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An Input-Output Hydroeconomic Model to Asses the Economic Pressure on Water Resources in Tuscany

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AN INPUT-OUTPUT HYDRO-ECONOMIC MODEL TO ASSESS THE ECONOMIC PRESSURE ON WATER RESOURCES IN TUSCANY

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Abstract

In this work, an input-output hydro-economic model methodology is applied for the Tuscany region in Italy. The model integrates the input-output table (for the year 2017) of the regional economy developed by IRPET with a satellite account of flows of water resources between the hydrological system and the economy. Three innovations are incorporated with respect to previous literature: i) a methodology for calculating the extended water demand (ED) (blue, green and grey water) by economic sector; ii) the reclassification of the ED by extracting and demanding sectors; and iii) the construction of new indicator of economic pressure on water resources (EWEI: Extended Water Exploitation Index) based on the ED and a measure of water supply (Feasible Supply: FS) taking into account technological and institutional constraints to the exploitation of water resources. The empirical model is built based on economic and hydrological data generated by the different national and regional institutions. The model provides estimates of the net water demand and the extended water demand generated by 56 economic sectors, considering both the extracting and the demanding sector classification. The proposed indicator of pressure supports a better understanding of the linkages existing between economic activities and the regional hydrological system and a more accurate assessment of pressures on water resources.

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

JEL Classification: C67, Q25, Q50

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1 INTRODUCTION

Input-output models (IO) have been widely used to study water use in economic systems determining direct and indirect water consumed by industries in order to satisfy the final demand (Lenzen et al., 2013; Ridoutt et al., 2018; Velazquez, 2006; Guan and Hubacek 2008) and for the estimation of virtual water flows and water footprint at regional, national and global scale (Feng et al., 2011; Duarte et al, 2016; Arto et al, 2016). IO models have also been used to estimate the water balance, obtaining the water demand based on the economic model and determining the water supply based on water availability data (Cámara and Llop, 2020; Garcia-Hernandez and Brouwer, 2021). The latter works, however, do not consider the water demand component required for dilution of pollutants present in water discharges (grey water). Cámara and Llop (2020) consider the net demand (withdrawals minus discharges) while Garcia-Hernandez and Brouwer (2021) consider only water withdrawals.

The work of Guan and Hubacek (2008) uses an input-output model to determine the extended demand of water, defined as the net demand (including blue and green water) plus the water required for pollutants dilution (grey water), for North China. Grey water is estimated based in a mixing model developed by Xie (1996) using the COD (chemical oxygen demand) as an indicator of pollution. While the interactions between the economic system and the natural hydrological system are modeled, indicators of economic pressure over water resources (balance between demand and supply of water) are not included in their work. In addition, the extended water demand associated with each industry is not calculated, since grey water is calculated only for the whole region.

In literature, several indicators of pressure on water resources have been proposed, among which the following stand out: i) the water exploitation index (WEI), which corresponds to the ratio between blue water withdrawals and natural availability net of the ecological flow (European Environmental Agency, 2005); ii) the WEI+, an upgraded version of the WEI, which incorporates also returns from water uses, therefore taking into account the net water demand (Faergemann, 2012; European Environmental Agency, 2020); iii) the water availability index (WAI) or withdrawals to availability (WTA) ratio, defined as the ratio of water withdrawals to renewable water availability (OECD, 2015; Garcia-Hernandez and Brouwer, 2021; Pfister et al., 2009). A threshold value of 20% for all the mentioned indicators is used as a water scarcity or sustainability criterion. This threshold has been recommended and used to identify presence of some degree of water stress, while a value of 40% has been proposed to differentiate moderate and severe shortages, without any specific considerations of regulation capacity and extraction feasibility (Raskin et al., 1997; Alamo et. al, 2000, Pfister et al., 2009, CIRCABC, 2012).

In this paper we develop an input-output hydro-economic model to assess the economic pressure on water resources, considering three components of the hydrological system: surface water, groundwater and the natural hydrological cycle (precipitation and evapotranspiration). The main innovations of the model with respect to previous studies are: i) the development of a methodology for disaggregating the extended water demand by economic sector, ii) the reclassification of water demand by producing and demanding sectors, and iii) the proposition of an improved indicator of pressure on water resources based on the extended demand and a measure of the "feasible" water supply.

To calculate the water demand for dilution by 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). The chemical oxygen demand COD is considered as an indicator of the quality of the water bodies, since it corresponds to the most important indicator of water quality in industrial sectors (Meng et al., 2018). We use a modified version of the model proposed by Xie et al. (2016) to estimate requirements of water for dilution by economic sector, considering that water for dilution come from the hydrological system with a given level of pollution.

In the proposed 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 will refer to an "extracting sector" classification. The input-output matrix, through the intermediate flows of goods and services, allows us to reclassify the net demand and the extended demand of water by "demanding sector", that is, a new distribution that considers the direct and indirect pressure of each economic sector on the different water bodies of the hydrological system. The calculation of the dilution requirement by industry allows the reclassification of this component too and, therefore, of the whole extended demand.

We propose an indicator of economic pressure corresponding to the ratio of the extended demand (groundwater and surface water components) to the feasible supply. The feasible groundwater supply is quantified considering long-term recharge within a technical range of abstraction. The feasible supply of surface water is equal to runoff minus ecological flow, but also considers technical (extraction capacity) and institutional (water concessions) constraints. The indicator considered in this study considers both blue water scarcity and water quality stress (Wang et al., 2021), and basically corresponds to the WEI+ indicator but including gray water and considering a feasible measure of supply. For this reason, we call it Extended Water Exploitation Index (EWEI). The definition of the EWEI allows to calculate a different feasible supply depending on whether the hydrology corresponds to a dry, medium or wet year. The more the hydrology is distant from the average year, the more technical and institutional constraints are important. The EWEI is a more prudent indicator with respect to the WEI (and other similar indicators).

We applied the model to the Tuscany region of Italy, integrating the input-output table (for the year 2017) of the regional economy developed by IRPET (2021) with a satellite account (ground water, surface water and hydrological cycle) of the flows of water resources generated in the hydrological system by production activities.

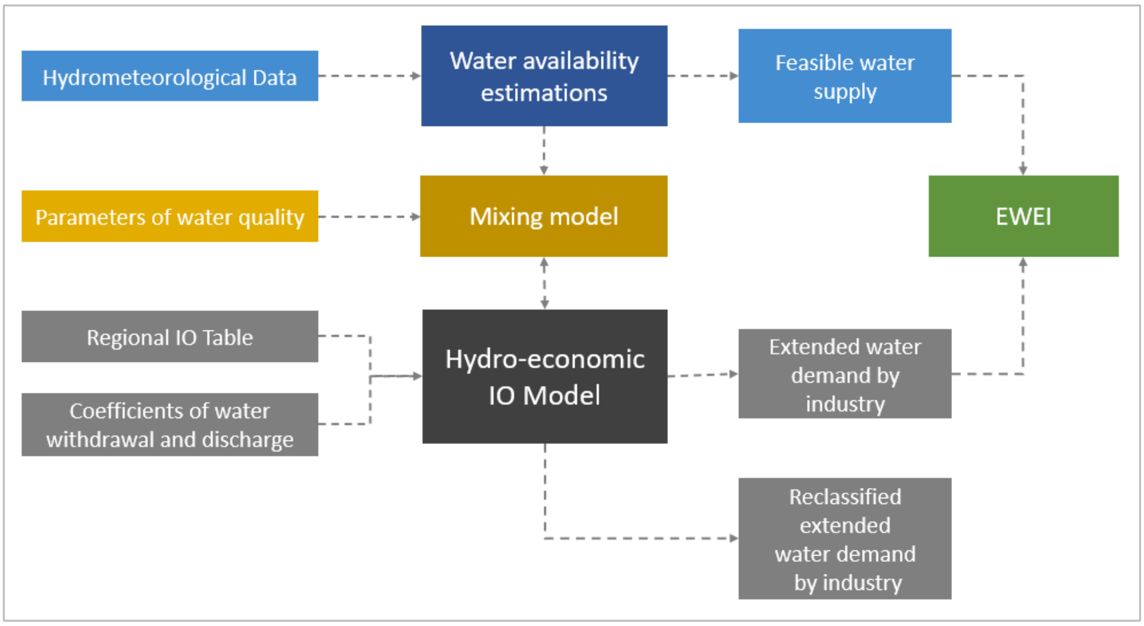
The Tuscany regional Government as well as other agencies involved in various ways in the management and control of regional water resources made available a wide set of information sources used to reconstruct the following components of the regional hydrological balance: i) the water withdrawals (classified by water body) generated by the various production activities existing in Tuscany (classified as "industries" according to the NACE classification); ii) the water discharges to the hydrological system made by each industry classified by water body and by levels of water quality according to the quality thresholds allowed by the different uses (e.g., civil, industrial).

