface and groundwater bodies when the demand for water exceeds the natural supply of green water. Discharge coefficients also change because withdrawing water from surface and groundwater bodies involves losses in the use of water for irrigation. The dilution water requirement coefficients change in all industries directly discharging polluted water into water bodies, depending on runoff and groundwater recharge, which affect the concentration of pollutant in the receiving bodies.

Equations (6), 7) and (8) present the water intensity coefficients as a function of a deterministic average value plus a time-varying term, which depends on the hydrological conditions:

[8] The blue component of water demand is the object of water management policy, despite also the green component contributes to the water balance of the economy. In our empirical framework the green component is considered in modelling the endogenous variation of blue water demand for agriculture.

$$f^s_{k,i,t} = f^s_{k,i} + \mathcal{F}^{\mathrm{s}}_{\mathrm{k,i,t}}(p^{\mathrm{s}}_{\mathrm{t}}, v^{\mathrm{s}}_{\mathrm{t}}) \tag{6}$$

$$r^s_{k,i,t} = r^s_{k,i} + \mathcal{R}^{\mathrm{s}}_{\mathrm{k,i,t}}\,(p^{\mathrm{s}}_{\mathrm{t}}, v^{\mathrm{s}}_{\mathrm{t}}) \tag{7}$$

$$w^s_{k,i,t} = w^s_{k,i} + \mathcal{H}^{\mathrm{s}}_{\mathrm{k,i,t}}[z^{\mathrm{s}}_{\mathrm{t}}, q^{\mathrm{s}}_{\mathrm{t}}, \mathcal{R}^{\mathrm{s}}_{\mathrm{k,i,t}}(p^{\mathrm{s}}_{\mathrm{t}}, v^{\mathrm{s}}_{\mathrm{t}})] \tag{8}$$

where p^s_t, v^s_t, z^s_t *and* q^s_t are respectively precipitations, evapotranspiration, groundwater recharge and surface water runoff in subregion *s* for year *t*, obtained with the hydrological model.

Using equations (6) to (8) it is possible to write a general expression for the extend demand from water body *k*, in year *t* associated with industry *i* in LMA *s*:

$$e^s_{k,i,t} = e^s_{k,i} + \left[\mathcal{F}^{\mathrm{s}}_{\mathrm{k,i,t}}(p^s_t, v^s_t) + \mathcal{R}^{\mathrm{s}}_{\mathrm{k,i,t}}\,(p^s_t, v^s_t) + \mathcal{H}_{\mathrm{k,i,t}}\left[z^s_t, q^s_t, \mathcal{R}_{\mathrm{k,i,t}}(p^s_t, v^s_t)\right]\right] \cdot x^s_i \tag{9}$$

Note that $\mathcal{F}^s_{k,i,t}(p^s_t, v^s_t) = 0$ and $\mathcal{R}^s_{k,i,t}\,(p^s_t, v^s_t) = 0$ for non-agricultural sectors, and $\mathcal{H}_{k,i,t}[q^s_t, z^s_t, \mathcal{R}_{k,i,t}(p^s_t, v^s_t)] = 0$ for non-discharging sectors. Section C in the Supplementary Material details how the stochastic components of the extended demand have been modelled.

4.4 The EWEI Indicator

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

$$EWEI^S_t = \frac{\sum_{i=1}^{m}\sum_{k=1}^{2}(f^s_{k,i,t} - r^s_{k,i,t} + w^s_{k,i,t}) \cdot x^s_i}{z^{s,feas}_t + q^{s,feas}_t} \tag{10}$$

where the sums considers *m* industries and two water bodies (groundwater and surface water). The variables $z^{s,feas}_t$ and $q^{s,feas}_t$ are the groundwater and surface water *feasible* supplies.

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

The limitations to the use of groundwater are different. Groundwater is a stock that varies according to the annual recharge. Consequently, the annual extraction depends more on the long-term average recharge than that of a single year. Unlike surface water, if the recharge in a given year is low, it is still possible to extract a larger quantity (reservoir effect); conversely, when the recharge is high, there are technical and institutional limitations to extraction (withdrawals capacity, concession). To be sustainable the average feasible supply should be equal to the average recharge (non-decreasing groundwater stock condition). The annual withdrawals will vary around the average recharge and will be a little lower than the actual recharge in a rainy year and higher in a dry year. This is the reason why concessions are usually awarded for a slightly higher value than the annual sustainable recharge.

In equation (10) $z^{s,feas}_t$ and $q^{s,feas}_t$ are defined as follows:

$$z_t^{s,feas} = \begin{cases} \bar{z}^s(1-\varepsilon^s) & if \;\; z_t^s < \bar{z}^s(1-\varepsilon^s) \\ \bar{z}^s(1+\varepsilon^s) & if \;\; z_t^s > \bar{z}^s(1+\varepsilon^s) \\ z_t^s & if \;\; z_t^s \in [\bar{z}^s(1-\varepsilon^s), \bar{z}^s(1+\varepsilon^s)] \end{cases} \quad (11)$$

$$q_t^{s,feas} = \begin{cases} q_t^s - \delta^s \bar{q}^s & if \;\; \delta\bar{q}^s \le q_t^s \le \theta^s q^s + \delta\bar{q}^s \\ \theta^s \bar{q}^s & if \;\; q_t^s > \theta^s \bar{q}^s + \delta\bar{q}^s \\ 0 & if \;\; q_t^s < \delta\bar{q}^s \end{cases} \quad (12)$$

where

z_t^s	:	Groundwater recharge volume in year t in subregion *s*
$\bar{z}^s$	:	Long-term groundwater recharge volume in subregion *s*
ε^s	:	Parameter defining the range of groundwater feasible availability in subregion *s*
q_t^s	:	Runoff volume in year t (multivariate model)
$\bar{q}^s$	:	Long-term runoff volume in subregion *s*
δ^s	:	Minimum ecological flow as proportion of mean runoff in subregion *s*
θ^s	:	Maximum volume of concessions as proportion of mean runoff in subregion *s*

We use a value of $\varepsilon^s = 13\%$ and $\delta^s = 20\%$ for all subregions. The value of θ^s depends on the concessions active in each subregion, estimated based on information from regional Hydro-geological Service (SIR)[9] according with the with methodology proposed by Venturi et al. (2014).

4.5 Endogenous scarcity threshold

Conditions of scarcity emerge when the demand for water exceeds the feasible supply. A critical issue is the choice of the period within which demand and supply are compared. So far, we considered the year as a reference period. Water demand and supply, however, varies also within every single year. Consequently, an average *annual* EWEI (for a given territory) lower than 1 could still hide temporary conditions of scarcity. This is the reason why in environmental studies the volumetric measures of water footprint of whole economies are weighted for scarcity through some mathematical transformations of annual pressure indicators like the EWEI. This is, for instance, the case of the Water Stress Index (WSI) proposed by Pfister and colleagues (2009), a logistic transformation of the ratio of total annual freshwater withdrawals to hydrological availability[10]. WSI varies between 0.01 to 1; usually a value of 0.2 is considered as a threshold for moderate scarcity, while 0.4 delimits situations of severe scarcity.

In the present analysis we use the model itself to define a water scarcity threshold for the annual regional EWEI, considering the intra-annual variability of water demand and supply and the geographical differentiation in the hydro-economic system. Different form the approach of (Pfister et al., 2009) our threshold is endogenous, depending on the economic structure and the hydrological conditions of each subregion *s*.

Let e^s and u^s the annual extended demand and the feasible supply in region *s,* including both groundwater and surface water. The sub-regional EWEI for a generic month *i* can be expressed as:

[9] https://www.sir.toscana.it/strati-gis.

