An input-output hydro-economic model to assess the economic pressure on water resources.

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Abstract

This study develops a hydroeconomic input-output (IO) model to evaluate the pressures that economic activities exert on water resources. For a better understanding of the sectoral and total impacts, three innovations are incorporated with respect to previous literature: i) the development of a methodology for disaggregating the extended water demand (blue water plus grey water) by economic sector, ii) the use of the IO side of the model to reclassify water demand by "extracting" and "demanding" sectors, and iii) the proposition of an improved indicator of pressure on water resources based on a "feasible" measure of water supply. Empirically tested in the Tuscany region (Italy), our findings reveal significant changes in the structure of economic pressures when adopting the proposed approach. When assessing direct total water withdrawals, agriculture accounts for 61% and manufacture for 20% of regional pressures. However, when considering only the demand for water resources exposed to scarcity reclassified by demanding sectors, agriculture falls to 5% and manufacture rises to 54%. By incorporating grey water in water demand and a "feasible" measure of supply, the regional water exploitation indicator increases from 0.05 to 0.19, and can even reach 0.30 with dry hydrological conditions, beyond the threshold for moderate scarcity (0.20). The unbalance between water supply and demand worsen even more when considering the balance of surface waters only (1.16). The proposed model can support an in-depth analysis of an economy's water footprint,

allowing impacts to be mapped from specific industries to particular water bodies. This information can support decisions about sustainable water management at the national and regional levels.

Key words: Input-output, extended water demand, feasible water supply, extended water exploitation index, Tuscany

JEL Classification: C67, Q25, Q50

1. Introduction

Input-output (IO) models have been widely used to quantify the direct and indirect water consumed by industries in order to satisfy the final demand (Velazquez, 2006; Guan and Hubacek 2008; Lenzen et al., 2013; Ridoutt et al., 2018). A typical use of input-output models extended to water resources is for structural analysis. A wide literature has been developed in the last years on the concept of water-energy-food (WEF) nexus, aiming at studying the structural interdependencies among human needs, production activities and natural resources and the related social, technological and environmental constraints (White et al., 2018; Xiao et al., 2019; Deng et al., 2020; Lee et al 2021). A further field of application of environmentally extended IO models is the analysis of virtual water flows among countries and the quantification of the water footprint at the regional, national and global scale (Feng et al., 2011; Duarte et al, 2016; Arto et al, 2016; Sturla et al 2023).

IO models are also used to assess the water balance of the economy, comparing an estimate of water demand based on economic modelling with a measure of water supply based on hydrological data (Cámara and Llop, 2020; Garcia-Hernandez and Brouwer, 2021). Studies, however, differ on how the demand for water generated by human activities is defined. Cámara and Llop (2020), for instance, consider the net demand (withdrawals minus discharges) while Garcia-Hernandez and Brouwer (2021) consider only water withdrawals. Furthermore, these studies do not consider grey water, i.e. the water required for dilution of pollutants present in water discharges.

In a paper on North China, Guan and Hubacek (2008) use an IO model to determine an "extended" demand of water, defined as the net demand (including blue and green water) plus the water required for pollutants dilution (grey water). Grey water is estimated based on a mixing model developed by

Xie (1996), using the chemical oxygen demand (COD) as an indicator of pollution. Grey water requirements (and, as a consequence, the extended demand), however, is quantified only for the whole economy. Furthermore, in modeling the interactions between the economy and the natural hydrological system, these authors do not quantify any indicator of economic *pressure* over water resources.

In literature, several indicators of pressure on water resources have been proposed. The water exploitation index (WEI) corresponds to the ratio between blue water withdrawals and natural availability net of the ecological flow (European Environmental Agency, 2005). An improved version of the WEI (WEI+) subtracts returns to water bodies, therefore considering the *net* water demand (Faergemann, 2012; European Environmental Agency, 2020; Casadei et al., 2020). In other studies, the water availability index (WAI) or withdrawals to availability (WTA) ratio is defined as the ratio of water withdrawals to renewable water availability (OECD, 2015; Garcia-Hernandez and Brouwer, 2021; Pfister et al., 2009). A conventional threshold value of 20% for all the mentioned indicators is used as a water scarcity criterion. This threshold has been recommended to identify the presence of some degree of water stress, while a value of 40% has been proposed to differentiate moderate from severe shortages, without any specific considerations of regulation capacity and extraction feasibility (Raskin et al., 1997; Alcamo et. al, 2000, Pfister et al., 2009, CIRCABC, 2012).

Based on this background, the objective of this paper is to develop an input-output hydroeconomic model to evaluate the economic pressure on water resources in a more comprehensive way than previous studies. The main innovations of our approach are: i) the development of a methodology for disaggregating the extended water demand (including grey water requirements) by economic sector, ii) the use of the IO side of the model to reclassify water demand by "extracting" and "demanding" sectors, and iii) the proposition of an improved indicator of pressure on water resources based on a "feasible" measure of water supply.

To calculate the grey water demand for each economic sector, a mixing model is solved that considers the capacity of surface and groundwater to degrade organic matter, not only the standard model based on the mass continuity equation of the dough (Hoekstra 2011). We use a modified version of the model proposed by Xie et al. (1996) to estimate the requirements of water for dilution by economic sector, considering that water for dilution is supplied by the hydrological system with a given level of pollution.

In our model some industries withdraw and return water directly from/to the hydrological system while others do so only through the water supply and the sewerage services. When considering only the direct withdrawals from water bodies, we refer to "extracting industries". The input-output matrix, through the intermediate flows of goods and services, allows us to reclassify the water demand by "demanding sector", that is, a new distribution of water uses that considers the direct *and* indirect pressure of economic sectors on water resources.

The indicator of pressure on water resources proposed in this study corresponds to the WEI+ indicator but including grey water also in the numerator and considering a *feasible* measure of supply as a denominator. The groundwater supply considers long-term recharge within a technical range of abstraction. The supply of surface water includes also technical (extraction capacity) and institutional (water concessions) constraints. According to our Extended Water Exploitation Index (EWEI) the feasible supply depends on hydrology conditions. The more the hydrology is distant from the average year, the more technical and institutional constraints are important.

We implement the model for the Tuscany region of Italy. Using hydrometeorological information, the water availability is determined, from which the feasible supply is estimated. The mixing model depends on water quality parameters, the effect of water availability on the COD concentration in water bodies and the water discharges from the IO hydro-economic model (two-way arrow in Figure 1). Based on the results of the mixing model (dilution water coefficients), water withdrawal and discharge coefficients and the IO regional table, the hydro economic model allows to calculate the extended water demand by extracting industry and reclassify it by demanding industry. Finally, based on the extended water demand and the feasible supply, the EWEI indicator is obtained.

The paper is organized as follows. Section 2 presents the structure of the input-output model extended to water resources, including the methodology for estimating water requirements for dilution and the reclassification of the extended demand by demanding industry. Section 3 presents the proposed pressure indicator, based on the model's output and on information about surface and groundwater availability in the region. Section 4 describes data and methods used to implement the empirical model for Tuscany. Section 5 presents the results for the reference year in terms of net and extended water demand classified by industry and water body and an assessment of the overall level of pressure on water resources in Tuscany based on the EWEI. Section 6 presents a discussion of the main results and of methodological limitations of the study. Finally, section 7 provides concluding remarks and suggestions for future research.

2 The hydro-economic model

2.1 Hydro-economic water flows

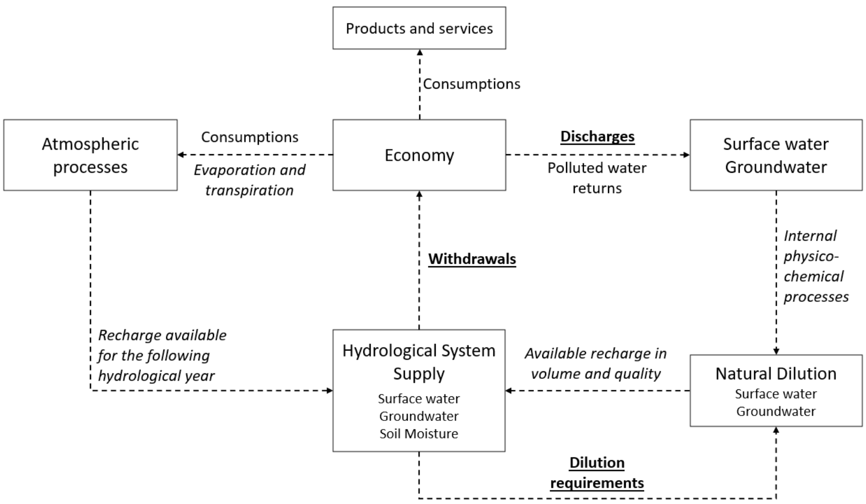
Following Guan and Hubacek (2008) we consider the extended demand approach, which include the water withdrawals for productive[1] uses minus the discharges of water to the hydrological system plus the unavailable water for qualitative balance of water bodies (water requirements to dilute the pollution).

The economic system withdraws water from underground and surface sources (blue water) and from rain and soil moisture (green water). After productive uses, water can be divided into: i) water discharged to surface and groundwater, ii) water consumptions incorporated in products and consumed in services, iii) water consumptions by evaporation and transpiration into the atmosphere, and iv) water removed from the immediate water environment (Kenny et al., 2019; Macknick et al., 2012).

[1] In this study, we are interested in water used for production. That is, we assume that water for domestic uses is provided by the water supply industry. Actually, there are also direct withdrawals by households from groundwater and surface water bodies whose relevance, however, depends on the case study. I Tuscany, this component of the household demand for water does not exceed 3% of total and has not been considered in this study.

Figure 1 presents a schematic illustration of the water flows in the hydro-economic system. The productive system extracts water from the hydrological system supply (*withdrawals*), that is, surface water, groundwater, precipitation and soil moisture (the latter two components associated with agriculture). A part of this water is consumed (goods and services, evaporation and transpiration); the remaining part is discharged with pollution to groundwater and surface water (*discharges*). By means of physical-chemical processes and fresh water from the hydrological system reserved for quality restoration (*dilution requirements*), the restored water is available again for use in the production system (in volume and quality). Water that returns to the atmosphere is not considered as a recharge within the reference period of the model (one year).

Figure 1. Scheme of the hydro-economic input-output model



Source: Own elaborations

It is important to note that the concept of net water demand (withdrawals minus discharges), widely used in the literature to estimate the water exploitation index (WEI+) (Faergemann, 2012; European Environmental Agency, 2020) considers only the *volume* of water. The concept of extended water demand used in the present study to calculate the extended water exploitation index (EWEI), conversely, considers both water volume and water *quality*.

2.2 Input-output hydro-economic model

We consider an economic system with *n* productive sectors (industries) and a water system with *m* water sources (or water bodies) to build an environmentally extended IO model (Miller and Blair, 2009).

Let A_d[2] be the matrix of coefficients that represents the structure of intermediate consumptions per unit of output of production activities, calculated from the domestic flows input-output table. The total production of the *n* industries can be calculated from the following equation:

$$x = (I - A_d)^{-1}y \tag{1}$$

where x is the vector of gross output of the industries, y is the vector of the final demand and I is the unit matrix. In the hydro-economic approach, the model is expanded to link the level of activation of each industry with exchange flows between production activities and the water bodies composing the hydrological system. Let:

f_k be the (n x 1) vector of the unit water withdrawal coefficients (m^3/€) of industries from the water body k.

r_k be the (n x 1) vector of the unit water discharge coefficients (m^3/€) of industries to the water body k.

w_k be the (n x 1) vector of the unit water for dilution requirement coefficients (m^3/€) of industries for the water body k.

The extended water demand (n x 1) vector e_k for the water body k, disaggregated by industry, is given by:

$$e_k = \left(\widehat{f_k} - \widehat{r_k} + \widehat{w_k}\right)(I - A_d)^{-1}y, \qquad k = 1, \dots, m \tag{2}$$

[2] For the purposes of this paper, the matrix of direct coefficients for domestic production is calculated following the methodology of Weber et al. (2008). This method assumes that each economic sector and final demand category uses imports in the same proportions.

The hat symbol indicates the diagonalization of the vector. By repeating the operation for the m bodies of water considered in the model it is possible to constitute the (n x m) matrix ED representing the extended water demand of the n productive sectors from the m bodies of water:

$$ED = \hat{x}(F - R + W) \tag{3}$$

where the (n x m) matrices F, R and W represent respectively the withdrawal, discharge and dilution requirements coefficients by industry and water body.

The total extended demand of water associated with the entire economy, by water source, can be represented by the (m x 1) vector TED:

$$TED = (F - R + W)'x \tag{4}$$

where the symbol ' represents the transposed matrix. The *net* water demand (ND) can be calculated in an analogous way simply excluding from equations (2) to (4) the terms referring to water requirement for dilution (vectors w_k and matrix W).

2.3 Water requirements for dilution

In this section we show how the (n x 1) vector w_k, which was defined in the previous section, is calculated to determine the water requirements for pollutants dilution by economic sector and by water body k.

We use a mixing model considering the chemical oxygen demand (COD) parameter based on the model developed by Xie (1996) (Xie-Model, hereafter) and used by Guan and Hubacek (2008) to estimate the extended demand for the whole economy. This model considers that pollutants are diluted as a result of three effects: mixing with fresh water with a lower concentration, chemical reactions before entering the water bodies and chemical reactions after entering the water bodies. The first component refers to the surface waters and groundwater existing in the discharge areas and the additional water required when this is not enough. This additional water corresponds to grey water.

(For more details see Appendix A). In this work, we improve the Guan and Hubacek's approach as follows:

- the water requirement for dilution associated with each production sector is estimated (only for the whole economy in the Xie-Model);
- the dilution water is considered to have a COD concentration similar to the water available for productive use (COD equal to zero in the Xie-Model);
- the worst case is assumed, i.e., when there is no availability of water in the receiving bodies (total natural supply in the Xie-Model).