Based on the collected information and the proposed methodology, a hydro-economic model of the Tuscan economy has been developed. Net demand (ND) and extended demand (ED) are estimated by industry, an analysis is made based on the classification by producing and demanding sectors, the EWEI is calculated for the whole region and compared with the WEI and the scarcity thresholds defined in the literature.

In this study, we use the definition of the United States Geology Survey (USGS), to differentiate water withdrawals and water consumptions. Water 'withdrawals' are defined as the amount of water removed from the ground or diverted from a surface water source for use, while water 'consumptions' refer to the amount of water that is evaporated, transpired, incorporated into products or crops, or otherwise removed from the immediate water environment (Kenny et al., 2019; Macknick et al., 2012). Thus, the economic system discharges (used for quantifying the extended demand) are estimated as the economic water withdrawals minus the economic water consumptions. In this sense we also use the principle of all physical input-output tables, that is, the use of the material balance, which indicates that the mass of the inputs is equal to the mass of the outputs and wastes generated (Hoekstra and Van Den Bergh, 2002).

Figure 1 presents a schematic of the hydro-economic analysis developed in this study. With 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). Based on the results of the mixing model (dilution water coefficients), water withdrawal and discharge coefficients, and the IO regional table, the hydro economic IO model allows to calculate the extended water demand and the reclassified extended water demand. Finally, based on the extended water demand and the feasible supply, the EWEI indicator is obtained.

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



Source: Own elaboration

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 sectors. Section 3 presents the proposed water resources pressure indicator, based on the model's outputs and on information about surface and groundwater availability in the region. Section 4 describes the data and methods used to implement the empirical model. Section 5 presents the results for the reference year in terms of net and extended water demand (by extracting and demanding sectors), 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 provides concluding remarks and suggestions for future research.

2 THE HYDRO-ECONOMIC MODEL

2.1 Hydro-economic water flows

Following the Guan and Hubacek (2008) we consider the extended demand approach, which include the water withdrawals for productive[3] 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 contained in products and services, iii) water consumptions by evaporation and transpiration into the hydrological cycle, and iv) water removed from the immediate water environment[4]. (Kenny et al., 2019; Macknick et al., 2012).

Figure 2 presents a schematic illustrating 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), part of this water is consumed (products and services, evaporation and transpiration) and, the other part, is discharged with pollution to groundwater and surface water (*discharges*). By means of physical-chemical processes and water from the hydrological system reserved for quality restoration (*dilution requirements*), the restored water can be made available again for use in the production system (in volume and quality). Water that returns to the atmospheric hydrological cycle is not considered as recharge within the economic analysis period.

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[5]) (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) considers both water volume and water *quality*.

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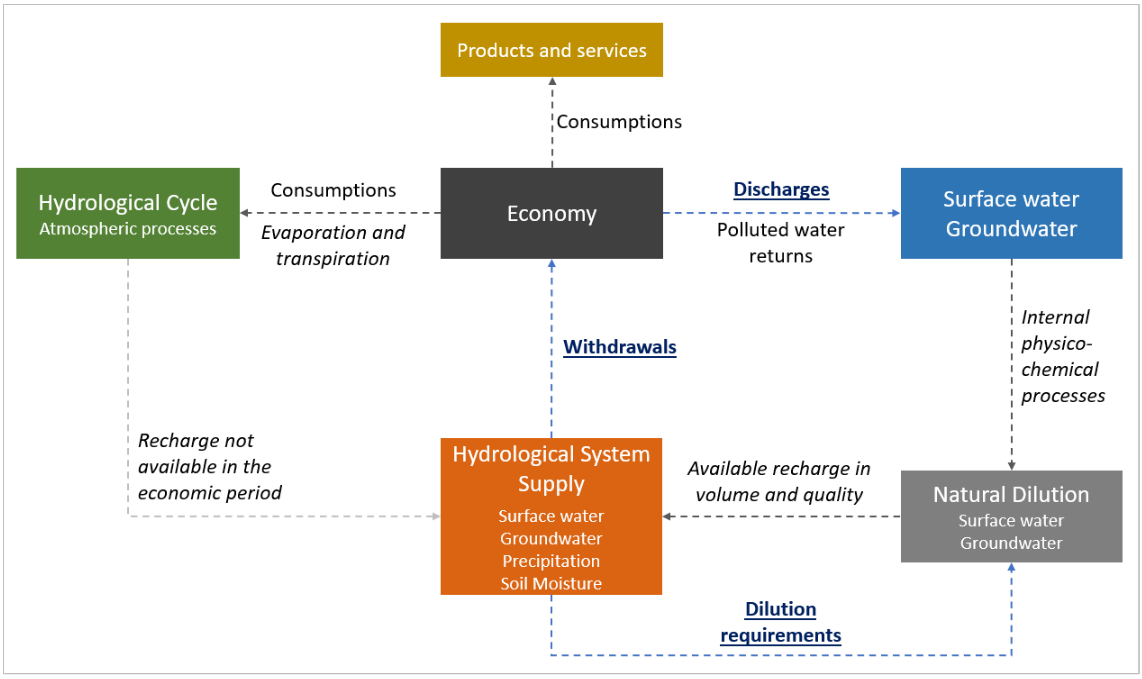
[3] In this study, we are interested in water used for production. That is, we assume that domestic water is provided by water supply industry. Actually, there are direct withdrawals by households from groundwater and surface water bodies whose relevance, however, depends on the case study. For the case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

[4] In this work we do not consider this component important since more than 95% of the surface of the analysis region are watersheds draining within the territory of the analysis.

[5] We will use WEI to refer to the WEI+ indicator, i.e., considering net demand instead of withdrawals.

Figure 2. Water flows in the hydro-economic systems



Source: Own elaboration

2.2 Input-output hydro-economic model

We consider an economic system with *n* productive sectors 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[6] 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 $(n \times 1)$ vector of the unit water withdrawal coefficients (m^3/€) of industries from the water body k.

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[6] 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.

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 (nx1) vector e_k for the water body k, disaggregated by industry, is given by:

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

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:

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

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

$$d_k = (\widehat{f_k} - \widehat{r_k})(I - A_d)^{-1}y, \qquad i = 1, \ldots, m \tag{5}$$

In the same way of equations (3) and (4), the (n x m) matrix ND (net water demand by economic sectors) and the (m x 1) vector TND (total net water demand associated with the entire economy, by water source), are obtained:

$$ND = \hat{x}(F - R) \tag{6}$$

$$TND = (F - R)'x \tag{7}$$

2.3 Water requirements for dilution

In this section we show how is calculated the (n x 1) vector w_k, defined in the previous section, for the estimation of the water requirements for pollution of each economic sector and by water body k.

A mixing model is proposed 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. In this work we consider the following extensions to the above-mentioned model:

- 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 (zero in the Xie-Model).
- The worst case is assumed, i.e., when there is no more water in the water bodies than the water required for dilution (total natural supply in the Xie-Model).

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

$$w_{kj} = \frac{u_{kj}}{x_j} \tag{8}$$

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.[7]

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

$$u_{kj} = \left[\frac{k_{2_k} \cdot c_{p_{kj}} - c_{s_k}}{k_{1_k} \cdot c_s - c_{0_k}}\right] \cdot q_{p_{kj}} \tag{9}$$

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
$c_{p_{kj}}$: 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

---

[7] For the case of this study $m = 3$ (groundwater, surface water and hydrological cycle), 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 the water discharged in surface and groundwater bodies, but not the water that returns to the hydrological cycle.