[10] The ratio corresponds to the Water to Availability (WTA) index and is calculated correcting natural water supply according to the presence of storage capacities available in different watersheds (Pfister et al., 2009)

$$EWEI_i^s = \frac{(1-\alpha^s)\cdot\frac{e^s}{12} + \alpha^s\cdot\frac{u^s}{12}\cdot a_i^s}{(1-\beta^s)\cdot\frac{e^s}{12}\cdot c_i^s + \beta^s\cdot\frac{u^s}{12}\cdot b_i^s} \tag{13}$$

where

$\alpha^s = \frac{e_{Var}^s}{e^s}$ is the share of the extended demand corresponding to industries with intra-annual variability

$\beta^s = \frac{u_{sw}^s}{u^s}$ is the share of surface water feasible supply

$a_i^s = \frac{e_{Var,i}^s}{e_{Var}^s/12}$ is the intra-annual distribution coefficient of the extended demand from industries with intra-annual variability for month *i*

$b_i^s = \frac{u_{sw,i}^s}{u_{sw}^s/12}$ is the intra-annual distribution coefficient of surface water feasible supply for month *i*

$c_i^s = \frac{u_{gw,i}^s}{u_{gw}^s/12}$ is the intra-annual distribution coefficient of groundwater feasible supply for month *i*

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

$$EWEI_i^s = \frac{(1-\alpha^s) + \alpha^s a_i^s}{(1-\beta^s)c_i^s + \beta^s b_i^s} EWEI^s \tag{14}$$

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

$$ST^s = \min_i \frac{(1-\beta^s)c_i^s + \beta^r b_i^s}{(1-\alpha^s) + \alpha^s a_i^s} \tag{15}$$

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

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

The scarcity threshold (ST_m^s) with integrated groundwater and surface water management will correspond to the value of the expression in equation (15) maximized by the sets of c_i^r and b_i^r values:

$$ST_m^s = \max_{c_i^s, b_i^s}\left[\min_i \frac{(1-\beta^s)c_i^s + \beta^r b_i^s}{(1-\alpha^s) + \alpha^s a_i^s}\right] \tag{16}$$

Of course, this threshold is less restrictive than the threshold considering only natural scarcity conditions (ST^s).

For groundwater, management is always possible. We consider that $c_i^r \in (1-\lambda^s, 1+\lambda^s)$, where λ^s corresponds to the percentage by which the groundwater supply in month *i* can be above or below the average monthly supply. A similar approach could be adopted for surface water also. However, due to the lack of complete and reliable information on regulation infrastructures in our analysis we consider only the groundwater regulation, defining the scarcity threshold with groundwater optimal management (ST_g^s) as follows:

$$ST_g^s = \max_{c_i^s}\left[\min_i \frac{(1-\beta^s)c_i^s + \beta^r b_i^s}{(1-\alpha^s) + \alpha^s a_i^s}\right] \quad (17)$$

4.6 Hydro-economic equilibrium

Local hydro-economic equilibrium (LHEE) for subregion *s* is defined as the situation where the annual $EWEI^s$ is less than or equal to the ST_g^s calculated considering the average hydrological conditions. Regional Hydro-Economic Equilibrium (RHEE) is defined as a situation where all LMA satisfy the LHEE conditions. That is, there is no water stress in any subregion *s*. Using equation (4) the RHEE condition can be written as:

$$\frac{(\mathbf{v_{blue}^s} + \mathbf{v_{grey}^s})^T \cdot \mathbf{L^s} \cdot \mathbf{y}}{u^s} \leq ST_g^s \quad ,\forall s \quad (18)$$

where $\mathbf{v_{blue}^s}$ and $\mathbf{v_{grey}^s}$ corresponds to the (*m* x *1*) vectors of blue (groundwater and surface water) and grey (water for dilution) water use intensity coefficients by industry in subregion *s*, considering average hydrological conditions. The feasible supply u^s is also considered for the average hydrological conditions.

The opportunity cost of the regional hydro-economic equilibrium is the minimum reduction in output that would be required to bring all subregions to the LHEE condition. The optimization problem has the objective function of maximizing production (minimum reduction) by varying the final demand without restrictions in deficit subregions (where the final demand supplied by the LMA economy system could be zero).

The final demand in each subregion is modified on the basis of the control variable ϕ^s. The production vector x is redefined as:

$$x = \mathbf{L} \cdot \widehat{\boldsymbol{\Phi}} \cdot \mathbf{y} \quad (19)$$

where $\widehat{\boldsymbol{\Phi}}$ is a diagonal matrix (*mn* x *mn*) containing *m* times the value of ϕ^s for each of the *n* subregions. The optimization problem is:

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

$$s.t.$$

$$\frac{(\mathbf{v_{blue}^s} + \mathbf{v_{grey}^s})^{\mathrm{T}} \cdot \mathbf{L^s} \cdot \widehat{\boldsymbol{\Phi}} \cdot \mathrm{y}}{u^s} \leq ST_g^s \quad , \quad \forall s \quad (20)$$

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

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

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

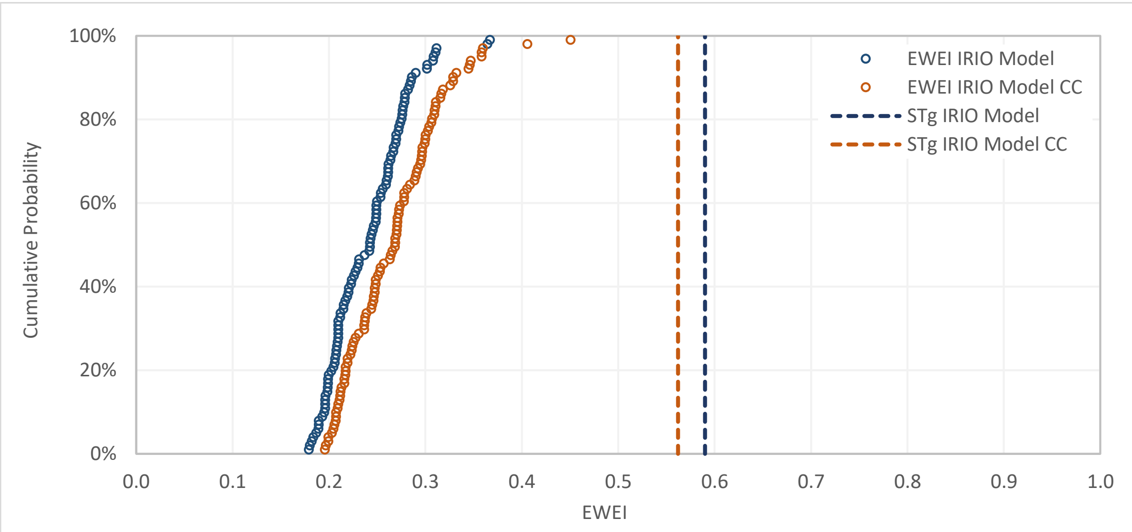
$$HEEC = \boldsymbol{\epsilon}' \cdot (\mathbf{x}^* - \mathbf{x}^\mathbf{b}) \tag{21}$$

The opportunity cost refers to the regional hydro-economic equilibrium (RHEE). When using an ILMAIO model, any reductions in production necessary to satisfy each local hydro-economic equilibrium (LHEE) in any subregion *s* will have an impact on all the other sub-regions (with and without deficit). The ILMAIO model developed in this study allows to study the reduction of production in each of the *n* subregions necessary to ensure the *regional/LMA* hydro-economic equilibrium. The HEEC strictly depends on the hydrologic *and* the economic structure of the region.

