INTEGRATING AN MRIO HYDRO-ECONOMIC MODEL WITH A PHYSICALLY-BASED HYDROLOGICAL MODEL TO CHARACTERIZE WATER SCARCITY IN LOCAL ECONOMIES OF CENTRAL ITALY

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Contents

I. Objetives

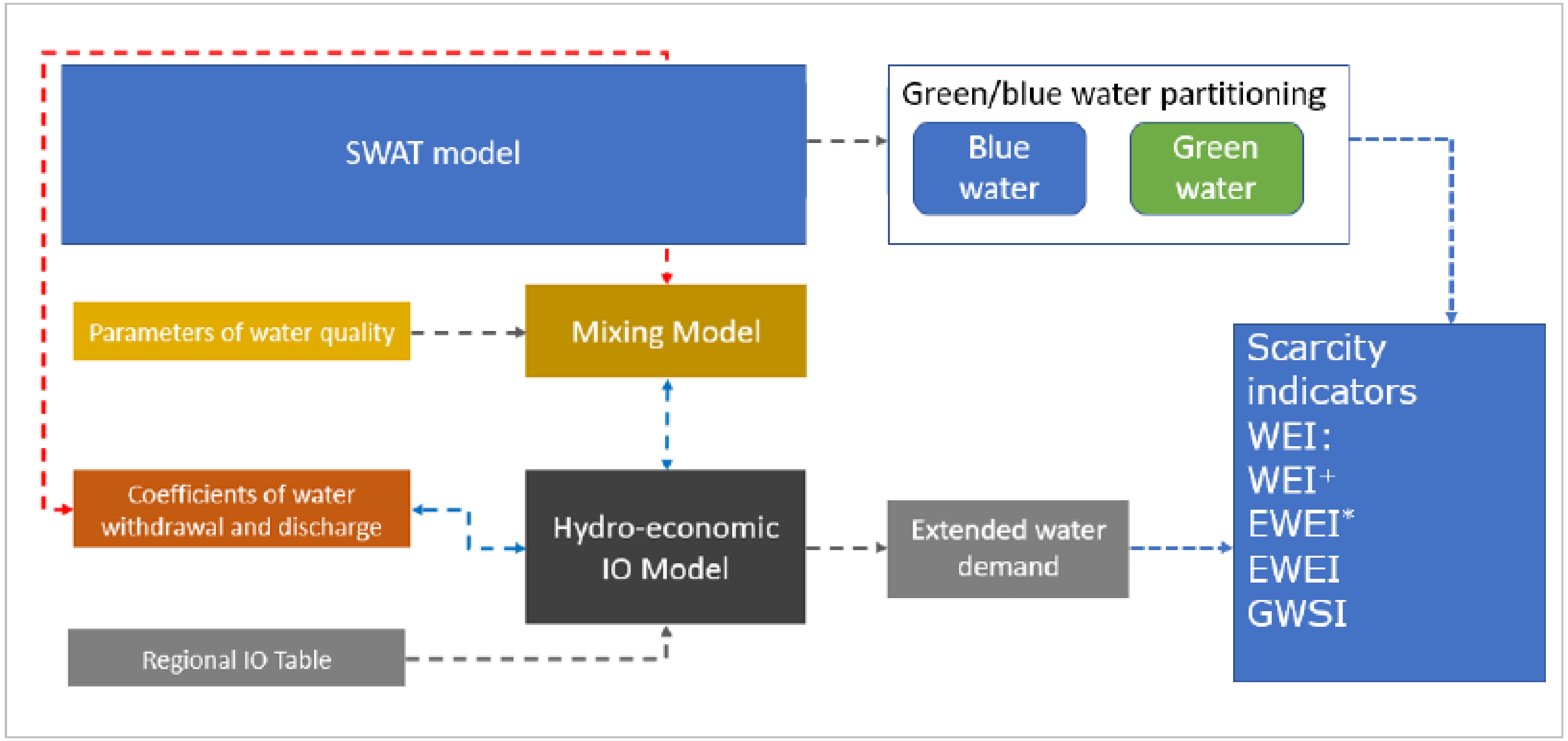
Objetives

- Integrate physical hydrological modeling (SWAT) with a multiregional input–output hydro-economic model (MRIO) to assess water demand and supply across local labor systems (LLS).
- Harmonize spatial units by aligning hydrological sub-basins with economic regions (LLS) to enable geographically relevant water resource analysis.
- Evaluate water scarcity using multiple indicators, capturing the interplay between green, blue, and gray water, and accounting for both natural and feasible supply conditions.