Let assume that vector w_k comes from a (m x n) matrix W whose elements w_{kj} represent the coefficients of water for dilution (m^3/€) referred to the body of water k and the industry j:

$$w_{kj} = \frac{u_{kj}}{x_j} \tag{5}$$

where, u_{kj} (m^3/year) is the element of the $(m \times n)$ matrix U representing the water required for dilution (including losses) in the water body k by the economic sector j, while x_j (€) corresponds to the total output of sector j.[3]

The following expression (mixing model) is used to estimate u_{kj}:

$$u_{kj} = \left[\frac{k_{2_k} \cdot c_{p_{kj}} - c_{s_k}}{k_{1_k} \cdot c_s - c_{0_k}}\right] \cdot q_{p_{kj}} \tag{6}$$

where:

k_{1_k}: total reaction rate of pollutants after entering the water body k

k_{2_k}: pollution purification rate before entering the water body k

$q_{p_{kj}}$: discharges into the water body k associated with industry j

[3] For the case of this study $m = 3$ (groundwater, surface water and soil moisture), however, the third column of the matrix W (and the matrix U) corresponds to zeros, since the water for dilution is only required to purify water discharged in surface and groundwater bodies.

$c_{p_{kj}}$: COD concentration in the discharges to the water body k associated with economic sector j

c_{s_k}: standard COD concentration in water body k

c_{0_k}: COD concentration in water body k

The standard COD concentration c_{s_k} refers to a low level of pollution associated with good water quality in water bodies. The water used for dilution has a concentration equal to that of the receiving water bodies (c_{0_k}).

Note that in equation (6) the discharge corresponds to $q_{p_{kj}} = r_{kj} \cdot x_j$, obtained through the hydro-economic input-output model.

The COD concentration in water bodies is a parameter that depends on the hydrological system (c_{0_k}), decreasing when water availability is higher and increasing when it is lower. In the case of this study, the concentration associated to an average availability is considered in the base analysis and modified to calculate the water exploitation index in case of dry and wet hydrology.

Appendix A (Supplementary Materials) presents the development of the mixing model by explaining in detail the differences between our study and the Xie-Model.

2.4 Reclassification by demanding sectors

The input-output matrix, through the intermediate flows of goods and services, allows to reclassify the net demand and the extended demand of water by "demanding sectors", that is, according to a new distribution that considers the direct and indirect pressure of each economic sector on the different water bodies of the hydrological system.

It is possible to rewrite equation (2) based on (1),

$$e_k = \left(\widehat{f_k} - \widehat{r_k} + \widehat{w_k}\right) \cdot x, \qquad k = 1, \dots, m \tag{7}$$

The coefficients in vectors f_k, r_k and w_k are different from zero only for production activities that actually withdraw and return water from/to water bodies. Despite all production activities require and discharge water (although to a different extent), the withdrawals and the discharges of water from/to different bodies of the hydrological system are actually carried out only by a limited number of industries (*extracting sectors*). For example, the largest part of service activities purchase water from the water supply sector and discharges water throughout the sewerage service sector. Referring to equation (7) would provide only a partial view of the interdependencies existing between the economy and the hydrological system.

It is of interest to know the use of water reclassified by *demanding sector*s. This was done adding to the total direct use of water of each sector the "virtual" demand of water from other sectors associated with the purchase of intermediate inputs; and subtracting the "virtual" sales of water to other sectors *via* the supply of intermediate inputs as well.

The vector of "virtual" water sales associated with water source k is,

$$s_k = \left(\widehat{f_k} - \widehat{r_k} + \widehat{w}_k\right) A_d x \qquad (8)$$

The vector of "virtual" water purchases associated with water source k is,

$$p_k = \hat{x} A_d' (f_k - r_k + w_k) \qquad (9)$$

Thus, the reclassified water extended demand vector ($\tilde{e}_k$) for the water source k can be written combining equations (7), (8) and (9).

$$\tilde{e}_k = e_k - s_k + c_k = \left(\widehat{f_k} - \widehat{r_k} + \widehat{w}_k\right)(x - A_d x) + \hat{x} A_d' (f_k - r_k + w_k) \qquad (10)$$

Repeating this procedure for each of the *m* water sources, the (*n* x *m*) matrix RED is obtained, representing the extended demand from the *m* bodies of water reclassified by demanding sector. The reclassified extended water demand (*n* x *m*) matrix RED can be written as:

$$RED = \left(\hat{x} - \widehat{A_d x} + \hat{x} A_d'\right)(F - R + W) \qquad (11)$$

Following an similar procedure, it is possible to find the expressions for the reclassified *net* demand vector ($\tilde{d}_k$) for the water source k and the (*n* x *m*) matrix RND representing the extended demand from the *m* water bodies reclassified by demanding sectors.

3 An indicator of economic pressure on water resources

3.1 Water supply

In the previous section, the economic demand for water has been defined. An analysis of economic pressures on water resources must also consider water availability. Most of the literature has used the natural water supply net of a minimum ecological flow (Faergemann, 2012; European Environment Agency, 2020; OECD, 2015; García-Hernández and Brouwer, 2021; Pfister et al., 2009). However, it is not realistic to assume that it will be possible to extract all available surface and groundwater. In practice, in addition to environmental restrictions there are technical and institutional constraints. In the following sections, the natural water supply is characterized based on the hydrological components and a way to correct the natural supply is proposed based on technical and institutional factors.

3.2 Natural supply

Our water supply indicator considers blue water supply and does not include green water (precipitation and soil moisture). To determine the water supply it is necessary to know the components of the hydrological simplified regional balance (Braca et al., 2021, 2022) for a year t, which are precipitation (P_t), evapotranspiration (E_t), groundwater recharge (I_t), runoff (R_t) and the variation in soil moisture (ΔV). The balance equation is:

$$P_t = E_t + I_t + R_t + \Delta V_t \tag{12}$$

The annual natural supply of groundwater and surface water (S_t^{nat}) is equal to the sum of the recharge of the aquifers and the runoff:

$$S_t^{nat} = I_t + R_t \tag{13}$$

This natural supply is variable from year to year, so a long-term natural supply is defined, based on long-term groundwater recharge and average runoff.

$$S^{nat} = I + R \tag{14}$$

For the construction of the WEI (European Environmental Agency, 2005), WEI+ (Faergemann, 2012; European Environmental Agency, 2020), WTA (OECD, 2015; Pfister et al., 2009) and WAI (Garcia-Hernandez and Brouwer, 2021) indicators, a version of the long-term natural supply net of the environmental requirements, i.e. the ecological flow (EF), is used. In our notation we define the natural supply with ecological flow as:

$$S = I + R - EF \tag{15}$$

3.3 Feasible supply

We define a "feasible" water supply taking into account environmental, technical, and institutional limitations to natural water supply. The management of renewable but limited resources must consider these aspects that constrain the use of water by the economic system. In the following, the feasible supply is characterized in a detailed and formal way.

The technical, institutional, and environmental limitations that characterizes the feasible supply for surface water are the following. First of all, although rivers are renewed year after year, not all the runoff of water can be used for economic purposes. On one hand, in the years of high flow, the possibility to capture and accumulate water (hydraulic works) is limited; moreover, it could not be possible to extract all the natural supply of water because the active concessions do not allow it. Second, it is not environmentally sustainable to extract all available water as a minimum "ecological" flow is required for the aquatic ecosystem to continue to thrive and provide their services. A "feasible" measure of water supply must take into account that it is possible to withdraw water only up to a certain maximum quantity.

The proposed definition of a feasible supply of surface water is based on the following assumptions:

- the maximum amount of surface water extraction is defined by the sum of the maximum withdrawals allowed by current concessions; the assumption we make here is that the concessions have been efficiently awarded, considering all technical and hydrological aspects;
- the surface water supply is considered to be limited by a minimum "ecological" flow, as a constraint to environmental sustainability;
- the maximum concessions levy is defined as $M\bar{R}$, where M is a factor not necessarily less than 1 and $\bar{R}$ is the average annual runoff;

- the minimum ecological flow is defined as $E\bar{R}$, where $E \in (0,1)$;
- the "feasible" annual average runoff is strictly lower than the $\bar{R}$ value.

Summing up the value of R_t^{feas} is:

$$R_t^{feas} = \left\{ \begin{array}{cc} R_t - E\bar{R} & if\ E\bar{R} < R_t < M\bar{R} + E\bar{R} \\ M\bar{R} & if\ R_t > M\bar{R} + E\bar{R} \\ 0 & if\ R_t < E\bar{R} \end{array} \right\} \quad (16)$$

The technical, institutional, and environmental limitations that affect the feasible supply of groundwater are different. Groundwater corresponds to a stock that varies according to the annual recharge; consequently, the extraction annually available depends more on the average annual top-up than on the top-up of the 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. The feasible supply can be equal to the *average* recharge (which ensures sustainability, i.e., a non-decreasing groundwater stock); however, there are some variations that depend on the stock of the resource and the amount of water that infiltrates during the year. In a scenario in which there is no over-exploitation of the aquifers, that is, there are no large variations in the stock, it makes sense to assume that sustainable extraction will be around the average recharge, that is, it will be a little lower in a rainy year and a little higher in a dry year. In general, groundwater concessions are awarded for a slightly higher value than the annual sustainable recharge, since there are years in which it would not be possible to extract the *actual* recharge (due technical limitations, especially for small users) and other years when it is possible to extract more than the *average* recharge.

The proposed definition of a feasible supply of groundwater is based on the following assumptions:

- the sum of the groundwater concessions (D) is the feasible upper supply limit;
- the difference between the sum of the concessions and the average annual recharge $(D - \bar{I})$, defines a share B by which the average recharge can be increased to calculate the feasible supply ($B = \frac{D-\bar{I}}{\bar{I}}$) where $B \in (0,1)$ and $\bar{I}$ is the average annual recharge;

– the feasible groundwater supply (that can be drawn in one year) will be in the range $[\bar{I}(1-B), \bar{I}(1+B)]$;

Summing up the value of I_t^{feas} is:

$$I_t^{feas} = \begin{cases} \bar{I}(1-B) & if \;\; I_t < \bar{I}(1-B) \\ \bar{I}(1+B) & if \;\; I_t > \bar{I}(1+B) \\ I_t & if \;\; I \in [\bar{I}(1-B), \bar{I}(1+B)] \end{cases} \tag{17}$$

Consequently, if the distribution of I is symmetrical around the average, the feasible annual average supply will be equal to the value $\bar{I}$.

The feasible supply for a year t (FS_t) can be defined as:

$$FS_t = I_t^{feas} + R_t^{feas} \tag{18}$$

The long-run feasible supply (FS) corresponds to the average over time (N years):

$$FS = I^{feas} + R^{feas} = \frac{1}{N}\sum_t^N I_t^{feas} + \frac{1}{N}\sum_t^N R_t^{feas} \tag{19}$$

This correction made to the natural supply of water allows for a more precise approach to the availability of water in the study region. The formulation considers that a series of N years of the hydrological components is available. The longer the series, the more representative of the long-term this defined feasible supply will be. In the next section, an indicator of pressure on water resources is defined considering the proposed measure of water availability.

3.4 An extended water exploitation index

We propose a new indicator of economic pressure on water resources, the Extended Water Exploitation Index (EWEI), comparing the extended demand for groundwater and surface water, and the feasible supply. It basically corresponds to the WEI+ indicator (ratio of net demand to natural supply) but including grey water and considering environmental, technical and institutional constraints in the use of water.

Using equations (3) and (19) the EWEI can be written as:

$$EWEI = \frac{i\sum_{k=1}^{2}\left(\widehat{f_k} - \widehat{r_k} + \widehat{w_k}\right)' \cdot x}{I^{feas} + R^{feas}} \tag{20}$$

Where i is a (1 x n) vector of ones, which allows summing the extended water demand associated with each economic sector. The sum considers groundwater and surface water, $k = \{1,2\}$. Considering equation (1) the EWEI can be expressed in terms of the final demand:

$$EWEI = \frac{i\sum_{k=1}^{2}\left(\widehat{f_k} - \widehat{r_k} + \widehat{w_k}\right)' (I - A_d)^{-1} y}{I^{feas} + R^{feas}} \tag{21}$$

The other indicators proposed in the literature assume a perfect substitutability between groundwater and surface water, which is not necessarily true. For this reason, in our analysis we also consider the EWEI separately for groundwater and surface water[4].

4 Case study

The proposed model was empirically implemented for the Tuscany region (Central Italy). The regional Government as well as other agencies involved in various ways in the monitoring and management of regional water resources made available a wide set of data sources to reconstruct the following components of the model: i) an input-output table of the Tuscan economy (reference year 2017) properly disaggregated; ii) the water withdrawals (classified by water body) by production activity existing in Tuscany (NACE classification); iii) the industries' water discharges to the hydrological system by water body and by level of water quality; iv) the regional hydrological balance and the feasible supply of water.

[4] The EWEI can vary from 0 to values not necessarily lower than 1, that would correspond to an extended demand equal to the feasible supply. As the index is calculated for a whole region and with reference to a one-year period, its value is likely to be largely lower than 1. The intra-annual variability of natural supply as well as the uneven spatial distribution of water resources, however, suggest that situations of water scarcity could exist also in presence of low values of the index. This justify the value of the conventional scarcity thresholds adopted in environmental studies (largely lower than 1) and described in section 1.

In what follows we provide a summary of the main data used and the assumption made in building the model. A detailed documentation of the empirical implementation can be found in Appendix B (Supplementary Materials).