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 (9) 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; it is modified, however, to estimate the EWEI for dry and wet hydrology.

Appendix 1 presents the development of the mixing model explaining in detail the differences with the Xie-Model.

2.4 Reclassification by demanding sectors

The input-output matrix, through the intermediate flows of goods and services, allows us to reclassify the net demand and the extended demand of water by "demanding sectors", that is, 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 (5) based on (1),

$$e_k = \left(\widehat{f_k} - \widehat{r_k} + \widehat{w_k}\right) \cdot x, \qquad k = 1, \dots, m \tag{10}$$

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 different extent), the withdrawals and the discharges of water 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 service sector and discharges water throughout the sewage service sector. Referring to equation (10) would provide only a partial view of the interdependencies existing between the economic and the hydrological system.

It is of interest to know the use of water reclassified by *demanding sector*s. This can be 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,

$$s_k = (\widehat{f_k} - \widehat{r_k} + \widehat{w}_k)A_d x \tag{11}$$

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

$$p_k = \hat{x}A'_d(f_k - r_k + w_k) \tag{12}$$

Thus, the reclassified water extended demand vector ($\tilde{e}_k$) for the water source k can be written based on equations (10), (11) and (12).

$$\tilde{e}_k = e_k - s_k + c_k = (\widehat{f_k} - \widehat{r_k} + \widehat{w}_k)(x - A_d x) + \hat{x}A'_d(f_k - r_k + w_k) \tag{13}$$

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 sectors. The reclassified extended water demand (n x m) matrix RED can be written as:

$$RED = (\hat{x} - \widehat{A_d}x + \hat{x}A'_d)(F - R + W) \tag{14}$$

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

$$\tilde{d}_k = e_k - s_k + c_k = (\widehat{f_k} - \widehat{r_k})(x - A_d x) + \hat{x}A'_d(f_k - r_k) \tag{15}$$

$$RND = (\hat{x} - \widehat{A_d}x + \hat{x}A'_d)(F - R) \tag{16}$$

3 AN INDICATOR OF ECONOMIC PRESSURE ON WATER RESOURCES

The previous sections have characterized the economic demand for water (net an extended). The economic pressure on water resources must also consider the supply of water. The indicators used in the literature (Faergemann, 2012; European Environmental Agency, 2020; OECD, 2015; Garcia-Hernandez and Brouwer, 2021; Pfister et al., 2009) consider an approach associated with natural supply (discounting ecological flow). However, not all surface and groundwater can be extracted; actual withdrawals depend, besides environmental considerations, also on technical and institutional aspects.

3.1 Natural supply

To determine the water supply it is important 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), runoff (R) and the soil moisture (ΔV). The balance equation is:

$$P_t = E_t + I_t + R_t + \Delta V_t \tag{17}$$

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

$$S_t^{nat} = I_t + R_t \tag{18}$$

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.

$$S^{nat} = I + R \tag{19}$$

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 discounting the environmental requirements, i.e. the ecological flow (EF), is used. In our notation we can define the natural supply with ecological flow as:

$$S = I + R - EF \tag{20}$$

The water supply indicator considers blue water supply only, as in the studies cited above, and does not include green water (precipitation and soil moisture).

3.2 Feasible supply

We define a feasible supply to take into account environmental, technical, and institutional limitations to natural water supply. The problem of pressure on resources and the definition of scarcity must take into account 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.

3.2.1 Surface water

The technical, institutional, and environmental limitations that characterizes the feasible supply for surface water are the following:

- although rivers are renewed year after year, it is clear that not all the runoff of water can be used for economic purposes;
- in the years of high flow, the possibility to capture and accumulate water (hydraulic works) is limited.;
- in the years of high flow, it could not be possible to extract all the water because the concessions do not allow it;
- it is not environmentally possible to extract all available water as there must be a minimum "ecological" flow; as this sustainability condition for surface water bodies is not incorporated into the model, the Feasible 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 the following:

- 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, taking into account 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 $E \in (0,1)$;
- when R_t is less than $M\bar{R} + E\bar{R}$ and greater than $E\bar{R}$, the feasible runoff value (R_t^{feas}) is equal to R_t;
- when R_t is greater than $M\bar{R} + E\bar{R}$, the feasible runoff value is $M\bar{R}$;
- for the case in which $R_t - E\bar{R} < 0$, there will be no availability of surface water for economic uses;
- as a result, the feasible annual average runoff will be strictly lower than the $\bar{R}$ value.

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

$$R_t^{feas} = \begin{Bmatrix} R_t - E\bar{R} & if\ E\bar{R} < R_t < M\bar{R} + E\bar{R} \\ M\bar{R} & if\ R_t > M\bar{R} + E\bar{R} \\ 0 & if\ R_t < E\bar{R} \end{Bmatrix} \qquad (21)$$

3.2.2 Groundwater

The technical, institutional, and environmental limitations that characterizes the feasible supply of groundwater are:

- 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 year is low, it is still possible to extract a larger quantity (reservoir effect);
- when the recharge is high, there are technical limitations to extraction;
- the feasible recharge can be equal to the average recharge (which ensures sustainability, i.e., a non-decreasing groundwater stock), which is why there are no limitations on the part of the concessions (which are assumed to be equal to or lower than the average annual recharge)

The proposed definition of the feasible supply of groundwater is the following:

- the sustainable extraction is assumed equal to the average recharge; 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 fact, in general, groundwater concessions are awarded for a slightly higher value than sustainable recharge, since there are years in which it is not possible to extract the average recharge (technical limitations, especially for small users) and other years in that it is possible to extract more than the average recharge;
- 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;
- it is assumed that the feasible groundwater supply (that can be drawn in one year) will be in the range $[\bar{I}(1-B), \bar{I}(1+B)]$;
- when I_t is lower than $\bar{I}(1-B)$, the feasible supply value (I_t^{feas}) is $\bar{I}(1-B)$;

- when I_t is greater than $\bar{I}(1+B)$, the feasible supply value is $\bar{I}(1+B)$;
- when I_t is in the range$[\bar{I}(1-B), \bar{I}(1+B)]$, the feasible supply value is I_t;
- consequently, as the distribution of I is symmetrical, the feasible annual average supply will be equal to the value $\bar{I}$.

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

$$I_t^{feas} = \left\{ \begin{matrix} \bar{I}(1-B) & if\ I_t < \bar{I}(1-B) \\ \bar{I}(1+B) & if\ I_t > \bar{I}(1+B) \\ I_t & if\ I \in [\bar{I}(1-B), \bar{I}(1+B)] \end{matrix} \right\} \tag{22}$$

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

$$FS_t = I_t^{feas} + R_t^{feas} \tag{23}$$

The long-run feasible supply (FS) corresponds to the average over time (N years) in equation (22):

$$FS = I^{feas} + R^{feas} \tag{24}$$

Where,

$$I^{feas} = \frac{1}{N} \sum_{t}^{N} I_t^{feas}$$

$$R^{feas} = \frac{1}{N} \sum_{t}^{N} R_t^{feas}$$

3.3 An extended water exploitation index

We propose a new indicator of economic pressure on water resources, taking into account the total extended demand for groundwater and surface water, and the feasible supply. It basically corresponds to the WEI indicator (net demand and natural supply) but including grey water and considering technical and institutional constraints to the use of water, for this reason we call it Extended Water Exploitation Index (EWEI).

Using equations (5) and (24) the EWEI can be written as:

$$EWEI = \frac{i \sum_{k=1}^{2} \left(\widehat{f_k} - \widehat{r_k} + \widehat{w_k} \right)' \cdot x}{I^{feas} + R^{feas}} \tag{25}$$

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:

$$EWEI = \frac{i^T \sum_{k=1}^{2} \left(\widehat{f_k} - \widehat{r_k} + \widehat{w_k} \right)' (I - A_d)^{-1} y}{I^{feas} + R^{feas}} \tag{26}$$

The other indicators proposed in the literature assume a perfect substitutability between groundwater and groundwater, which is not necessarily true. For this reason, we also define the EWEI separately for groundwater ($EWEI_{gw}$) and surface water ($EWEI_{sw}$):

$$EWEI_{gw} = \frac{i^T \left(\widehat{f_{gw}} - \widehat{r_{gw}} + \widehat{w_{gw}} \right)' (I - A_d)^{-1} y}{I^{feas}} \tag{27}$$

$$EWEI_{sw} = \frac{i^T \left(\widehat{f_{sw}} - \widehat{r_{gw}} + \widehat{w_{gw}} \right)' (I - A_d)^{-1} y}{R^{feas}} \tag{28}$$

4 DATA FOR THE CONSTRUCTION OF THE MODEL

4.1 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 of Economic Planning for 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 criterion 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 by 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[8]. 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[9]). Table 1 reports the value of output for the main groups of agricultural activities in the 10 Tuscan provinces.

