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# INCORPORATING HYDROLOGICAL VARIABILITY INTO A HYDRO-ECONOMIC INPUT-OUTPUT MODEL. AN APPLICATION TO TUSCANY

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**Abstract**

The recent work of Rocchi and Sturla (2021) estimates the economic pressure on water resources in Tuscany using an input-output (IO) model with an average hydrology. The present work considers the inter-annual hydrologic variability, which has an effect on both the supply and demand of water and, therefore, on the extended water exploitation index (EWEI). A multivariate hydrological model is built to generate synthetical annul series of precipitation, evapotranspiration, runoff and groundwater recharge. The interaction between hydrology and the economy generates two endogenous effects in the model: i) changes in water withdrawals and discharges coefficients in the agricultural industry due to variations in precipitation and evapotranspiration, and ii) changes in water requirements for dilution coefficients in all discharging industries due to variations in runoff and groundwater recharge. Based on Monte Carlo simulations, the inter-annual variability of the extended demand and the feasible supply of water are calculated for the Tuscan economy. The cumulative probability distribution of the EWEI indicator is confronted to the scarcity thresholds proposed in the literature. A methodology to incorporate the intra-annual variation of both the extended demand and the feasible supply is also proposed, obtaining the probability distribution of the EWEI for the critical month, as a more accurate indicator of water scarcity.

**Key Words.** Input-output, hydrological variability, agriculture, water quality, Montecarlo simulations, water exploitation, Tuscany.

**JEL Classification.** C67**,** Q25, Q50

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**Summary**

## 1 INTRODUCTION

Economic activities use water resources directly by the extraction of the resource from water bodies and indirectly as virtual water embodied in the purchases of intermediate goods (Allan, 1993). The pressure of the economic system on water resources is a fundamental issue in the challenges for the sustainable use of water (European Environmental Agency, 2021), asking for modeling pressures as the effect of the economic system on the water balance, i.e., the relationship between economic demand and hydrological supply of water.

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 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 work of Guan and Hubacek (2008) use an input-output model to determine the extended demand of water, defined as the withdrawals minus restitutions plus the water required for pollutants dilution (grey water), for Northern 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. Rocchi and Sturla (2021) use the extended demand approach incorporating improvements and extensions to the Guan and Hubacek (2008) model and developing a pressure indicator based on the feasible water supply, the Extended Water Exploitation Index (EWEI). Different from previous indicators EWEI accounts for dilution requirements and technical and institutional constraints to water supply (European Environmental Agency, 2005, 2020; Faergemann, 2012; OECD, 2015). The model is applied to Tuscany, Italy. Both studies, however, consider hydrology deterministically (average hydrology, fixed use coefficients, fixed water body COD concentrations, etc.)

Although some studies evaluate the pressure on water resources considering the water supply for a dry, average and wet year (Rocchi and Sturla, 2021) or considering a climate change average hydrology (Garcia-Hernandez and Brouwer, 2021), so far there are no studies that integrate an extended IO model with hydrological variability, representing it direct effects on water availability and it indirect/endogenous effects on water demand.

Integrating economic and hydrological models taking into account the hydrological structure in a more realistic way, has been recognized in literature as a necessary development of studies on the exploitation of water resources. Including the hydrologic structure in hydro-economic models has made significant advances in assessing the impacts of water policy instruments (Exposito et al., 2020). The development of hydro-economics models suitable to represent in a proper way the variability of the hydrological system, considering also technical and institutional aspects, may provide better management options and economic values (Julien et al., 2009). Combining economic management concepts and performance indicators with an improved level of understanding of a hydrological system can provide results and knowledge more directly relevant to water management decisions and policies (Heinz et al., 2007).

Hydrological variability and uncertainties are essential for understanding phenomena related to productive water use (Hemri et al., 2005; Todini, 2011). The variability of hydrological processes can be incorporated into economic models through stochastic multivariate approaches for the generation of synthetic series of the main hydrological components, such as precipitation and runoff, showing an important spatial-temporal correlation (Yevjevieh, 1987). Zhang (2018) and Ercolani and Castelli (2018), recommend the Monte Carlo methodology for the analysis of water flows variability and their impacts on human and environmental systems.

In this study we integrate a multivariate stochastic hydrologic model with an environmentally extended input-output model. The hydro-economic model is based on the development of Rocchi and Sturla (2021), i.e., considering the extended demand approach (using a mixing model for dilution requirements) and a "feasible" measure of supply to calculate the EWEI indicator

The hydrological model allows us to obtain synthetic series of precipitation, evapotranspiration, runoff and groundwater recharge. The hydrological variability generates two endogenous effects in the hydro economic model: i) changes in water withdrawals and discharges coefficients in the agricultural sector, due to variations in precipitation and evapotranspiration, and ii) changes in water requirements for dilution coefficients in all discharging industries, due to variations in runoff and groundwater recharge.

Agriculture uses green water (precipitation and soil moisture) and blue water (groundwater and surface water). For dry hydrological years agriculture has to extract more blue water to replace the missing green water. Moreover, when evapotranspiration is higher (lower), more (less) blue water will be required for irrigation. The hydrological model allows to know the variations in precipitation (proxy for green water availably) and evapotranspiration (proxy for blue water requirements). With the economic IO model, it is possible to estimate the volumes of water that will be required to a greater or lesser extent from groundwater and surface water. As a result of this endogenous process, the coefficients of water withdrawal and discharge in the agricultural sector change according to the natural hydrological variability, generating a corresponding variability in the extended demand.

The calculation of water required for dilution depends on the concentration of COD in the receiving bodies, as runoff and groundwater recharge vary, thus changing the volume required to restore the water quality. The mixing model integrated in the proposed hydro-economic model, considers the water discharges estimated with the IO model, generating a change in the extended demand of all discharging sectors. In the case of agriculture, a second order endogenous effect is generated, i.e., precipitation and evapotranspiration (and the IO model) generate a change in the discharge, which is used to re-calculate the grey water with the mixing model.

By means of Monte Carlo simulations, the proposed model allows estimating the extended demand and the feasible supply for *n* hydrological years, i.e., the economic structure is confronted with various hydrological types of year, compatible with a given climate scenario. Thus, it is possible to obtain a probability distribution of the indicator of economic pressure on water resources, the EWEI. This novel analysis by means of an input-output model provides a more realistic representation of the hydro-economic system, considering the interannual hydrological variability.

A further development of the proposed model considers also intra annual hydrological variability to estimate the EWEI for the critical month, i.e., the month in which the ratio of extended demand to feasible supply is highest. The proposed methodology considers the disaggregation of the extended demand between agriculture and the other production activities to account for the intra-annual variability of demand for irrigation, and of the intra-annual variability of feasible supply due to the variation of surface runoff.

The joint incorporation of interannual and intra-annual variability allows a better characterization of the levels of pressure/exploitation on water resources, thus better approximating the definition of critical thresholds for the proposed exploitation indicator. The thresholds proposed in literature usually consider the annual average hydrology and are not specific to each hydro-economic situation. This is the case of thresholds, defined for the demand/supply indicators, of 20% for moderate scarcity and 40% for severe scarcity (Raskin et al., 1997; Alamo et. al, 2000, Pfister et al., 2009). In any case, the stochastic EWEI can be compared with these values, determining how many times they are exceeded. In addition, it is interesting to compare the EWEI with the Water Exploitation Index in its version that measures the ratio between net demand and natural supply net of the ecological flow ($WEI^{+}$: Faergemann, 2012; European Environmental Agency, 2020).

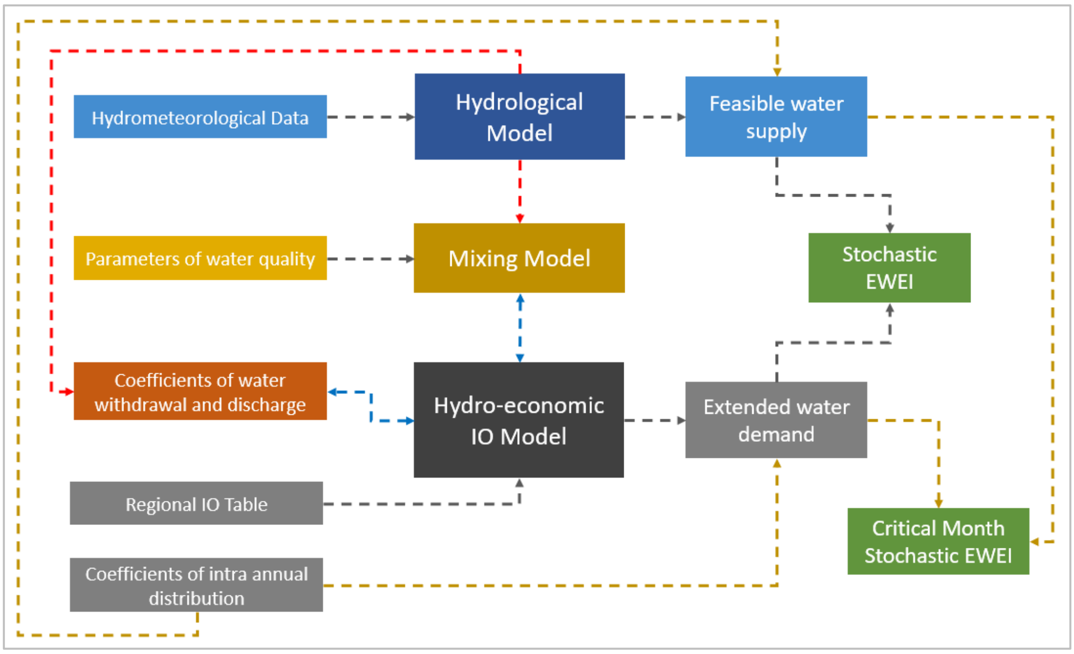
The model is applied to the Tuscany region in Italy, which presents an important interannual hydrological variability (Crisci, et al., 2002; Fatichi and Caporali, 2009; D'Oria, et al., 2017, 2018). The input-output matrix, water use coefficients (average hydrology) and water quality parameters used in the study by Rocchi and Sturla (2021) are considered. The study by Rocchi and Sturla (2021) found a value of 0.19 for the EWEI for the mean hydrology. In the present work the variability of this indicator is analyzed considering

100 years of hydrology and its effects on feasible supply and extended water demand previously discussed.

In section 2, a multivariate normal hydrological model is built to generate synthetic series of precipitation, evapotranspiration, surface runoff and groundwater recharge. Section 3 presents the input-output hydro-economic model with hydrological variability, considering the methodology to recalculate the water withdrawal and discharge coefficients in the agricultural sector due to variability of precipitation and evapotranspiration, the inclusion of the dependence of COD concentration on surface runoff and groundwater recharge in the mixing model, and the methodology to account for intra-annual variability (critical month). Section 4 presents the main results of the study, the probability distribution of the extended demand by industry, the reclassification of the extended demand by demanding industries, the changes in the composition of agricultural water bodies, the probability distribution of the EWEI indicator and the results for the critical month. Finally, the discussion in Section 5, highlights the contribution of this work to the understanding of hydro-economic dynamics in Tuscany.

Figure 1 provides a schematic of the hydro-economic model with hydrological variability developed in this study. The red arrows represent the effects of hydrologic variability transmitted to the extended demand (through water withdrawal and discharge coefficients and COD concentration in water bodies). The blue arrows represent two-way effects, primarily due to the need to re-estimate agricultural water use coefficients in the IO model and the volume required for dilution in all discharging sectors through the mixing model. The yellow arrows represent the links (ex post endogenous effects) for the estimation of the EWEI in the critical month.

Figure 1. Scheme of the IO model with hydrological variability.




Source: Own elaboration

# 2 HYDROLOGICAL MODEL

## 2.1 Hydrological time series

Rocchi and Sturla (2021) generates a series for the water balance in Tuscany (Braca et al., 2021, 2022) with the components: precipitation (P), evapotranspiration (E), groundwater recharge (I), and runoff (R). This series contains 40 years, and its statistics are presented in Table 1.

Table 1. Statistics of the hydrological series of Tuscany (1971-2010)

| Statistics | P | E | I | R |
|---|---|---|---|---|
| Mean ($Mm^3$) | 20,269 | 11,892 | 4,155 | 3,802 |
| S. Deviation ($Mm^3$) | 3,084 | 1,129 | 1,258 | 1,157 |
| C. Variation | 15% | 9% | 30% | 30% |
| Skewness | 0.2 | -0.2 | 0.4 | 1.3 |

Source: Own elaboration base on Rocchi y Sturla (2021).

These series have been analyzed to evaluate their normality and linear independence; this in order to build a model that allows to generate synthetic hydrological series in Tuscany[3].

The test used for normality is the Jarque-Bera test (Hamilton, 2010), in which the null hypothesis that the distribution is normal for each of the 4 series is rejected. Regarding linear independence, the Ljung-Box autocorrelation test is used (Hamilton, 2010), where the null hypothesis of linear independence of the series is not rejected in any of them. The main results are shown in Table 2 and Table3.

Table 2. Normality Test to hydrological series

| Parameter | P | E | I | R |
|---|---|---|---|---|
| JB Statistic | 0.63 | 0.33 | 0.94 | 8.33 |
| p-value | 0.66 | 0.83 | 0.53 | 0.79 |
| H0 (Normality) | Not rejected | Not rejected | Not rejected | Not rejected |

Source: Own elaboration

Table 3. Autocorrelation Test to hydrological series

| Parameter | P | E | I | R |
|---|---|---|---|---|
| LB Statistic | 0.02 | 0.06 | 1.30 | 0.78 |
| p-value | 0.88 | 0.81 | 0.25 | 0.37 |
| H0 (Independence) | Not rejected | Not rejected | Not rejected | Not rejected |

Source: Own elaboration

[3] The value of runoff in 2010 is an anomalous figure within the series, excessively high. As this datum does not correspond to the precipitation of the same year, it has not been considered in the normality and independence analysis.

According to these results, the hydrological series can be considered independent and identically distributed, which is usual in annual series, while the temporal structure of autocorrelation in climates such as Tuscany is appreciated on a monthly or daily scale (Te Chow, 2010).