I. Methodology

Scheme of the model

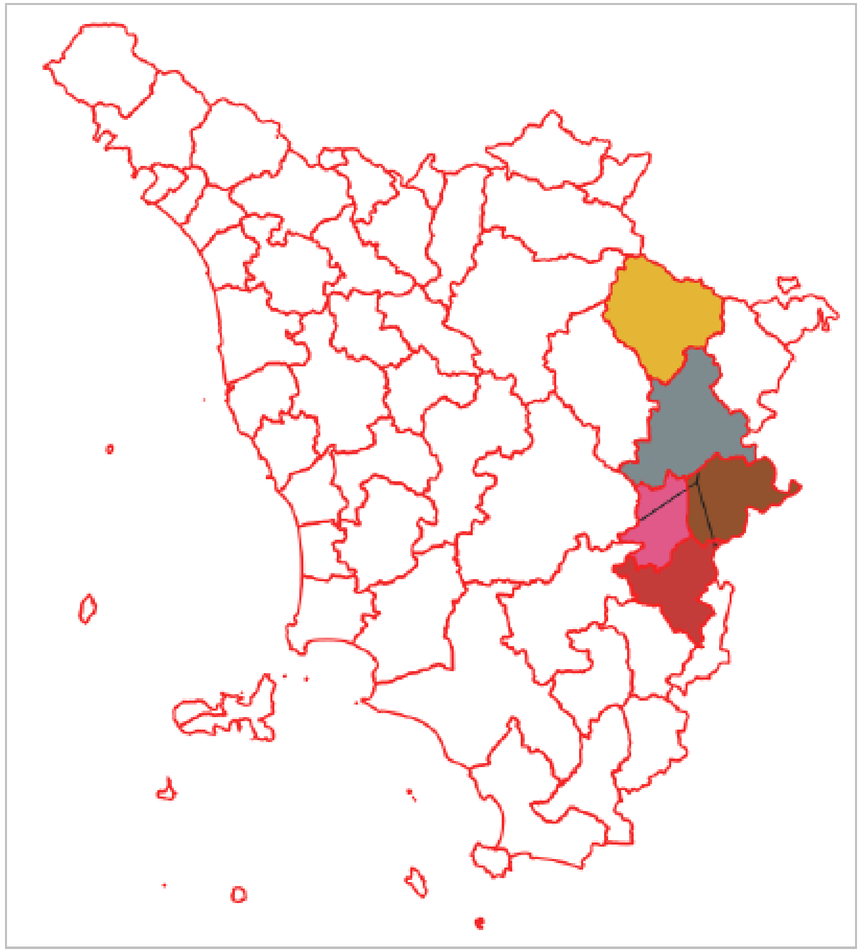
Figure 1. Schematic representation of the methodology



Source: Own elaboration

Study area

Figure 2. Study area (5 LLS)