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

[9] 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[10].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, 2019). 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[11]. 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

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

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

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)[12]. 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. 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.

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[12] 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 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.

4.2 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.

4.2.1 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.

4.2.2 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

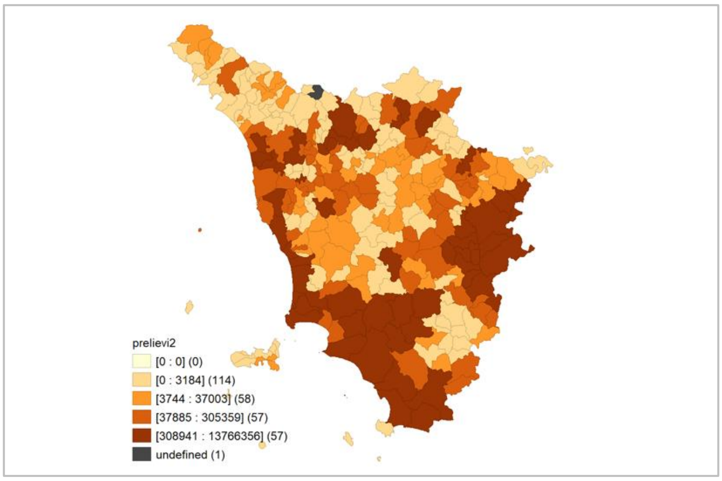
Table 5 presents a summary of the estimated annual average withdrawal by crop groups. Figure 3 shows the geographic distribution (at the municipal level) of withdrawals expressed in absolute value.

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)

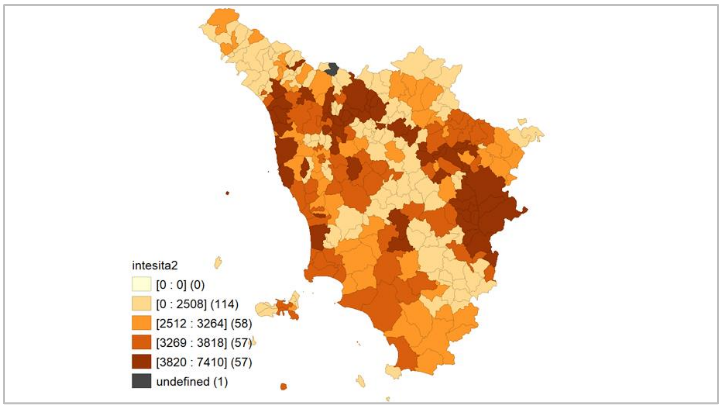


Source. Own elaborations of ARTEA data

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.

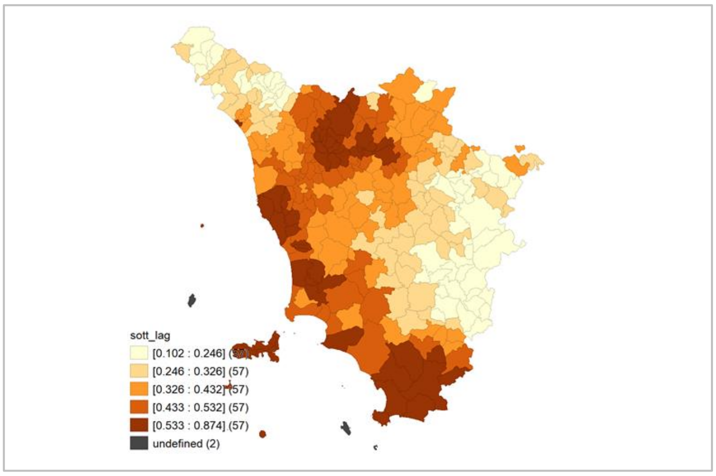
Figure 4. Intensity of irrigation withdrawals in Tuscany (m^3/ha)



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

4.2.3 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

4.2.4 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.

4.3 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[13].

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 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[14] 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[15], while the rest comes from self-supply sources disaggregated

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

14 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.

15 Data provided by the Tuscany region.

according to the same percentages used in water disaggregation for irrigation use.

Table 9. Average annual water withdrawals for livestock rearing
Tuscani, 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.

4.4 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;
- estimation 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%. (ISTAT, 2021)[16].

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%

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[16] 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.

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 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

4.5 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. 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

4.6 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 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 share of different sources in water withdrawals and the water discharge coefficients were calculated using information from the Exiobase[17] 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 withdrawals by industry.

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 hydrological cycle, 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

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

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 elaboration

4.7 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 (Water Resources of Italy, 2020).

A methodology is defined for each macro-sector to properly characterize its discharges.

4.7.1 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.

$$c_a = \frac{c_c \cdot q_c + c_l \cdot q_l}{q_c + q_l} \tag{29}$$

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). For the irrigation use of water, the concentration of discharges (c_c) is considered equal to COD=50mg/l (Water Resources of Italy, 2020).

4.7.2 Manufacture

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

$$c_m = \beta \cdot c_m^T + (1 - \beta) \cdot c_m^U \tag{30}$$

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.

4.7.3 Sewerage

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

$$c_s = \alpha \cdot c_s^T + (1-\alpha) \cdot c_s^U \tag{31}$$

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).

4.7.4 Summary

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	$c_{az} = \dfrac{c_a \cdot q_a + c_z \cdot q_z}{q_a + q_z}$	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

4.8 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.

4.9 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 (ISTAT, 2021) 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 (2021)

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:

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

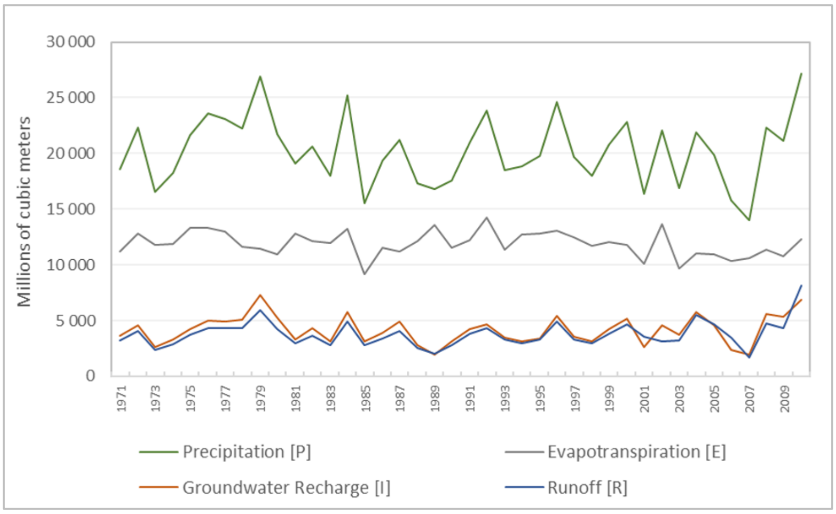
Table 20 shows the mean, standard deviation, coefficient of variation, and skewness for the components of the hydrological cycle in the period 1971-2010, for Tuscany. Figure 6 shows the four components of the hydrological balance for Tuscany for the 1971-2010 period.

Table 20. Statistics of the extended hydrological series for Tuscany (1971-2010)

Year	Precipitation [P]	Evapotranspiration [E]	Groundwater recharge [I]	Runoff [R]
Mean (Mm^3)	20,269	11,892	4,155	3,803
S. Deviation (Mm^3)	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).