4.1 The input-output table of Tuscany.

The model is based on the input-output table (year 2017) of the Tuscan economy developed by the Regional Institute for Economic Planning of Tuscany. The classification of production activities (56 industries) already represented, as separate industries, some of the key sectors in the exchange water flows between the economy and the environment (water supply services, sewerage services, electricity power production and other activities with an intensive use of water). Agriculture, an industry that makes an intensive use of water resources for both crop irrigation and livestock rearing, was disaggregated into 8 subsectors corresponding to General Farm Types defined by the EU Regulation 1242/2008 (farms specialized respectively in fieldcrops, horticulture, permanent crops, grazing livestock, granivores, farms with mixed cropping, mixed livestock, mixed crops-livestock).

4.2 Water withdrawals and discharge coefficients

For each industry, water requirements and discharge coefficients were estimated using different bibliographic and research data.

For agriculture, the estimation of irrigation needs was first developed at the municipal level, considering the specific irrigation requirements of each group of crops based on the climate conditions of each municipality. The total withdrawals at the municipal level were divided between underground (wells and springs) and surface sources of supply (reservoirs, lakes, rivers and streams) using the information available in the 2010 General Agricultural Census at the municipal level. The two sources of supply are substantially balanced at the regional level, representing respectively 49.6% and 50.4% of total withdrawals. The estimates of water withdrawals by crop typology were then reclassified into the eight sub-sectors of agriculture using the data of the census of Tuscan agriculture[5]. The discharge coefficients were quantified as a share of water withdrawals. This amount depends on losses due to inefficiency of irrigation systems (30% of total withdrawals) and natural losses of soil moisture by evaporation (discharges to the atmosphere). Natural losses were quantified as a percentage of green water withdrawals, based on technical coefficients from literature. We assumed that the whole amount of discharges due to inefficiency of irrigation systems returns to ground water bodies.

The estimation of water use coefficients for livestock production activities was based on technical literature about the needs of water per head of livestock per day. Specific coefficients by species and typology of livestock unit (age, production type) were applied to the composition of the regional herd. The estimated total consumption was then distributed among the different FTs based on their share in the rearing of Livestock Units according to standard results from the FADN public database. Discharges were quantified as a fixed proportion of withdrawals (13%) and assumed to be returned only to groundwater bodies.

For the estimation of the water withdrawal and discharge coefficients in the water supply industry, the information on water billed in the region for the year 2016 was used. Secondary data published by ISTAT (2021) were used to disaggregate water withdrawals between ground and surface sources. The discharges correspond to water losses in the distribution network; we assumed that all of these losses are discharged to groundwater, constitute groundwater recharge and are not contaminated.

For the production of the electricity sector, all the existing generators in Tuscany and their annual energy production, for the year 2018, were considered at the municipality level (GSE, 2022). Water consumption corresponds mainly to evaporation in hydroelectric, thermoelectric and geothermal power plants, and was considered as a discharge to the atmosphere. Total withdrawals and discharges were considered to be from and towards surface sources.

Water requirements for manufacture activities have been quantified using non-published national data

[5] Details are provided in Supplementary materials, Appendix B.

provided by ISTAT (2019). Starting from the water withdrawals coefficients of the Italian economic activities provided by ISTAT, average coefficients were obtained according to the regional composition of the 29 aggregated manufacturing sectors represented in the IO table, using the permanent census of manufacturing activities. The implicit assumption is that, different from agriculture, the average water requirements of manufacture are not affected by location. Water discharge coefficients were calculated using information from the Exiobase database. Ratios and shares for Italian manufacturing activities resulting from Exiobase were applied to the estimated water withdrawals by industry. The distribution of water extraction coefficients between groundwater and surface water was based on secondary data and reasonable *ad hoc* assumptions.

4.3 Quality of discharged water and mixing model

Water quality is measured based on the chemical oxygen demand (COD, in mg/L). This parameter was assigned to water returned by macro-sectors discharging water directly to water bodies: agriculture, manufacture and sewerage. The Water Supply Industry is not considered because its returns are of water with low COD concentration (losses in aqueducts). A methodology was defined for each macro-sector to properly characterize the quality of its discharges.

For the reaction rate of pollutants after entering the water body parameter (k_{1_k}) in equation (6), we consider a value (dimensionless) of 2.80 and 3.64 for groundwater and surface water, respectively. For the pollution purification rate before entering the water body parameter (k_{2_k}) we consider a value (dimensionless) of 0.82 and 1.00 for groundwater and surface water, respectively (Guan and Hubacek, 2008).

The standard COD concentration in water bodies (c_{s_k}) is considered equal to 20 mg/l the value for which waters are classified as unpolluted and can be used without prior treatment (Rossi and Benedini, 2020). The COD concentration in water bodies (c_{0_k}) is assumed to be equal to the standard COD concentration for an average hydrological year. In the sensitivity analysis for wet and dry hydrological years, it is assumed a value of 17.5 mg/l and 22.5 mg/l, respectively.

4.4 Hydrological Balance and natural supply

Starting from the information on the hydrological balance for Tuscany provided by ISTAT, the average natural supply of surface and groundwater has been calculated as the sum of surface water, groundwater and rainfall directly captured by the agriculture sector. Regarding the feasible supply, the total volume of surface water concessions registered by the Regional Hydrological Service (SIR, 2021) corresponds to 2,473 Mm^3. This amount, however, is about 70% of the total, as many of the concession's records do not include information on the volume. A maximum value of 3,636 Mm^3 has been estimated by Venturi (2014). The average annual runoff is 3,802 Mm^3, thus the value of parameter M for the calculation of the feasible surface water supply corresponds to 95.6% (3,802 Mm^3).

For the ecological flow, a value of $E = 20\%$ is considered. This means that surface water bodies will always show a minimum flow rate equivalent to 20% of the average annual flow. This is a rather conservative value (Moccia et al., 2020; Rossi and Caporali, 2021).

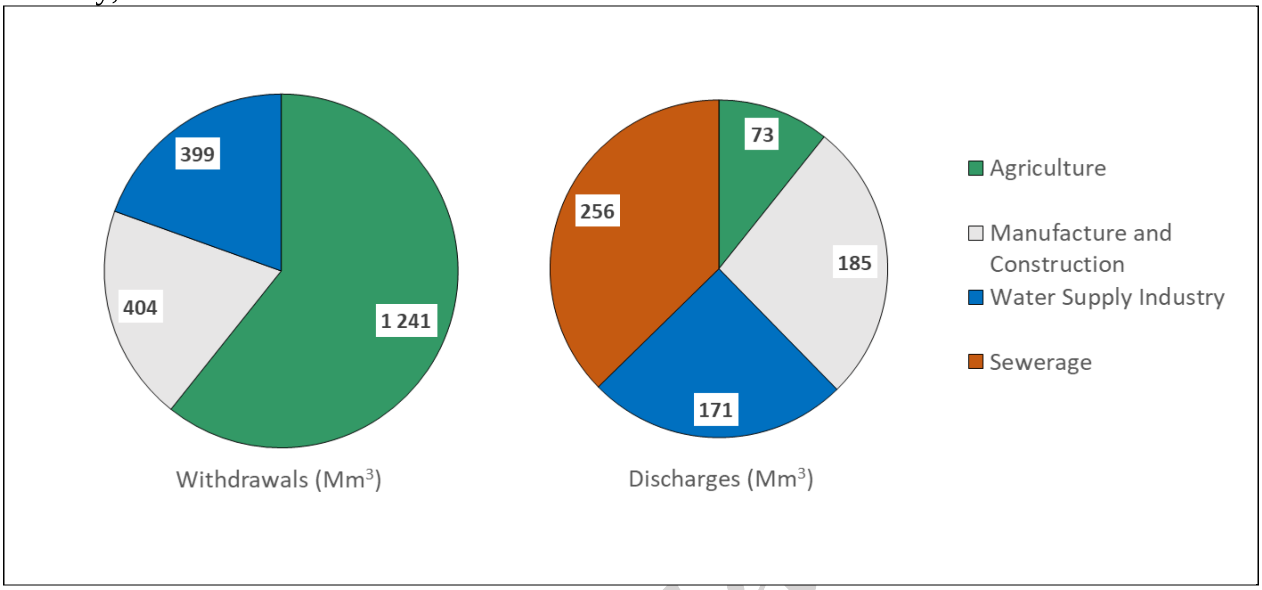
The maximum value of the groundwater concessions is 4,704 Mm^3, consistent with the interannual regulation of water supply, while the average annual recharge is 4,155 Mm^3 (SIR, 2021). Hence, to quantify the groundwater feasible supply, a value of $B = \frac{D-\bar{I}}{\bar{I}} = \frac{4{,}704-4{,}155}{4{,}155} = 13\%$ is considered.

5 Results

5.1 Withdrawals and Discharges

The volume of water withdrawals and discharges by water-extracting macro-sectors (direct or "not reclassified" water use) is shown in figure 2. The total volume of water withdrawn by the Tuscan economic system considering all sources (groundwater, surface water and soil moisture) corresponds to 2,043 Mm^3. The total volume of discharges is equal to 685 Mm^3 (33% of withdrawals), with Sewerage services representing about 37% of total. The total *net* demand (withdrawals minus discharges) is equal to 1,359 Mm^3, corresponding to the volume of water incorporated into products. Agriculture, the only sector using green water, represents about 86% of total net demand.

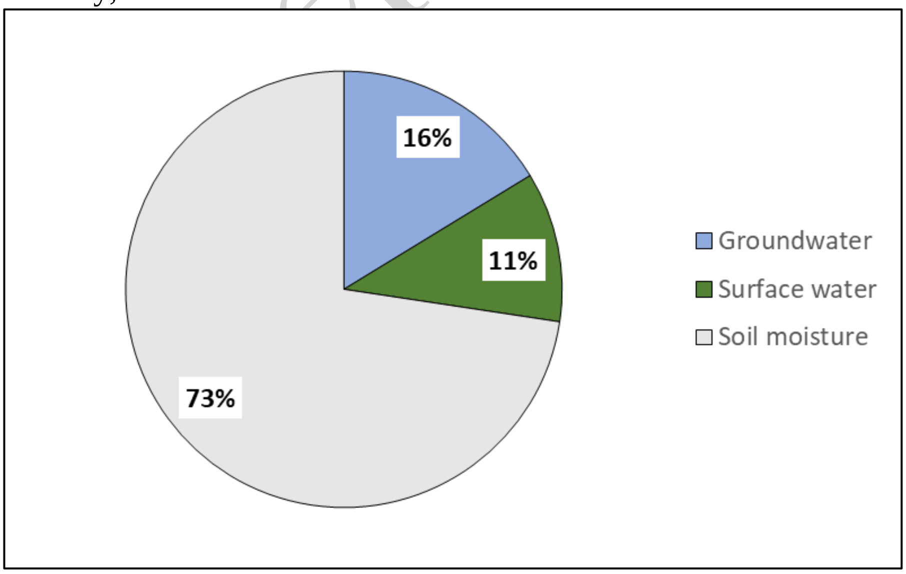
Figure 2. Water withdrawals and discharges by macro sector
Tuscany, 2017 - Mm^3.



Source: Own elaborations

The exclusive use of green water by agriculture is reflected also in the distribution of the net water demand by water source (figure 3). The soil moisture (987 Mm^3) represents the 73% of total, with groundwater (221 Mm^3, 16%), surface water (151 Mm^3, 11%) playing only a minor role.

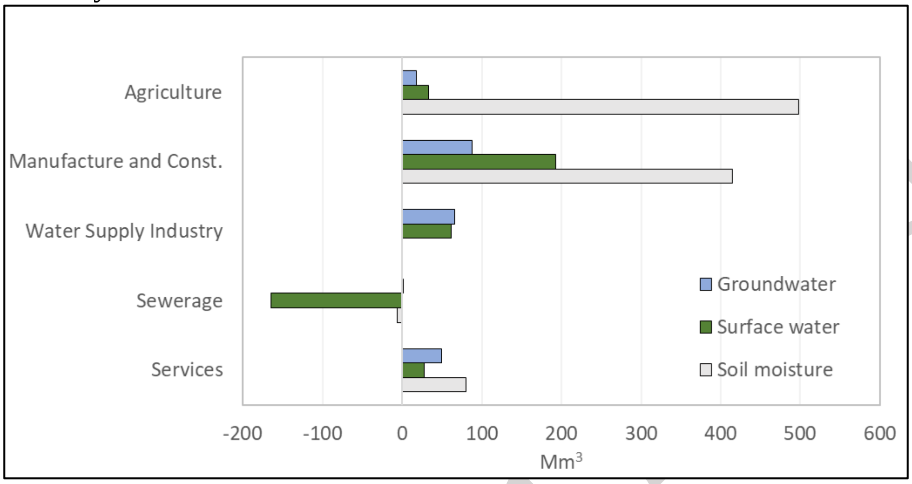
Figure 3. Net water demand by water source
Tuscany, 2017 - Mm^3



Source: Own elaborations

Figure 4 shows the net demand reclassified by demanding macro-sectors and divided by water source. Services, for example, which neither directly extract nor discharge water from/to water bodies, account for a reclassified net demand of 158 Mm^3, since they purchase both water (from the water supply sector) and other inputs from extracting sectors. The component of the net demand supplied by the soil moisture is now distributed among different production activities, with manufacturing “indirectly” using a relevant share of green water.