5. Results

The average EWEI for the whole region under the base (historical) hydrological scenario is equal to 0.24. The cumulative probability distribution of the regional EWEI is represented in Figure 2, for the base and climate change (CC) scenarios. In the latter, the EWEI increases from 0.24 to 0.27, the variance increases by 24% and the skewness increases by 24%.

Figure 2. EWEI cumulative probability distribution and Scarcity threshold
Whole Tuscany - Base and Climate Change scenario



Source: own elaborations

Nonetheless, although the maximum EWEI increases up to 0.45, it still remains largely below the scarcity threshold (0.562). However, the situation changes dramatically when considering the spatial heterogeneity of the hydro-economic conditions within the region.

Table 1 shows the spatial statistics considering the average hydrology conditions (the mean of 100 simulations) for the extended demand (blue and grey water) for surface and ground water, the component water required for dilution (grey water) and the total feasible supply. Grey water represents 66% of the extended demand, which in turn corresponds to 24% of the feasible supply (a regional EWEI of 0.24). Regarding the first order spatial autocorrelation, water for dilution has the highest value of the Moran Index (0.369)[11].

Table1. Spatial statistics for demand and supply of water

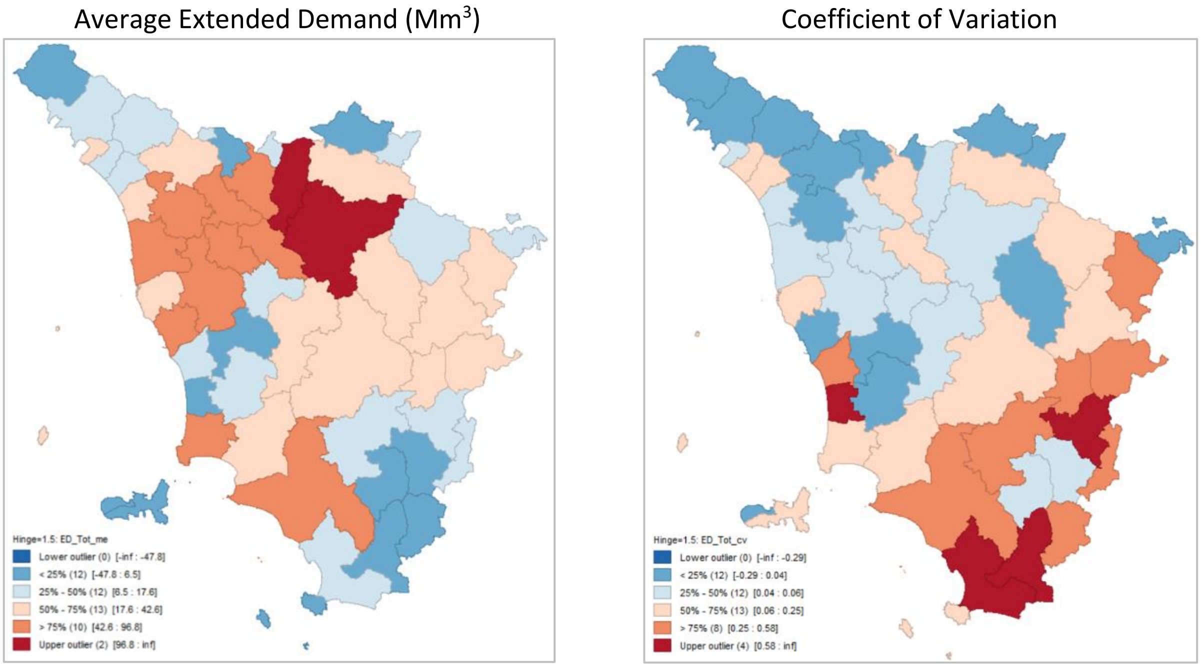
[11] Section D of Supplementary Materials provides the average results for the 42 LMA

Spatial Statistics	Extended demand (gw+sw)	Water for dilution	Feasible supply
Mean (Mm^3)	28.0	18.4	118.8
SD (Mm^3)	32.7	23.6	133.2
CV	117%	129%	112%
Skewness	2.5	2.4	1.9
Min (Mm^3)	0.0	0.0	3.3
Max (Mm^3)	159.3	113.0	514.6
Moran Index (1st ord.)	0.270	0.369	0.294

Source: own elaborations

The maps in Figure 3 analyses the extended demand across the LMA. The spatial distribution of water demand is uneven. The highest values are present, as expected, in LMA corresponding to the metropolitan area of Firenze (Florence) and Prato (upper outliers in the regional distribution), along the basin of the Arno River, as well as in some LMA along the shoreline of the region. The interannual variability of water demand also shows a clear geographic pattern. Southern Tuscany presents a higher variability, due to the replacement of green water by blue water in agriculture and the changes in the demand for grey water due to a stronger variation in the natural supply.

Figure 3. Average Extended demand (blue and grey water) in LMA
Volumes (Mm3) and Coefficient of Variation

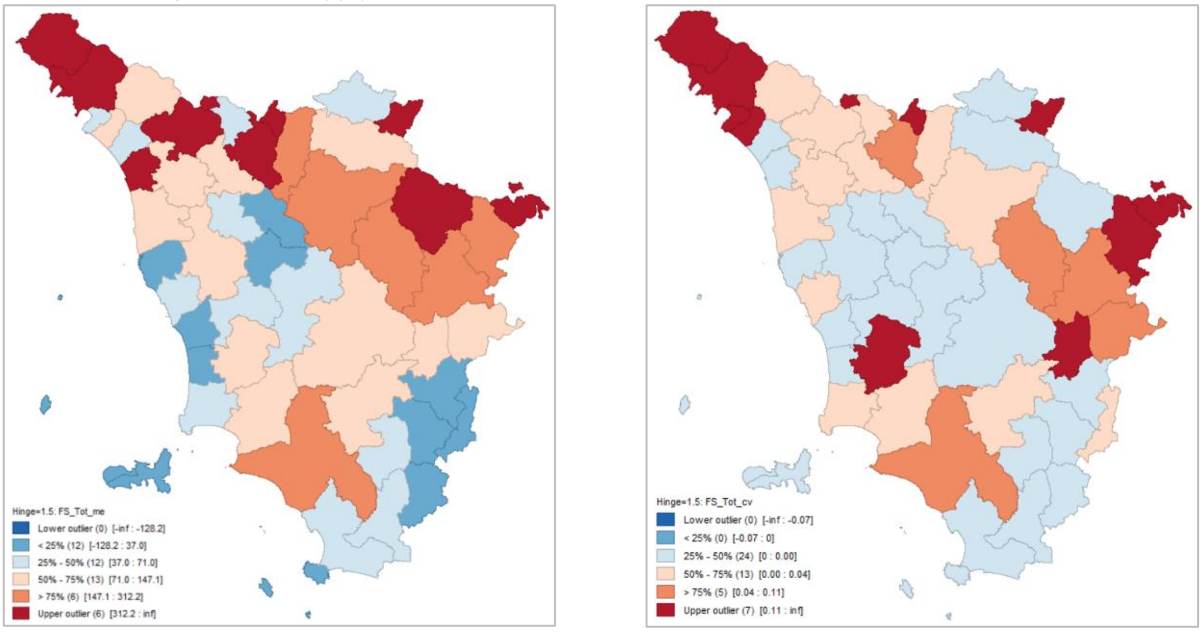


Source: own elaborations

As for the feasible supply, Figure 4 presents the average value and the coefficient of variation by LMA. A higher feasible supply can be found in the Northern part of the region and in the upper areas of Tuscany (Appennine mountains). A similar spatial pattern of variability can be observed, mainly linked to the higher variability of precipitations. Another relevant factor affecting the spatial distribution of the feasible supply are water concessions, limiting the use of surface water. There is a high heterogeneity among LMA in the Ms parameter (ratio between concessions and surface runoff), showing an average of 38.5% and a coefficient of variation of 124%. In 19 out of 49 LMA the Ms parameter is lower than 9 % of the surface runoff, while in 13 LMA is over 50%. All these conditions generate the spatial distribution of the feasible supply, making it quite different from the natural availability.