4.10 Feasible Supply

The total volume of surface water concessions registered by the Regional Hydrological Service (SIR, 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 (Moccia et al., 2020; Rossi and Caporali, 2021).

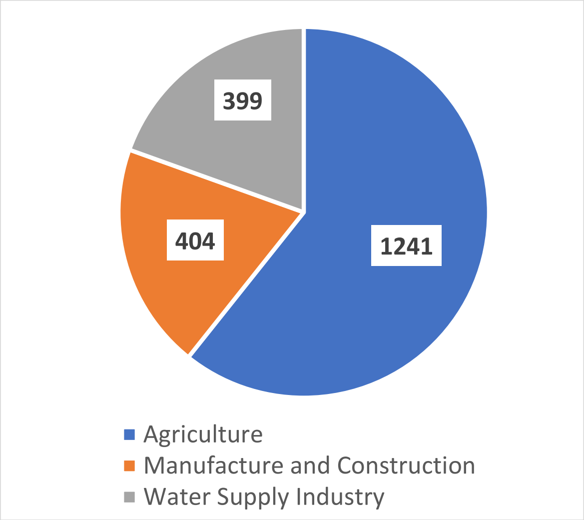
For the groundwater recharge, a value of $B = 13\%$ is considered. This value is calculated as $B = \frac{D-\bar{I}}{\bar{I}} = \frac{4{,}704-4{,}155}{4{,}155} = 13\%$. The maximum value of the concessions is 4,704 Mm^3 while the average annual recharge is 4,155 Mm^3 (SIR, 2021). The total value of groundwater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

5 RESULTS

5.1 Withdrawals and Discharges

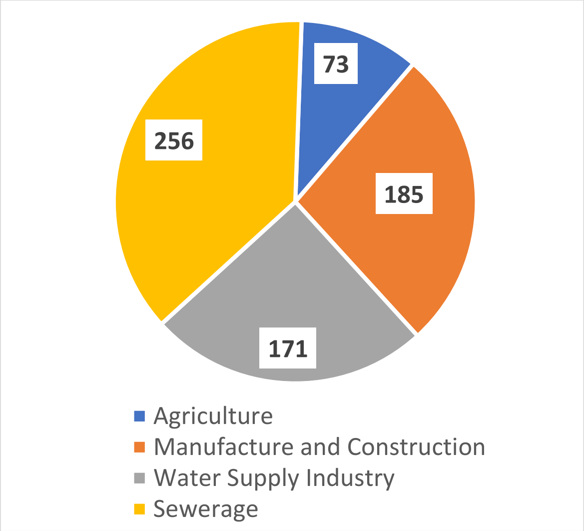
Figure 7 shows the volume of water withdrawals by extractive macro-sectors (direct or "not reclassified" water use); the total volume corresponds to 2,043 Mm^3. Figure 8 shows the volume of direct water discharges associated with the economic macro-sectors; the total volume is 685 Mm^3. Thus, the total net demand corresponds to 1,359 Mm^3 considering all the water sources (groundwater, surface water and hydrological cycle).

Figure 7. Water withdrawals by macro sectors (Mm^3, all water sources)



Source: Own elaboration

Figure 8. Water discharges by macro sectors (Mm^3, all water sources)

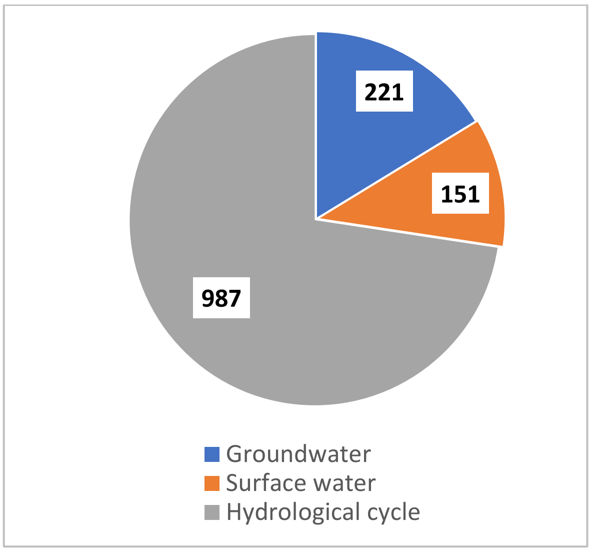


Source: Own elaboration

5.2 Net Water Demand

The total net water demand (withdrawals minus discharges) is distributed among groundwater (221 Mm^3, 16%), surface water (151 Mm^3, 11%) and the hydrological cycle (987 Mm^3, 73%), as shown in Figure 9.

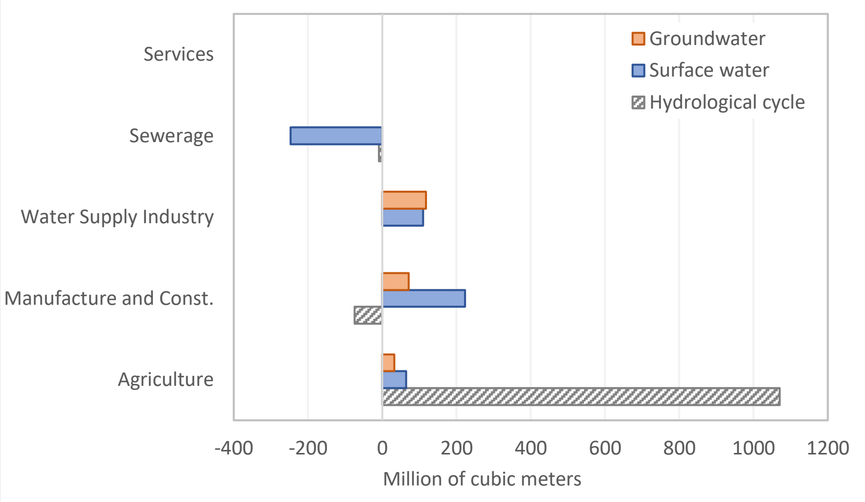
Figure 9. Net water demand by water source (Mm^3, all macro sectors)



Source: Own elaboration

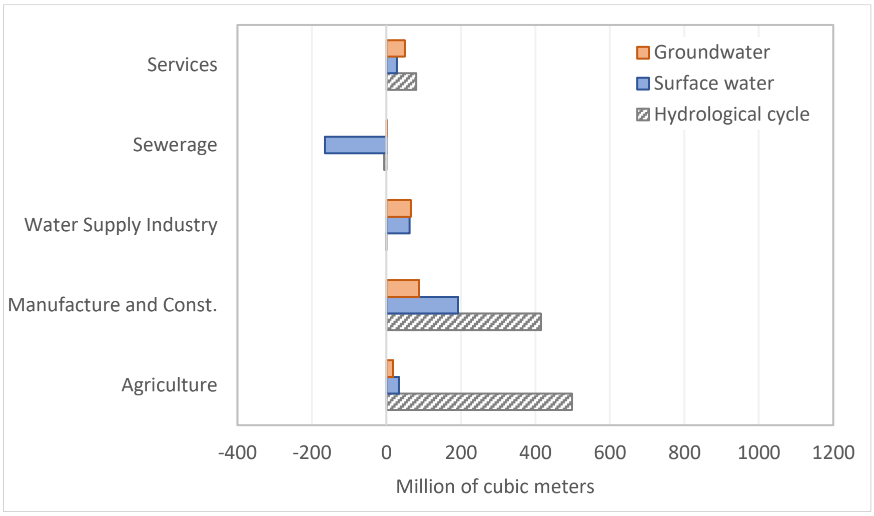
Figure 10 shows the net water demand by extracting macro-sectors and by water source. Figure 11 shows the same results considering the reclassification by demanding sectors. For example, the Service macro sector, which neither directly extract nor discharge water from/to water bodies, accrues for a reclassified net demand of 158 Mm^3, since it purchases both water from the water supply sector and other inputs from the extractive sectors.

Figure 10. Net water demand by macro sectors and water sources (not reclassified).



Source: Own elaboration

Figure 11. Net water demand by macro sectors and water sources (reclassified).