Figure 4. Net water demand by demanding macro sector and by water source
Tuscany 2017 - Mm^3



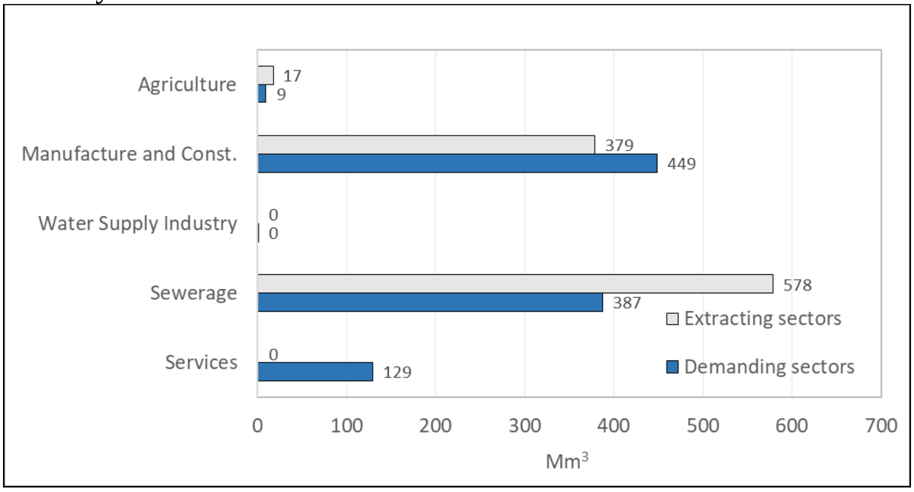
Source: Own elaborations

5.2 Water for dilution and extended demand

Different from Guan and Hubacek (2008) the demand of water for dilution has been calculated for each industry separately. Of the total demand of grey water (974 Mm3), 17 Mm^3 accrue to Agriculture (2%), 379 Mm^3 to Manufacturing and Constructions (39%) and 578 Mm^3 to the Sewerage sector (59%). The Water Supply industry discharges water with standard quality while Services discharges water through the Sewerage network.

The breakdown of grey water by industry allows for its reclassification by demanding sector. Figure 5 compares direct and reclassified water requirements for dilution by macro-sector. Services increase from zero to 129 Mm^3 in the reclassified case, accounting for a share of grey water requirements of Sewerage services and of other industries from which it purchases inputs. Also Manufacturing increases its demand for grey water (from 379 to 449 Mm^3).

Figure 5. Water for dilution by extracting and demanding macro sector
Tuscany 2017 - Mm^3

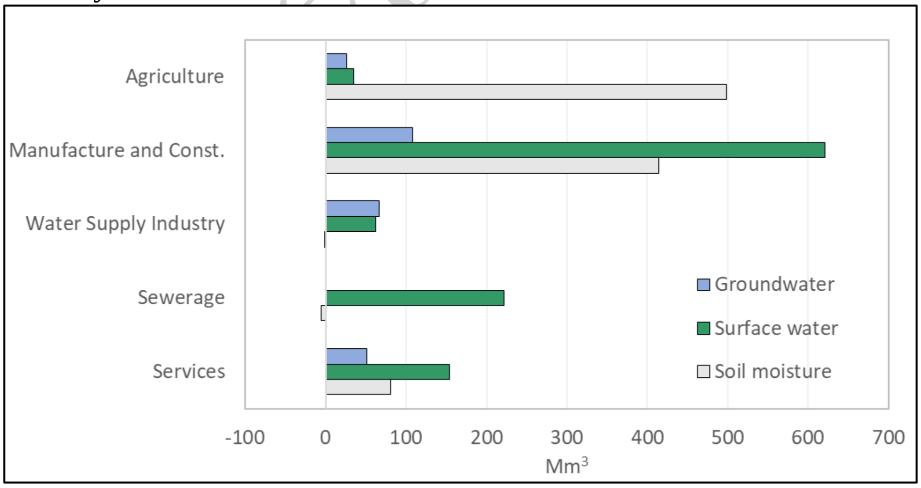


Source: Own elaborations

Grey water is a major component of water demand of Tuscany. The total *extended* water demand (total net demand plus total water for dilution), is equal to 2,333 Mm^3 (+72% compared to the net demand). A prominent role is now played by surface bodies (1,094 Mm^3) that supply 47% of water. Groundwater (252 Mm^3) and soil moisture(988 Mm^3) supply the extended demand for 11% and 42% respectively.

Figure 6 shows the extended water demand classified by demanding sectors and water body. Manufacturing is the main user of water resources, accounting for 1,144 over 2,333 Mm^3 (49%) of the extended demand, mostly relying (54%) on surface bodies.

Figure 6. Extended water demand by demanding macro sector and by water source
Tuscany 2017 - Mm^3



Source: Own elaborations

A complete breakdown of the components of net and extended demand reclassified by demanding sector for the 56 industries represented in the IO is available in Appendix C (Supplementary Materials).

5.3 Economic pressure on water resources

The extended demand for water for the reference year includes also water requirements supplied by soil moisture to agriculture (green water). To assess the pressures of the economy on regional renewable resources, only the components of demand supplied by surface and ground water bodies (blue and grey water) are considered. In this section the extended demand of groundwater and surface water is compared with the corresponding *feasible* supply.

Table 1 provides some summary results for Tuscany. The regional extended demand is equal to 1,346 Mm^3. The natural supply corresponds to 7,958 Mm^3. The ecological flow corresponds to 761 Mm^3. The feasible supply amounts to 7,030 Mm^3, about 88% of the natural supply; the reduction is due to the constraints on supply associated with surface waters.

The pressure indicator EWEI proposed in this study is compared with the standard indicator WEI+, considering only net demand and the natural supply net of the ecological flow.

Table 1. Economic pressure of the economy on water resources
Tuscany, 2017 – Mm^3 and pressure indicators

	Total	Ground-water	Surface water
Net water demand (Mm^3)	372	221	151
Extended water demand (Mm^3)	1 346	252	1 094
Natural supply minus ecological flow (Mm^3)	7 197	4 155	3 042
Feasible supply (Mm^3)	7 030	4 155	2 875
WEI+	***0.052***	***0.053***	***0.05***
EWEI	***0.191***	***0.061***	***0.381***

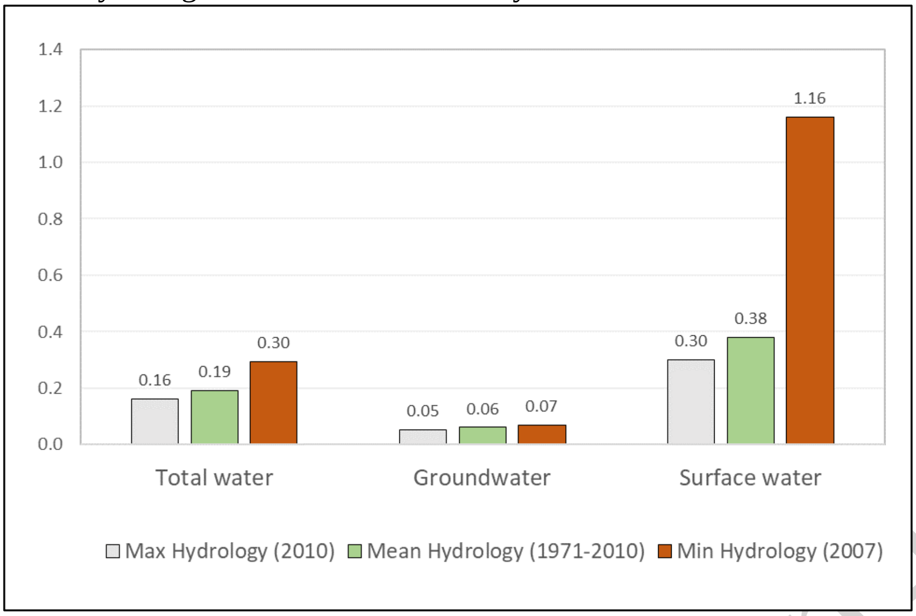
Source: Own elaborations

In the reference year of the analysis (2017) the groundwater recharge component was included in the interval assuring the maintenance of the groundwater stock in the long-run. Therefore, the feasible supply of groundwater is equal to the natural supply. In the case of surface water, constraints in water exploitation reduce to 2,875 Mm^3 the “feasible” supply (compared to 3,042 of natural supply). The results show that at the regional level the overall use of water generated by the economy is still compatible with the available resources, also when natural, technical, and institutional constraints to water use are taken into account. When the thresholds proposed in the literature for these indicators are considered (Raskin et al., 1997; Alcamo et. al, 2000; Pfister et al., 2009; CIRCABC, 2012), the WEI+ is well below the 20% limit. However, when considering the EWEI indicator, the situation in Tuscany appears to be close to a moderate scarcity.

As explained in section 3, the denominator of the EWEI ratio depends on the values assumed by the hydrology in the average year. However, the components of the hydrological balance are random variables that can largely differ from the mean values both upward and downward. It could be interesting to assess what would be the pressure on water resources when natural components of the balance show extreme values. Figure 7 shows the results of such a sensitivity analysis, comparing the values assumed by the EWEI with a feasible supply calculated with reference to a mean hydrological situation and to two extreme cases corresponding to the years with the best (2010) and the worst (2007) hydrological supply in the reference period (1970 – 2010).

When considering the standard thresholds, it is interesting to note that in a dry year, the EWEI value (0.3) would indicate that Tuscany is in moderate scarcity (0.4 being the limit for *severe* scarcity). Despite this value of the EWEI still implies a safety margin between the extended demand and the feasible supply, it should be considered that the regional mean annual value of the EWEI hides a wide variability of the hydrological balance at the sub-regional level, with possible critical local situations. Moreover, the breakdown by water sources shows relevant differences between ground and surface water. The former faces a quite stable pressure, due to the reservoir effect of the stock. Conversely, in the case of surface water, a worsening of the hydrological scenario could lead to a relevant increase of pressures, with a surface water EWEI almost three times greater (1.16 vs. 0.38 for the average hydrology scenario). In a critical year the extended demand of surface water in Tuscany would exceed by 16% the feasible supply.

Figure 7. Sensitivity analysis of EWEI indicator
Mean hydrological balance vs. extreme years



Source: Own elaborations

6 Discussion

The model proposed in this study allows a more comprehensive understanding of sectoral economic pressures on water resources. Unlike previous studies, which only consider the sectoral disaggregation in blue water uses, this study also allows the identification of grey water associated with each economic activity. Along the same lines, this study makes it possible to evaluate the direct and indirect pressures on the different bodies of water, through a reclassification by demanding sectors based on the IO model. Furthermore, the flexibility of the proposed methodology allows evaluating changes in the pressure structure when considering different approaches.

The case study is eloquent regarding the significant changes that the pressure structure can present. When considering withdrawals, a classification of demand by extracting sector and all water sources in the quantification of supply, agriculture represents 61% of regional pressures, manufacturing 20%, and the water supply industry 19%. On the other hand, when considering the extended demand, a classification of demand by demanding sector, and only water sources actually exposed to scarcity (groundwater and surface water), agriculture represents 5%, manufacturing 54%, the water supply industry 10%, sewerage 16%, and services 5%. These differences can be explained by three reasons: i) the high green water component in water demand for agriculture, ii) the high grey water requirements in manufacturing and sewerage (86% of the total), and iii) the relationship between the purchase and sale of intermediate inputs with embodied water, that is positive for manufacturing, sewerage and services.

These results show that mapping the sectoral structure is sensitive to the goals pursued in water management. If incentives are to be generated to reduce the direct and indirect pressures of economic activities on the quantity and quality of groundwater and surface water, an approach by demanding sector should be adopted.

The developed model also takes care of the role of resources availability in the analysis of the economic impact on water system. Specifically, a new indicator (EWEI) is proposed, which considers the requirements for blue and grey water (extended demand), and adjusts the natural supply to consider environmental, technical, and institutional restrictions (feasible supply). Previous studies, also when including the grey component of water demand, only correct the natural supply for environmental restrictions.

Once again, the case study exemplifies the differences in the water resource exploitation indicator when aspects not addressed in previous studies are considered. The indicator predominantly used in the literature (WEI+) present a value of 0.05; however, the EWEI (0.19) indicates that the Tuscany region is very close to the threshold of moderate scarcity (0.2) for an average hydrological year. The numerator of the WEI+ pressure indicator on water resources compares two quantities of water (withdrawals and discharges) of different quality. As quality is a factor affecting the potential use of water, our results confirm that a correction is necessary, as proposed by Guan and Hubacek (2008) and replicated in this study.

A significant difference is observed when disaggregating pressure indicators for groundwater and surface waters. For surface waters, the proposed indicator has a value of 0.381, significantly higher than the corresponding value of the WEI+ indicator. This means that when technical and institutional constraints are considered in determining the feasible supply, surface water resources in Tuscany show a situation of almost severe scarcity (threshold 0.4). The denominator of the standard WEI+ indicator contributes to an underestimation of pressures.

To account for variations in climate, this study estimates the EWEI for the driest and wettest hydrology within a 40-year period (1971-2010). The results show that Tuscany, in case dry hydrology, experiences moderate scarcity (0.30) on average but with huge differences between groundwater (0.07) and surface water (1.16) resources. This suggests that the region's most significant water management problems, when incorporating water quality requirements and technical and institutional constraints, concern the surface water component of the resource.

Regarding the limitations and assumptions of the proposed model, the following key elements should be highlighted. First, natural variability also applies within the same year. The annual average values of the hydrological balance components completely conceal different situations within each year in terms of natural and feasible water supply. An annual sustainable average pressure could imply critical situations during periods of the year when the natural water supply is lower.

Second, it has been assumed that agriculture extracts a certain amount of water for each euro of production directly from soil moisture. However, this assumption is only valid in years with average or above-average hydrology. In the case of dry years, agriculture extracts more from groundwater and surface waters (mainly for irrigation), increasing pressure on these resources.

Third, both the economy and the hydrological system also exhibit a geographical variability. The distribution of water intakes for irrigation clearly shows that pressures on water resources depend on the location of productive activities and the distribution of water resources in the regional territory. Critical local situations could be compatible with a sustainable global balance between extended demand and feasible water supply at the regional level.

Finally, water resource exploitation indicators, both in the standard version (WEI+) and in the extended version proposed in this study (EWEI), assume a perfect substitutability between groundwater and surface waters in the economic use. This is not necessarily the case, especially at the regional level, where there are strong geographical constraints on the movement of water resources. For this reason, even considering an average hydrology, Tuscany could be exposed to critical situations also at the regional level.