Figure 4 Feasible supply (Groundwater and surface water) Volumes (Mm3) and Coefficient of Variation

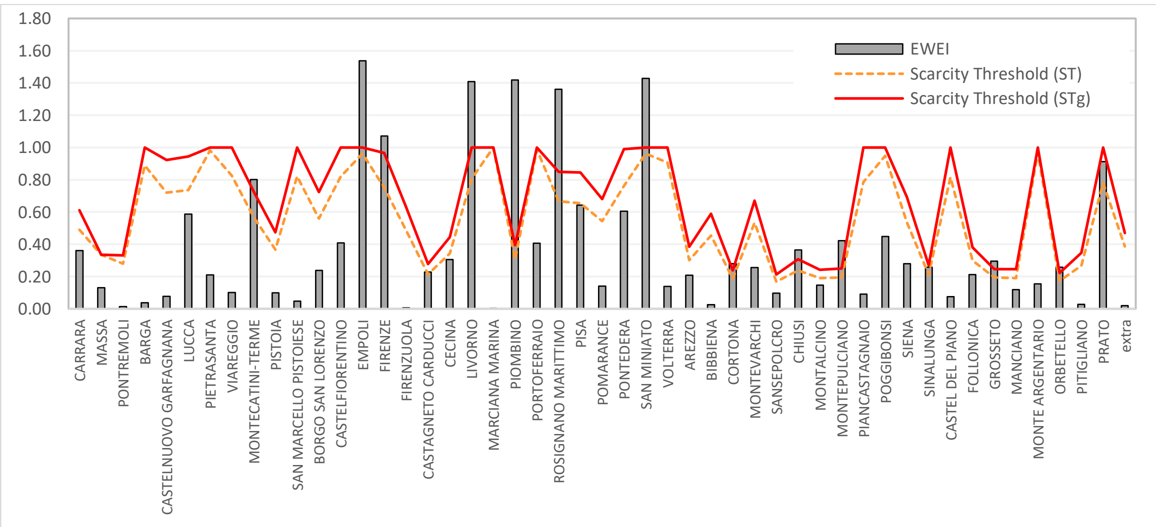
Average Feasible Supply (Mm^3) | Coefficient of Variation



Source: own elaborations

The different geographic patterns of demand and supply generate the spatial distribution of pressures on water resources in Tuscany. Figure 4 graphically shows the average annual EWEI by LMA, comparing it with the scarcity thresholds (with and without optimal management of groundwater resources). In 12 out of 49 LMA the EWEI is higher than 0.4 and in five of them it is higher than 0.9. Scarcity conditions are present despite the region, on average, shows a modest EWEI (0.24) and would be classified in conditions of non-scarcity by indirect, aggregate measures of water stress[12].

Figure 5. Average EWEI, ST and STg by LMA



Source: own elaborations

Interestingly, scarcity at the sub-regional level is not simply an occasional condition due to the natural variability in the hydrological variables (table 2). In 14 out 49 LMA the EWEI exceeds the local scarcity

[12] The logaritmic transformation proposed by (Pfister et al., 2009) applied to the regional EWEI yields a WSI equal to 0.04, largely below the conventional threshold for moderate scarcity.

threshold (STg) on average every 4 years (25%). In 5 LMA the overexploitation of water resources is a permanent condition.

Table 2 Frequency EWEI greater than STg

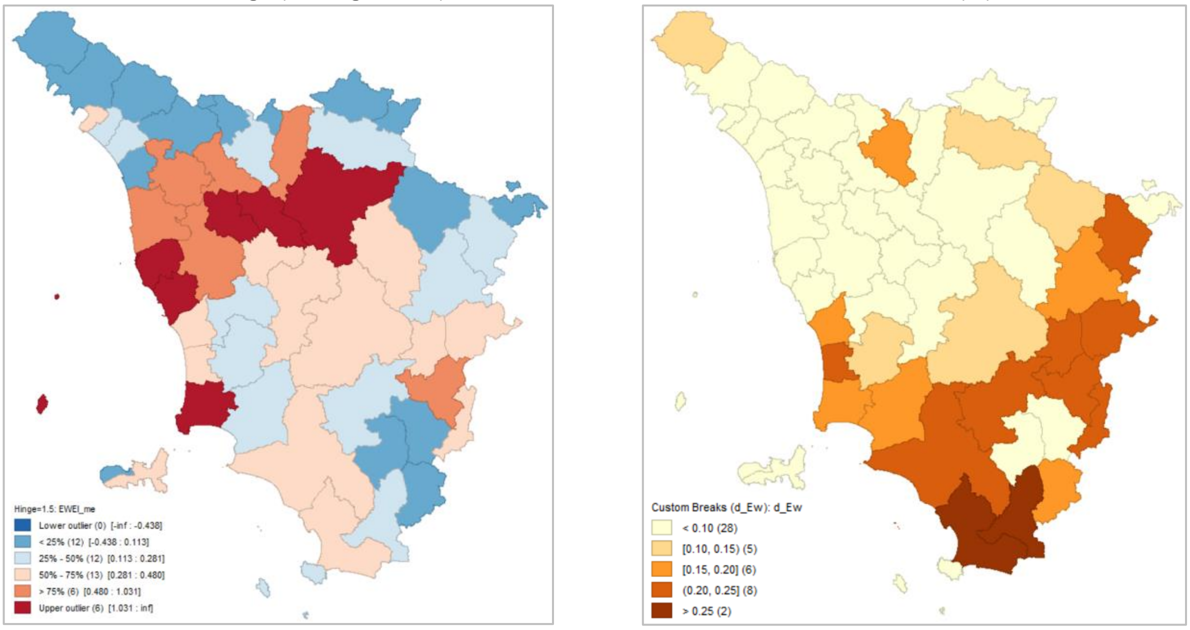
Frequency in 100 years	Number of LMA
0	27
1-24	8
25-49	6
50-74	2
75-99	1
100	5

Source: own elaborations

The water balance of the region would be worsened under a climate change scenario. The EWEI would present an increase in all LMA, but with a heterogeneous spatial effect. Figure 6 shows the EWEI recalculated for the climate change scenario and (right panel) its percentage change compared with the base scenario. A greater effect can be observed in Southern Tuscany, mainly due to the higher presence of agriculture, a sector that has to replace more intensively green water with blue water. For 10 LMA the change is greater than 20% and for 2 LMA it is greater than 25% (Table 3).