## 2.2 Multivariate model

The hydrological series for Tuscany come from a normal distribution and do not present a linear autocorrelation structure. It is then possible to represent them by means of a multivariate normal model, through which values can be generated for *n* years, that is, synthetic series longer than the 40-year recording period.

The vector $\vec{X}$ represents all the components of the hydrological balance, $\vec{\mu}$ the mean and $\Sigma$ the matrix of variances and covariances. The multivariate model collects the relationship between the different components.

$$\vec{X} = (\vec{P}, \vec{E}, \vec{I}, \vec{R})$$

$$\vec{X} \sim \mathcal{N}_4(\vec{\mu}, \Sigma)$$

Based on hydrological statistics we have the vector of sample averages. The variance and covariance matrix is presented in Table 4.

$$\vec{\mu} = (20{,}269\ ;\ 11{,}892\ ;\ \ 4{,}155\ ;\ 3{,}802)$$

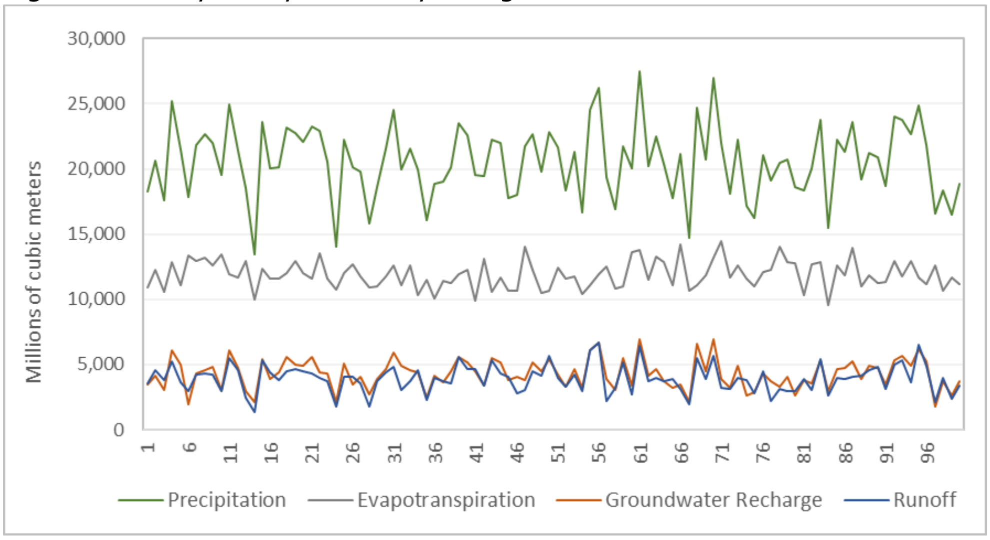
Table 4. Variance and covariance matrix in ($Mm^3$)

| Var-Cov | P | E | I | R |
|---|---|---|---|---|
| P | 9,513,099 | 1,709,308 | 3,603,712 | 3,058,521 |
| E | 1,709,308 | 1,274,309 | 230,111 | 127,168 |
| I | 3,603,712 | 230,111 | 1,581,925 | 1,313,728 |
| R | 3,058,521 | 127,168 | 1,313,728 | 1,337,715 |

Source: Own elaboration

In this way, a model is available that allows the generation of synthetic hydrological series for Tuscany. The simulation for 100 years that is used in the input-output model of this study is presented in Figure 3. Table 5 presents the statistics of the 100-year series, where it can be seen that the model replicates the structure of the historical series quite well, especially the coefficient of variation where differences of more than 10% are not detected.

Figure 3. 100-year Synthetic hydrological series




Source: Own elaboration

Table 5. Statistics of the 100-year Synthetic hydrological series

| Statistics | P | E | I | R |
|---|---|---|---|---|
| Mean ($Mm^3$) | 20,269 | 11,892 | 4,155 | 3,802 |
| S. Deviation ($Mm^3$) | 2,766 | 1,068 | 1,140 | 1,075 |
| C. Variation | 13% | 9% | 27% | 27% |
| Skewness | -0.1 | 0.2 | 0.1 | 0.1 |

Source: Own elaboration

# 3 INPUT-OUTPUT MODEL WITH HYDROLOGICAL VARIABILITY

## 3.1 Input-output model, extended demand and EWEI indicator

This section presents the formulation of the extended demand in the IO model and the EWEI indicator develop by Rocchi and Sturla (2021), and a general approach to model the changes in the extended water demand when considering hydrological variability which will be detailed and formalized in the following sections.

### *3.1.1 Extended demand*

Let $A_d$ the *(n x n)* matrix of technical coefficients that represents the structure of intermediate consumptions per unit of output of production activities, calculated from the domestic flows input-output table (*n*=56 industries in this study). The total production of the *n* industries can be calculated from the following equation (Miller and Blair, 2008):

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

where $x$ is the (*n x 1*) vector of gross output of the industries, $y$ is the (*n* x *1*) vector of the final demand and $I$ is the (*n* x *n*) unit matrix.

The extended water demand (*n* x *1*) vector $e_k$ from the water body *k* (disaggregated by industry) is defined considering the environmentally extended approach for input-output models (Miller and Blair, 2008):

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

where $f_k$, $r_k$ and $w_k$ represent the (*n* x *1*) water use coefficient vectors (in $m^3/€$) of withdrawal, discharge and dilution requirements, from water body *k* (groundwater, surface water and hydrological cycle). The hat symbol indicates the diagonalization of the vector.

The reclassified water extended demand (*n* x *1*) vector $\tilde{e}_k$ from the water body *k,* represents the extended water demand by demanding sectors. This reclassified demand is computed substracting the *virtual sales of water* to other sectors and adding the *virtual purchases of water* to other sectors[4].

$$\tilde{e}_k = \left(\widehat{f_k} - \widehat{r_k} + \widehat{w}_k\right)(x - A_d x) + \hat{x} A'_d (f_k - r_k + w_k) \tag{3}$$

### *3.1.2 EWEI indicator*

The extended water exploitation index (EWEI) is defined as the ratio between the water extended water demand and feasible water supply for a year *t*.

[4] A detailed analysis of the reclassification can be found in Rocchi and Sturla (2021).

Feasible supply takes into account environmental, technical and institutional constrains to the use of water (Sturla and Rocchi, 2021).

$$EWEI_t = \frac{\sum_{k=1}^{2}(f_k - r_k + w_k)' \cdot (I - A_d)^{-1} y}{I_t^{feas} + R_t^{feas}} \tag{4}$$

where the sum considers groundwater and surface water, $k = \{1,2\}$. $I^{feas}$ and $R^{feas}$ represent the groundwater and surface water feasible supply, respectively.

$$I_t^{feas} = \begin{cases} \bar{I}(1-B) & if \;\; I_t < \bar{I}(1-B) \\ \bar{I}(1+B) & if \;\; I_t > \bar{I}(1+B) \\ I_t & if \;\; I \in [\bar{I}(1-B), \bar{I}(1+B)] \end{cases} \tag{5}$$

$$R_t^{feas} = \begin{cases} R_t - E\bar{R} & if \;\; E\bar{R} < R_t < M\bar{R} + E\bar{R} \\ M\bar{R} & if \;\; R_t > M\bar{R} + E\bar{R} \\ 0 & if \;\; R_t < E\bar{R} \end{cases} \tag{6}$$

where,

| | |
|---|---|
| $I_t$ | : Groundwater recharge volume in year t (multivariate model) |
| $\bar{I}$ | : Groundwater recharge mean volume |
| $B$ | : Parameter defining the range of groundwater feasible availability |
| $R_t$ | : Runoff volume in year t (multivariate model) |
| $\bar{R}$ | : Runoff mean volume |
| $E$ | : Ecological flow as proportion of mean runoff |
| $M$ | : Maximum volume of concessions as proportion of mean runoff |

Rocchi and Sturla (2021) use this indicator to define the economic pressure on water resources for an average hydrology, carrying out a sensitivity analysis for a dry and a wet year, but considering deterministic water use coefficients (i.e., a constant extended water demand). In this work we incorporate a time-varying component in the water use coefficients (hydrological dependence), thus considering the variability both of the extended water demand and the feasible water supply.

### *3.1.3 Extended demand and EWEI with hydrological variability*

When hydrologic variability is considered, the water use coefficients change according to the components of the hydrologic cycle. Let us first define the extended demand associated with water body *k*, industry *i* in the year *t:*

$$e_{k,i,t} = (f_{k,i,t} - r_{k,i,t} + w_{k,i,t}) \cdot x_i \tag{7}$$

For simplicity of notation, we use $x_i$ , which in the Leontief model represents the *i* component of the $(I - A_d)^{-1}y$ vector. It is not within the scope of this study to simulate variations in final demand; however, with the model it is possible to evaluate the response of the economic system to final demand exogenous shocks.

Withdrawal coefficients will change for agricultural sectors, due to changes in precipitation and evapotranspiration (obtained from the hydrological model), which implies higher or lower withdrawals from surface and groundwater bodies. Discharge coefficients also change with hydrological variability, due to the fact that a variation in water withdrawals modifies the irrigation losses volume (assumed as a fixed proportion of withdrawals). The dilution requirement coefficients will also change for all industries that discharges polluted water, depending on runoff and groundwater recharge, which define the concentration of pollutant in the receiving bodies (i.e., the water quality of the dilution water). The latter coefficients depend indirectly on precipitation and evapotranspiration, due to their estimation as a function of discharge volume.

A general scheme for extended water demand dependence in hydrology is defined (that will be detailed in next sections). Equations (7), (8) and (9) present the water use coefficients, each of which can be written as a function of its deterministic value (Rocchi and Sturla, 2021) plus the time-varying term ($\mathcal{F}_{k,i,t}$, $\mathcal{R}_{k,i,t}$, $\mathcal{H}_{k,i,t}$) which depends on hydrological variability.

$$f_{k,i,t} = f_{k,i} + \mathcal{F}_{k,i,t}(P_t, E_t) \tag{7}$$

$$r_{k,i,t} = r_{k,i} + \mathcal{R}_{k,i,t}(P_t, E_t) \tag{8}$$

$$w_{k,i,t} = w_{k,i} + \mathcal{H}_{k,i,t}[I_t, R_t, \mathcal{R}_{k,i,t}(P_t, E_t)] \tag{9}$$

Using equations (6) to (9) it is possible to write the water extended demand associated with water body *k*, industry *i* and year *t*.

$$e_{k,i,t} = e_{k,i} + \left[\mathcal{F}_{k,i,t}(P_t, E_t) + \mathcal{R}_{k,i,t}(P_t, E_t) + \mathcal{H}_{k,i,t}[I_t, R_t, \mathcal{R}_{k,i}(P_t, E_t)]\right] \cdot x_i \tag{10}$$

Note that $\mathcal{F}_{k,i,t}(P_t, E_t) = 0$ and $\mathcal{R}_{k,i,t}(P_t, E_t) = 0$ for non-agricultural sectors, and $\mathcal{H}_{k,i,t}\left[I_t, R_t, \mathcal{R}_{k,i,t}(P_t, E_t)\right] = 0$ for non-discharging sectors.

By summing the extended groundwater and surface water demand for all industries, it is possible to express the EWEI indicator for a hydrological year $t$:

$$EWEI_t = \frac{\sum_{i=1}^{N} \sum_{k=1}^{2} e_{k,i,t}}{I_t^{feas} + R_t^{feas}} \tag{11}$$

The EWEI also can be defined separately for groundwater $EWEI_t^{gw}$ and surface water $EWEI_t^{sw}$ :

$$EWEI_t^{gw} = \frac{\sum_{i=1}^{N} e_{gw,i,t}}{R_t^{feas}} \tag{12}$$

$$EWEI_t^{sw} = \frac{\sum_{i=1}^{N} e_{sw,i,t}}{I_t^{feas}} \tag{13}$$

The following sections detail the methodology for estimating the time-varying terms of the water use coefficients, for the case of agriculture withdrawals and discharges, and water requirements for dilution.

Note that the reclassified water extended demand of equation (3) can also be calculated with the hydrological variability effects, considering the time-varying terms of the water use coefficients.

## 3.2 Variability of agricultural water demand

An important part of the water used by agriculture corresponds to green water, that is, water obtained directly from soil moisture, which is strongly dependent on rainfall (Te Chow, 2010). In this study we consider that this type of water come from hydrological cycle (previously defined), and each agricultural sub-sector has a withdrawal coefficient for this type of water. In the absence of regional soil moisture (long period) time series, we assume the variability of precipitation as a proxy for the variability of water captured directly from the hydrologic cycle by agriculture. Another reason to consider the variability of precipitation is the fact that a regional aggregate value of soil moisture is not representative of the actual availability of green water for the agricultural sector (Braca et al., 2021, 2022), i.e., it is not reasonable to confront agriculture green water requirements with the total regional soil moisture content, since not all areas are used for agriculture. A consequence of using an aggregated estimate of soil moisture at the regional level would be that a green water deficit would be never detected for agriculture , which is a much stronger and unrealistic assumption than using precipitation to determine the variability of effective green water use.

Since the withdrawal coefficients are representative of an average hydrology, we consider that when precipitation is less than average (less availability of green water), the agricultural industry must withdraw more groundwater and surface water to make up for this deficit and maintain the level of agricultural production for the reference economic year. The total green water deficit is considered, i.e., the deficit associated with irrigated and non-irrigated agriculture. Specifically, we consider that the withdrawals from the hydrological cycle is reduced in a proportion given by the quotient between the respective year's precipitation and the average annual precipitation.

Regarding blue water, the groundwater and surface water withdrawals of irrigated agriculture depends on climatic conditions such as temperature and radiation, and these requirements are well represented by evapotranspiration, which is correlated with water requirements by crops (Te Chow, 2010). The deterministic water withdrawal coefficients are representative of an average hydrological year (Rocchi and Sturla, 2021), however, these coefficients should be higher or lower depending on the specific conditions of each hydrological year (the time-varying term of the stochastic withdrawals coefficients). Given that a regional evapotranspiration series is available, we consider that the irrigation water withdrawals (groundwater and surface water) change due to annual evapotranspiration variations. These changes due to evapotranspiration correspond exclusively to irrigation requirements.

