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

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

Keywords: input-output, extended water demand, feasible water supply, extended water exploitation index, Tuscany.
JEL Codes: C67, Q25, Q50.

1. INTRODUCTION

Input-output (IO) models have been widely used to quantify the direct and indirect water consumed by industries in order to satisfy the final demand (Velazquez, 2006; Guan and Hubacek 2008; Lenzen et al., 2013; Ridoutt et al., 2018). A typical use of input-output models extended to water

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resources is for structural analysis. A wide literature has been developed in the last years on the concept of water-energy-food (WEF) nexus, aiming at studying the structural interdependencies among human needs, production activities and natural resources and the related social, technological and environmental constraints (White et al., 2018; Xiao et al., 2019; Deng et al., 2020; Lee et al 2021; Meng et al., 2017). A further field of application of environmentally extended IO models is the analysis of virtual water flows among countries and the quantification of the water footprint at the regional, national and global scale (Feng et al., 2011; Duarte et al, 2016; Arto et al, 2016; Sturla et al 2023 and 2024; Wang et al., 2021).

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

In a paper on North China, Guan and Hubacek (2008) use an IO model to determine an "extended" demand of water, defined as the net demand (including blue and green water) plus the water required for pollutants dilution (grey water). Grey water is estimated based on a mixing model developed by Xie (1996), using the chemical oxygen demand (COD) as an indicator of pollution. Grey water requirements (and, as a consequence, the extended demand), however, is quantified only for the whole economy. Furthermore, in modeling the interactions between the economy and the natural hydrological system, these authors do not quantify any indicator of economic *pressure* over water resources.

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

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

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

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

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

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

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

2. THE HYDRO-ECONOMIC MODEL

2.1. Hydro-economic water flows

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

The economic system withdraws water from underground and surface sources (blue water) and from rain and soil moisture (green water). After productive uses,

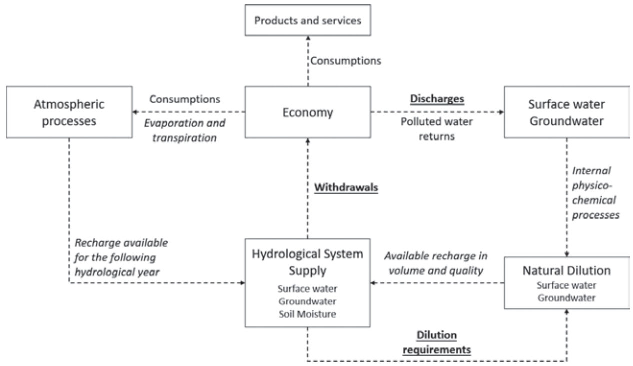

Figure 1. Scheme of the hydro-economic input-output model. Source: Own elaborations.

water can be divided into: i) water discharged to surface and groundwater, ii) water incorporated in products and consumed in services, iii) water consumptions by evaporation and transpiration into the atmosphere, and iv) water removed from the immediate water environment (Kenny et al., 2019; Macknick et al., 2012).

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

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

2.2. Input-output hydro-economic model

We consider an economic system with n productive sectors (industries) and a water system with m water

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

sources (or water bodies) to build an environmentally extended IO model (Miller and Blair, 2009).

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

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

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*.
r_k be the $(n \times 1)$ vector of the unit water discharge coefficients (m^3/€) of industries to the water body *k*.
w_k be the $(n \times 1)$ vector of the unit water for dilution requirement coefficients (m^3/€) of industries for the water body *k*.

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

$$e_k = (\widehat{f_k} - \widehat{r_k} + \widehat{w_k})\,(I - A_d)^{-1}y,\; k = 1,\ldots,m \quad (2)$$

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 $(n \times m)$ matrix *ED* representing the extended water demand of the *n* productive sectors from the *m* bodies of water:

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

where the $(n \times m)$ 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 $(m \times 1)$ vector *TED*:

$$TED = (F - R + W)'x \quad (4)$$

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

2.3. Water requirements for dilution

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

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

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

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

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

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

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

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

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

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

where:
k_{1_k}: total reaction rate of pollutants after entering the water body k;
k_{2_k}: pollution purification rate before entering the water body k;
$q_{p_{kj}}$: discharges into the water body k associated with industry j;
$c_{p_{kj}}$: COD concentration in the discharges to the water body k associated with economic sector j;
c_{s_k}: standard COD concentration in water body k;
c_{0_k}: COD concentration in water body k.