Figure 6. Average EWEI in a climate change scenario
(Climate change and % change from Base scenario)

Climate change (Average EWEI) CC vs. Base (%)



Source: own elaboration

Table 3. Increase in EWEI with climate change

EWEI increase	Number of LMA
0-9%	28
10-14%	5
15-19%	6
20-25%	8
>25%	2

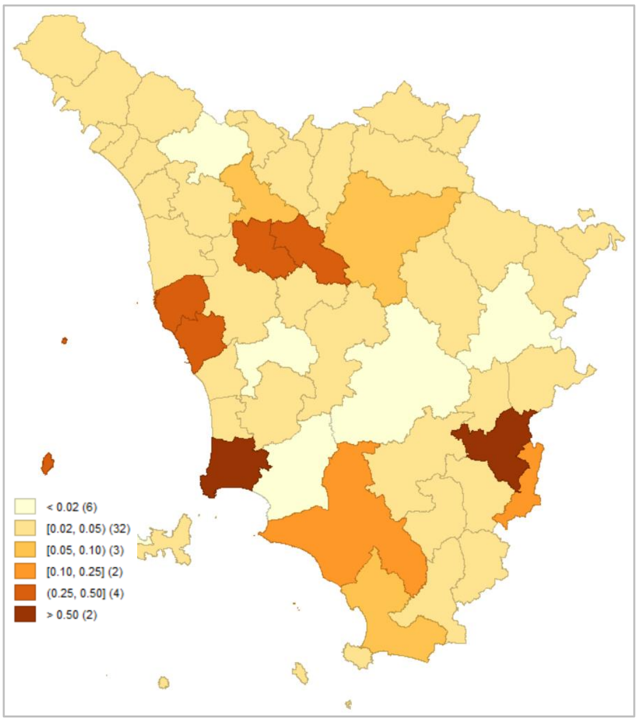
Source: own elaborations

The opportunity cost of the hydro-economic equilibrium has been defined in this study as the minimum reduction of the regional output compatible with the balance between demand and supply of water in all

LMA. The estimated cost for the regional hydro-economic equilibrium in Tuscany is 21,298 Million of Euro, corresponding to the 9.94% of the total production in Tuscany in the reference year (2017).

Since the whole ILMAIO model is used in calculating the regional HEEC, output necessarily falls in all LMA and the inter-industry linkages within and among LMA affect the spatial distribution of the cost. Figure 7 provides a map representing the output reduction. It can be seen that in 43 out 49 LMA the reduction of production is greater than 2%, in 11 LMA is greater than 5%, in 8 LMA is greater than 10% and in 6 of them it is greater than 25% (Table 3).

Figure 7. Opportunity Cost of the regional Hydro-economic Equilibrium.
Base scenario - Value of Output decrease (%)



Source: own elaborations

With climate change the regional HEEC would increase to 30,035 million euros (14% of total output), 8,737 M€ more than in the baseline scenario. For 11 LMA the percentage increase of the cost compared to the baseline scenario would be higher than 2.5% (Figure 8). Table 4 compares the two scenarios. To reach the regional hydro-economic equilibrium with climate change, all LMA would need to reduce their output more than 2% (only 43 in the base case) and for 10 LMA the output decrease would be larger than 25% (only 6 in the base case).

Figure 8
Impact of climate change on HEEC
% variation

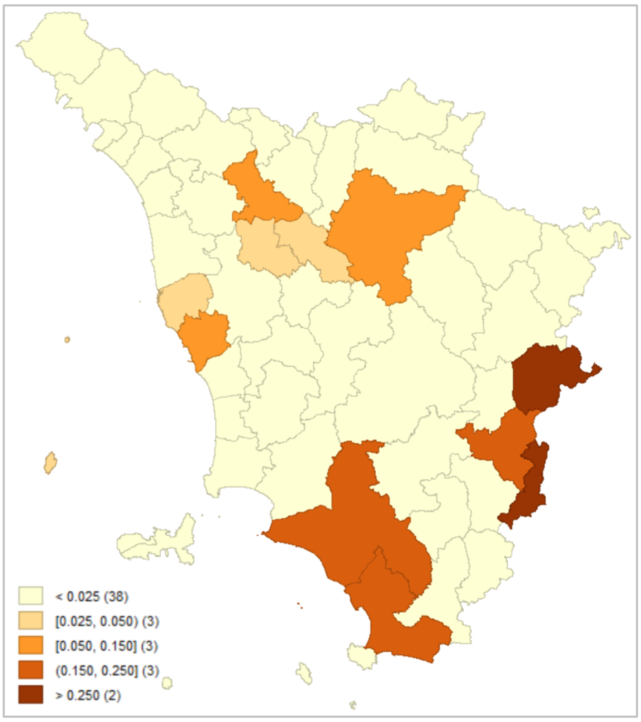


Table 4. Output decrease in LMA with hydroeconomic equilibrium
Climate change vs. Base scenario, % values

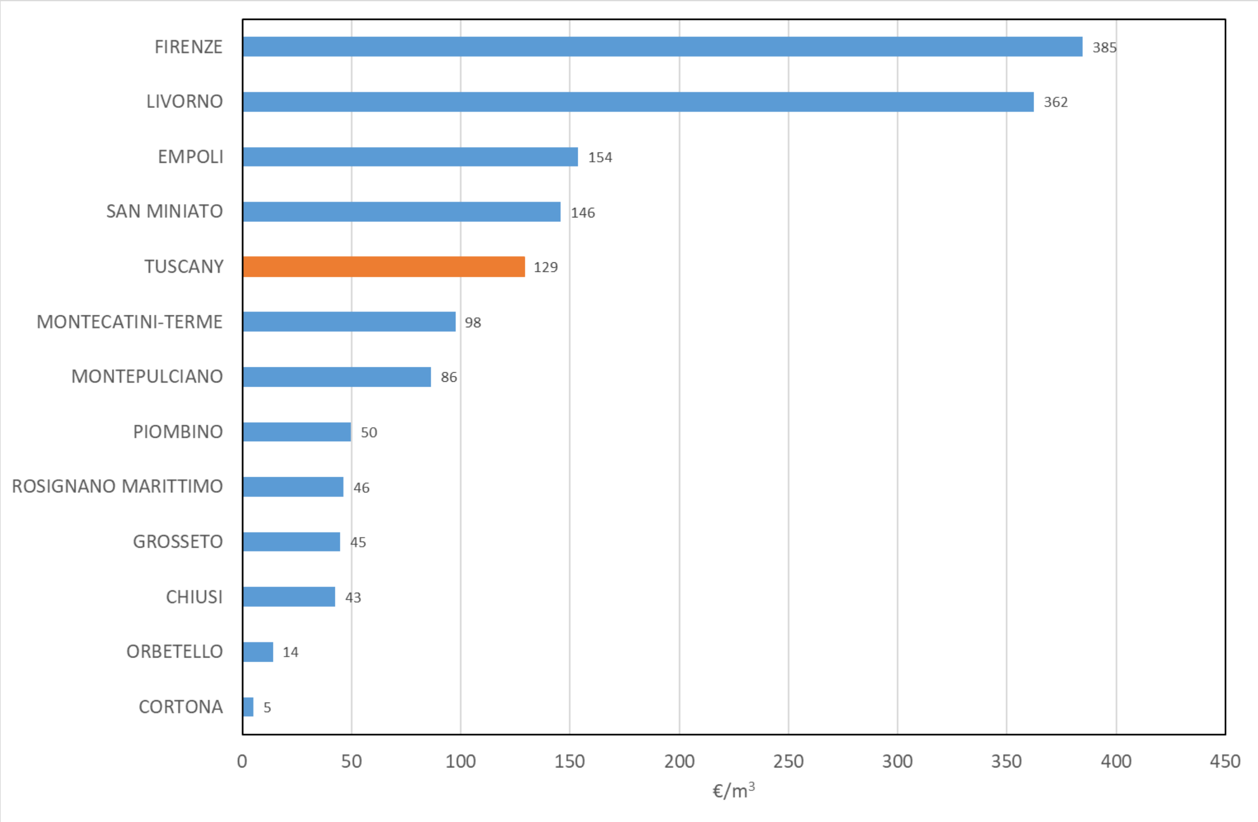
Reduction of Prod.	Number of LMA	
	Base scenario	Climate change
<2%	6	0
2-5%	32	36
5-9%	3	1
10-24%	2	2
25-49%	4	8
>50%	2	2

Source: own elaborations

It is interesting to look also at the unitary cost of HEE, i.e. the cost necessary to reduce by one cubic meter the extended demand exceeding the feasible supply. The average excess of water demand in the base hydrological scenario is equal to 172 Mm^3, corresponding to an overall RHEE cost 21,298 M€. Different LMA show different unbalances in water exploitation and, due to their mix of industries, contribute in a different extent to the regional output. Consequently, the unitary cost varies across LMA, showing how worth is for the regional economy to overexploit water resources in different sub-regional areas.