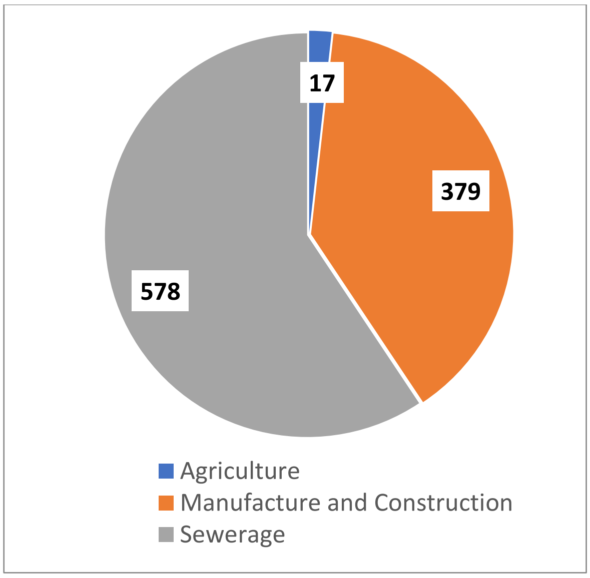


Source: Own elaboration

5.3 Water for dilution

Figure 12 shows the dilution water needs by macro-sector (associated with discharges of contaminated water directly to groundwater and surface water courses). Of the total dilution water demand (974 Mm3), 17 Mm^3 correspond to the agriculture macro-sector (2%), 379 Mm^3 to the Manufacturing and Construction macro-sector (39%) and 578 Mm^3 to the Sewerage macro-sector (59%). The Water Supply Industry macro sector discharges water with standard quality and the services sector discharges all of its contaminated water to the Sewerage macro sector.

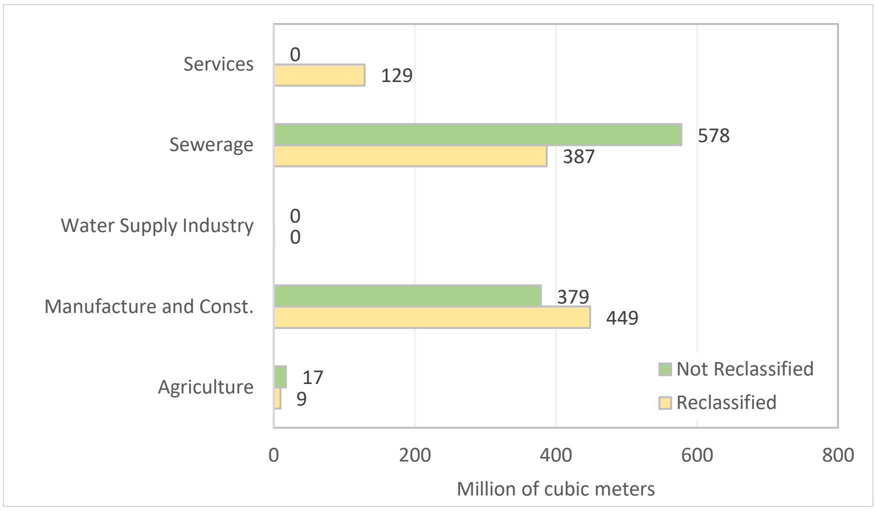
Figure 12. Water for dilution by macro sector (Mm^3, groundwater and surface water sources)



Source: Own elaboration

The demand of water for dilution has been calculated for each economic sector, not only for the whole regional economy as in Guan and Hubacek (2008). This also allows for a reclassification of the productive sectors based on their production, purchases and sales to other sectors. In this way, it is possible to know how much dilution water a sector indirectly demands. Figure 13 shows a comparison between direct and reclassified (or indirect) dilution water requirements by macro sector. The increase in the services sector (zero value in the non-reclassified case and 129 Mm^3 in the reclassified case) is due to the fact that it uses the services of the Sewerage to discharge its water and to the goods it buys from other manufacturing sectors.

Figure 13. Water for dilution by macro sector
(not reclassified and reclassified).

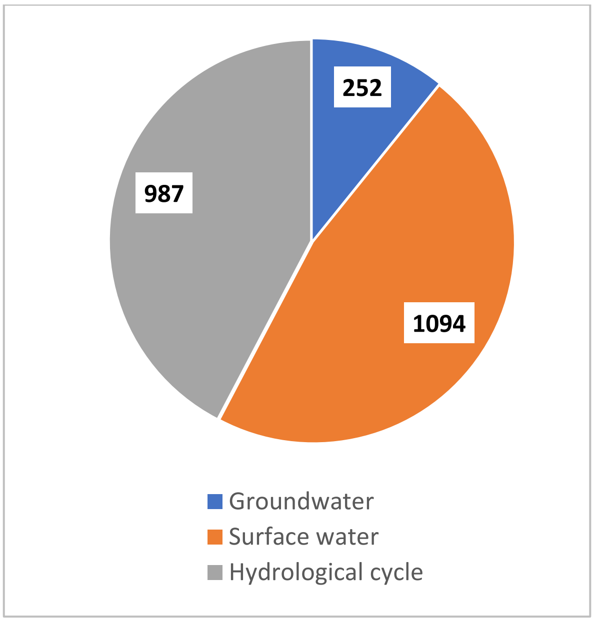


Source: Own elaboration

5.4 Extended Water Demand

The total extended water demand (total net water demand plus total water for dilution), equal to 2,333 Mm^3, is distributed among groundwater (252 Mm^3, 11%), surface water (1,094 Mm3, 47%) and the hydrological cycle (988 Mm^3, 42%), as shown in Figure 14.

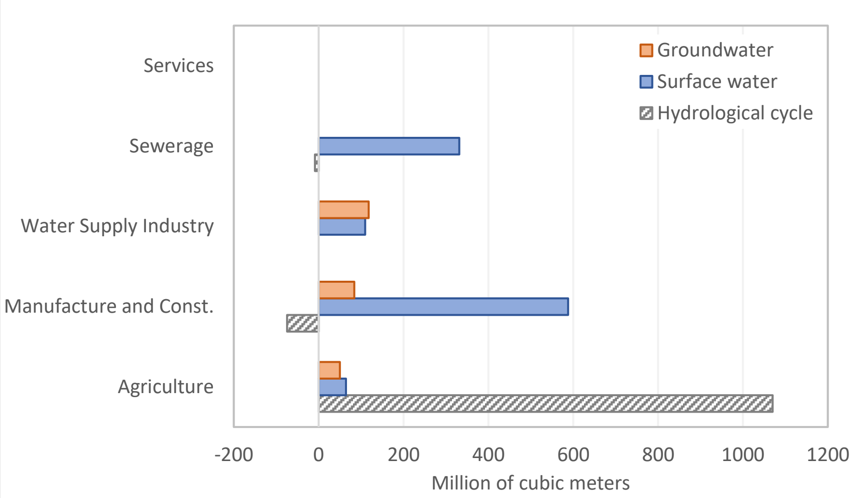
Figure 14. Extended water demand by water source (Mm^3, all macro sectors)



Source: Own elaboration

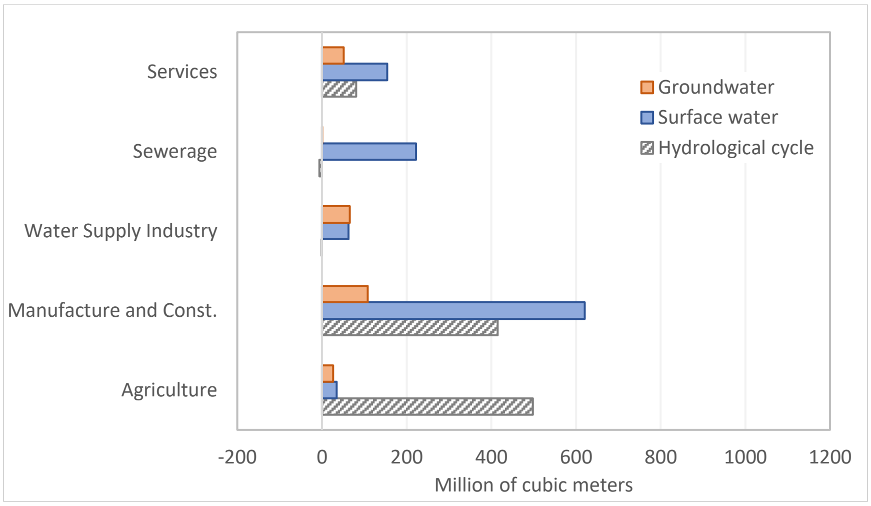
Figure 15 shows the extended water demand by extracting macro-sectors and by water source. Figure 16 shows the same results considering the reclassification by demanding sectors.