7 Conclusions

The article proposes a multisectoral and environmentally extended input-output model that represents in detail the links between the economy and the hydrological system. Water flows are mapped between economic activities and different components of the hydrological system, considering withdrawals, discharges, and the water requirements necessary to maintain the qualitative balance of the hydrological system (Extended Demand). A classification by extracting and demanding sectors is used to allocate pressures on water resources considering the both direct and indirect impacts through the purchase and the sale of intermediate inputs. To assess the water balance, an extended water exploitation indicator (EWEI) is proposed that considers a correction of the natural supply based on environmental, technical and institutional restrictions.

By empirically testing the model in the Italian region of Tuscany, our results show significant changes in the structure of sectoral pressures when considering the more comprehensive approach proposed. On average, the hydrological system of Tuscany is capable of supplying the water needed by the regional economy for medium hydrological conditions. However, the region could present moderate scarcity problems for dry years and serious scarcity problems in the case of surface waters.

The developed model can support an in-depth analysis of the water footprint of a regional economy, for example, to map pressures on water resources from specific industries to specific water bodies, and support decisions in water management both at the national and regional level.

The identified limitations suggest the direction for further refinement of the model. The interannual and intra-anual variability of the hydrological balance must be modelled. This extension of the model could allow not only to associate a measure of its potential variability with the average results, but also to simulate the impact of climate change scenarios. Furthermore, it is necessary to endogenously model the change in the composition of water sources used by agriculture, an activity that in dry years uses a greater amount of groundwater and surface water to make up for the lack of soil moisture.

Finally, the decomposition of the model at the subregional level could allow an evaluation of the geographical distribution of impacts on water resources and the possible existence of unsustainable local situations also within a sustainable global regional scenario.

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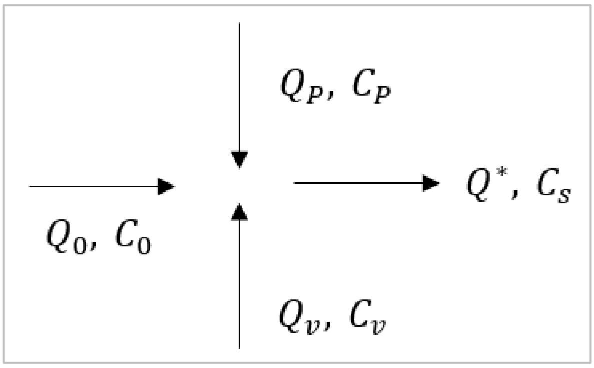
Supplementary Materials

Appendix A

Consider a mixing model in which the inputs correspond to the water present in the water body, the water discharged by an industry and the water required for dilution (each represented by a volume and a pollution concentration); and the output corresponds to the total volume of water with a standard concentration (a good water quality level for the hydrological system).

Figure A.1. Scheme with inputs and outputs of the mixing model



Source: Own elaborations

where,

Q_0	:	Volume of water in the water body before discharge
C_0	:	COD concentration in the water body before discharge
Q_P	:	Volume of water of the industrial discharge
C_P	:	COD concentration in the industrial discharge
Q_v	:	Volume of water for dilution
C_v	:	COD concentration in the dilution water
Q^*	:	Total volume of water after mixing
C_s	:	COD standard concentration after mixing

Applying conservation of mass law (without intermediate chemical reactions), the mass balance can be represented as follows:

$$Q_0\, C_0 + Q_p\, C_p + Q_v\, C_v = Q\, C_s + Q_v\, C_s \qquad \text{(A.1)}$$

where,

$$Q = Q_0 + Q_p \qquad \text{(A.2)}$$

Xie (1996) and Guan and Hubacek (2008) model (Xie-Model) considers chemical reactions, introducing two parameters representing the decay of the pollutant mass (COD):

k_1 : total reaction rate of pollutants after entering the water bodies

k_2 : pollution purification rate before entering the water bodies

Considering these parameters, the mass balance equation (A.1) becomes:

$$Q_0\, C_0 + K_2\, Q_p\, C_p + Q_v\, C_v = Q\, C_s + K_1\, Q_v\, C_s \qquad \text{(A.3)}$$

Thus, the volume of water required for dilution in is:

$$Q_v = \frac{1}{K_1\, C_s - C_v}\left[Q_0\, C_0 + K_2\, Q_p\, C_p - Q\, C_s\right] \qquad \text{(A.4)}$$

The Xie-Model assumes that the water for dilution does not have pollutants ($C_v = 0$), then the volume of water required for dilution can be written as:

$$Q_v^{Xie-Model} = \frac{1}{k_1\, C_s}\left[Q_0\, C_0 + k_2\, Q_p\, C_p - Q\, C_s\right] \qquad \text{(A.5)}$$

As explained in the methodology, in this study, two modifications of the Xie-Model are considered:

i. The dilution water comes from the hydrological system $(C_v = C_0)$
ii. The unfavorable case is considered, i.e., when there is no availability of water in the receiving bodies $(Q_0 = 0)$

Imposing conditions (i) and (ii) on the equation (A.4), the volume of water dilution requirements in our model can be expressed as:

$$Q_v^{RS} = \frac{1}{k_1\, C_s - C_0}\left[Q_p \cdot (k_2\, C_p - C_s)\right] \qquad \text{(A.6)}$$

This equation for dilution water has three relevant consequences to our estimates. Firstly, it corresponds to a more realistic representation of the COD concentration in the dilution water. Secondly, the worst case hypothesis is conservative rule in reserving a volume for dilution within the hydrological system. Finally, it is possible to calculate dilution requirements for each industry, not just for the whole economy, as in the case of Guan and Hubacek (2008) model.

Appendix B

Breakdown of the agricultural branch in the input-output table of the Tuscany region.

Agriculture is an industry that, in some of its sectors, makes intensive use of water resources for both crop irrigation and livestock rearing. In the regional table provided by the Regional Institute for Economic Planning of Tuscany (IRPET), agriculture is represented as a single branch, hiding under an average figure the diversification of agricultural production activities that characterizes the sector at the regional level. We carried out a disaggregation of agriculture in the table to provide a better representation of production activities, making the model suitable to support the management of water policy at the regional level.

The breakdown of any of the industries represented in an input-output table should take into account the accounting conventions adopted in disaggregating the production account. Specifically, each industry represents an aggregation of production units classified according to the similarity of the production process. The basic criterion concerns the nature of the product: all the production activities producing the same good have to be added into a single industry. In the case of agriculture, most production units are typically multi-product, often performing several production processes (different crops and/or livestock holdings); therefore, the disaggregation into sub-sectors asks for a suitable classification criterion of production activities.

According to accounting conventions (Eurostat, 2013), multi-product production units should be classified into different industries depending on the production process that generates the largest value-added quota. In principle, this criterion would require the availability of microeconomic information to subdivide the input use of the production units among the different production processes actually carried out. Whereas this information is barely available for other industries, it is even more difficult to find it in the case of agriculture, where small family-owned enterprises predominate. In the breakdown, therefore, the accounting criterion must necessarily be approximated using alternative and practicable forms of classification.

One possible solution is to disaggregate the agriculture industry by distinguishing subgroups of production units classified by Farm Type (FT). The FT is a farm classification criterion defined at European Union level and used in economic analyses to support sector policies (Common Agricultural Policy). The FT classification is also applied by ISTAT in carrying out the General Census of agriculture and the periodic surveys on agricultural holdings. The current classification by FT is defined by Regulation 1242/2008 which identifies 8 general FTs (farms specially specialized respectively in fieldcrops, horticulture, permanent crops, grazing livestock, granivores, farms with mixed cropping, mixed livestock, mixed crops-livestock) that in turn can be disaggregated, according to a hierarchically organized nomenclature, into 14 main, 21 principal and 61 particular FTs.

The FT is assigned to holdings based on structural data (hectares of different crops, livestock units) weighted by standard economic values estimated at the regional level. In particular, according to the current regulation, the specialization of agricultural holdings is determined according to the contribution of each production process to the standard output of the farm. Standard output is calculated by multiplying the physical size of each production process (hectares, livestock units) by a standard unit value, estimated at the regional level. The FT is then assigned following a prevalence rule that could be defined "of two-thirds": for example, farms where the standard output produced from annual crops (made on arable land) exceeds 2/3 of the total are considered "specialized in fieldcrops". Mixed FT are assigned when no production process reaches this prevalence quota. A similar mechanism is used to assign FT to lower levels of the hierarchy (for example, within arable crop farms to identify "cereal-specialized" farms).

For the construction of the model, we disaggregated agriculture into 8 subsectors. The adoption of the FT as a criterion of disaggregation of agriculture has a number of advantages:

- The classification of the FT, although not identical, is substantially consistent with the reference accounting conventions for the classification of economic activities (NACE classification).
- The main sources of statistical information, both primary (microeconomic data) and secondary (official statistics published by ISTAT) on Italian agriculture use this method of disaggregation of the sector.
- The distribution of farms by FT is available for Tuscany at the municipal level (2010 Agricultural Census data). This makes it possible to relate water withdrawals for agricultural uses with the composition of the industry by FT.

The disaggregation of the agriculture account in the IO table into subsectors started with a breakdown of regional agricultural output at the municipal level. The value of agricultural output at the regional level is estimated by ISTAT within the national accounts system (Eurostat, 2013) using the “single farm” approach. The latter is based on aggregate estimates at the chosen territory level. Istat publishes agricultural accounts at the regional level on a yearly basis[6]. The regional estimates are based on several survey-based and administrative sources of information on quantity produced and prices of products. Based on data published by Istat, the regional output has been first disaggregated at the province level (NUTS 3 level according to the European Nomenclature of Territorial Units for Statistics[7]). Table 1 reports the value of output for the main groups of agricultural activities in the 10 Tuscan provinces.

[6] Estimates are available on the official data warehouse dati.istat.it.

[7] https://ec.europa.eu/eurostat/web/nuts/nuts-maps

Table 1. Value of agricultural output by production activity and province
Tuscany, 2017 - (M€)

Production activities	Arezzo	Firenze	Grosseto	Livorno	Lucca	Massa Carrara	Pisa	Pistoia	Prato	Siena	Totale
Cereals	15	9	24	6	2	0	21	2	1	26	106
Industrial and pulse crops	9	3	10	3	1	0	8	1	0	10	46
Horticultural crops	16	4	60	22	12	7	7	3	1	4	137
Other arable land	1	1	9	1	0	0	1	0	0	4	19
Fodder crops	3	5	15	2	1	3	5	2	0	7	44
Flowers and nursery crops	44	7	90	17	30	0	58	517	18	15	797
Vineyard wine	38	104	68	24	3	5	21	6	2	137	409
Olive oil	10	39	17	8	8	3	10	8	2	19	124
Other permanent crops	9	2	4	1	2	0	1	0	0	1	22
Dairy cattle	3	8	20	1	2	0	2	0	0	3	38
Beef cattle	13	9	16	5	6	1	3	1	0	5	59
Sheeps and goats	6	5	38	2	3	1	4	1	0	14	75
Pigs	45	7	9	3	1	0	17	1	0	15	97
Poultry	51	21	25	5	5	0	5	1	0	17	130
Other livestock products	45	12	74	5	4	1	9	7	0	13	171
Forest productions	82	40	38	6	10	6	18	13	2	20	235
Other activities	41	41	59	17	23	2	17	77	0	23	301
Total	**432**	**319**	**577**	**128**	**113**	**29**	**209**	**641**	**26**	**335**	**2 809**

Source: own elaboration on ISTAT data

Estimates at the province level have been further disaggregated at the municipality level using administrative data generated by the implementation of agricultural policy. The regional Government's agency managing the public support to Tuscan agriculture (ARTEA) publishes every year georeferenced information on cultivated crops and irrigated areas at a single-field geographic scale[8].Despite this information refers only to the areas benefiting of some form of policy support, the whole sample represents the largest part of Tuscan agriculture, excluding only small-scale farming activities, very often carried out for self-consumption only. In 2017, the reference year of the analysis, the ARTEA dataset accounted for 638,606 ha of cultivated areas, a total comparable with the Istat's estimate of total Utilized Agricultural Area based on the permanent register of Tuscan Holdings (646,265. ha: cfr. ISTAT, 2019a). The ARTEA dataset was used to disaggregate the value of crops output. As for the output from livestock rearing activities, the source of information used to disaggregate the province totals was the National Register of Livestock managed by the National Veterinary Information System[9]. The public database provides information of the number of heads reared by species at the municipality level.

Finally, the value of output at the municipality level has been disaggregated among different Farm Types based on the share of Utilized Agricultural Area cultivated by each FT, according to the last General Census of Agriculture (2010)[10]. The output by FT was then summed up at the regional level. According to data availability the output of agriculture was eventually divided into 8 Farm Types.

[8] The shape files for Tuscan provinces ("Piani colturali grafici") are available in a public repository at the URL https://dati.toscana.it/organization/artea.

[9] https://www.vetinfo.it/j6_statistiche/#/

[10] The information is quite distant in time from the reference year of the model. However, the geographical pattern of the production sector in terms of economic size and product orientation of farms, is strongly affected by permanent geographical drivers likely to slowly change through time.

Table 2 shows the final classification of FT adopted. The 8 groups result from a re-aggregation of the 14 main FT of the FADN classification.