The graph in Figure 9 compares the unitary cost of the 12 LMA where the average annual EWEI exceeds the STg. Water over-exploitation in these sub-regional areas is 96% of total.

Figure 9
Unitary cost of hydroeconomic equilibrium
€/m³ – Different LMA and regional Average



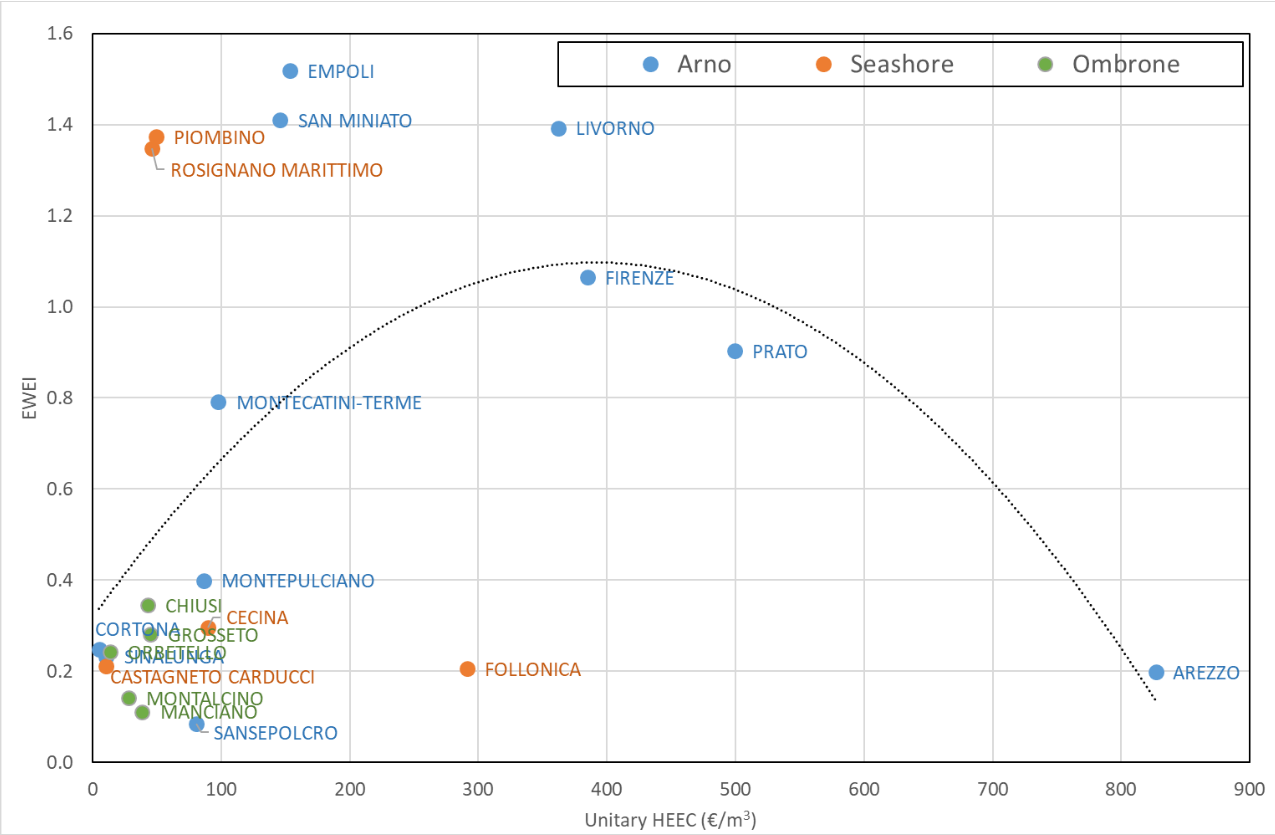
Source: own elaborations

The average unitary cost for the whole region is 129 €/m³. Four LMA contribute the most to this average level, with a unitary cost beyond the regional mean, in two cases (Firenze and Livorno – Leghorn -, two major urban areas) more than doubling it. While also Empoli and San Miniato are areas with a relevant concentration of manufacture, the LMA showing a unitary cost below the regional average have different characteristics, including both important industrial districts (Piombino, Rosignano Marittimo) and areas where agriculture and services play a more relevant role in the industry mix (Montecatini, Montepulciano, Grosseto). A useful benchmark for comparison is the average tariff paid for water supplied by the Water Supply industry, that in the reference year (2017) was equal to 3 €/m³. Only Cortona shows a unitary cost of the same magnitude (5 €/m³). According to the European regulation the tariff is inclusive of a cost recovery component as well as of a "resource and environmental cost" component. Figure 7 suggests that the adverse environmental consequences of water resources over-exploitation could be more than compensated by the economic use of water. Or, conversely, that the current regulation of tariffs is unable to correctly represent the environmental costs of an unsustainable use of water resources.

The scatterplot in Figure 10 provides a further insight on how the Tuscan economy uses its water resources. The graph represents all the LMA where the demand exceeds the feasible supply in years with critical hydrological conditions, despite on average their EWEI could remain within the sustainability limits[13]. The coordinates representing LMAs are the local unitary cost of hydro-economic equilibrium (€/m³) and the average EWEI. The dots' colour allows distinguishing the hydrological basin each LMA belongs to.

[13] The LMA of Pisa is the only case non included in the graph, showing a disproportionate unitary cost (>40.000€/m3) and an almost negligible excess of water demand beyond STg.

Figure 10
Water exploitation at the subregional level
Average unitary HEEC (€/m3) and EWEI by LMA and hydrological basin



Source: own elaborations

In LMA on the left side of the graph a positive relation between the average exploitation level of water resources and the unitary cost seems to emerge. This is somehow an expected result, showing that the structural economic dynamics followed a path suitable to maximise the economic rent of water use as scarcity conditions progressively impose narrower constraints to production. The average EWEI increases moving from LMA where a major role is played by agriculture and tourism (in the Ombrone basin, in part of LMA in the seashore basin and in the higher segment of the Arno basin like Sansepolcro, Sinalunga, Cortona and Montepulciano) to LMA where manufacture is a fundamental component of the production system (Montecatini, Empoli, San Miniato, Rosignano Marittimo and Piombino). An inverse relation, however, is shown by LMA on the right side of the graph. These LMA (Livorno, Firenze, Prato and Arezzo) are all metropolitan and urban areas, where a relatively high value of the local HEEC is associated with a small average excess (m^3 of water) of the extended demand beyond the feasible supply, whatever the average level of the EWEI (decreasing moving from the left to the right of the graph). A possible interpretation of this pattern of data could rely on the urban nature of these local economies. On one side, major urban centers tend to develop where water availability doesn't represent a major environmental constraint. Moreover, beyond a given level of geographical concentration, economic activities develop regardless of environmental constraints, following agglomeration economies that favour a shift of the industry mix towards high value added production activities (such as advanced services).