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

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

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

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

2.4. Reclassification by demanding sectors

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

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

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

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

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

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

$$s_k = (\widehat{f_k} - \widehat{r_k} + \widehat{w_k})\ A_d x \qquad (8)$$

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

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

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

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

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

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

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

3. AN INDICATOR OF ECONOMIC PRESSURE ON WATER RESOURCES

3.1. Water supply

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

3.2. Natural supply

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

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

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

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

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

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

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

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

3.3. Feasible supply

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

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

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

- the maximum amount of surface water extraction is defined by the sum of the maximum withdrawals allowed by current concessions; the assumption we make here is that the concessions have been efficiently awarded, considering all technical and hydrological aspects;
- the surface water supply is considered to be limited by a minimum "ecological" flow, as a constraint to environmental sustainability;
- the maximum concessions levy is defined as $M\bar{R}$, where M is a factor not necessarily less than 1 and $\bar{R}$ is the average annual runoff;
- the minimum ecological flow is defined as $E\bar{R}$, where $E \in (0,1)$;
- the "feasible" annual average runoff is strictly lower than the $\bar{R}$ value.

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

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

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

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

- the sum of the groundwater concessions (D) is the feasible upper supply limit;
- the difference between the sum of the concessions and the average annual recharge (D - $\bar{I}$), defines a share B by which the average recharge can be increased to calculate the feasible supply ($B = \frac{D-I}{\bar{I}}$) where $B \in (0,1)$ and I is the average annual recharge;
- the feasible groundwater supply (that can be drawn in one year) will be in the range $[\bar{I}(1 - B), \bar{I}(1 + B)]$; Summing up the value of I_t^{feas} is:

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

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

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

$$FS_t = I_t^{feas} + R_t^{feas}$$

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

$$FS = I_t^{feas} + R_t^{feas} = \frac{1}{N}\sum_t^N I_t^{feas} + \frac{1}{N}\sum_t^N R_t^{feas}$$

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

3.4. An extended water exploitation index

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

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

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

where i is a $(1 \times n)$ vector of ones, which allows summing the extended water demand associated with each economic sector. The sum considers groundwater and surface water, k={1,2}.

Considering equation (1) the EWEI can be expressed in terms of the final demand:

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

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

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

4. CASE STUDY

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

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

4.1. The input-output table of Tuscany.

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

4.2. Water withdrawals and discharge coefficients

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

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

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

For the estimation of the water withdrawal and discharge coefficients in the water supply industry, the information on water billed in the region for the year 2016 was used. Secondary data published by ISTAT (2019b) were used to disaggregate water withdrawals between ground and surface sources. The discharges correspond to water losses in the distribution network; we assumed that all of these losses are discharged to groundwater, constitute groundwater recharge and are not contaminated.

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

Water requirements for manufacture activities have

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

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

4.3. Quality of discharged water and mixing model

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

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

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

4.4. Hydrological Balance and natural supply

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

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

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

5. RESULTS

5.1. Withdrawals and Discharges

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

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

Figure 4 shows the net demand reclassified by demanding macro-sectors and divided by water source. Services, for example, which neither directly extract nor discharge water from/to water bodies, account for a