Table 2. Breakdown of agriculture into sub-sectors

IDROREGIO classification	FADN 14 Main Types of Farming
Fieldcrops	(15) Specialist COP
	(16) Specialist other fieldcrops
	(60) Mixed crops
Horticulture	(20) Specialist horticulture
Wine and olive oil	(35) Specialist wine
	(37) Specialist olives
Other permanent crops	(36) Specialist orchards - fruits
	(38) Permanent crops combined
Milk	(45) Specialist milk
Other grazing livestock	(48) Specialist sheep and goats
	(49) Specialist cattle
Granivores	(50) Specialist granivores
Mixed farms	(70) Mixed livestock
	(80) Mixed crops and livestock

Source: own elaboration on FADN classification

The value added produced by each sub sector of regional agriculture was estimated applying an average value added/output ratio by Farm Type. The statistical information used to define specific ratios for each FT is the sample of farms surveyed in Italy by the National Research Council Center for Agriculture (CREA) under the European Farm Accounting Data Network (FADN). 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.

Table 3 shows the shares of output and value added accruing to each subsector.

Table 3. Output and value added shares by FT

Tuscany, 2017 – Percentage values

Farm Type	Output	Value Added
Fieldcrops	7.7%	6.4%
Horticulture	38.6%	43.2%
Wine and olive oil	22.8%	21.1%
Other permanent crops	2.7%	2.3%
Specialist milk	1.8%	1.3%
Other grazing livestock	5.3%	5.8%
Granivores	2.0%	2.3%
Mixed	19.1%	17.7%

Source: own elaboration

Based on the same information the School of Agriculture, Forests, Food and Environmental Science at the University of Basilicata, built a satellite account of Tuscan agriculture for 2016 (SAFE, 2020). The satellite account was used as an additional information to disaggregate the intermediate costs of each sub-sector according to the industry classification of the regional IO table.

Water withdrawals and discharge coefficients for irrigation

The estimation of water withdrawal coefficients for irrigation uses was carried out in three steps:

a) estimates of the average potential irrigation needs of Tuscan agriculture;
b) estimate of total irrigation intakes;
c) attribution of intakes to the sub-sectors of Tuscan agriculture.

Methodology for estimating irrigation needs

The estimation of irrigation needs has been first developed at the municipal level based on the ARTEA database.

The municipalities were aggregated by irrigation districts on the basis of geographical and climatic similarities. To each climatic area a unit irrigation need has been assigned for different groups of crops, derived from bibliographic and research data, mainly from experimental tests carried out by irrigation extension services in Tuscany.

Since most of the experimental data on irrigation needs relate mainly to the Val di Chiana, Val di Cornia and Grosseto areas, the determination of the irrigation needs of the other areas has been carried out using specific conversion coefficients. The coefficients were defined by comparing the potential evapotranspiration (ETP) measured by the meteorological stations present in each irrigation district with those of the reference zones for experimental studies.

Specific assumptions have been made on irrigation needs of crops with peculiar water requirements, such as nursery production or tobacco cultivation in Val di Chiana and Valtiberina areas.

Estimation of total irrigation water intakes

Based on ISTAT surveys, in the last 20 years in Tuscany the trend of irrigation has been downward: the areas actually irrigated have decreased by about 30% in the period 2000 to 2010 alone. Based on ISTAT's inter-census surveys and the information collected by regional extension services, it is assumed that in recent years the overall irrigated areas remained substantially stable, but with a redistribution among different types of crops, due to the variability of crop systems. The availability of water is, in fact, a limiting factor for the increase in irrigated crops.

Table 4 reports the total irrigated area for each crop group according to the ARTEA database.

Table 4. Irrigated areas by crop group

2017 - (hectares)

Crop Group	ha
Maize and sorghum	5 015
Industrial crops	2 421
Horticultural crops	7 868
Fodder and leguminous crops	4 713
Other arable land	5 998
Flowers and nursery crops	1 922
Olive	584
Vineyard	1 731

Other permanent crops	1 632
Other crops	615
Total	32 498

Source. Own elaborations of ARTEA data

The estimates of irrigation needs described above provides average theoretical irrigation intakes by municipality and by hectare of crop typology. The total withdrawals for irrigation include an additional amount of water corresponding to an average efficiency level of 70% in the use of water. The total withdrawals have been calculate multiplying the unitary water withdrawal coefficients to the total areas cultivated for each crop typology resulting from the ARTEA database

Table 5 presents a summary of the estimated annual average withdrawals by crop groups. Figure 3 shows the geographic distribution (at the municipal level) of withdrawals expressed in absolute value.

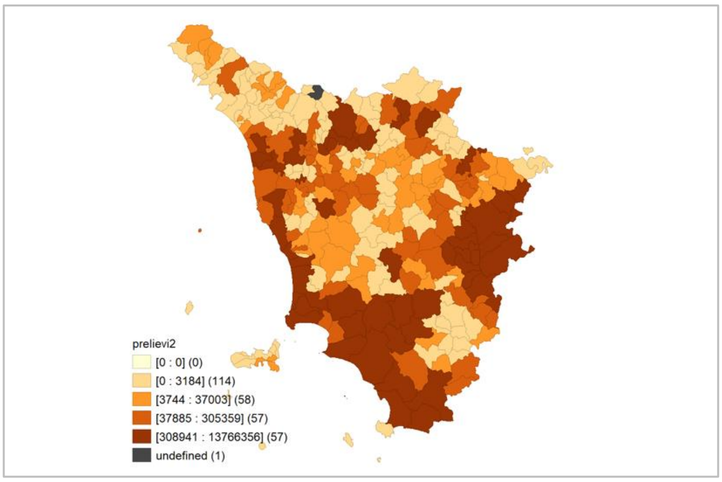
Table 5. Water withdrawals for irrigation by crop group

2017 - (Thousand m^3)

Crops	000 m^3
Maize and sorghum	23 983
Industrial crops	7 662
Horticultural crops	30 170
Fodder and leguminous crops	14 268
Other arable land	19 756
Flowers and nursery crops	13 849
Olive	1 138
Vineyard	3 640
Other permanent crops	6 190
Other crops	799
Total	121 454

Source. Own elaborations of ARTEA data

Figure 3. Average annual water withdrawals for irrigation purposes in the municipalities (m^3)

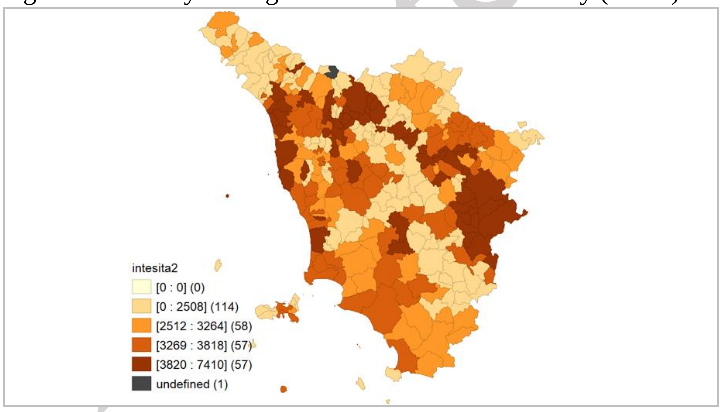


Source. Own elaborations of ARTEA data

It is also interesting to represent territorial differentiation of intensities in the use of water for irrigation. Figure 4 shows the average withdrawals of irrigation water per hectare of irrigated area. The intensity pattern roughly follows the availability of water resources, with the highest intensities along the basin of river Arno.

The withdrawals at the municipal level have been divided between underground sources (wells and springs) and surface sources of supply (reservoirs, lakes, rivers and streams) from the information available in the 2010 General Agricultural Census at the municipal level. The two sources of supply are substantially balanced at the regional level, representing respectively 49.6% and 50.4% of total withdrawals.

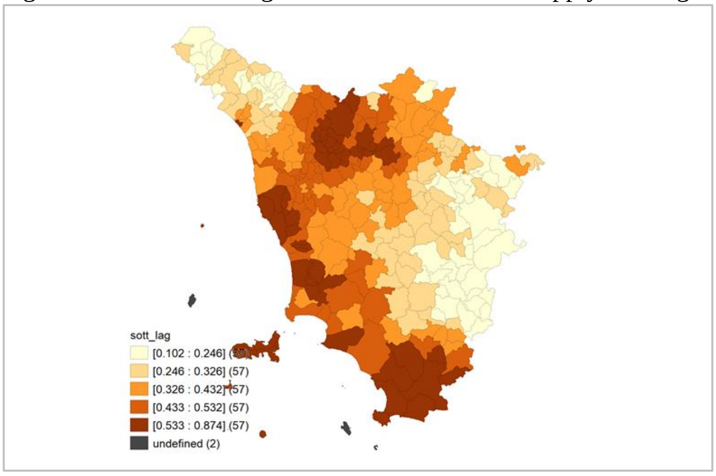
Figure 4. Intensity of irrigation withdrawals in Tuscany (m^3/ha)



Source. Own elaborations of ARTEA data

Figure 5 represents the share of water withdrawals served by underground sources in each municipality and allows to evaluate the territorial distribution of water extraction modalities for irrigation.

Figure 5. Share of underground sources on water supply for irrigation



Source. Own elaborations of ARTEA and ISTAT data

Allocation of irrigation withdrawals to the subsectors of Tuscany agriculture

The estimates of water withdrawals by crop typology have been reclassified into the eight sub-sectors of Tuscan agriculture. A particular elaboration of the data of the census of Tuscan agriculture made it possible to map the withdrawals at the municipal level to the withdrawals that can be attributed to each subsector of regional agriculture. First, the water withdrawals for irrigation calculated for each municipality have been divided among farm types according to their share of UAA. Second, the total withdrawals assigned to each FT were subdivided between surface and ground water according to the share of each source of water provisioning at the municipality level resulting from the General Census of Agriculture.

Table 6 summarizes the average annual withdrawals from each subsector of regional agriculture.

Table 6. Water withdrawals for irrigation by Farm Type and water source. 2017 - (Thousand m^3)

Farm Type	Ground water	Surface water	Total
Fieldcrops	22 769	23 203	45 972
Horticulture	5 034	2 633	7 667
Wine and olive oil	7 230	8 530	15 761
Other permanent crops	8 541	10 645	19 186
Specialist milk	3 545	3 591	7 136
Other grazing livestock	2 145	2 144	4 289
Granivores	320	711	1 030
Mixed	9 618	10 796	20 414
Total	59 202	62 252	121 454

Source. Own elaborations

Withdrawal and discharge coefficients for irrigation

Table 7 reports the average withdrawal coefficients of subsectors of agriculture in Tuscany by water body. The values are expressed as cubic meters of water per Euro of gross output. Beside withdrawals coefficients for blue water (ground and surface water bodies) the table reports also green water coefficients, i.e. the water used by crops provided by the natural water cycle (soil moisture available for rainfed agriculture).

The inclusion of green water (used only by agriculture) allows to define a complete water balance for agriculture.

Table 7. Average annual irrigation withdrawals and discharge coefficients of agricultural subsectors by water body - Tuscany, 2017 (m^3/€)

Farm Type	Withdrawals			Discharges		
	Ground water	Surface water	Hydro. cycle	Ground water	Surface water	Hydro. cycle
Fieldcrops	0.09646	0.09830	1.78838	0.04495	0.00000	0.07187
Horticulture	0.00424	0.00222	0.05930	0.00149	0.00000	0.00238
Wine and olive oil	0.00986	0.01163	0.19737	0.00496	0.00000	0.00793
Other permanent crops	0.09523	0.11870	1.96382	0.04937	0.00000	0.07892
Specialist milk	0.06400	0.06483	1.25399	0.02973	0.00000	0.05039
Other grazing livestock	0.01105	0.01105	0.23986	0.00510	0.00000	0.00964
Granivores	0.00518	0.01150	0.19860	0.00385	0.00000	0.00798
Mixed farms	0.01709	0.01918	0.37954	0.00837	0.00000	0.01525

Source: own elaboration

Table 7 provides also the discharge coefficients, representing the share of water returned to water bodies. The amount of water not incorporated into final products depends on losses due to inefficiency of irrigation systems (30% of total withdrawals) and natural losses of soil moisture by evaporation (discharges to the hydrological cycle). Natural losses have been quantified as a percentage of green water withdrawals, based on technical coefficients from literature. We assumed that the whole amount of discharges due to inefficiency of irrigation systems returns to ground water bodies.

Water withdrawals and discharge coefficients for livestock rearing

The estimation of water use coefficients for livestock production activities was based on technical literature about the needs of water per head of livestock per day. A non-published study carried out by the National Research Council Center for Agriculture (CREA) to quantify water requirements of the Italian livestock sector was the main source of this information. Specific coefficients by species and typology of livestock unit (age, production type) were applied to the composition of the regional herd. Table 8 summarizes the average coefficients used in this version of the model for each type of livestock[11].

Table 8. Year water consumption coefficients for livestock breeding

Livestock type	m^3/head
Cattle	23.2
Pigs	4.2
Sheeps and goats	3.1
Poultry	0.1
Rabbits	0.4
Equines	14.0

Source. Own elaboration on CREA data

Total water consumptions for livestock were calculated by multiplying unit coefficients by the

[11] The figures reported in the table are averages of the needs for each typology of livestock weighted for the composition of the herd.

number of livestock heads reared in Tuscany. The estimated total consumption was then distributed among the different FTs based on their share in the rearing of Livestock Units[12] according to standard results from the FADN public database. Water requirements of each subsector were allocated between ground and surface water in the same proportion of irrigation withdrawals.

As shown in Table 9, the estimated total water consumption for breeding is around 4.4 Mm^3, concentrated for the most part, as expected, in farms specialized in herbivore breeding. In the table, the total is also divided by supply source.

Approximately 1 Mm^3 is supplied by public drinking water distribution networks[13], while the rest comes from self-supply sources disaggregated according to the same percentages used in water disaggregation for irrigation use.