Figure 15. Extended water demand by macro sectors and water sources (Mm^3)



Source: Own elaboration

Figure 16. Reclassified extended water demand by macro sectors and water sources (Mm³)



Source: Own elaboration

5.5 Economic pressure on water resources

The total extended demand for water for the reference year (2017) corresponds to 2,333 Mm³. As discussed in section 3, the extended demand of groundwater and surface water and the feasible supply of groundwater and surface water are considered for the calculation of the EWEI.

The extended groundwater-surface water demand corresponds to 1,346 Mm³. The natural supply corresponds to 7,985 Mm³ while the feasible supply amount to 7,030 Mm³. The feasible supply represents about 88% of the natural supply, the reduction is due to the constraints on supply associated with surface waters. The ecological flow corresponds to 761 Mm³.

Table 21 shows the EWEI (proposed in this study) and the standard indicator WEI (considering only net demand), both for the total renewable supply (groundwater plus surface water) and for a single water body.

Table 21. Economic pressure on water resources indicators

Variable	Total	Groundwater	Surface water
Net water demand (Mm³)	372	221	151
Extended water demand (Mm³)	1346	252	1094
Natural supply minus ecological flow (Mm³)	7197	4155	3042
Feasible supply (Mm³)	7030	4155	2875
WEI	**0.052**	**0.053**	**0.050**
EWEI	**0.191**	**0.061**	**0.381**

Source: Own elaboration

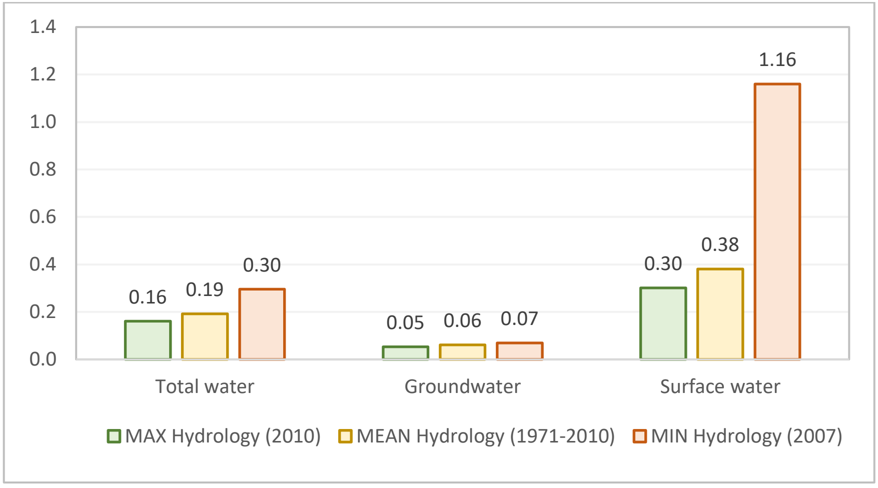
In the reference year the groundwater recharge component of the natural supply was included in the interval assuring the maintenance of the groundwater stock in the long-run. Therefore, the feasible supply of groundwater is equal in the natural and feasible version of the EWEI.

The results show that at the regional level the overall use of water generated by the economy is still compatible with the available water resources, also when natural, technical, and institutional constraints to water use are taken into account. If the thresholds proposed in the literature for these indicators are considered (Raskin et al., 1997; Alamo et. al, 2000; Pfister et al., 2009; CIRCABC, 2012), the WEI is well below the 0.2 limit for severe scarcity. However, when considering the EWEI indicator, the situation in Tuscany is close to moderate scarcity.

As explained in section 3, the denominator of the EWEI ratio depends on the values that the components of the hydrological balance show 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 could have been the pressure on water resources in a year when natural components of the balance showed extreme values, given the structure of the economy observed in the reference year. Figure 17 shows the results of such a sensitivity analysis, comparing the EWEI with feasible supply calculated with reference to a mean hydrological situation and two extreme cases referring to the years with the best (2010) and the worst (2007) hydrological supply in the observed period.

When considering the standard thresholds, it is interesting to note that for a dry year, the EWEI value (0.3) would indicate that Tuscany is in moderate scarcity (0.4 being the limit for *severe* scarcity). The breakdown by water sources shows relevant differences between ground and surface water supply. 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 almost tripling in the case of minimum natural supply observed during the reference period (1.16 vs. 0.38 in the average hydrology scenario). Despite this value of EWEI still implies a safety margin between the extended demand and the feasible supply, it should be considered that the regional average yearly value of the EWEI could hide a wide variability of the hydrological balance at the sub-regional level, with possible critical local situations.

Figure 17. Sensitivity analysis of EWEI indicator
Mean hydrological balance vs. extreme years



Source: Own elaboration

6 CONCLUSIONS

The paper presented a multi-sector, environmentally extended input-output model representing in a detailed way the linkages between the economy and the hydrological system in Tuscany. Water flows between economic activities and the hydrological system (disaggregated by water body) have been quantified both in terms of withdrawals and discharges. Moreover, also the requirements of water necessary to maintain the qualitative balance of the hydrological system have been considered, calculating the demand for water. The proposed accounting framework allowed the use of a wide set of data from different sources to increase the quality of the empirical implementation of the model.

The model can support an in-depth analysis of the water footprint of the regional economy, for example to map the pressures on water resources from specific sectors of production activity to specific water bodies.

The results show that overall, the hydrological system of Tuscany is able to supply the water required by the regional economy. However, looking at such a result, it should be considered that the model represents an annual average scenario aggregated at the regional level. This could hide critical features of the hydro-economic regional system due to different sources of geographic and temporal variability.

First of all, the natural supply of water (and the corresponding hydrological scenario) presents a natural variability showing extreme situations even in absence of any specific climatic trends. A sensitivity analysis based on the natural variability of the regional hydrological balance in Tuscany during the last 40 years showed that the pressures on water resources could change to a relevant extent, mainly in the case of surface waters.

Second, natural variability also applies *within* a single year. Average annual values for the components of the hydrological balance completely hide different situations within each single year in terms of natural and feasible supply of water. A sustainable average pressure on an annual basis could imply critical situations during periods of the year when the natural supply of water is lower.

Third, it has been assumed that agriculture captures a given amount of water for each Euro of output directly from precipitation (green water). This assumption, however, is valid only in years with average or higher hydrology. In case of dry years, agriculture extracts more water from groundwater and surface water sources (mainly for irrigation), increasing the pressure on these resources.

Fourth, both the economy and the hydrological system show extreme geographic variability. The distribution of water intakes for irrigation presented in chapter 4 clearly shows that the pressure on water resources depends on the location of production activities and the distribution of water resources across the regional territory. Critical local situations could be compatible with an overall sustainable balance between net demand and feasible supply of water at the regional level.

Fifth, the indicators of exploitation of water resources, both in the standard (WEI) and in the extended version proposed in this paper, assume for the whole renewable water supply a perfect substitutability between groundwater and surface water. This is not necessarily the case, especially at the regional level where there are strong geographic restrictions on the movement of water resources. It is for this reason that, even considering an average hydrology, the situation in Tuscany is worrying at regional level when considering the requirements for dilution and a feasible supply.

The last consideration supports the modification of the Water Exploitation Index proposed in this study. First of all, the numerator of the WEI+ indicator of pressure on water resources compares two amounts of water (withdrawals and discharges) of different quality. As quality is a factor affecting the potential use of water a correction, as proposed by Guan and Hubacek 2008 and replicated in this study, seems necessary. Furthermore, also the denominator of the standard WEI+ indicator, assuming that the whole natural supply (albeit net of the ecological flow) is available, contributes to an underestimation of pressures, as several technical and institutional constraints are likely to limit the availability of water for economic uses. In this study we propose a measure of the *feasible* supply taking into account these constraints. The comparison between the standard WEI+ and the EWEI measure of pressures shows that also at the aggregate, regional level, these corrections could change the assessment of water scarcity in Tuscany (up to a moderate scarcity situation.