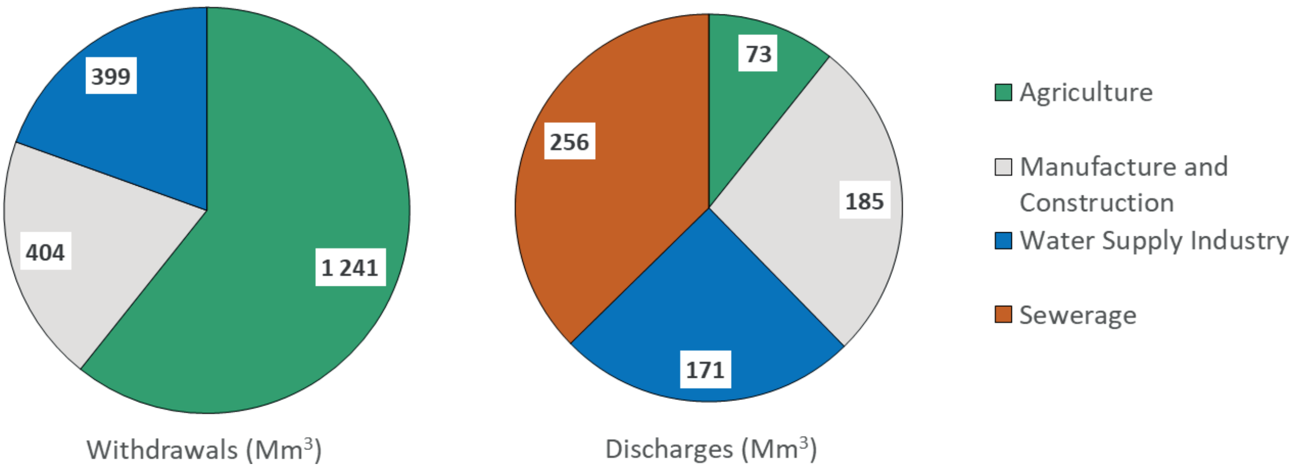

Figure 2. Water withdrawals and discharges by macro sector. Tuscany, 2017 - mm³. Source: Own elaborations.

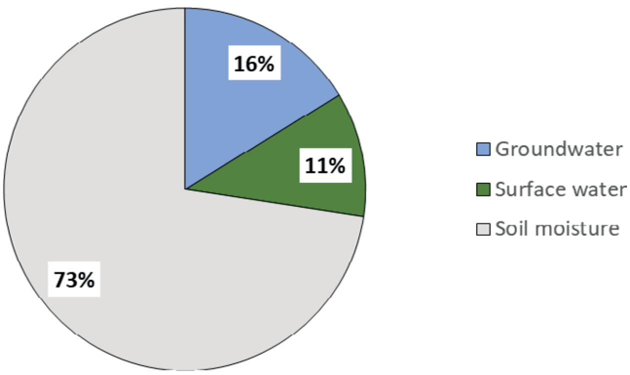

Figure 3. Net water demand by water source. Tuscany, 2017 - mm³. Source: Own elaborations.

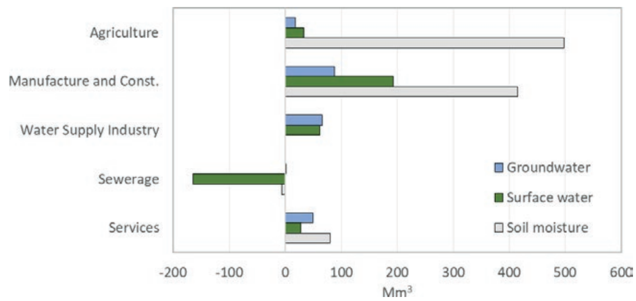

Figure 4. Net water demand by demanding macro sector and by water source. Tuscany 2017 - mm³. Source: Own elaborations.

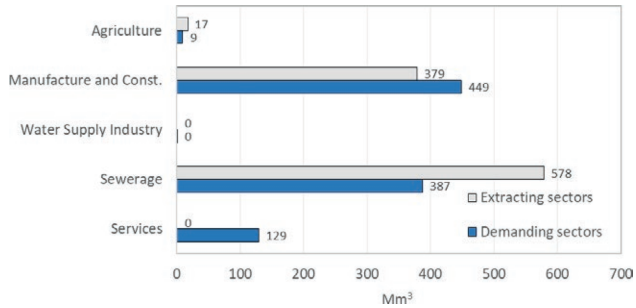

Figure 5. Water for dilution by extracting and demanding macro sector. Tuscany 2017 - mm³. Source: Own elaborations.

reclassified net demand of 158 mm³, since they purchase both water (from the water supply sector) and other inputs from extracting sectors. The component of the net demand supplied by the soil moisture is now distributed among different production activities, with manufacturing "indirectly" using a relevant share of green water.

5.2. Water for dilution and extended demand

Different from Guan and Hubacek (2008) the demand of water for dilution has been calculated for each industry separately. Of the total demand of grey water (974 mm³), 17 mm³ accrue to Agriculture (2%), 379 mm³ to Manufacturing and Constructions (39%) and 578 mm³ to the Sewerage sector (59%). The Water Supply industry discharges water with standard quality while Services discharges water through the Sewerage network.