6. Discussion

6.1 Theoretical implications

The study developed here, unlike previous water-extended IO models (Rocchi et al., 2024; Sturla and Rocchi, 2024), incorporates theoretical and methodological innovations, notably the concept of hydro-economic equilibrium (HEE) with endogenous scarcity thresholds and the cost of hydro-economic equilibrium (CHEE).

HEE allows characterizing water scarcity in each local economy based on the EWEI and STm. This characterization considers hydrological dynamics, enabling a more realistic modeling of the replacement of green water with blue water in agriculture, as well as the grey water requirements of sectors that discharge into aquatic ecosystems. EWEI values and their variations are assessed against endogenous scarcity thresholds. Previously, such models only considered thresholds from the literature, which do not allow for a localized characterization of water scarcity (Raskin et al., 1997; Alcamo et al., 2000; Pfister et al., 2009; CIRCABC, 2012). By incorporating intra-annual variability of supply and demand, together with optimal groundwater management, these thresholds offer a more realistic reflection of when a local economy is in hydro-economic equilibrium, taking into account its specific characteristics. This theoretical approach represents an evolution in environmentally extended water IO models, which—by tightly combining economic, hydrological, and water quality components—pave the way for a new generation of models we may call hydrologically extended IO models.

As for the CHEE, this concept is entirely new in the literature. Theoretically, it corresponds to an optimization problem in which production is maximized under the constraint that all local economies must be in HEE. The control variable is the vector of final demand, consistent with the demand-driven nature of the IO model. The use of a multiregional water-extended (or hydrologically extended) IO model is key, as it captures interregional and intersectoral productive relationships. Conceptually, the CHEE represents a short-run measure of the optimal level of production that depends on the overexploitation—both in quantity and quality—of water resources; in other words, it measures the cost in terms of forgone optimal output required to eliminate water scarcity. This concept provides a metric of the trade-off between production and sustainability in water use. While MRIO models do not capture price formation, substitution effects, or behavioral responses (as CGE models do, see section 6.4), they offer a structurally consistent, demand-driven, empirically grounded framework, compatible with biophysical extensions and aligned with national accounts (Cazcarro et al., 2025; United Nations, 2021; Obst and Eigenraam, 2016).

CHEE can also serve as a first step toward a more comprehensive environmental analysis of water use. Each cubic meter of water used beyond the local endogenous scarcity threshold is likely to generate adverse environmental impacts within and beyond the hydrological system. Temporary or permanent variations in ecosystem services (ES) in response to unsustainable water use could be compared with the CHEE, which represents the economic return from overexploitation. Moreover, this proposed opportunity cost could be used to economically value water ecosystem services (WES) using the opportunity cost method (Legesse et al., 2022; NCAVES and MAIA, 2022), for the first time within an IO modeling framework. Specifically, by maximizing the economy's value added instead of total output (in the optimization problem) and assuming that this value added represents the best alternative use of water, the value of provisioning and purification WES (provided by natural surface and groundwater sources) could be estimated. Regarding regulation services, the difference between the opportunity cost with and without optimal groundwater management could serve as a proxy for the value of groundwater-related regulation services.

6.2 Practical and policy implications

When looking at the average annual value of the EWEI, Tuscany appears to be a water-abundant region. Only 24% of the annual “feasible” supply of freshwater (adjusted to account for technological and institutional constraints) is needed to meet the demand for blue and grey water. According to standard approaches to water footprint analysis in environmental studies (Pfister et al., 2009), such an average would indicate an "absence of scarcity problems." However, the natural variability of water supply can nearly double the value of the regional indicator in critical years (even more so under climate change scenarios). Moreover, the uneven spatial distribution of water resources and economic activity leads to more frequent scarcity conditions at the subregional scale. In a base hydrological scenario (reproducing the natural variability of the past 40 years), an average of 172 million m³ of blue water is used under scarcity conditions—i.e., exceeding thresholds that ensure environmental sustainability (minimum ecological flows and non-decreasing aquifer stocks). In 5 out of 49 subregional areas, this condition is likely to be permanent. In 14 areas, water scarcity occurs at least once every four years, on average.

The relevance of these results goes beyond the empirical application of the model to support regional water policy decisions. The case of Tuscany shows how critical the scale of analysis is when using input–output models for water footprint assessment. The more aggregated the evaluation of water pressures, the less useful volumetric water footprint measures become for management and environmental analysis. Some forms of scarcity-based weighting of water pressures are used in global water footprint analyses (Wichelns, 2017; Ridoutt et al., 2018; Sturla et al., 2023). However, the adoption of standard methods and thresholds may not be sensitive enough to account for the extreme spatial heterogeneity in the distribution of water supply and demand. Applying such methodologies (Pfister et al., 2009) to a regional economy like Tuscany would indicate an almost complete absence of water scarcity problems; even more distorted might be national-level assessments of water pressures, such as those used in the global water footprint literature. Water scarcity issues arise and must be managed at the local level. Our findings call for caution when modeling water–economy interactions globally as a basis for designing sustainability strategies.

The inter-LMA structure of the regional IO table enabled an in-depth analysis of internal water–economy interdependencies in Tuscany. Local scarcity thresholds were defined, considering natural supply variability and the specific sectoral composition of each LMA. Trade flows among LMAs redefine the map of water pressures generated by exogenous economic shocks or policy-imposed restrictions on water use. These features make the model suitable for impact assessments supporting regional water management. We extended the structural analysis to estimate what we call the CHEE: the minimum reduction in regional output consistent with the absence of water scarcity conditions—not only at the regional level but also across all LMAs—holding the sectoral mix and water technologies constant. In the base hydrological scenario, the regional CHEE amounts to €21.298 billion, about 10% of regional output; under a climate change scenario, this rises to €30.035 billion (14% of total output). This value serves as a useful benchmark for evaluating regional water policies aimed at reducing water imbalances, both in quantitative and qualitative terms, as required by the EU regulatory framework. New regulations to improve discharge quality, promote more efficient irrigation technologies, or invest in water regulation infrastructure can all be assessed based on their ability to reduce the regional CHEE. Notably, the model’s interregional structure allows for assessing local investments in terms of the regional benefits they generate.

The model also allows for estimating the cost of hydro-economic equilibrium at the local level. The opportunity cost of reducing by one cubic meter the excess of demand over feasible supply varies across LMAs, and this variation should be considered when prioritizing investments and water management decisions under limited financial resources. Although the CHEE adopts a short-run, comparative static perspective, it can be readily extended to include choices among alternative technologies (Duchin and Levine, 2012) or to model the price impacts of regulatory measures on tariffs and concessions using Ghosh linkages (Dietzenbacher, 2002).

A key contribution of this study to public policy lies in the development of an indicator that quantifies, in monetary terms, the short-term production cost of achieving hydro-economic equilibrium. It is essential to clarify that this does not represent a recommendation to reduce production. Such an approach would be not only politically unacceptable, but also economically unfeasible and inefficient. Rather, the purpose of the indicator is to estimate the current value of economic output that is sustained through the overexploitation of water resources. Calculated at both regional and local levels, the indicator provides a measure of the opportunity cost of water use—namely, how much society is implicitly willing to overexploit one cubic meter of water to produce one monetary unit of output. From a policy perspective, this metric is not prescriptive but informative: it highlights the trade-offs involved in pursuing sustainability goals and offers a benchmark for evaluating alternative measures. In particular, it can guide the design of technological or institutional interventions aimed at reducing the reliance on unsustainable water use, under the condition that their implementation cost remains lower than the value currently generated through overexploitation. In this sense, the indicator serves as a practical tool to support economically sound and environmentally responsible water management strategies.