We assume that when evapotranspiration in a year is higher (lower) than the average annual evapotranspiration, irrigation water withdrawals will increase (decrease). The proportion in which these requirements increase or decrease will be given by the quotient between the respective year's evapotranspiration and the mean annual evapotranspiration.

Note that the situations described above can occur together or separately; this will depend on the particular conditions of each year. The annual evapotranspiration series is not significantly correlated with the annual rainfall series. Therefore, it is possible that in years with a rainfall higher than the average, additional water will be needed for irrigation as a result of higher evapotranspiration. Similarly, for years with low rainfall and low evapotranspiration, water withdrawals will decrease due to evapotranspiration, but increase due to lack of rainfall.

It is important to clarify that the proposed methodology corresponds to an approximation, taking into account the information available at the regional level for an extended period of time.

Since the agricultural sectors contain both crops and livestock activities (zootechnics), the crop component is considered for the hydrological variability effects. The withdrawal and discharge deterministic coefficients of the agricultural sectors can be broken down into the part requiring irrigation (irrigated crops and non-irrigated but potentially irrigated crops) and the part associated with livestock:

$$f_{k,i} = f_{k,i}^{irr} + f_{k,i}^{liv} \tag{14}$$

$$r_{k,i} = r_{k,i}^{irr} + r_{k,i}^{liv} \tag{15}$$

In this section, subscript *i* refers only to crop production activities.

The following subsections details the methodology used to modify the water withdrawal and discharge coefficients for a year, depending on the need to substitute green water with blue water (modeled using precipitation variability) and the variability of blue water requirements in irrigated agriculture (modeled using evapotranspiration variability).

### *3.2.1 Substitution of green water with blue water*

Let define $\mathcal{E}_t$ as the ratio of the precipitation in year $t$ $(P_t)$ to the average precipitation $(\bar{P})$:

$$\mathcal{E}_t \equiv \frac{P_t}{\overline{P}} \tag{16}$$

Let define $T_{i,t}^{P}$ as the additional groundwater and surface water withdrawals by the agricultural sector $i$, in year $t$, due to changes in precipitation. Then,

$$T_{i,t}^{P} = \begin{cases} (1-\mathcal{E}_t)\cdot f_{hc,i}^{irr}\cdot x_i\cdot\gamma & if\ \ \mathcal{E}_t < 1 \\ 0 & if\ \ \mathcal{E}_t \geq 1 \end{cases} \tag{17}$$

where,

$$\gamma = \frac{1}{1-\rho} \tag{18}$$

The parameter $\rho$ corresponds to the losses associated with the irrigation process. When irrigation is used to supply crops requirements, an additional water withdrawal due to irrigation inefficiency must be considered.

The term $f_{hc,i}^{irr}\cdot x_i$ corresponds to the water withdrawals from hydrological cycle for the average year (deterministic case).

To disaggregate the need for additional irrigation between groundwater and surface water, consider the following parameters:

$\delta_i$: proportion of groundwater irrigation of sector *i*

$\eta_i$: proportion of surface water irrigation of sector *i*

where,

$$\delta_i = \frac{f_{gw,i}^{irr}}{f_{gw,i}^{irr} + f_{sw,i}^{irr}} \tag{19}$$

$$\eta_i = \frac{f_{sw,i}^{irr}}{f_{gw,i}^{irr} + f_{sw,i}^{irr}} \tag{20}$$

Then, $T_{i,gw,t}^{P}$ and $T_{i,sw,t}^{P}$ correspond to the increase in the withdrawals of groundwater and surface water in sector $i$ for year $t$, respectively, to make up for the deficit of green water:

$$T_{i,gw,t}^{P} = \begin{cases} \delta_i\cdot\ (1-\mathcal{E}_t)\cdot\ f_{hc,i}^{irr}\cdot x_i\cdot\gamma & if\ \ \mathcal{E}_t < 1 \\ 0 & if\ \ \mathcal{E}_t \geq 1 \end{cases} \tag{21}$$

$$T_{i,sw,t}^{P} = \begin{cases} \eta_i\cdot\ (1-\mathcal{E}_t)\cdot\ f_{hc,i}^{irr}\cdot x_i\cdot\gamma & if\ \ \mathcal{E}_t < 1 \\ 0 & if\ \ \mathcal{E}_t \geq 1 \end{cases} \tag{22}$$

### 3.2.2 Change in blue water irrigation requirements

Let define $\theta_t$ as the ratio of the evapotranspiration in year $t$ $(E_t)$ to the average evapotranspiration $(\bar{E})$:

$$\theta_t \equiv \frac{E_t}{\bar{E}} \tag{23}$$

The change in the use of groundwater and surface water by agriculture due to interannual changes in evapotranspiration is defined as:

$$T_{i,t}^{E} = (\theta_t - 1) \cdot \left(f_{gw,i}^{irr} \cdot x_i + f_{sw,i}^{irr} \cdot x_i\right) \tag{24}$$

The terms $f_{gw,i}^{irr} \cdot x_i$ and $f_{sw,i}^{irr} \cdot x_i$ corresponds to the water withdrawals from groundwater and surface water for the deterministic case.

The additional withdrawals of groundwater and surface water is written as:

$$T_{i,gw,t}^{E} = \delta_i \cdot (\theta_t - 1) \cdot f_{gw,i}^{irr} \cdot x_i \tag{25}$$

$$T_{i,sw,t}^{E} = \eta_i \cdot (\theta_t - 1) \cdot f_{sw,i}^{irr} \cdot x_i \tag{26}$$

$T_{i,gw,t}^{E}$ and $T_{i,sw,t}^{E}$ correspond to the increase (decrease) in the withdrawals of groundwater and surface water in sector *i* for year *t*, due to the eventual increase (decrease) in blue water irrigation requirements.

### 3.2.3 Coefficients with hydrological variability

Adding the effect of precipitation (equations (21) and (22)) and evapotranspiration (equations (25) and (26)), and dividing by $x_i$, yields the stochastic component of the withdrawal coefficient for groundwater and surface water in agricultural sectors:

$$\mathcal{F}_{gw,i,t}(P_t, E_t) = \begin{cases} \delta_i \left[\left(\frac{\bar{P} - P_t}{\bar{P}}\right) \cdot f_{hc,i}^{irr} \cdot \gamma + \left(\frac{E_t - \bar{E}}{\bar{E}}\right) \cdot f_{gw,i}^{irr}\right] & if\ \mathcal{E}_t < 1 \\ \delta_i \left[\left(\frac{E_t - \bar{E}}{\bar{E}}\right) \cdot f_{gw,i}^{irr}\right] & if\ \mathcal{E}_t \geq 1 \end{cases} \tag{27}$$

$$\mathcal{F}_{sw,i,t}(P_t, E_t) = \begin{cases} \eta_i \left[\left(\frac{\bar{P} - P_t}{\bar{P}}\right) \cdot f_{hc,i}^{irr} \cdot \gamma + \left(\frac{E_t - \bar{E}}{\bar{E}}\right) \cdot f_{sw,i}^{irr}\right] & if\ \mathcal{E}_t < 1 \\ \eta_i \left[\left(\frac{E_t - \bar{E}}{\bar{E}}\right) \cdot f_{sw,i}^{irr}\right] & if\ \mathcal{E}_t \geq 1 \end{cases} \tag{28}$$

For the withdrawal coefficient associated with the hydrologic cycle, its stochastic component (negative) is:

$$\mathcal{F}_{hc,i,t}(P_t) = \begin{cases} \left(\dfrac{P_t - \bar{P}}{\bar{P}}\right) \cdot f_{hc,i}^{irr} & if\ \ \mathcal{E}_t < 1 \\ 0 & if\ \mathcal{E}_t \geq 1 \end{cases} \tag{29}$$

In this work we assume that discharges from the agricultural sector are entirely directed to groundwater. Considering $\alpha_i$ as the proportion of the discharged water with respect to the groundwater and surface water withdrawals for the agricultural sector *i*, it is obtained that the additional discharges due to hydrologic variability are:

$$\mathcal{R}_{gw,i,t}(P_t, E_t) = [\mathcal{F}_{gw,i,t}(P_t, E_t) + \mathcal{F}_{sw,i,t}(P_t, E_t)] \cdot \alpha_i \tag{30}$$

$$\mathcal{R}_{sw,i,t}(P_t, E_t) = 0 \tag{31}$$

where,

$$\alpha_i = \frac{r_{gw,i}^{irr}}{f_{gw,i}^{irr} + f_{sw,i}^{irr}} \tag{32}$$

Since hydrologic variability influences only the withdrawal and discharge coefficients of the agricultural sectors, the above equations are sufficient to characterize equations (7) and (8) of the input-output model.

Note that parameters $(\delta_i, \eta_i, \alpha_{i},)$ are all defined based on the average hydrological condition, that is, for the deterministic situation. It is assumed an irrigation losses in groundwater and surface water equal to $\rho = 30\%$, obtaining $\gamma = 1.42$ for all crops.

## 3.3 Variability of water demand for dilution

The deterministic coefficient $w_{k,i}$ of equation (9) is calculated by Rocchi and Sturla (2021) with a mixing model base on a mass balance of COD concentration with intermediate chemical reaction, improving a previous versions (Xie, 1996; Guan and Hubacek, 2008).

The $w_{k,i,t}$ term of equation (9), in this study, is calculated based on the same model, but considering time dependence and two endogenous effects:

- Discharges volumes from the agricultural sector depend on precipitation $(P_t)$ and evapotranspiration $(E_t)$, as discussed in the preceding section.
- The COD concentration in receiving water bodies depends on groundwater recharge $(I_t)$ and runoff $(R_t)$.

The coefficients of water requirements for dilution by water body *k* and industry *i* for the year *t*, is expressed as:

$$w_{k,i,t} = \frac{u_{k,i,t}}{x_i} \quad (33)$$

where, $u_{k,i,t}$ ($m^3$/year) is the water for dilution, which is calculated with the following mixing model:

$$u_{k,i,t} = \left[\frac{k_{2_k} \cdot c_{p_{k,i}} - c_{s_{k,t}}}{k_{1_k} \cdot c_{s_{k,t}} - c_{0_{k,t}}}\right] \cdot r_{k,i,t} \cdot x_i \quad (34)$$

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* |
| $r_{k,i,t} \cdot x_i$ | : | discharges into the water body *k* associated with industry *i* for year t |
| $c_{p_{k,i}}$ | : | COD concentration in the discharges to the water body *k* associated with industry *i* |
| $c_{s_{k,t}}$ | : | Standard COD concentration in water body *k* for year *t* |
| $c_{0_{k,t}}$ | : | COD concentration in water body *k* for year t |

Note that $r_{k,i,t} = r_{k,i} + \mathcal{R}_{k,i,t}(P_t, E_t)$ (equation (8)) is completely defined by the hydrological variability in the agricultural sectors. This is the first endogenous component.

Note also that $u_{k,i,t}$ is linearly dependent in the output $x_i$, and from equations (33) and (34) we can write $w_{k,i,t}$ as:

$$w_{k,i,t} = \left[\frac{k_{2_k} \cdot c_{p_{k,i}} - c_{s_{k,t}}}{k_{1_k} \cdot c_{s_{k,t}} - c_{0_{k,t}}}\right] \cdot r_{k,i,t} \quad (35)$$

The second endogenous component corresponds to $c_{0_{k,t}}$, the COD concentration in the water bodies. We propose an expression for this term that takes into account decreases in COD concentration due to wetter hydrology and increases in COD concentration due to drier hydrology; this is based on the fact that the discharge of organic matter (whose indicator used is COD) depends on the economic system, which, in the case of this work, is considered constant, or more generally, its variability is much smaller than the hydrologic variability.

The third endogenous component is $c_{s_{k,t}}$. When the concentration in the water bodies ($c_{0_{k,t}}$) is higher than the standard concentration in average conditions ($c_{s_k}$), the standard concentration for the year *t* ($c_{s_{k,t}}$) is considered to be that of the water body, since in the model the water for dilution come from the hydrological system. Then:

$$c_{s_{k,t}} = \begin{cases} c_{s_k} & if \quad c_{0_{k,t}} \leq c_{s_k} \\ c_{0_{k,t}} & if \quad c_{0_{k,t}} > c_{s_k} \end{cases} \tag{36}$$

To characterize $c_{0_{k,t}}$, we define the variable $\pi_{k,t}$ , based on the hydrological model, like the ratio between the supply volume in year $t$ and the mean supply volume, given by the hydrological model, for groundwater and surface water:

$$\pi_{gw,t} \equiv \frac{I_t}{\bar{I}} \tag{37}$$

$$\pi_{sw,t} \equiv \frac{R_t}{\bar{R}} \tag{38}$$

Let define the following parameters:

| | | |
|---|---|---|
| $c_{0_k}^{min}$ | : | Minimum concentration in water body *k* |
| $c_{0_k}^{max}$ | : | Maximum concentration in water body *k* |
| $c_{0_k}^{mean}$ | : | Mean concentration in water body *k* |
| $\pi_k^{min}$ | : | Ratio of minimum volume to average volume in water body *k* |
| $\pi_k^{max}$ | : | Ratio of maximum volume to average volume in water body *k* |
| $\pi_k^{mean}$ | : | Equal to 1 by definition |

A linear model is assumed to represent the relationship between the concentration in water bodies before discharge and hydrology (both surface and groundwater). The following linear relation is considered for $c_{0_{k,t}} \in (c_{0_k}^{min}, c_{0_k}^{max})$:

$$c_{0_{k,t}} = a \cdot \pi_{k,t} + b \tag{39}$$

where,

$$a = \frac{c_{0_k}^{max} - c_{0_k}^{min}}{\pi_k^{min} - \pi_k^{max}}$$

$$b = c_{0_k}^{mean} - a$$

For concentrations below the minimum and above the maximum, the ratio of the maximum concentration to the runoff or recharge level indicator (hydrology) is considered constant. Thus, the linear function is defined as follows:

$$c_{0_{k,t}} = \begin{cases} c_{0_k}^{min} & if \quad \pi_{k,t} \leq \pi_k^{min} \\ a \cdot \pi_{k,t} + b & if \quad \pi_k^{min} < \pi_{k,t} < \pi_k^{max} \\ c_{0_k}^{max} & if \quad \pi_{k,t} \geq \pi_k^{max} \end{cases} \tag{40}$$

With equations (36) and (40), the term $w_{k,i,t}$ expressed in equation (35) is characterized. Thus, the additional water for dilution with hydrological variability can be calculated as the difference between the time-varying model coefficient and deterministic model coefficient:

$$\mathcal{H}_{k,i,t}\left[I_t, R_t, \mathcal{R}_{k,i}(P_t, E_t)\right] = \left[\frac{k_{2_k} \cdot c_{p_{k,i}} - c_{s_{k,t}}}{k_{1_k} \cdot c_{s_{k,t}} - c_{0_{k,t}}}\right] \cdot r_{k,i,t} - w_{k,i} \tag{41}$$

With this last equation, the input-output model with hydrologic variability is fully determined, including endogenous changes in the water use coefficients, due to the natural hydrologic variability calculated by the multivariate model.