The issues discussed above also suggest the direction for further refinement of the model. Both inter and intra-annual variability of the hydrological balance could be included in the model. This extension of the model could allow not only to associate to average results a measure of their potential variability, but also to simulate the impact of climate change scenarios. The change in the composition of water sources used by agriculture, which is endogenous to hydrology, should be properly modeled; the same should be for the total requirements for irrigation, which depend on evapotranspiration (temperatures).

Finally, the breakdown of the model at the sub-regional level could allow better assessment of the geographic distribution of impacts on water resources and the possible existence of local unsustainable situations also within an overall sustainable regional scenario.

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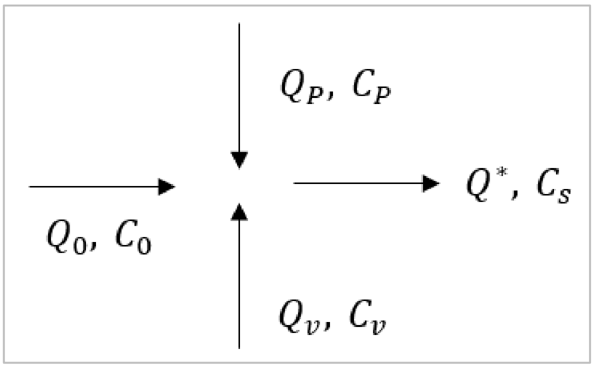
8 APPENDICES

8.1 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 elaboration

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:

$$Q_0\,C_0 + Q_p\,C_p + Q_v\,C_v = Q\,C_s + Q_v\,C_s \tag{A.1}$$

where,

$$Q = Q_0 + Q_p \tag{A.2}$$

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:

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

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

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

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:

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

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 the available water in the water body is equal to the dilution water requirement $(Q_0 = 0)$

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

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

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 is consistent with 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.

8.2 Appendix B

Table B.1. Not Reclassified Net Water Demand (ND) and Not Reclassified Extended Water Demand (ED) for 56 economic sector.

Sector	Macro-sector	Not Reclassified Net Water Demand (ND)			Not Reclassified Extended Water Demand (ED)		
		Groundwater	Surface water	Hydro Cycle	Groundwater	Surface water	Hydro Cycle
Arable land	Agriculture	12.2	23.2	405.0	18.4	23.2	405.0
Horticulture	Agriculture	3.3	2.6	67.6	4.3	2.6	67.6
Permanent crops	Agriculture	3.6	8.5	138.9	5.7	8.5	138.9
Grazing livestock	Agriculture	1.4	2.5	37.8	2.2	2.5	37.8
Granivores	Agriculture	0.1	0.9	9.1	0.3	0.9	9.1
Mixed crops farms	Agriculture	4.1	10.6	169.0	6.7	10.6	169.0
Mixed livestock farms	Agriculture	2.1	3.8	62.9	3.1	3.8	62.9
Mixed crops-livestock farms	Agriculture	5.9	12.3	179.9	9.3	12.3	179.9
Forestry and use of forest areas	Agriculture	0.0	0.0	0.0	0.0	0.0	0.0
Fishing	Agriculture	0.0	0.0	0.0	0.0	0.0	0.0
Mining and quarrying	Manufacturing	0.0	0.0	0.0	13.4	0.0	0.0
Food products and beverages	Manufacturing	16.3	-4.0	-0.1	16.3	11.7	-0.1
Textiles	Manufacturing	0.0	56.3	-0.7	0.0	127.8	-0.7
Wearing apparel	Manufacturing	0.0	2.7	0.0	0.0	6.1	0.0
Leather and related goods	Manufacturing	0.0	12.9	-0.2	0.0	29.3	-0.2
Footwear	Manufacturing	0.0	0.2	0.0	0.0	0.5	0.0
Wood and wood products	Manufacturing	0.0	1.6	0.0	0.0	3.6	0.0
Paper Printing and rec. media	Manufacturing	0.0	26.8	-0.3	0.0	58.0	-0.3
Coke and refined petroleum products	Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0
Chemical and chemical products	Manufacturing	27.6	16.1	-0.2	27.6	34.8	-0.2
Pharmaceutical products	Manufacturing	0.0	14.8	-0.1	0.0	21.2	-0.1
Rubber and plastic products	Manufacturing	0.0	3.0	-0.7	0.0	73.8	-0.7
Other non-metallic products	Manufacturing	0.0	3.4	-0.7	0.0	82.4	-0.7
Manufacture of basic metals	Manufacturing	0.0	4.3	0.0	0.0	9.7	0.0
Metal products	Manufacturing	0.0	7.6	-0.1	0.0	17.3	-0.1
Computers, electronic and optical equipment	Manufacturing	0.7	2.3	0.0	0.7	5.2	0.0
Electrical equipment	Manufacturing	0.8	3.0	0.0	0.8	6.8	0.0
Machinery and equipment n.e.c.	Manufacturing	9.6	0.1	0.0	9.6	2.0	0.0
Motor vehicles and other transportation means	Manufacturing	11.0	0.8	-0.2	11.0	20.4	-0.2
Furniture	Manufacturing	0.7	0.0	0.0	0.7	0.9	0.0
Jewelry	Manufacturing	0.1	0.0	0.0	0.1	0.2	0.0
Other manufacturing	Manufacturing	4.0	0.2	0.0	4.0	5.6	0.0
Repair and installation of equipment and systems	Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0
Electricity power generation	Manufacturing	0.0	70.8	-70.8	0.0	70.8	-70.8
Electricity Transmission and Distribution	Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0
Gas Steam Air conditioning	Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0
Water supply	Water Supply	117.9	110.0	0.0	117.9	110.0	0.0

Sector	Macro-sector	Not Reclassified Net Water Demand (ND)			Not Reclassified Extended Water Demand (ED)		
		Groundwater	Surface water	Hydro Cycle	Groundwater	Surface water	Hydro Cycle
Sewerage	Sewerage	0.0	-246.6	-8.9	0.0	331.4	-8.9
Waste management	Manufacturing	0.0	0.0	0.0	0.0	0.0	0.0
Construction	Construction	0.0	0.0	0.0	0.0	0.0	0.0
Wholesale and retail trade, repair of motor vehicle	Services	0.0	0.0	0.0	0.0	0.0	0.0
Transportation and storage	Services	0.0	0.0	0.0	0.0	0.0	0.0
Accommodation and food services	Services	0.0	0.0	0.0	0.0	0.0	0.0
Publishing, audiovisual, radio and television production	Services	0.0	0.0	0.0	0.0	0.0	0.0
Telecommunications	Services	0.0	0.0	0.0	0.0	0.0	0.0
IT and other information services	Services	0.0	0.0	0.0	0.0	0.0	0.0
Financial and insurance activities	Services	0.0	0.0	0.0	0.0	0.0	0.0
Real estate activities	Services	0.0	0.0	0.0	0.0	0.0	0.0
Professional and technical activities	Services	0.0	0.0	0.0	0.0	0.0	0.0
Scientific research and development	Services	0.0	0.0	0.0	0.0	0.0	0.0
Other service activities	Services	0.0	0.0	0.0	0.0	0.0	0.0
Public administration and defense; compulsory social security	Services	0.0	0.0	0.0	0.0	0.0	0.0
Education	Services	0.0	0.0	0.0	0.0	0.0	0.0
Health and social work activities	Services	0.0	0.0	0.0	0.0	0.0	0.0
Arts, entertainment, and recreation	Services	0.0	0.0	0.0	0.0	0.0	0.0
Other service activities	Services	0.0	0.0	0.0	0.0	0.0	0.0

Table B.2. Reclassified Net Water Demand (RND) and Reclassified Extended Water Demand (RED) for 56 economic sector.

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

Sector	Macro-sector	Reclassified Net Water Demand (RND)			Reclassified Extended Water Demand (RED)		
		Groundwater	Surface water	Hydro Cycle	Groundwater	Surface water	Hydro Cycle
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
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