Table 9. Average annual water withdrawals for livestock rearing Tuscany, 2017 (Thousands m^3)

Farm Type	Ground water	Surface water	Total
Fieldcrops	7	7	14
Horticulture	0	0	0
Wine and olive oil	4	5	8
Other permanent crops	0	0	0
Specialist milk	214	217	431
Other grazing livestock	391	391	782
Granivores	95	211	306
Mixed	1 346	1 510	2 856
Total	2 057	2 341	4 398

Source. Own elaboration

Table 10 shows the withdrawals and discharge coefficients per Euro of gross output that have been used in the model. As expected, they assume a value not negligible only in the case of farms specialised in livestock rearing.

Table 10. Average annual withdrawals and discharge coefficients for livestock rearing of agricultural subsectors by water body - Tuscany, 2017 (m^3/€)

Farm Type	Withdrawals (m^3/€)		Discharges (m^3/€)
	Ground water	Surface water	Ground water
Fieldcrops	0.00003	0.00003	0.00001
Horticulture	0.00000	0.00000	0.00000
Wine and olive oil	0.00001	0.00001	0.00000
Other permanent crops	0.00000	0.00000	0.00000
Specialist milk	0.00387	0.00392	0.00101
Other grazing livestock	0.00201	0.00201	0.00052
Granivores	0.00154	0.00342	0.00064
Mixed farms	0.00239	0.00268	0.00066

Source: own elaboration

Based on technical literature, discharges have been quantified as a fixed proportion of withdrawals (13%) and assumed to be returned only to groundwater bodies.

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12 Livestock Units are a standardized measure of the size of the holdings of the different domestic species obtained by weighing the number of animals raised with special coefficients. The coefficients defined by EC Regulation 1200/2009 have been adopted in this analysis.

13 Data provided by the Tuscany region.

Water withdrawal and discharge coefficients for water supply industry

The calculation of water withdrawal and discharge coefficients in the water supply industry required the following steps:

- calculation of the percentage of water losses;
- calculation of total water billed;
- estimation of total water withdrawals;
- disaggregation of withdrawn water by source;
- calculation of withdrawal and discharge coefficients.

Table 11 shows the water that enters the communal networks and the water actually supplied to the final users; the difference corresponds to water losses. Water losses for 2018 in the region amount to 42.9%[14].

Table 11. Estimation of water losses in the Water Supply Industry

Component	Volume (Mm^3)
Water Input Municipal Network	412
Water Output Municipal Network	236
Water Losses	177
Water Losses %	42.9%

Source. Own elaboration on Istat data

For the estimation of the water withdrawal coefficients, the information on water billed in the region for the year 2016 was used. (Autorità Idrica Toscana, 2017). Total water billed corresponds to 228 Mm^3. When water losses are taken into account, this value reaches a total of 398 Mm^3 (estimated based on the percentage of losses for 2018 as information for 2016 and 2017 is not available).

To disaggregate water between ground and surface sources, information from ISTAT (2021) is used. Table 12 shows the origin of the water used in the Water Supply Industry for 2018, as a percentage of the total water used.

Table 12. Sources of the water used by the Water Supply Industry

Source	Percentage
Rivers	23.6%
Lakes	4.2%
Wells	50.2%
Springs	22.1%

Source. Own elaboration on ISTAT data

The 27.7% (110 Mm^3) of water comes from surface sources while 72.3% (218 Mm^3) of water comes from groundwater sources. The discharges correspond to water losses (171 Mm^3); in this study it is assumed that all of these losses are discharged to groundwater, constitute groundwater recharge and are not contaminated (COD concentration equal to or better than the standard). Thus, Table 13 presents the water withdrawal and discharge coefficients, expressed in volume per monetary unit, calculated on the basis of the total output of the sector (501.4 M€). The table presents the withdrawal

[14] The figures in Table 8 do not exactly match the amounts used below, because this information is used only to estimate the percentage of losses.

and discharge coefficients used in matrices F and R (in cubic meters per Euro).

Table 13. Water supply industry withdrawal and discharge coefficients

Water Supply Industry	Coefficients (m^3/Euro)		
	Groundwater	Surface water	Hydro. cycle
Withdrawal	0.5754	0.2190	0.0000
Discharge	0.3407	0.0000	0.0000

Source. Own elaboration

Water withdrawal and discharge coefficient for electricity production

For the production of electricity sector, all the existing generators in Tuscany and their annual energy production, for the year 2018, have been considered at the municipality level (GSE, 2022). We assume that the generation in reference year (2017) had the same structure.

Considering the characteristics of the generation technologies, the most appropriate water coefficients for each unit of energy produced have been used (Macknick et al., 2012; Spang et al., 2014; Bakken et al., 2013).

In this way it is possible to determine for each generation technology in Tuscany the following quantities:

- water withdrawals;
- water consumptions;
- water discharges.

Water consumption correspond mainly to evaporation in hydroelectric, thermoelectric and geothermal power plants, and is considered as a discharge to the natural hydrological cycle (atmosphere). Water withdrawals are considered to be from surface sources and discharges (non-consumption associated with the hydrological cycle) are also considered to be towards surface sources. Coefficients are calculated dividing the total estimated water by the output of the input-output table, in its domestic production version.

Table 14 presents the electrical energy produced by each technology in Tuscany and the technical coefficients of water withdrawals, water consumption (or discharge to the hydrological cycle) and water discharge (to the surface water bodies), in units of volume per energy.

Table 14. Electricity production and water uses by technology

Technology	Electric Energy Production (GWh)	Withdrawal Coefficient (m^3/GWh)	Discharge Coefficient (m^3/GWh)	Consumption Coefficient (m^3/GWh)
Wind	226.4	0.0	0.0	0.0
Geothermal	6,201.2	3,406.9	681.4	2,725.5
Hydroelectric	532.5	21,800.0	0.0	21,800.0
Solar	956.5	97.2	0.0	97.2
Thermoelectric	9,760.5	5,526.7	1,105.3	4,421.4

Source. Own elaboration

Table 15 presents the total water (in cubic meters) used by the electric power generation sector, by water source and technology. Table 16 presents the withdrawal and discharge coefficients used in matrices F and R (in cubic meters per euro); the latter correspond to a value of the sector's domestic output in the input-output matrix equal to 2,130.6 M€.

Table 15. Water uses for electricity production in Tuscany

Technology	Surface water withdrawal (Mm^3)	Surface water discharge (Mm^3)	Hydrological cycle (Mm^3)
Wind	0.0	0.0	0.0
Geothermal	21.1	4.2	16.9
Hydroelectric	11.6	0.0	11.6
Solar	0.1	0.0	0.1
Thermoelectric	53.9	10.8	43.2
Total	86.8	15.0	71.8

Source. Own elaboration

Table 16. Electricity production withdrawal and discharge coefficients

Electricity Production	Coefficients (m^3/Euro)		
	Groundwater	Surface water	Hydrological cycle
Withdrawal	0.0000	0.0407	0.0000
Discharge	0.0000	0.0070	0.0337

Source. Own elaboration

Water withdrawal and discharge coefficients for manufacture

Water requirements of manufacture activities have been quantified using non-published data used by ISTAT to produce the report on "Water Use and Quality in Italy", published in 2019 (https://www.istat.it/it/archivio/234904). Based on several sources of information, both from direct surveys and administrative records, ISTAT provided water withdrawals coefficients for Italian economic activities disaggregated up to four digits (235 groups) of the classification of production activities (ATECO). Regional coefficients were obtained weighting the national ones according to the regional composition of the 29 aggregated manufacture sectors represented in the IO table resulting from the permanent census of manufacturing and construction activities. The implicit assumption is that, different from agriculture, the average water requirements of manufacture are not affected by location (as is conversely likely to be in the case of agriculture).

The water discharge coefficients were calculated using information from the Exiobase[15] database. Exiobase is a global multi-regional system of input-output-hybrid tables, i.e., extended to environmental components. It has been developed for research purposes by harmonizing existing input-output tables for several countries, linking them with tables of trade flows between countries and adding information and estimates on emissions and resource use from different productive sectors. Ratios and shares for Italian manufacturing activities resulting from Exiobase were applied to the estimated water discharges by industry.

[15] https://www.exiobase.eu/.

The distribution of water extraction coefficients for production activities between groundwater and surface water was based on reasonable *ad hoc* assumptions. In general, it was assumed that the sources of direct water supply for production activities were surface water bodies. For some industries, supply was divided between surface and groundwater based on the breakdown of sources for civilian use resulting from the 2015 ISTAT Water Census. As regard to water discharges, we assumed that, except for the Mining and Quarrying case, discharges were directed to surface water bodies. Finally, losses to the atmosphere, due to evaporation, were quantified as a fixed proportion of discharges to surface water bodies.

The sectors represented in Table 17 are those that directly withdraw from water bodies (extracting sectors). We hypothesize that water used in all other productive sectors is purchased from the water supply sector and discharged through the sewerage service sector.

Table 17. Average annual withdrawals and discharge coefficients by water body for manufacture - Tuscany, 2017 (m^3/€)

Industry	Withdrawals (m^3/€)	Discharges (m^3/€)		
	Surface water	Ground water	Surface water	Hydro. Cycle
Mining and quarrying	0.0060	0.00601	0.00000	0.00000
Food products, beverages and tobacco	0.0031	0.00000	0.00075	0.00003
Textiles and textile products	0.0174	0.00000	0.00425	0.00015
Wearing apparel; dressing and dyeing of fur	0.0007	0.00000	0.00018	0.00001
Leather and leather products	0.0024	0.00000	0.00059	0.00002
Footwear	0.0001	0.00000	0.00002	0.00000
Wood and wood products	0.0026	0.00000	0.00064	0.00002
Pulp, paper and paper products; publishing and printing	0.0076	0.00000	0.00172	0.00006
Chemicals, chemical products and man-made fibres	0.0162	0.00000	0.00159	0.00006
Pharmaceuticals, medicinal chemicals and botanical products	0.0054	0.00000	0.00053	0.00002
Rubber and plastic products	0.0118	0.00000	0.01008	0.00037
Other non-metallic mineral products	0.0106	0.00000	0.00909	0.00033
Basic metals	0.0011	0.00000	0.00027	0.00001
Fabricated metal products, except machinery and equipment	0.0029	0.00000	0.00071	0.00003
Office machinery and computers	0.0017	0.00000	0.00033	0.00001
Electrical and optical equipment	0.0028	0.00000	0.00056	0.00002
Machinery and equipment n.e.c.	0.0018	0.00000	0.00009	0.00000
Transport equipment	0.0040	0.00000	0.00120	0.00004
Furniture	0.0006	0.00000	0.00016	0.00001
Jewellery and related articles	0.0001	0.00000	0.00002	0.00000
Manufacturing n.e.c.	0.0118	0.00000	0.00287	0.00010
Repair and installation of machinery and equipments	0.0000	0.00000	0.00000	0.00000

Source: own elaborations

Quality of discharged water

Water quality is measured based on the chemical oxygen demand (COD, in mg/L). This parameter is assigned to returned water for the following economic macro-sectors (those that discharge water directly to groundwater and surface water bodies):

- Agriculture
- Manufacture
- Sewerage

The Water Supply Industry sector is not considered because its returns are of water with law concentration (losses in aqueducts). The Services macro-sector does not discharge contaminated water directly to water bodies, discharging 100% of water through the Sewerage services.
The law concentration, in the case of this study, corresponds to the quality of surface water and groundwater that can be withdrawn for economic use without prior treatment. We consider the parameter COD=20 mg/l, value for which waters are classified as unpolluted.
A methodology is defined for each macro-sector to properly characterize its discharges.

Agriculture

The activities included in the agriculture macro-sector use and discharge water for both irrigating crops and breeding livestock. The discharge concentration (c_a) is calculated as a weighted average.

$$c_a = \frac{c_c \cdot q_c + c_l \cdot q_l}{q_c + q_l} \tag{B.1}$$

The values of q_c and q_l corresponds to the discharge's volumes estimated for the hydro-economic model. The quality of the discharge of polluted water (c_l) is considered to be equal to COD=100mg/l which corresponds to the emission limit for urban and industrial wastewater reaching the ground (Decreto Legislativo Acque n.125 del 11/05/99[16]). For the irrigation use of water, the concentration of discharges (c_c) is considered equal to COD=50mg/l (Water Resources of Italy, 2020).

Manufacture

It is assumed that a percentage (β) is treated before discharge while the remaining share (1- β) is discharged untreated. Thus, the COD concentration of this macro-sector (c_m) is defined as:

$$c_m = \beta \cdot c_m^T + (1 - \beta) \cdot c_m^U \tag{B.2}$$

where c_m^T represents the concentration of the treated discharges, considering a value of COD=160mg/l which corresponds to the maximum emission limit in surface water (Decreto Legislativo Acque n.125 del 11/05/99). For the case of untreated discharged water c_m^U , it is considered a quality equal to COD=500mg/l which corresponds to the sewage emission limit (Decreto Legislativo Acque n.125 del 11/05/99). It is assumed $\beta = 20\%$.
The electric energy production sector is not considered among the sectors that discharge contaminated water, since its returns do not contain organic wastes, only increases in temperature, which dissipates along the surface watercourses.

[16] https://www.gazzettaufficiale.it/eli/id/1999/07/30/099A6464/sg

Sewerage

It is considered that a percentage (α) is treated and discharged at the grade concentration and the other part $(1\text{-}\alpha)$ is discharged untreated. The COD concentration of the Sewerage macro-sector (c_s) is defined as:

$$c_s = \alpha \cdot c_s^T + (1-\alpha) \cdot c_s^U \qquad \text{(B.3)}$$

For the treated water (c_s^T) it is considered a COD=125mg/l, which corresponds to the emission limit for urban wastewater plants (Decreto Legislativo Acque n.125 del 11/05/99). For the untreated water (c_s^T) we consider that it is discharged with the maximum concentration allowed in the sewerage networks (COD=500mg/l) (Decreto Legislativo Acque n.125 del 11/05/99).