The following values for the model parameters of COD concentration and runoff/recharge ratios are considered in this study:

| | | |
|---|---|---|
| $c_{s_k}$ | = | 20 mg/l |
| $c_{0_k}^{min}$ | = | 15 mg/l |
| $c_{0_k}^{max}$ | = | 25 mg/l |
| $c_{0_k}^{mean}$ | = | 20 mg/l |
| $\pi_k^{min}$ | = | 0.5 |
| $\pi_k^{max}$ | = | 1.5 |
| $\pi_k^{mean}$ | = | 1.0 |

## 3.4 Critical Month

Up to this point, the EWEI has been proposed on the basis of the extended water demand and annual feasible supply of water, for groundwater and surface water. The incorporation of interannual variability (hydrological supply) allows a better approximation to reality; however, it is possible that pressures on water resources occur at smaller time scales.

The EWEI is defined as the ratio of extended demand to feasible supply, for the whole water resources and separately for groundwater and surface water. In this section we propose a methodology to approximate the EWEI at monthly scales.

#### 3.4.1 Feasible supply

In the case of groundwater, since this water body has a storage capacity, we do not consider an intra annual distribution factor. Then the feasible groundwater supply in month *j* and year *t* is:

$$IM_{j,t}^{feas} = \frac{1}{12} I_t^{feas} \tag{42}$$

We conversely model the feasible surface supply in month *j* and year *t* as follows:

$$RM_{j,t}^{feas} = \frac{1}{12} R_t^{feas} \cdot g_{R,j} \tag{43}$$

where $g_{R,j}$ is the surface water supply factor associated with month *j*.

The feasible supply of groundwater and surface water in month *j* and year *t*, is written as:

$$FSM_{j,t} = \frac{1}{12} \left[ R_t^{feas} \cdot g_{R,j} + I_t^{feas} \right] \tag{44}$$

#### 3.4.2 Extended demand

Regarding the demand for water, we assume that it is constant throughout the year, except for agriculture (Venturi et. Al, 2014).

Since we need to calculate the extended demand for groundwater and surface water separately, in the case of agriculture we consider equation (10), which includes the hydrological variability. The extended demand of the agricultural sub-sectors in month *j* and year *t*, for groundwater ($AED_{j,t}^{gw}$) and surface water ($AED_{j,t}^{sw}$) is defined as follows:

$$ADM_{j,t}^{gw} = \frac{1}{12} \cdot \sum_s e_{s,gw,t} \cdot g_{A,j} \tag{45}$$

$$ADM_{j,t}^{sw} = \frac{1}{12} \cdot \sum_s e_{s,sw,t} \cdot g_{A,j} \tag{46}$$

Where the subscript *s* represents the agricultural sub-sectors and $g_{A,j}$ is the monthly agricultural extended demand factor associated with month *j*. The same factor is assumed for all agricultural sub-sectors.

Total groundwater extended demand for month *j* in year *t* ($EDM_{j,t}^{gw}$) and total surface water extended demand for the month *j* and the year *t* ($EDM_{j,t}^{sw}$) can be written using equation (10), (44) and (45):

$$EDM_{j,t}^{gw} = \frac{1}{12}\sum_{q} e_{q,gw,t} + \frac{1}{12} \cdot \sum_{s} e_{s,gw,t} \cdot g_{A,j} \tag{47}$$

$$EDM_{j,t}^{sw} = \frac{1}{12}\sum_{q} e_{q,sw,t} + \frac{1}{12} \cdot \sum_{s} e_{s,sw,t} \cdot g_{A,j} \tag{48}$$

Where the subscript $q$ represents the non-agricultural sectors.

### *3.4.3 EWEI of the Critical Month*

The critical month corresponds to the month in which the EWEI reaches its maximum ($CM$). Reformulating equations (11), (12) and (13), and using equations (42), (43), (47) and (48), the EWEI of the critical month is calculated as follows:

$$EWEI_{t,CM} = \max_{j} \frac{EDM_{j,t}^{gw} + EDM_{j,t}^{sw}}{IM_{j,t}^{feas} + RM_{j,t}^{feas}} \tag{49}$$

$$EWEI_{t,CM}^{gw} = \frac{EDM_{CM,t}^{gw}}{IM_{CM,t}^{feas}} \tag{50}$$

$$EWEI_{t,CM}^{sw} = \frac{EDM_{CM,t}^{sw}}{RM_{CM,t}^{feas}} \tag{51}$$

### *3.4.4 Data for the estimations*

For water supply, the seasonal runoff factors correspond to the average measured for the Arno River, the most important surface watercourse in Tuscany (Autorità di distretto dell’Appennino Settentrionale, 2021). Table 6 shows the monthly surface water supply factors.

Table 6. Monthly surface water supply factors

| Month | $g_{R,j}$ |
|---|---|
| Jan | 1.655 |
| Feb | 1.788 |
| Mar | 1.579 |
| Apr | 1.349 |
| May | 0.923 |
| Jun | 0.517 |
| Jul | 0.190 |
| Aug | 0.137 |
| Sep | 0.251 |
| Oct | 0.606 |
| Nov | 1.381 |
| Dec | 1.624 |

Source: Autorità di distretto dell’ Appennino Settentrionale (2021)

For surface and groundwater demand from agriculture, the seasonal variation estimated by Venturi et al. (2014) is considered. Table 7 shows the monthly agricultural water demand factors.

Table 7. Monthly agricultural demand factors

| Month | $g_{A,j}$ |
|---|---|
| Jan | 0.064 |
| Feb | 0.064 |
| Mar | 0.064 |
| Apr | 0.097 |
| May | 0.719 |
| Jun | 2.877 |
| Jul | 4.992 |
| Aug | 2.587 |
| Sep | 0.343 |
| Oct | 0.064 |
| Nov | 0.064 |
| Dec | 0.064 |

Source: Venturi et al. (2014).

## 3.5 Montecarlo procedure for the model

The input-output model applied to Tuscany by Rocchi and Sturla (2021) considers the average values of hydrology, which translates into deterministic results (single value) for the extended demand and the EWEI.

The following procedure is applied *n* times to obtain the stochastic results. In each step the section where the methodology can be found is indicated:

1. With the multivariate hydrological model, an annual value is generated for each component of the hydrological balance: precipitation, evapotranspiration, surface runoff and groundwater recharge (section 2.2)
2. Withdrawals and water discharges are calculated with the IO model and the deterministic coefficients of water use (section 3.1.1).
3. Corrections are made to the withdrawal and discharge coefficients using the proposed model for agriculture (section 3.2), based on precipitation and evapotranspiration.
4. The withdrawals and water discharges for the agricultural sector are recalculated (section 3.2.3).
5. Based on the results of the IO model discharges (corrected in the previous point), surface runoff and groundwater recharge, the water dilution coefficients are estimated using the mixing model (section 3.3).
6. The IO model is used to estimate the volumes of water required for dilution (section 3.1.3).
7. The input-output model procedure is carried out to obtain the water extended demand by industry and water body (section 3.1.3).

8. The reclassification of the extended demand for water is carried out, considering the approach of demanding industries.
9. The feasible supply is calculated based on surface runoff and groundwater recharge (section 3.1.2).
10. The EWEI is calculated for the year considering the water extended demand and the feasible supply (section 3.1.3).
11. The EWEI for the critical month is calculated (section 3.4)
12. The results are recorded, and the cycle is started again in 1), *n* times.

These results are presented and detailed in the next section with *n*=100 years.

## 3.6 Data for the model

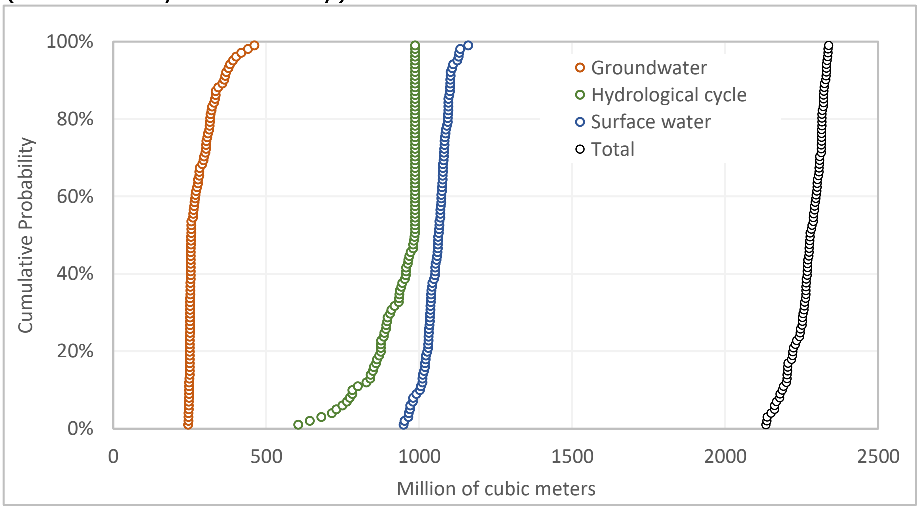
We consider the input-output matrix of the Tuscany region, for the year 2017, with 56 industries (IRPET, 2021). The water withdrawal and restitution coefficients for the average hydrology condition (deterministic coefficients), the water quality parameters for the mixing model and the parameter to calculate the feasible supply correspond to those used by Rocchi and Sturla (2021). The new parameters included in this study have been detailed in sections 3.3 and 3.4.

# 4 Results

## 4.1 Total and macro-sectors extended water demand

A first is the cumulative distribution function of the extended water demand of all industries, both total and disaggregated by water body (Figure 4). This is a fundamental outcome of the model allowing to study the probability distribution of the extended demand, given by all the sources of variability included. Table 8 shows the main statistics for each of the distributions represented in the graph.

Figure 4. Cumulative probability of extended water demand (total and by water body)




Source. Own elaboration

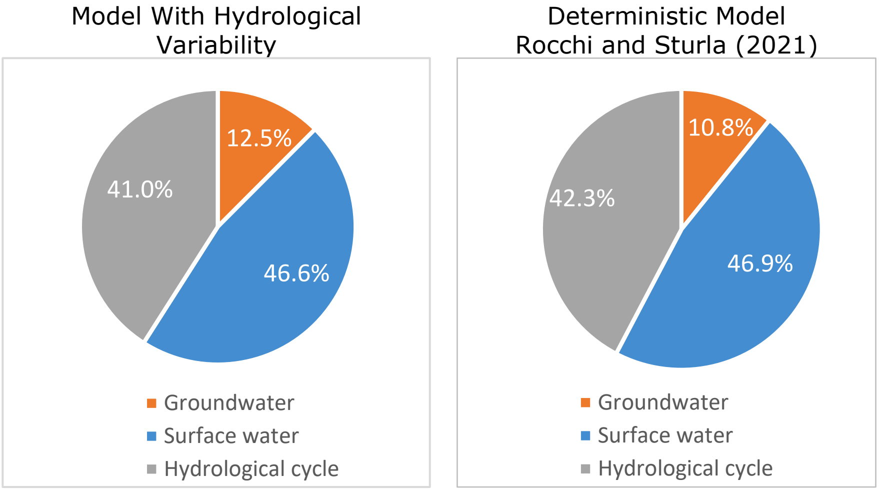
Table 8. Summary statistics of the extended demand by water body

| Water body | Mean ($Mm^3$) | S. Deviation ($Mm^3$) | C. Variation (%) |
|---|---|---|---|
| Groundwater | 283.4 | 48.2 | 17.0% |
| Surface water | 1057.3 | 41.8 | 4.0% |
| Hydrological cycle | 930.2 | 86.4 | 9.3% |
| Total | 2271.0 | 52.9 | 2.3% |

Source. Own elaboration

The comparison of the total extended demand calculated with the present model and the deterministic results of Rocchi and Sturla (2021) is relevant due to the role played by agriculture and water for dilution (endogenous effects in the model). As can be seen in Figure 5, for the model with hydrological variability developed in this study there is a decrease from 42.3% to 41% (-36.9 $Mm^3$) in the use of surface water and an increase from 10.8% to 12.5% in the case of groundwater (+29.9 $Mm^3$). In the case of surface water, while agricultural demand increases by 30.4 $Mm^3$ (years in which there is insufficient precipitation), the water required for dilution decreases by 67.3 $Mm^3$, due to the variability of the concentration in the mixing model; the effect of the dilution requirement dominates. For surface waters, agricultural demand increases by 32.5 $Mm^3$ and dilution water decreases by 2.6 $Mm^3$; the effect of agricultural demand dominates. The percentage of water demand from the hydrological cycle (green water) decreases from 46.9% to 46.6% (-56.8 $Mm^3$) only due to the effect of hydrological variability on the agricultural sector.

Figure 5. Structure of extended water demand by water body




Source. Own elaboration

Regarding the extended demand by macro-sectors, Tables 9 and 10 present the summary statistics by water body, for the case of the extended demand (extracting sectors) and the reclassified extended demand (demanding sectors).