The breakdown of grey water by industry allows for its reclassification by demanding sector. Figure 5 compares direct and reclassified water requirements for dilution by macro-sector. Services increase from zero to 129 mm³ in the reclassified case, accounting for a share of grey water requirements of Sewerage services and of other industries from which it purchases inputs. Also Man-

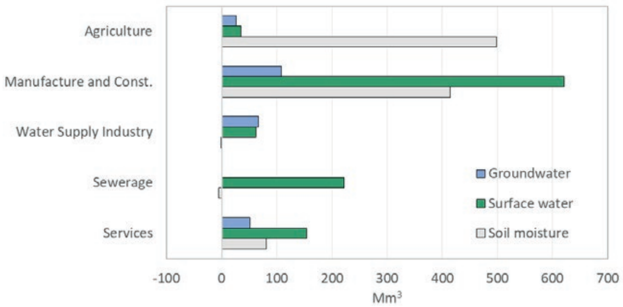

Figure 6. Extended water demand by demanding macro sector and by water source. Tuscany 2017 - mm³. Source: Own elaborations.

Table 1. Economic pressure of the economy on water resources. Tuscany, 2017 – mm³ and pressure indicators.

	Total	Ground-water	Surface water
Net water demand (mm³)	372	221	151
Extended water demand (mm³)	1 346	252	1 094
Natural supply minus ecological flow (mm³)	7 197	4 155	3 042
Feasible supply (mm³)	7 030	4 155	2 875
WEI+	0.052	0.053	0.05
EWEI	0.191	0.061	0.381

Source: Own elaborations.

ufacturing increases its demand for grey water (from 379 to 449 mm³).

Grey water is a major component of water demand of Tuscany. The total *extended* water demand (total net demand plus total water for dilution), is equal to 2,333 mm³ (+72% compared to the net demand). A prominent role is now played by surface bodies (1,094 mm³) that supply 47% of water. Groundwater (252 mm³) and soil moisture (988 mm³) supply the extended demand for 11% and 42% respectively.

Figure 6 shows the extended water demand classified by demanding sectors and water body. Manufacturing is the main user of water resources, accounting for 1,144 over 2,333 mm³ (49%) of the extended demand, mostly relying (54%) on surface bodies.

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

5.3. Economic pressure on water resources

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

Table 1 provides some summary results for Tuscany. The regional extended demand is equal to 1,346 mm³. The natural supply corresponds to 7,958 mm³. The ecological flow corresponds to 761 mm³. The feasible supply amounts to 7,030 mm³, about 88% of the natural supply; the reduction is due to the constraints on supply associated with surface waters.

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

In the reference year of the analysis (2017) the groundwater recharge component was included in the interval assuring the maintenance of the groundwater stock in the long-run. Therefore, the feasible supply of groundwater is equal to the natural supply. In the case of surface water, constraints in water exploitation reduce to 2,875 mm³ the "feasible" supply (compared to 3,042 of natural supply). The results show that at the regional level the overall use of water generated by the economy is still compatible with the available resources, also when natural, technical, and institutional constraints to water use are taken into account. When the thresholds proposed in the literature for these indicators are considered (Raskin et al., 1997; Alcamo et. al, 2000; Pfister et al., 2009; CIRCABC, 2012), the WEI+ is well below the 20% limit. However, when considering the EWEI indicator, the situation in Tuscany appears to be close to a moderate scarcity.

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

When considering the standard thresholds, it is interesting to note that in a dry year, the EWEI value

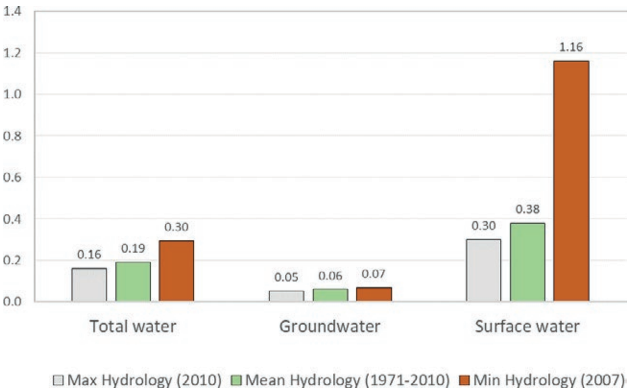

Figure 7. Sensitivity analysis of EWEI indicator. Mean hydrological balance vs. extreme years. Source: Own elaborations.

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

6. DISCUSSION

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

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

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

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

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

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

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

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

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

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

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

7. CONCLUSIONS

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

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

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

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

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

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