Summary of pollution concentrations

Table 18 presents a summary of the components of the water returns that are discharged with COD concentration higher than the law concentration. The parameters (percentage) have been calculated considering the relation between the total volume returned to water bodies and the volume of polluted water associated to each macro-sector. Returns of water with law concentration are not considered because they do not increase the amount of water required for pollution dilution.

Table 18. Summary of polluted concentration in water discharges

Macro-sectors	Type of discharge	Concentration Formula	Parameters	COD (mg/l)
Agriculture and Zootechnics	Untreated Agriculture	$c_{az} = \frac{c_a \cdot q_a + c_z \cdot q_z}{q_a + q_z}$	Depends on the IO model	50
	Untreated Zootechnies			100
Manufacture	Treated	$c_m = \beta \cdot c_m^T + (1-\beta) \cdot c_m^U$	$\beta = 80\%$	160
	Untreated		$1-\beta = 20\%$	500
Sewerage	Treated	$c_s = \alpha \cdot c_s^T + (1-\alpha) \cdot c_s^U$	$\alpha = 95\%$	125
	Untreated		$1-\beta = 5\%$	500

Source: Own elaboration

Mixing model

For the reaction rate of pollutants after entering the water body parameter (k_{1_k}) we consider a value (dimensionless) of 2.80 and 3.64 for groundwater and surface water, respectively. For the pollution purification rate before entering the water body parameter (k_{2_k}) we consider a value (dimensionless) of 0.82 and 1.00 for groundwater and surface water, respectively (Guan and Hubacek, 2008).

The standard COD concentration in water bodies (c_{s_k}) is considered equal to 20 mg/l (Rossi and Benedini, 2020) for both groundwater and surface water. The COD concentration in water bodies (c_{0_k}) is assumed to be equal to the standard COD concentration for an average hydrological year. In the sensitivity analysis for wet and dry hydrological years, it is assumed a value of 17.5 mg/l and 22.5

mg/l, respectively.

Hydrological Balance and natural supply

In section 3.1 the variables of the hydrological cycle have been listed: precipitation (P), evapotranspiration (E), groundwater recharge (I), runoff (R) and the soil moisture (ΔV).

The Italian Institute of Statistics provides information for each of these random variables (except soil moisture, not considered in this study) in the period 2001-2010 in the Tuscany region (Table 19).

Table 19. Hydrological cycle components for Tuscany (2001-2010)

Year	Precipitation [P] (Mm^3)	Evapotranspiration [E] (Mm^3)	Groundwater recharge [I] (Mm^3)	Runoff [R] (Mm^3)
2001	16,398	10,070	2,606	3,551
2002	22,056	13,639	4,548	3,112
2003	16,923	9,655	3,742	3,195
2004	21,868	11,007	5,772	5,489
2005	19,880	10,922	4,571	4,704
2006	15,819	10,317	2,343	3,438
2007	14,027	10,616	1,979	1,704
2008	22,324	11,361	5,634	4,735
2009	21,119	10,750	5,336	4,356
2010	27,161	12,278	6,830	8,124

Source. Own elaboration based on ISTAT data (https://seriestoriche.istat.it/)

Given the low length of the records (10 years), the time series for Tuscany has been extended based on the series referring of the Northern Apennines District (Autorità di distretto dell'Appennino Settentrionale, 2021) for the period 1971-2010. In this way, it has been possible to generate a 40-year record for each of the variables of the hydrological cycle. The methodology for extending the series for Tuscany (Te Chow, 2010) corresponds to an adjustment of the Northern Apennines District data based on the common period, that is, the data for Tuscany in the missing period (1971-2000) will have the same structure than in the Northern Apennines District but will be different in level.

Let us consider the variables X and Y that represent each of the components of the hydrological cycle ($P,\ E,\ I,\ R$) of the series for Tuscany and for the Northern Apennines District, respectively.

$\bar{X}^{CP}$: Mean variable for the Tuscany in the common period 2001-2010

X_t^{LP}: Variable year t for Tuscany in the period 1971-2000.

$\bar{Y}^{CP}$: Mean variable of the Northern Apennines District in the common period 2001-2010

Y_t^{LP}: Variable year t of the Northern Apennines District in the period 1971-2000.

Thus, the unknown variable X_t^{LP} is calculated for each year of the long period as:

$$X_t^{LP} = Y_t^{LP} \cdot \frac{\bar{X}^{CP}}{\bar{Y}^{CP}}$$

Table 20 shows the mean, standard deviation, coefficient of variation, and skewness for the components of the hydrological cycle in the period 1971-2010, for Tuscany. Figure 6 shows the four components of the hydrological balance for Tuscany for the 1971-2010 period.

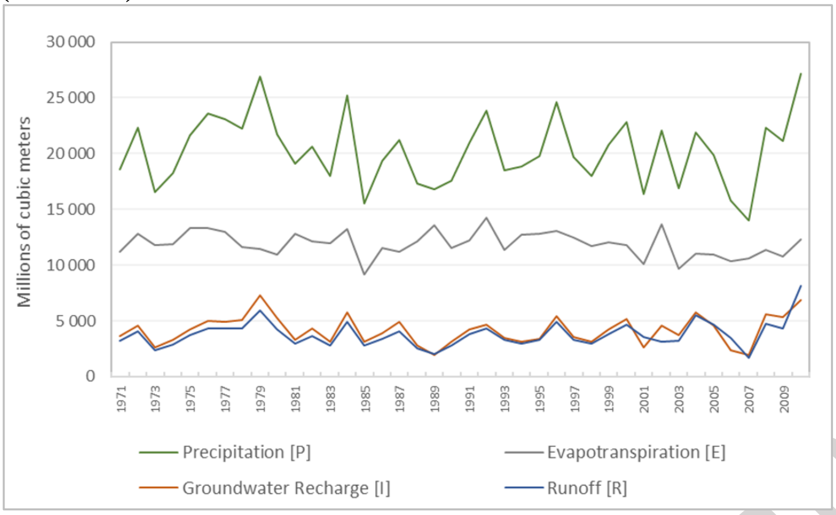
Table 20. Statistics of the extended hydrological series for Tuscany

(1971-2010)

Year	Precipitation [P]	Evapotranspiration [E]	Groundwater recharge [I]	Runoff [R]
Mean (Mm³)	20,269	11,892	4,155	3,803
S. Deviation (Mm³)	3,084	1,129	1,258	1,156
C. Variation	15%	9%	30%	31%
Skewness	0.2	-0.2	0.4	1.3

Source. Own elaboration

Figure 6. Extended hydrological series for Tuscany
(1971-2010)



Source. Own elaboration

With these data, the average natural supply of surface and groundwater can be constructed for the calculation of the EWEI. The total supply, as described in section 3.1, corresponds to the sum of surface water, groundwater and rainfall directly captured by the agriculture sector (a part of the variable P).

Feasible Supply

The total volume of surface water concessions registered by the Regional Hydrological Service (Settore idrologico e Geologico regionale, 2021) corresponds to 2,473 Mm^3, however, this volume is about 70% of the total, due to the fact that many of the concession's records do not present information on the volume. A maximum value of 3,636 Mm^3 has been estimated (Venturi, 2014). The average annual runoff is 3,802 Mm^3, thus the value of parameter M for the calculation of the feasible surface water supply corresponds to 95.6% (3,802 Mm^3).

For the ecological flow, a value of $E = 20\%$ is considered. This means that surface water bodies will always have an average flow rate equivalent to 20% of the average annual flow. This is a rather conservative value, especially considering that it is assumed at a regional scale (Rossi and Caporali, 2021).

For the groundwater recharge, a value of $B = 13\%$ is considered. This value is calculated as $B = \frac{D-\bar{I}}{\bar{I}} = \frac{4{,}704-4{,}155}{4{,}155} = 13\%$. The maximum value of the concessions is 4,704 Mm^3 while the average annual recharge is 4,155 Mm^3 (SIR, 2021). The total value of groundwater concessions is consistent with the fact that aquifers allow for interannual regulation of water supply.

Appendix C

Reclassified Net Water Demand (RND) and Reclassified Extended Water Demand (RED) for 56 industries.

Sector	Macro-sector	Reclassified Net Water Demand (RND)			Reclassified Extended Water Demand (RED)		
		Groundwater	Surface water	Hydro Cycle	Groundwater	Surface water	Hydro Cycle
Arable land	Agriculture	1.7	3.0	46.7	2.4	3.2	46.7
Horticulture	Agriculture	3.9	3.5	61.5	4.8	3.9	61.5
Permanent crops	Agriculture	3.2	7.0	101.1	4.8	7.3	101.1
Grazing livestock	Agriculture	0.5	0.9	12.8	0.7	0.9	12.8
Granivores	Agriculture	0.1	0.4	3.7	0.2	0.4	3.7
Mixed crops farms	Agriculture	3.3	8.4	131.3	5.3	8.4	131.3
Mixed livestock farms	Agriculture	0.8	1.5	23.6	1.2	1.5	23.6
Mixed crops-livestock farms	Agriculture	4.4	8.7	117.5	6.6	8.9	117.5
Forestry and use of forest areas	Agriculture	0.1	0.2	-0.1	0.1	0.2	-0.1
Fishing	Agriculture	0.0	0.1	0.0	0.0	0.1	0.0
Mining and quarrying	Manufacturing	0.0	-1.8	-0.1	10.8	2.8	-0.1
Food products and beverages	Manufacturing	20.7	8.7	208.5	24.2	33.6	208.5
Textiles	Manufacturing	7.9	58.0	232.1	11.6	113.8	232.1
Wearing apparel	Manufacturing	0.4	10.8	-0.2	0.4	25.7	-0.2
Leather and related goods	Manufacturing	2.4	15.0	6.3	2.6	35.2	6.3
Footwear	Manufacturing	0.2	2.2	-0.1	0.2	7.5	-0.1
Wood and wood products	Manufacturing	0.1	1.3	-0.8	0.1	6.0	-0.8
Paper Printing and rec. media	Manufacturing	0.4	17.0	-0.9	0.5	61.8	-0.9
Coke and refined petroleum products	Manufacturing	0.3	-1.0	-0.2	1.7	9.8	-0.2
Chemical and chemical products	Manufacturing	26.5	13.5	-0.8	26.6	42.3	-0.8
Pharmaceutical products	Manufacturing	0.7	12.9	1.7	0.7	28.5	1.7
Rubber and plastic products	Manufacturing	0.4	1.4	1.5	0.5	42.7	1.5
Other non-metallic products	Manufacturing	0.3	-1.8	-0.8	0.4	62.0	-0.8
Manufacture of basic metals	Manufacturing	0.3	8.7	-2.9	0.5	16.7	-2.9
Metal products	Manufacturing	0.1	6.4	-0.4	0.2	15.6	-0.4
Computers, electronic and optical equipment	Manufacturing	1.5	2.3	1.5	1.5	8.6	1.5
Electrical equipment	Manufacturing	1.2	2.0	0.0	1.2	9.3	0.0
Machinery and equipment n.e.c.	Manufacturing	9.9	2.4	-0.6	9.9	7.6	-0.6
Motor vehicles and other transportation means	Manufacturing	10.6	-0.9	-0.2	10.6	28.0	-0.2
Furniture	Manufacturing	0.5	0.7	0.0	0.5	2.6	0.0
Jewelry	Manufacturing	0.2	0.5	-0.2	0.2	1.5	-0.2
Other manufacturing	Manufacturing	2.0	0.4	0.1	2.0	3.4	0.1
Repair and installation of equipment and systems	Manufacturing	0.1	0.8	-0.3	0.1	1.3	-0.3
Electricity power generation	Manufacturing	0.1	21.6	-22.6	0.3	25.3	-22.6
Electricity Transmission and Distribution	Manufacturing	0.0	6.2	-6.4	0.0	6.8	-6.4
Gas Steam Air conditioning	Manufacturing	0.1	4.7	-0.8	0.2	5.7	-0.8
Water supply	Water Supply	66.0	62.1	-0.5	66.0	62.4	-0.5
Sewerage	Sewerage	0.0	-165.1	-6.0	0.0	221.9	-6.0
Waste management	Manufacturing	0.1	-0.1	0.4	0.1	1.7	0.4
Construction	Construction	0.7	0.8	0.8	0.8	14.9	0.8
Wholesale and retail trade, repair of motor vehicle	Services	3.1	-3.7	30.4	3.8	25.9	30.4
Transportation and storage	Services	0.5	-3.8	-0.1	0.6	15.9	-0.1
Accommodation and food services	Services	7.7	8.9	42.1	8.5	13.8	42.1
Publishing, audiovisual, radio and television production	Services	0.0	0.0	0.1	0.0	0.4	0.1
Telecommunications	Services	0.5	0.2	0.0	0.5	1.5	0.0
IT and other information services	Services	0.1	-0.5	0.1	0.1	1.8	0.1
Financial and insurance activities	Services	0.2	0.6	0.0	0.2	2.6	0.0
Real estate activities	Services	0.2	0.5	0.4	0.3	2.6	0.4
Professional and technical activities	Services	1.1	-5.9	1.5	1.1	16.5	1.5
Scientific research and development	Services	0.4	1.4	1.3	0.5	3.3	1.3
Other service activities	Services	0.5	1.0	5.4	0.6	7.1	5.4

Sector	Macro-sector	Reclassified Net Water Demand (RND)			Reclassified Extended Water Demand (RED)		
		Groundwater	Surface water	Hydro Cycle	Groundwater	Surface water	Hydro Cycle
Public administration and defense; compulsory social security	Services	33.0	32.7	-0.3	33.1	33.1	-0.3
Education	Services	0.5	1.4	0.2	0.6	1.7	0.2
Health and social work activities	Services	1.0	-9.3	-0.7	1.0	21.4	-0.7
Arts, entertainment, and recreation	Services	0.4	1.1	1.6	0.4	2.4	1.6
Other service activities	Services	0.2	2.9	-1.1	0.2	4.2	-1.1

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