Table 9. Summary statistics of water extended demand by macro-sector and water body (by extracting sector)

| Macro-sector | Groundwater | | | Surface water | | | Hydrological cycle | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean ($Mm^3$) | SD ($Mm^3$) | Cv | Mean ($Mm^3$) | SD ($Mm^3$) | Cv | Mean ($Mm^3$) | SD ($Mm^3$) | Cv |
| Agriculture | 82.5 | 48.7 | 59% | 95.0 | 44.8 | 47% | 1013.3 | 86.4 | 9% |
| Manufacture | 83.1 | 0.8 | 1% | 562.8 | 21.5 | 4% | -74.1 | 0.0 | 0% |
| Water Supply | 117.9 | 0.0 | 0% | 110.0 | 0.0 | 0% | 0.0 | 0.0 | NA |
| Sewerage | 0.0 | 0.0 | NA | 289.5 | 36.2 | 13% | -8.9 | 0.0 | 0% |
| Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |

Source. Own elaboration

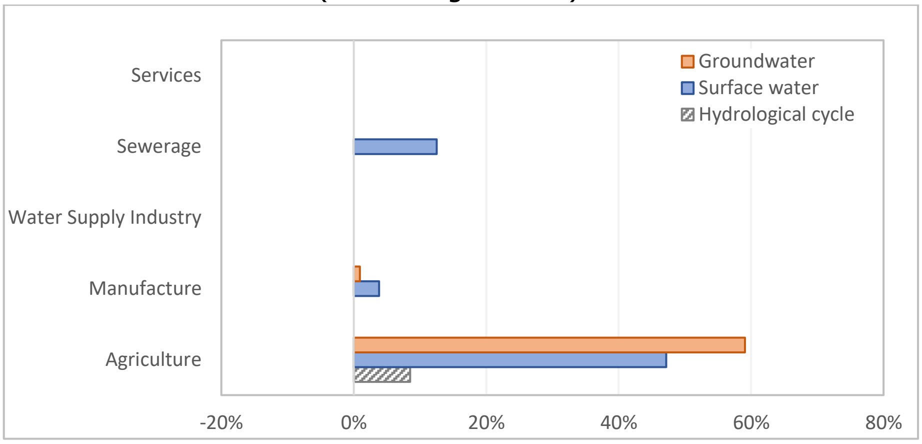
Table 10. Summary statistics of reclassified extended water demand by macro-sector and water body (by demanding sectors)

| Macro-sector | Groundwater | | | Surface water | | | Hydrological cycle | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean ($Mm^3$) | SD ($Mm^3$) | Cv | Mean ($Mm^3$) | SD ($Mm^3$) | Cv | Mean ($Mm^3$) | SD ($Mm^3$) | Cv |
| Agriculture | 41.3 | 22.8 | 55% | 49.0 | 20.8 | 43% | 471.6 | 40.3 | 9% |
| Manufacture | 121.7 | 20.9 | 17% | 604.1 | 18.6 | 3% | 389.9 | 37.8 | 10% |
| Water Supply | 66.0 | 0.0 | 0% | 62.3 | 0.0 | 0% | -0.5 | 0.0 | 0% |
| Sewerage | 0.0 | 0.0 | 1% | 193.9 | 24.3 | 13% | -6.0 | 0.0 | 0% |
| Services | 54.4 | 4.5 | 8% | 148.0 | 5.7 | 4% | 75.2 | 8.2 | 11% |

Source. Own elaboration

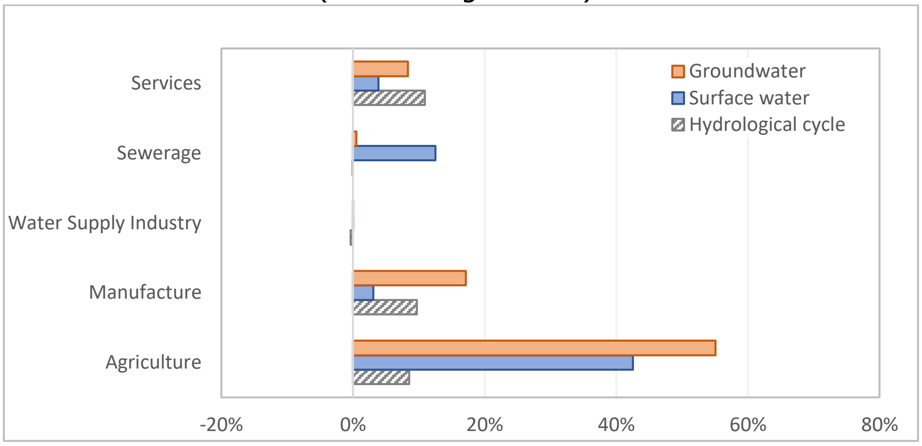
Figures 4 and 5 illustrate the coefficient of variation of the extended and the reclassified extended water demand by industry and water body.

Figure 4. Extended demand by macro-sector and water body. Coefficient of variation (extracting sectors)




Source. Own elaboration

Figure 5. Reclassified extended demand by macro-sector and water body Coefficient of variation (demanding sectors)




Source. Own elaboration

In the case of extracting sectors, services and water supply industry do not present any variability of the extended demand, the first one because it does not use water directly from the water bodies and the second one because it discharges good quality water and does not need water for dilution (not affected by hydrologic variability). For the reclassified extended demand (demanding sectors approach) manufacture and services are the industries which generates more impacts, due to their purchases (direct and indirect) from the agricultural and sewerage industries. Manufacture industry increases from 1% to 17% its coefficient of variation for groundwater and from 0% to 10% for hydrological cycle water, while services reach a values of 8%, 4% and 11% for groundwater, surface water and hydrological cycle water. The water supply industry in only slightly influenced by agriculture and sewerage, since it does not purchase intermediate goods in large quantities from agriculture and sewerage. Sewerage industry is not affected by agriculture in a significant extent.

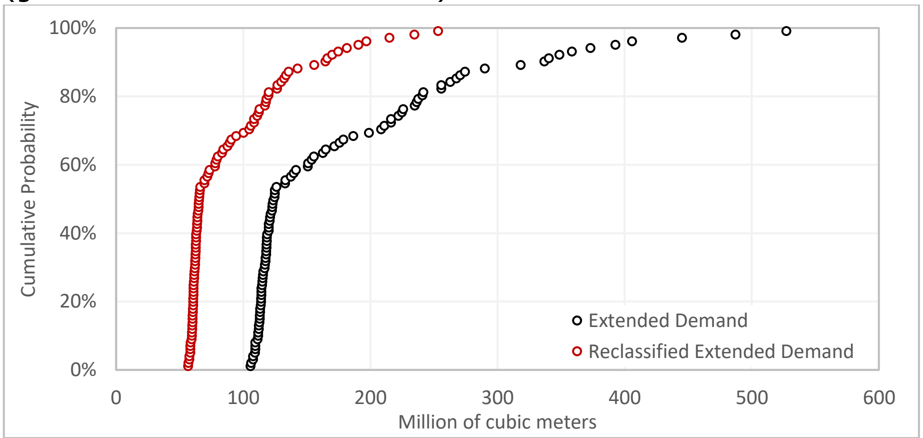
*Appendix A* provides the result (mean, standard deviation and coefficient of variation) for the extended and the reclassified extended demand for the 56 industries represented in the IO table, by water body.

## 4.2 Variability of the extended water demand in agriculture

Agriculture is particularly important in the developed model since hydrologic variability affects its withdrawal and discharge coefficients, directly due to changes in precipitation and evapotranspiration, and also indirectly, due to the increase of discharges generating changes in the water required for dilution (modulated by surface runoff and groundwater recharge).

Figure 6 and Table 11 show the cumulative probability of the extended and the reclassified extended demand for groundwater and surface water in agriculture. For the reclassified case, the demand is lower (-49%) because agriculture is a sector selling rather than buying virtual water to other industries. In addition, it can be defined as a sector selling water demand variability, which is reflected in the fact that its standard deviation is 53% lower in the reclassified case.

Figure 6. Cumulative probability of water extended demand in Agriculture (groundwater and surface water)




Source. Own elaboration

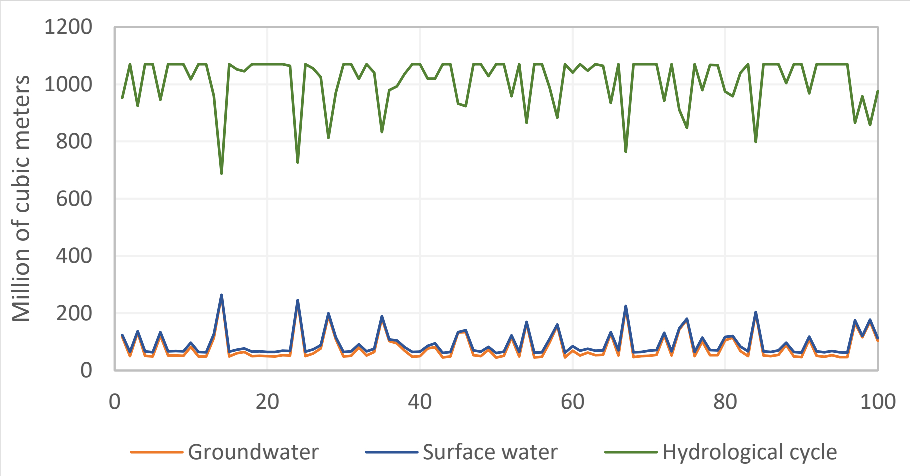
Table 10. Summary statistics of agriculture extended water demand (groundwater and surface water)

| Statistics | Extended Demand | Reclassified Extended Demand | Differences |
|---|---|---|---|
| Mean ($Mm^3$) | 177.5 | 90.3 | -49% |
| S. Deviation ($Mm^3$) | 93.5 | 43.6 | -53% |
| C. Variation | 52.70% | 48.30% | -8% |

Source. Own elaboration

Figure 7 shows a graph with the 100 years simulation of the extended demand for water in agriculture, for each water body. The high covariance between the series can be appreciated. This clearly shows how in the years in which there is no rainfall (green line) the agricultural sector must extract more water from surface water bodies (blue line) and groundwater bodies (orange line). The extended demand of the agricultural sector is influenced by the dilution requirements only for groundwater, however, as previously mentioned, this effect is not very significant.

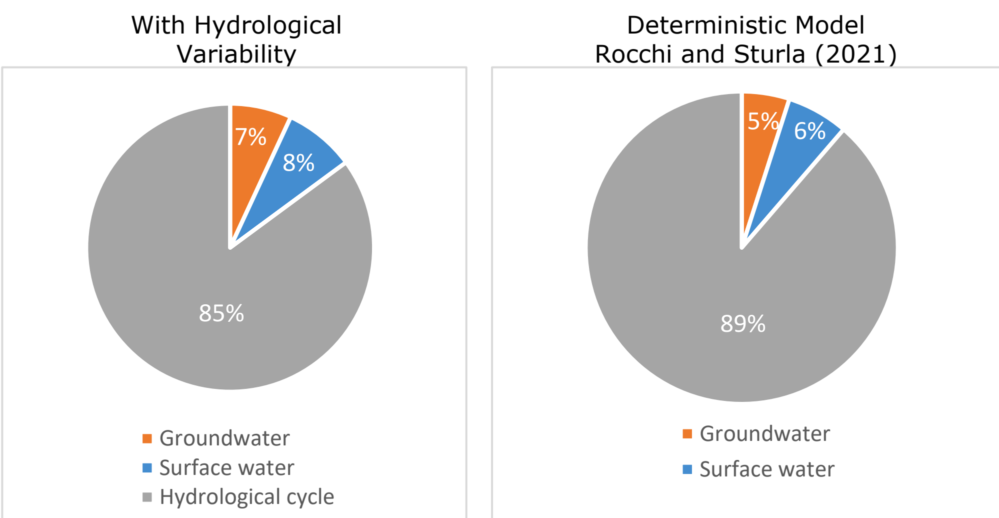
Figure 7 Extended water demand in agriculture by water body




Source. Own elaboration

As can be seen in the Figure 8, when comparing the new results with the deterministic model results, agriculture increases the share of its withdrawals from groundwater from 5% to 7% (16 $Mm^3$), from surface water from 6 % to 8% (17 $Mm^3$) and decreases the water that it captures directly from the natural environment from 89% to 885% (-37 $Mm^3$). This is consistent with the incorporation of the endogenous variability in the model. The sum of these changes is null as agriculture consumes on average the same amount of water, changing only its composition.

Figure 8. Structure of agriculture extended water demand by water source (by extracting sectors)



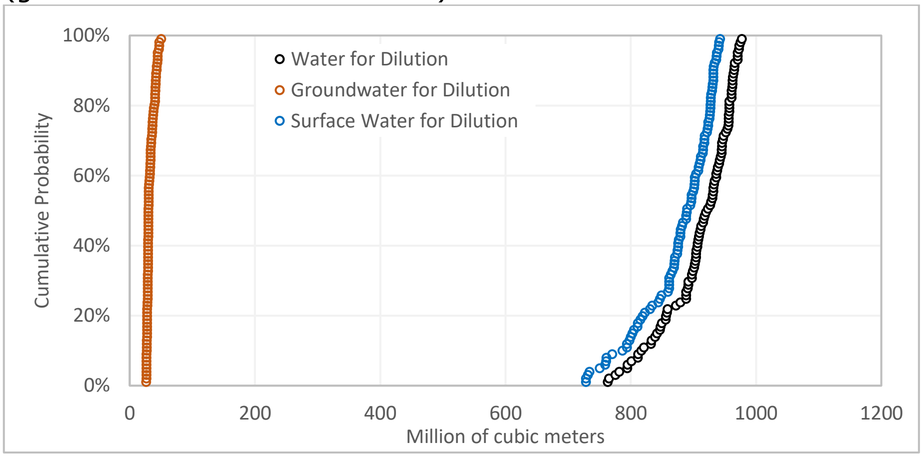

Source. Own elaboration

## 4.3 Variability of water demand for dilution

The mixing model used to determine the water required for dilution depends on surface runoff and groundwater recharge (hydrological variability). This affects the COD concentration in the receiving bodies of the discharges, where a quantity of water is reserved for dilution. Likewise, for the agricultural sector, dilution (ground) water depends on changes in the use coefficients due to precipitation and evapotranspiration (second order effect of hydrological variability).