Another important policy implication relates to the implementation of the Natural Capital Approach (NCA) in Italy (NCAVES and MAIA, 2022; United Nations, 2021). Among the most essential natural resources—supporting directly or indirectly most ecosystem services (ES)—is water. Water is closely associated with provisioning, purification, and regulation services, including physical regulation, flood protection, and chemical condition (CICES: Haines-Young & Potschin, 2018), and underpins a wide array of services such as nutrient cycling, sediment retention, erosion control, recreation, and tourism (United Nations, 2021; TEEB, 2010; MEA, 2005). Implementing the NCA in the context of WES requires both their quantification and economic valuation, which this study advances, leaving for future work the implementation of monetary valuation of WES and natural water capital (NWC). The substantive contribution of an IO model lies in its capacity to capture both the direct and indirect economic contributions of WES to the national economy—a gap still largely unaddressed in the international literature and highly relevant for Tuscany (and Italy). Bridging this knowledge gap requires methodological tools that link economic structures with hydrological ecosystems.

6.3 Limitations and future work

The model developed in this study has five main limitations: (i) the use of a stochastic rather than a physically based hydrological model; (ii) the absence of climate change projections; (iii) the inability to capture extreme events occurring at short temporal scales; (iv) the simplified treatment of surface and groundwater as independent sources, overlooking their dynamic interactions; and (v) the inherent limitations of the input–output framework in estimating the CHEE, including its linearity and lack of behavioral responses.

Regarding the hydrological model, although it represents a significant effort to estimate hydrological components at the LMA level through detailed analysis (supplementary material) consistent with watershed-scale hydrological processes, it could be improved by adopting a physically based hydrological model (e.g., SWAT, WEAP, InVEST), which would represent a substantial advancement. The main limitation lies in the fact that a physically based model could better simulate the substitution of green water with blue water in agriculture based on green water scarcity (i.e., soil moisture), whereas the current model uses precipitation as a proxy. However, developing such a model for the entire region at the sub-basin scale (to later aggregate at the LMA level) would be extremely complex, costly, and time-consuming. An additional aspect concerns the ecological flow threshold used to define feasible supply, which in this study is considered as a fixed proportion of runoff; moving toward a model capable of more accurately reproducing ecological flows would enhance both hydrological and institutional realism (Sturla and Figueroa, 2025). Despite these limitations, the developed hydrological model—which incorporates precipitation variability (uncertainty)—represents a fundamental step forward.

Regarding climate change projections, this study does not aim to represent hydrological components under future climate change scenarios using global circulation model outputs. These models provide precipitation and temperature data under different socioeconomic scenarios (IPCC, 2021), which can be used to estimate runoff and groundwater recharge through non-stationary time series, thus exposing the productive structure to more realistic future climate scenarios (Distefano et al., 2025). What has been done in this study is a sensitivity analysis based on the main expected effects of climate change on precipitation in Tuscany: a decrease in average annual precipitation and an increase in its variability. In this sense, while not within its core scope, the study partially addresses a highly relevant dimension. This is, in the authors' view, a valuable contribution that will serve as a foundation for future work involving climate data extraction, downscaling to sub-basin and LMA levels, and the estimation of runoff and groundwater recharge under climate change. Finally, it should be noted that the BIGBANG platform (ISPRA, 2024) will be highly useful for incorporating climate change into the model, as it is currently producing gridded hydrological data under climate change scenarios.

Regarding extreme events, which may be highly relevant for water policy, the model developed does not allow for their representation. This is because such events occur at daily or even hourly scales, while the input–output model operates at an annual temporal resolution, disaggregated to monthly data only for the purpose of calculating scarcity thresholds. This limitation is difficult to overcome within the structure of this type of model and would require the use of physically based hydrological models with high temporal resolution (e.g., hourly). Nevertheless, the model developed could offer insights into which local economies are more exposed to such extreme events—whether related to excess or scarcity. This represents a highly relevant topic for future research.

As for the limitations of the MRIO framework, it does not simulate market behavior, price adjustments, or substitution elasticities, as CGE models do. As a demand-driven linear system with fixed technical coefficients, the MRIO model cannot capture behavioral responses to policy shocks or dynamic price interactions. Nevertheless, its structural consistency with national accounts and the transparency of its assumptions make it particularly well suited for integration with the SEEA-EA framework (United Nations, 2021). The model structure also provides a solid empirical foundation for the future development of multiregional CGE models based on SAMs and integrated with water-related components—positioning MRIO as a complement, rather than a substitute, for behavioral modeling. This is a necessary future step, especially if the goal is to estimate the value of WES related to purification, provisioning, and regulation (e.g., groundwater) in order to operationalize the implementation of the NCA in Tuscany.

An important limitation of the current model lies in its treatment of surface water and groundwater as independent sources. While this disaggregation is analytically useful—especially given the greater pressure observed on surface water in Tuscany—it overlooks key hydrological interactions between the two sources. In particular, the model does not capture dynamic recharge relationships, such as the infiltration of surface water contributing to groundwater replenishment during wet seasons, nor does it consider interannual storage dynamics. These processes can provide substantial resilience to the water system, especially in dry years, and their omission may lead to an overestimation of water scarcity risks. Although the model incorporates intra-annual groundwater management when estimating scarcity thresholds—thereby partially reflecting the buffering capacity of aquifers—future work should explore more integrated representations of the hydrological cycle. This could include explicit modeling of surface–groundwater interactions and the regulation capacity of existing reservoirs, thereby enhancing the model's realism and its policy relevance under climate variability and change.

A final element related to future work involves using the model to estimate the water footprint (WF) within the Tuscany region for each local economy, spatially disaggregated and accounting for both physical water scarcity (SWF) and social water scarcity (SoSWF), as demonstrated, for example, in Sturla et al. (2023). The input–output approach is particularly well suited for this type of analysis, which can contribute to a deeper understanding of hydro-socioeconomic linkages within the region and help identify those local economies that generate the greatest volumetric, scarcity-related, and socially driven water impacts.

7. Conclusions

This study examines water scarcity in the regional economy of Tuscany using an ILMAIO model extended to capture the interactions between the economic system and hydrological variability. A key feature of the model is the strong integration between hydrology and economics, which allows for a detailed analysis of how fluctuations in water availability affect local production systems. Unlike traditional approaches, this model incorporates both the average and stochastic variability of water supply and demand—considering their volume and composition by source—at a spatially disaggregated level.

The results reveal a high degree of heterogeneity in water scarcity across the region, confirming insights from previous studies. One of the main methodological contributions of this work is the endogenous estimation of water scarcity thresholds and the calculation of the Cost of Hydro-Economic Equilibrium (CHEE). These tools offer an innovative alternative to the fixed thresholds commonly used in the literature, enabling a context-specific understanding of scarcity and overexploitation. The CHEE provides a monetary estimate of how much current economic output depends on unsustainable water use—both in terms of quantity and quality—and how much society would need to "spend" (through technological or institutional means) to transition toward a sustainable water economy.

In its current form, the model already provides valuable support for water policy in Tuscany. It enables regional authorities to identify local economies most exposed to scarcity, assess trade-offs between production and sustainability, and design targeted interventions such as water-use efficiency improvements, technological upgrades, or expansion of water storage infrastructure.

Finally, the model offers a robust foundation for quantifying and valuing natural water capital (NCA) in the region. By linking hydrological limits, economic structures, and the consequences of overexploitation, it contributes directly to the integration of water-related ecosystem services into public policy, environmental planning, and ecosystem accounting frameworks.

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