Figure 9 shows the cumulative probability of dilution requirements for ground, surface and total water. Although surface water is much higher, for groundwater there is a higher coefficient of variation, due to the aforementioned second order effect. Table 11 presents the mean, standard deviation and coefficient of variation for each case.

Figure 9. Cumulative probability of water requirements for dilution (groundwater and surface water)




Source. Own elaboration

Table 11. Summary statistics of water requirements for dilution

| Statistics | Water for Dilution | Groundwater for Dilution | Surface water for Dilution |
|---|---|---|---|
| Mean ($Mm^3$) | 909.2 | 33.3 | 875.9 |
| S. Deviation ($Mm^3$) | 55.0 | 6.1 | 57.7 |
| C. Variation | 6.0% | 18.2% | 6.6% |

Source. Own elaboration

The model with hydrological variability shows a decrease in the water required for dilution compared to the deterministic model, due to the fact that in wet years the water required is lower while in dry years the water required must reach a standard defined by the concentration of COD in the water bodies, since there are no water resources available of lower quality. In the case of groundwater, there is an increase due to increased withdrawals by agriculture, which discharges only to groundwater (this effect dominates over that of concentration). In the case of surface water, where the greatest water requirement for dilution is concentrated, a decrease can be observed (no effect of agriculture). Table 12 presents the comparison with the deterministic model by water body.

Table 12. Water for dilution. Comparison with deterministic model

| Water for Dilution | Model with Hydrological Variability | Deterministic Model (Rocchi and Sturla, 2021) | Differences |
|---|---|---|---|
| Groundwater ($Mm^3$) | 33.3 | 30.7 | 8.50% |
| Surface water ($Mm^3$) | 875.9 | 943.2 | -7.10% |
| Total ($Mm^3$) | 909.2 | 973.9 | -6.60% |

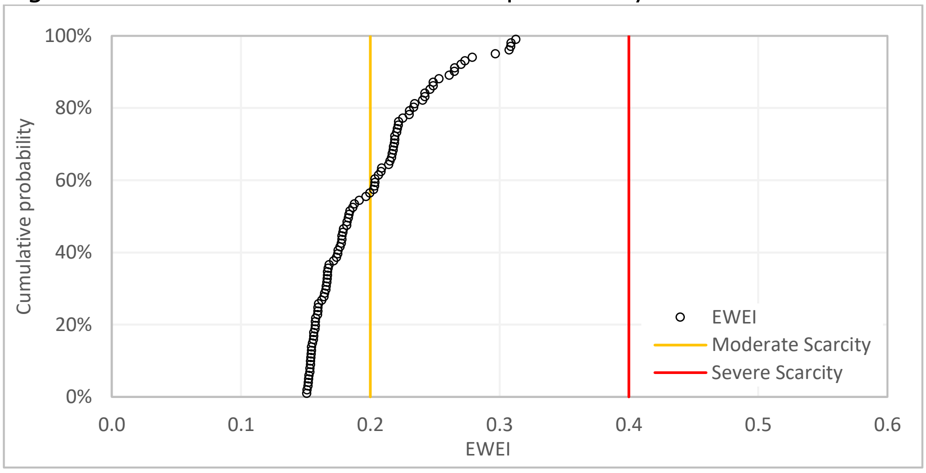
Source. Own elaboration

## 4.4 Stochastic EWEI

The EWEI indicator for the pressure of the economic system on water resources in this study corresponds to a probability distribution function for the 100 simulated hydrological years. These results are presented considering also a frequency analysis, i.e., the number of times the indicator is above a certain threshold. The values of 0.2 and 0.4 are considered, which represent, according to the literature, thresholds for moderate and severe water scarcity, respectively (Raskin et al., 1997; Alamo et. al, 2000, Pfister et al., 2009).

Considering the EWEI for the total resource (Figure 10), it presents an average value of 0.20 with a standard deviation of 0.04 (Table 13). In 43 over 100 years the threshold of 0.2 is exceeded while the threshold of 0.4 is never exceeded (Table 14).

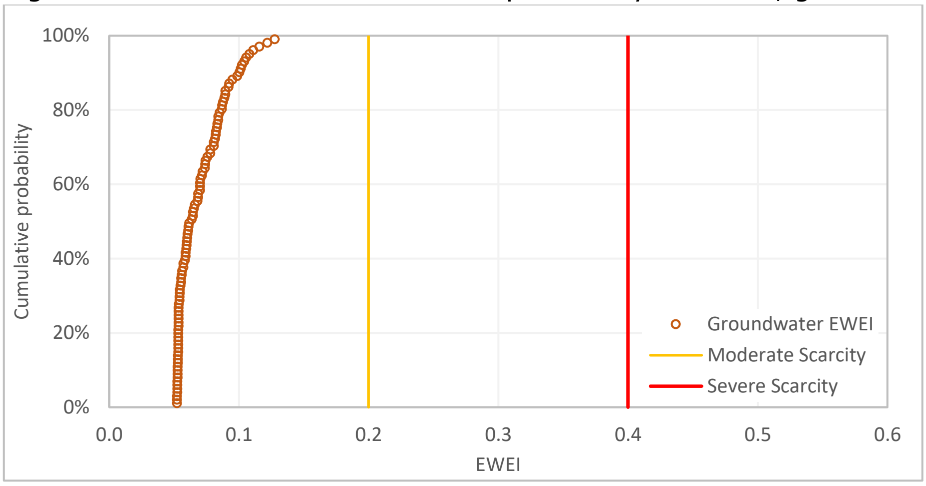
Figure 10. Cumulative distribution of probability for EWEI




Source. Own elaboration

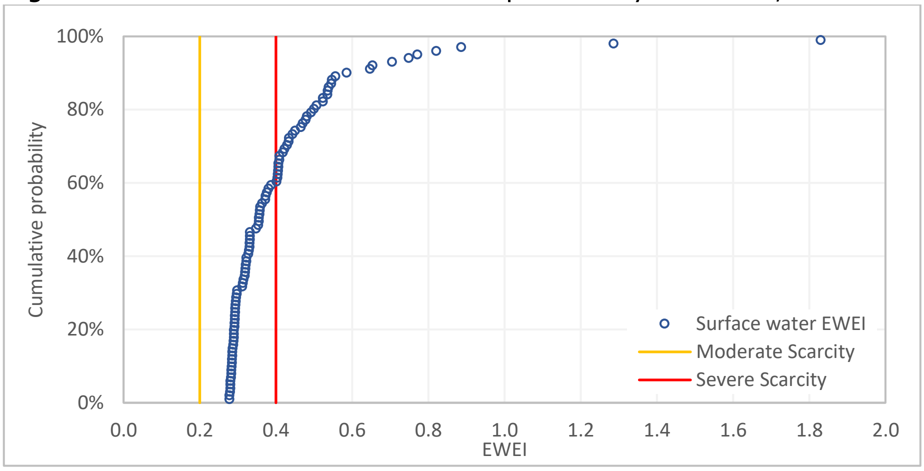
When groundwater and surface water are considered separately, the results change. For groundwater (Figure 10) the average EWEI value is 0.07 and the thresholds of 0.2 and 0.4 are not exceeded in any year. For surface water (Figure 10) the average EWEI value is 0.42, the 0.2 threshold is always exceeded in 100 years while the 0.4 threshold is exceeded in 40 over 100 years. Moreover, it can be seen that in 2 years the threshold of 1.0 is exceeded, i.e., the extended demand exceeds the feasible supply.

Figure 10. Cumulative distribution of probability for EWEI, groundwater




Source. Own elaboration

Figure 11. Cumulative distribution of probability for EWEI, surface water




Source. Own elaboration

Table 13 presents the mean, standard deviation and the coefficient of variation for the EWEI. Table 14 presents the frequency analysis for the EWEI.

Table 13. Summary statistics for the EWEI

| Statistics | EWEI | Groundwater EWEI | Surface water EWEI |
|---|---|---|---|
| Mean (Mm3) | 0.20 | 0.07 | 0.42 |
| Standard Deviation (Mm3) | 0.04 | 0.02 | 0.21 |
| Coefficient of Variation | 0.22 | 0.27 | 0.50 |

Source. Own elaboration

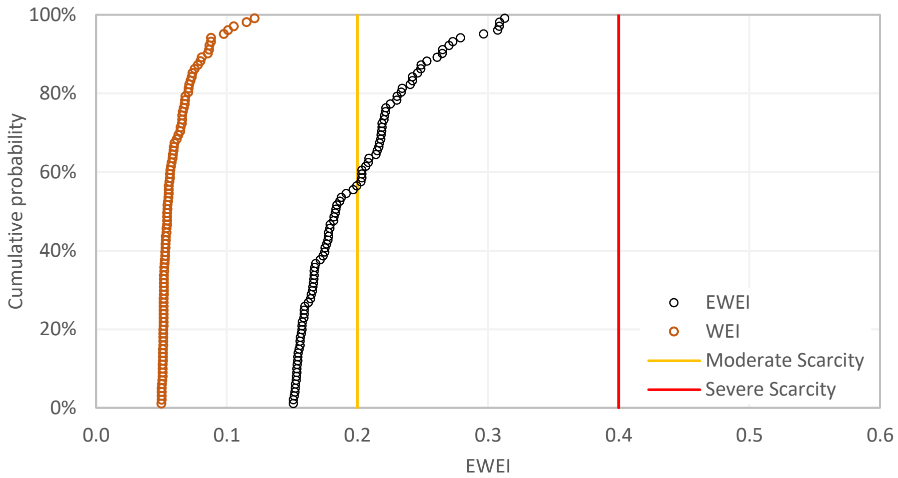
Table 14. Frequency analysis for the EWEI by water body (number of years exceeding a given threshold)

| Threshold | EWEI | Groundwater EWEI | Surface water EWEI |
|---|---|---|---|
| 0.2 | 43 | 0 | 100 |
| 0.4 | 0 | 0 | 40 |
| 0.6 | 0 | 0 | 9 |
| 0.8 | 0 | 0 | 4 |
| 1.0 | 0 | 0 | 2 |

Source. Own elaboration

The EWEI can be compared with the WEI$^+$ for the total resource (Figure 12). The WEI$^+$ is calculated as the net demand (withdrawals minus discharges) divided by the long-term natural supply net of the ecological flow (Faergemann, 2012; European Environmental Agency, 2020). The average value of the WEI$^+$ is 0.06 while the standard deviation is 0.01, 4 times lower than that of the EWEI, the latter due to the fact that there is no assumed variability in supply. It can be seen that the WEI$^+$ for Tuscany never exceeds the thresholds of 0.2 and 0.4.

Figure 12. Cumulative distribution of probability for EWEI and WEI$^+$




Source. Own elaboration

The comparison of the results obtained with the deterministic model of Rocchi and Sturla (2021) is also interesting. Table 15 shows a summary where it can be seen that the average EWEI for the total resources, groundwater and surface water rises due to the introduction of hydrological variability. The most significant change occurs in the case of surface water where the EWEI increases from 0.38 to 0.42. The WEI$^+$ also increases for all three cases but remaining largely below the moderate stress threshold, varying from 0.05 to 0.06.

Table 15. Comparison of the IPRI with the deterministic model

| IPRI/ Water body | Model with hydrological variability | | Deterministic Model (Rocchi and Sturla, 2021) | |
|---|---|---|---|---|
| | EWEI | WEI$^+$ | EWEI | WEI$^+$ |
| Total | 0.20 | 0.06 | 0.19 | 0.05 |
| Groundwater | 0.07 | 0.06 | 0.06 | 0.05 |
| Surface water | 0.42 | 0.06 | 0.38 | 0.05 |

Source. Own elaboration

## 4.5 Critical Month EWEI

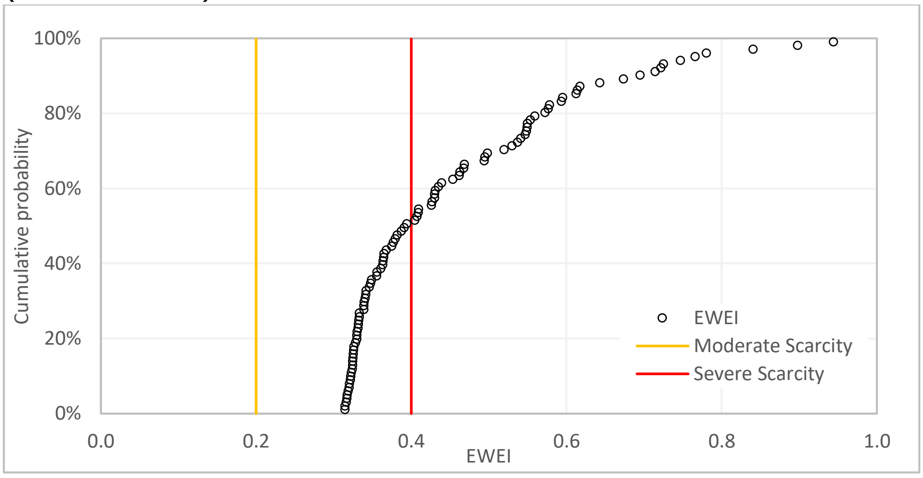
The critical month is the one when the EWEI is maximum considering the intra-annual distribution of extended demand (agriculture) and feasible supply (surface water). Based on the information available, this month in Tuscany corresponds to July.

The literature thresholds for moderate and severe shortages are also used on a monthly scale (Garcia-Hernandez, 2021), so they have been included in the critical month analysis.

Figure 13 shows the cumulative probability for the EWEI in critical month considering all water resources. The mean value is 0.45 (Table 16), the threshold of 0.2 (moderate shortage) is always exceeded, the threshold of 0.4 (severe shortage) 49 times. In no case the value of 1 is exceeded (Table 17), i.e., in Tuscany the extended demand does not exceed the feasible supply for any month in any year of the Monte Carlo simulation.

This result is quite interesting, since it suggest an alternative to the thresholds defined and recommended by the literature. A critical threshold taking to account hydrological variability could be represented by an average annual EWEI compatible with the condition that the index never exceeds the value of 1 both considering the interannual and intra annual variability (critical month with hydrological variability) and assuming a perfect substitution between surface and groundwater.

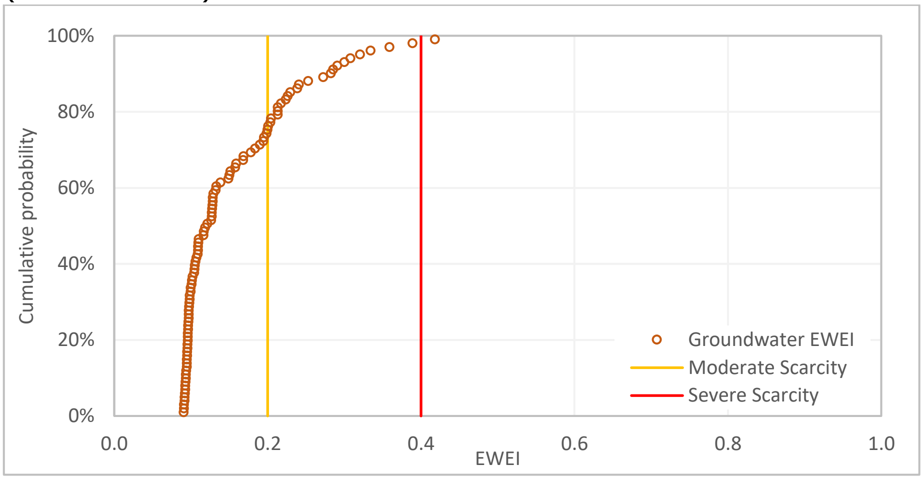
Figure 13. Cumulative distribution of probability for EWEI, total water resource (Critical Month).




Source. Own elaboration

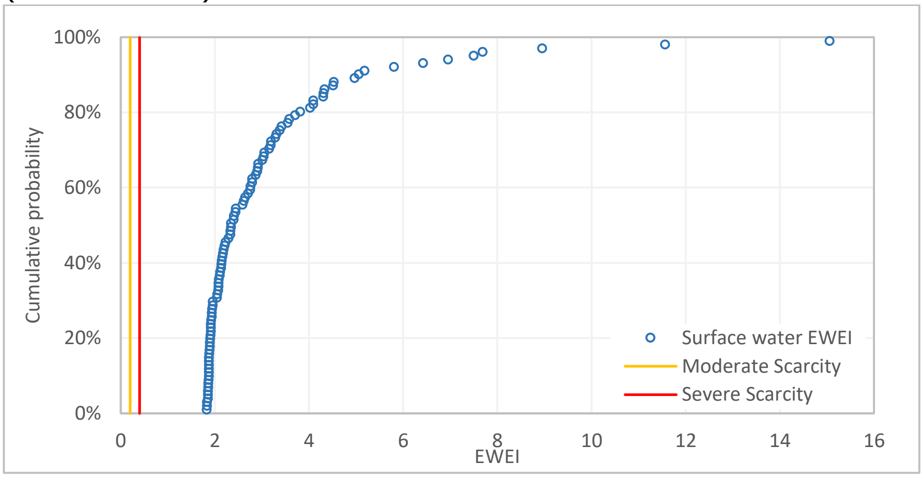
Figure 14 and Figure 15 show the critical month EWEI for groundwater and surface water. The situation is much more asymmetric than in the annual case. For groundwater the average value is 0.15 and the threshold of 0.4 is exceeded only once; conversely, for surface water the situation is quite worrying, the EWEI taking an average value of 3.11 and exceeding 1 in all the years (extended demand greater than feasible supply). That is, without considering the intra-annual regulation capacity of surface water resources, there is always a deficit in the critical month.

Figure 14. Cumulative distribution of probability for IPRI, groundwater (Critical Month).




Source. Own elaboration

Figure 15. Cumulative distribution of probability for IPRI, surface water (Critical Month).




Source. Own elaboration

Table 16. Summary statistics for the EWEI, Critical Month

| Statistics | EWEI | Groundwater EWEI | Surface water EWEI |
|---|---|---|---|
| Mean (Mm3) | 0.45 | 0.15 | 3.11 |
| Standard Deviation (Mm3) | 0.15 | 0.08 | 2.03 |
| Coefficient of Variation | 0.32 | 0.49 | 0.65 |

Source. Own elaboration

Table 17. Frequency analysis for the EWEI, Critical Month (number of years exceeding a given threshold)

| Threshold | EWEI | Groundwater EWEI | Surface water EWEI |
|---|---|---|---|
| 0.2 | 100 | 24 | 100 |
| 0.4 | 49 | 1 | 100 |
| 0.6 | 15 | 0 | 100 |
| 0.8 | 3 | 0 | 100 |
| 1.0 | 0 | 0 | 100 |

Source. Own elaboration

# 5 DISCUSSION AND CONCLUSIONS

The model proposed by Rocchi and Sturla (2021) develops the extended demand approach (Guan and Hubacek), improving the mixing model (Xie, 1996), with a more realistic incorporation of the water actually used for dilution and the estimation of the extended demand for each industry. In addition, the study proposes the concept of feasible supply and the EWEI indicator. This is applied to the Tuscan economy, considering the average hydrology and performing a sensitivity analysis of the EWEI based on minimum and maximum hydrology, but without incorporating hydrological variability and its endogenous effects in the analysis.

The model proposed in this study considers hydrologic variability through a multivariate model, generating synthetic series of precipitation, evapotranspiration, surface runoff and groundwater recharge. The integration of this model with the IO model and the mixing model allows the incorporation of two endogenous effects: i) changes in water withdrawals and discharges in the agricultural sector due to variations in precipitation and evapotranspiration; and ii) changes in water requirements for dilution in all discharging industries due to variations in runoff and groundwater recharge.

For the case of agriculture, the proposed methodology considers the variation of precipitations as a proxy for the variation of water captured from the hydrological cycle (green water), due to the non-existence of long period soil moisture series and the fact that regional values of this component could not be considered as completely available for agriculture. In addition, also the effects of variability in evapotranspiration on water withdrawals are considered. This model allows to add a variable component to the water withdrawal and discharge coefficients.

To include hydrological variability in the dilution water requirements, the change in the concentration of groundwater and surface water bodies is considered, based on the surface runoff and groundwater recharge series obtained with the hydrological model. This allows for a more realistic representation of grey water demand, since the water reserved for dilution comes from the same water bodies where polluted water is discharged. Using the model, variability in the dilution water use coefficients is obtained, also considering the second-order endogenous effect due to the change in agricultural discharges.

Based on a Monte Carlo simulation for 100 hydrological years, a probability distribution of the extended demand by extracting and demanding sector was obtained. Based on the feasible supply, the EWEI with hydrological variability was estimated, obtaining an average value of 0.20, slightly higher than 0.19 of the deterministic model of Rocchi and Sturla (2021), due to the increase of water demand in the agricultural sector (replacement of green by blue water in dry years) and the decrease of water for dilution due to the higher standard concentration in dry years.

A frequency analysis was carried out for the EWEI. In 49 over 100 years the value of 0.2 defined in the literature as the threshold for moderate scarcity is exceeded, while the value of 0.4, defined in the literature as the threshold for severe scarcity, is never exceeded. However, when groundwater and surface water are considered separately, while for groundwater the thresholds of 0.2 and 0.4 are not exceeded in any year, for surface water the 0.2 threshold is always exceeded while the 0.4 threshold is exceeded in 40 years. In 2 over 100 years the threshold exceeds the value of 1, i.e., the extended demand exceeds the feasible supply.

These are relevant results because although Tuscany for 49% of the hydrological scenarios would be in a moderate scarcity condition according to the standard thresholds, this is supported by two relevant assumptions: i) the perfect substitution between surface and groundwater, and ii) the annual resolution of the analysis. The first element can be deepened by separating the indicator by water body, as has been done in this study, or by performing a hydro-economic analysis at a smaller spatial resolution. The second element has been considered in this study by proposing a methodology to determine the EWEI on a monthly scale, in particular for the critical month, based on the intra-annual disaggregation of the extended demand and the feasible supply.

For the critical month (July) an average EWEI of 0.45 is obtained, always exceeding the threshold of moderate scarcity and that of severe scarcity in 49 years; the value of 1 for the EWEI is conversely never exceeded . The situation is much worse when considering surface water only, with the value of 1 exceeded in all years.

The EWEI for the critical month has been compared with the thresholds proposed in the literature, since they have been used also on a monthly scale (Garcia-Hernandez 2021). From the results clearly emerges the reasons why these thresholds are much lower than 1: the indicators used in the literature on water scarcity consider an annual time scale and average hydrological conditions as a consequence the thresholds have to be conservative enough to take into account interannual and intra-annual hydrological variability, as well as technical and institutional aspects.

A central element of the analysis carried out in this study is the fact that the EWEI indicator itself already includes inter-annual and intra-annual hydrological variability (both for the demand and supply) and technical and institutional aspects associated with water availability (assuming only a *feasible* supply). Thus, it constitutes a tool for a specific analysis of the Tuscan case study, dispensing from the use of standard thresholds defined in the literature. The model allows to know how many years the extended demand exceeds the feasible supply (EWEI>1) in the critical month; a condition that could be considered for the definition of a critical threshold for the average annual value of the EWEI specific for Tuscany, based on the maximum number of years that that an excess of demand over supply is allowed to occur. Based on the results it is possible to affirm that Tuscany, at regional scale and considering a perfect substitution between surface and groundwater, doesn't not present water scarcity (in quantity and quality) because the extended demand is always lower than the feasible supply considering the worst case (critical month in the driest year). However, the regional scale of the analysis still remains as a major limitation to a better characterization of water scarcity, which will be addressed in future developments.

The input-output model with hydrological variability constitutes an important contribution to the literature and to the design of public policies, since it allows a better understanding of the relationship between the economic and water systems, including the essentially stochastic nature of hydrological processes, which is reflected in the results for the extended water demand and the economic pressure indicator. The model offers powerful tools for answering questions in the current context of climate change and increasing pressure on water resources. Three specific applications can be mentioned. First, to assess what would happen under climate change scenarios, which can be easily represented by modifying the parameters of the normal multivariate model or by incorporating hydrological climate change series for Tuscany obtained from hydroclimatic models. Second, to evaluate the economic benefits, in a context of hydrological uncertainty, of investing in water infrastructure for an efficient water use; depending on the industries in which the investment is planned, the technical coefficients of water use (deterministic) can be modified, for example by varying parameters such as the irrigation efficiency in agriculture. Third, it is possible to evaluate the effect on the EWEI (in probabilistic terms) of changes in surface water concessions, of the incorporation of stronger environmental restrictions on minimum ecological flows, and of changes in the COD concentration limits in the discharges of the different industrial sectors (decrease in grey water).

Among future developments, and consistently with the findings of the previous paragraph, it is important to take into consideration the temporal and spatial limitations (hydrology and economy) of the model. In the analysis an approximation of the hydrological variability of the extended demand and feasible supply at a monthly level has been carried out, however, it would be possible to achieve greater precision based on a more detailed modeling of the hydrology at a monthly scale, considering a statistical or a physical-based hydrological model, thus achieving greater reliability in the results. It is also possible, with more information on the regional economic structure, to disaggregate the extended demand for other sectors of the Tuscan economy that may present significant variations in water use within the year.

For what concerns the spatial dimension of the analysis, the model considers the whole Tuscany as the unit of analysis. However, both in hydrological and economic terms the spatial units for more relevant analyses should be smaller, basins or sub-basins in the case of hydrology and local systems in the case of the economy. Such a spatial precision corresponds to an important challenge regarding the gathering and disaggregation of data, as well as greater computational efforts. A better approximation of the trade-off between green and blue water in agriculture could be achieved by considering a hydro-economic model with higher spatial resolution and accurately determining the amount of soil moisture available, i.e., the supply of green water. Finally, with respect to water requirements for dilution, it is possible to improve the model by considering more and possibly better water quality indicators (not only chemical oxygen demand), as long as reliable data from specific measurements and modeling, where available.

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# 7 APPENDICES

## 7.1 Appendix A. Extended water demand statistics for 56 industries

Table A-1. Water extended demand for 56 industries

| Industry | Macro-sector | Groundwater | | | Surface water | | | Hydrological cycle | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean ($Mm^3$) | Std ($Mm^3$) | Cv | Mean ($Mm^3$) | Std ($Mm^3$) | Cv | Mean ($Mm^3$) | Std ($Mm^3$) | Cv |
| Arable land | Agriculture | 30.9 | 18.7 | 60% | 34.5 | 16.6 | 48% | 383.5 | 32.5 | 8% |
| Horticulture | Agriculture | 7.1 | 4.1 | 58% | 3.9 | 1.9 | 49% | 64.0 | 5.4 | 8% |
| Permanent crops | Agriculture | 9.7 | 5.9 | 61% | 12.7 | 6.1 | 48% | 131.5 | 11.2 | 8% |
| Grazing livestock | Agriculture | 3.4 | 1.8 | 52% | 3.6 | 1.5 | 43% | 35.8 | 3.0 | 8% |
| Granivores | Agriculture | 0.5 | 0.3 | 50% | 1.3 | 0.5 | 40% | 8.6 | 0.7 | 8% |
| Mixed crops farms | Agriculture | 11.4 | 7.0 | 62% | 15.8 | 7.6 | 48% | 160.1 | 13.6 | 8% |
| Mixed livestock farms | Agriculture | 5.1 | 2.9 | 57% | 5.6 | 2.6 | 46% | 59.5 | 5.0 | 8% |
| Mixed crops-livestock farms | Agriculture | 14.5 | 7.9 | 54% | 17.6 | 7.7 | 44% | 170.3 | 14.4 | 8% |
| Forestry and use of forest areas | Agriculture | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Fishing | Agriculture | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Mining and quarrying | Manufacturing | 12.4 | 0.8 | 6% | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Food products and beverages | Manufacturing | 16.3 | 0.0 | 0% | 10.6 | 0.9 | 9% | -0.1 | 0.0 | 0% |
| Textiles | Manufacturing | 0.0 | 0.0 | NA | 122.9 | 4.2 | 3% | -0.7 | 0.0 | 0% |
| Wearing apparel | Manufacturing | 0.0 | 0.0 | NA | 5.9 | 0.2 | 3% | 0.0 | 0.0 | 0% |
| Leather and related goods | Manufacturing | 0.0 | 0.0 | NA | 28.1 | 1.0 | 3% | -0.2 | 0.0 | 0% |
| Footwear | Manufacturing | 0.0 | 0.0 | NA | 0.5 | 0.0 | 3% | 0.0 | 0.0 | 0% |
| Wood and wood products | Manufacturing | 0.0 | 0.0 | NA | 3.5 | 0.1 | 3% | 0.0 | 0.0 | 0% |
| Paper Printing and rec. media | Manufacturing | 0.0 | 0.0 | NA | 55.8 | 1.8 | 3% | -0.3 | 0.0 | 0% |
| Coke and refined petroleum products | Manufacturing | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Chemical and chemical products | Manufacturing | 27.6 | 0.0 | 0% | 33.5 | 1.1 | 3% | -0.2 | 0.0 | 0% |
| Pharmaceutical products | Manufacturing | 0.0 | 0.0 | NA | 20.8 | 0.4 | 2% | -0.1 | 0.0 | 0% |
| Rubber and plastic products | Manufacturing | 0.0 | 0.0 | NA | 68.9 | 4.1 | 6% | -0.7 | 0.0 | 0% |
| Other non-metallic products | Manufacturing | 0.0 | 0.0 | NA | 76.9 | 4.6 | 6% | -0.7 | 0.0 | 0% |
| Manufacture of basic metals | Manufacturing | 0.0 | 0.0 | NA | 9.3 | 0.3 | 3% | 0.0 | 0.0 | 0% |
| Metal products | Manufacturing | 0.0 | 0.0 | NA | 16.6 | 0.6 | 3% | -0.1 | 0.0 | 0% |
| Computers, electronic and optical equipment | Manufacturing | 0.7 | 0.0 | 0% | 5.0 | 0.2 | 3% | 0.0 | 0.0 | 0% |
| Electrical equipment | Manufacturing | 0.8 | 0.0 | 0% | 6.5 | 0.2 | 3% | 0.0 | 0.0 | 0% |
| Machinery and equipment n.e.c. | Manufacturing | 9.6 | 0.0 | 0% | 1.9 | 0.1 | 6% | 0.0 | 0.0 | 0% |
| Motor vehicles and other transportation means | Manufacturing | 11.0 | 0.0 | 0% | 19.1 | 1.1 | 6% | -0.2 | 0.0 | 0% |
| Furniture | Manufacturing | 0.7 | 0.0 | 0% | 0.9 | 0.1 | 6% | 0.0 | 0.0 | 0% |
| Jewelry | Manufacturing | 0.1 | 0.0 | 0% | 0.2 | 0.0 | 6% | 0.0 | 0.0 | 0% |
| Other manufacturing | Manufacturing | 4.0 | 0.0 | 0% | 5.2 | 0.3 | 6% | 0.0 | 0.0 | 0% |
| Repair and installation of equipment and systems | Manufacturing | 0.0 | 0.0 | 0% | 0.0 | 0.0 | 6% | 0.0 | 0.0 | 0% |
| Electricity power generation | Manufacturing | 0.0 | 0.0 | NA | 70.8 | 0.0 | 0% | -70.8 | 0.0 | 0% |

| Industry | Macro-sector | Groundwater | | | Surface water | | | Hydrological cycle | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean ($Mm^3$) | Std ($Mm^3$) | Cv | Mean ($Mm^3$) | Std ($Mm^3$) | Cv | Mean ($Mm^3$) | Std ($Mm^3$) | Cv |
| Electricity Transmission and Distribution | Manufacturing | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Gas Steam Air conditioning | Manufacturing | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Water supply | Water Supply | 117.9 | 0.0 | 0% | 110.0 | 0.0 | 0% | 0.0 | 0.0 | NA |
| Sewerage | Sewerage | 0.0 | 0.0 | NA | 289.5 | 36.0 | 12% | -8.9 | 0.0 | 0% |
| Waste management | Manufacturing | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Construction | Construction | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Wholesale and retail trade, repair of motor vehicle | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Transportation and storage | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Accommodation and food services | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Publishing, audiovisual, radio and television production | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Telecommunications | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| IT and other information services | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Financial and insurance activities | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Real estate activities | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Professional and technical activities | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Scientific research and development | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Other service activities | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Public administration and defense; compulsory social security | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Education | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Health and social work activities | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Arts, entertainment, and recreation | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |
| Other service activities | Services | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA | 0.0 | 0.0 | NA |

Source. Own elaboration

Table A-2. Water extended demand reclassified for 56 industries

| Industry | Macro-sector | Groundwater | | | Surface water | | | Hydrological cycle | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean ($Mm^3$) | Std ($Mm^3$) | Cv | Mean ($Mm^3$) | Std ($Mm^3$) | Cv | Mean ($Mm^3$) | Std ($Mm^3$) | Cv |
| Arable land | Agriculture | 3.9 | 2.2 | 56% | 4.5 | 1.9 | 43% | 44.2 | 3.8 | 9% |
| Horticulture | Agriculture | 7.4 | 3.8 | 51% | 5.1 | 1.7 | 34% | 58.2 | 5.0 | 9% |
| Permanent crops | Agriculture | 7.7 | 4.3 | 56% | 10.3 | 4.4 | 43% | 95.7 | 8.1 | 9% |
| Grazing livestock | Agriculture | 1.1 | 0.6 | 52% | 1.3 | 0.5 | 40% | 12.1 | 1.0 | 9% |
| Granivores | Agriculture | 0.3 | 0.1 | 45% | 0.5 | 0.2 | 36% | 3.5 | 0.3 | 9% |
| Mixed crops farms | Agriculture | 8.9 | 5.4 | 61% | 12.4 | 5.9 | 48% | 124.4 | 10.5 | 8% |
| Mixed livestock farms | Agriculture | 2.0 | 1.1 | 56% | 2.2 | 1.0 | 44% | 22.3 | 1.9 | 8% |
| Mixed crops-livestock farms | Agriculture | 10.0 | 5.1 | 51% | 12.4 | 5.1 | 41% | 111.3 | 9.5 | 8% |
| Forestry and use of forest areas | Agriculture | 0.1 | 0.0 | 0% | 0.2 | 0.0 | 1% | -0.1 | 0.0 | 0% |
| Fishing | Agriculture | 0.0 | 0.0 | 8% | 0.1 | 0.0 | 2% | 0.0 | 0.0 | -5% |
| Mining and quarrying | Manufacturing | 10.0 | 0.6 | 6% | 2.5 | 0.3 | 11% | -0.1 | 0.0 | -15% |
| Food products and beverages | Manufacturing | 30.5 | 9.4 | 31% | 37.9 | 7.9 | 21% | 197.3 | 16.9 | 9% |
| Textiles | Manufacturing | 18.8 | 10.7 | 57% | 116.5 | 7.7 | 7% | 219.8 | 18.7 | 9% |
| Wearing apparel | Manufacturing | 0.4 | 0.0 | 1% | 24.7 | 0.9 | 4% | -0.2 | 0.0 | -2% |
| Leather and related goods | Manufacturing | 2.8 | 0.3 | 11% | 34.0 | 1.0 | 3% | 6.0 | 0.5 | 9% |
| Footwear | Manufacturing | 0.2 | 0.0 | 0% | 7.1 | 0.3 | 4% | -0.1 | 0.0 | 0% |
| Wood and wood products | Manufacturing | 0.1 | 0.0 | 19% | 5.7 | 0.3 | 5% | -0.8 | 0.0 | -3% |
| Paper Printing and rec. media | Manufacturing | 0.5 | 0.0 | 1% | 58.6 | 2.7 | 5% | -0.9 | 0.0 | -1% |
| Coke and refined petroleum products | Manufacturing | 1.6 | 0.1 | 4% | 9.1 | 0.6 | 7% | -0.2 | 0.0 | -21% |
| Chemical and chemical products | Manufacturing | 26.6 | 0.0 | 0% | 40.3 | 1.7 | 4% | -0.8 | 0.1 | -7% |
| Pharmaceutical products | Manufacturing | 0.8 | 0.1 | 13% | 27.5 | 0.9 | 3% | 1.6 | 0.2 | 12% |
| Rubber and plastic products | Manufacturing | 0.6 | 0.1 | 22% | 39.9 | 2.3 | 6% | 1.4 | 0.2 | 17% |
| Other non-metallic products | Manufacturing | 0.5 | 0.0 | 3% | 57.6 | 3.8 | 7% | -0.8 | 0.0 | -5% |
| Manufacture of basic metals | Manufacturing | 0.5 | 0.1 | 13% | 16.2 | 0.4 | 3% | -3.0 | 0.1 | -4% |
| Metal products | Manufacturing | 0.2 | 0.0 | 11% | 15.0 | 0.5 | 4% | -0.4 | 0.0 | -9% |
| Computers, electronic and optical equipment | Manufacturing | 1.6 | 0.1 | 5% | 8.2 | 0.3 | 4% | 1.4 | 0.1 | 10% |
| Electrical equipment | Manufacturing | 1.2 | 0.0 | 1% | 8.8 | 0.4 | 5% | 0.0 | 0.0 | -64% |
| Machinery and equipment n.e.c. | Manufacturing | 9.9 | 0.0 | 0% | 7.3 | 0.3 | 4% | -0.6 | 0.0 | -7% |
| Motor vehicles and other transportation means | Manufacturing | 10.6 | 0.0 | 0% | 26.0 | 1.7 | 7% | -0.2 | 0.0 | -13% |
| Furniture | Manufacturing | 0.5 | 0.0 | 1% | 2.5 | 0.1 | 4% | 0.0 | 0.0 | -31% |
| Jewelry | Manufacturing | 0.2 | 0.0 | 0% | 1.5 | 0.1 | 4% | -0.2 | 0.0 | 0% |
| Other manufacturing | Manufacturing | 2.0 | 0.0 | 0% | 3.2 | 0.2 | 5% | 0.1 | 0.0 | 18% |
| Repair and installation of equipment and systems | Manufacturing | 0.2 | 0.0 | 10% | 1.3 | 0.0 | 1% | -0.4 | 0.0 | -8% |
| Electricity power generation | Manufacturing | 0.3 | 0.0 | 3% | 25.0 | 0.2 | 1% | -22.6 | 0.0 | 0% |
| Electricity Transmission and Distribution | Manufacturing | 0.0 | 0.0 | 0% | 6.8 | 0.0 | 1% | -6.4 | 0.0 | 0% |
| Gas Steam Air conditioning | Manufacturing | 0.3 | 0.2 | 52% | 5.8 | 0.1 | 2% | -1.0 | 0.3 | -30% |

| Industry | Macro-sector | Groundwater | | | Surface water | | | Hydrological cycle | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean ($Mm^3$) | Std ($Mm^3$) | Cv | Mean ($Mm^3$) | Std ($Mm^3$) | Cv | Mean ($Mm^3$) | Std ($Mm^3$) | Cv |
| Water supply | Water Supply | 66.0 | 0.0 | 0% | 62.3 | 0.0 | 0% | -0.5 | 0.0 | 0% |
| Sewerage | Sewerage | 0.0 | 0.0 | 1% | 193.9 | 24.1 | 12% | -6.0 | 0.0 | 0% |
| Waste management | Manufacturing | 0.1 | 0.0 | 21% | 1.6 | 0.1 | 6% | 0.4 | 0.1 | 14% |
| Construction | Construction | 0.8 | 0.1 | 6% | 14.0 | 0.8 | 6% | 0.7 | 0.1 | 14% |
| Wholesale and retail trade, repair of motor vehicle | Services | 4.8 | 1.5 | 31% | 24.7 | 1.3 | 5% | 28.6 | 2.7 | 10% |
| Transportation and storage | Services | 0.7 | 0.1 | 18% | 14.6 | 1.1 | 8% | -0.3 | 0.2 | -83% |
| Accommodation and food services | Services | 9.8 | 2.0 | 20% | 14.7 | 1.7 | 12% | 39.7 | 3.6 | 9% |
| Publishing, audiovisual, radio and television production | Services | 0.0 | 0.0 | 22% | 0.4 | 0.0 | 7% | 0.1 | 0.0 | 15% |
| Telecommunications | Services | 0.5 | 0.0 | 2% | 1.5 | 0.1 | 5% | 0.0 | 0.0 | -202% |
| IT and other information services | Services | 0.1 | 0.0 | 5% | 1.6 | 0.1 | 8% | 0.0 | 0.0 | 28% |
| Financial and insurance activities | Services | 0.2 | 0.0 | 9% | 2.5 | 0.1 | 4% | -0.1 | 0.0 | -49% |
| Real estate activities | Services | 0.3 | 0.0 | 9% | 2.5 | 0.1 | 4% | 0.3 | 0.0 | 14% |
| Professional and technical activities | Services | 1.2 | 0.1 | 10% | 15.0 | 1.3 | 9% | 1.3 | 0.2 | 16% |
| Scientific research and development | Services | 0.6 | 0.1 | 18% | 3.2 | 0.1 | 3% | 1.2 | 0.2 | 16% |
| Other service activities | Services | 0.7 | 0.3 | 36% | 6.8 | 0.3 | 4% | 5.1 | 0.5 | 10% |
| Public administration and defense; compulsory social security | Services | 33.1 | 0.1 | 0% | 33.1 | 0.0 | 0% | -0.3 | 0.1 | -32% |
| Education | Services | 0.6 | 0.0 | 8% | 1.7 | 0.0 | 2% | 0.1 | 0.1 | 57% |
| Health and social work activities | Services | 1.1 | 0.1 | 7% | 19.2 | 1.9 | 10% | -0.8 | 0.1 | -16% |
| Arts, entertainment, and recreation | Services | 0.5 | 0.1 | 19% | 2.4 | 0.1 | 3% | 1.5 | 0.2 | 11% |
| Other service activities | Services | 0.3 | 0.1 | 27% | 4.2 | 0.1 | 1% | -1.2 | 0.1 | -11% |

Source. Own elaboration