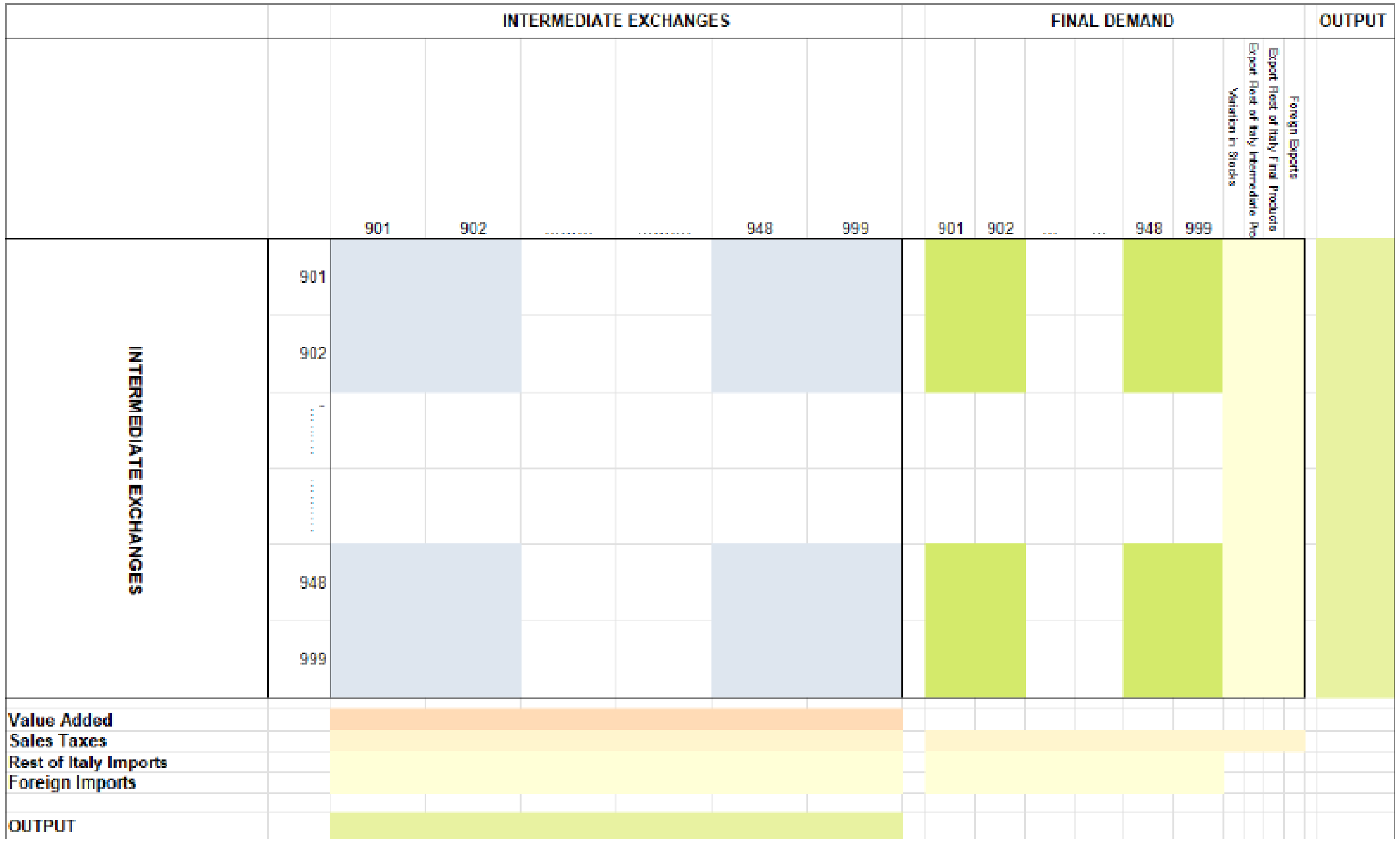
Source: Own elaboration

Figure 3. Sub-basins (5 LLS)

Source: Own elaboration

MRIO table

Figure 4. Structure of the IRIO table of Tuscany



Source: own elaboration based on IRPET (2021)

Water demand

- Withdrawals
- Net demand
- Extended demand

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

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

$$e_{k,i,t}^s = e_{k,i}^s + \left[F_{k,i,t}^s(S_t^s) + R_{k,i,t}^s\ (S_t^s) + H_{k,i,t}\left[I_t^s, R_t^s, R_{k,i,t}(S_t^s)\right] \right] \cdot x_i^s$$

Agriculture

$$F^s_{gw,i,t}(S^s_t) = \begin{cases} \dfrac{\delta^s_i \cdot \left(f^{s,irr}_{sm,i} \cdot x^s_i - SM^s_t\right) \cdot \gamma^s_i}{x^s_i} & if \;\; S^s_t < f^{irr}_{hc,i} \cdot x^s_i \\ 0 & if \;\; S^s_t \geq f^{irr}_{hc,i} \cdot x^s_i \end{cases}$$

$$F^s_{sw,i,t}(S^s_t) = \begin{cases} \dfrac{\eta^s_i \cdot \left(f^{s,irr}_{sm,i} \cdot x^s_i - SM^s_t\right) \cdot \gamma^s_i}{x^s_i} & if \;\; S^s_t < f^{irr}_{hc,i} \cdot x^s_i \\ 0 & if \;\; S^s_t \geq f^{irr}_{hc,i} \cdot x^s_i \end{cases}$$

$$F^s_{sm,i,t}(S^s_t) = \begin{cases} \dfrac{SM^s_t - f^{s,irr}_{sm,i} \cdot x^s_i}{x^s_i} & if \;\; S^s_t < f^{irr}_{hc,i} \cdot x^s_i \\ 0 & if \;\; S^s_t \geq f^{irr}_{hc,i} \cdot x^s_i \end{cases}$$

Grey water

$$w_{k,i,t}^{s} = \frac{u_{k,i,t}^{s}}{x_i^{s}}$$

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

$$\pi_{gw,t}^{s} \equiv \frac{I_t^{s}}{I^{s}}$$

$$\pi_{sw,t}^{s} \equiv \frac{R_t^{s}}{R^{s}}$$

$$c_{0_{k,t}}^{\ s} = \begin{cases} c_{0_k}^{\ min} & if\ \pi_{k,t} \le \pi_k^{min} \\ a \cdot \pi_{k,t} + b & if\ \pi_k^{min} < \pi_{k,t}^{s} \\ c_{0_k}^{\ max} & if\ \pi_{k,t} \ge \pi_k^{max} \end{cases}$$

$$c_{s_{k,t}}^{\ s} = \begin{cases} c_{s_k}^{\ s} & if\ \ c_{0_{k,t}}^{\ s} \le c_{s_k} \\ c_{0_{k,t}}^{\ s} & if\ \ c_{0_{k,t}}^{\ s} > c_{s_k} \end{cases}$$

Water supply

Natural ecological supply (ES) refers to the long-term natural water supply net of the ecological flow requirement.

$$ES^s = \bar{I}^s + (1 - E)\bar{R}^s$$

The estimation of feasible water supply follows the methodology proposed by Rocchi et al. (2021), which incorporates environmental, institutional, and technical constraints into the natural supply of surface and groundwater.

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

$$R_t^{s,feas} = \left\{ \begin{array}{cc} R_t^s - E\bar{R}^s & if \;\; E\bar{R}^s \leq R_t^s \leq M^s\bar{R}^s + E\bar{R}^s \\ M^s\bar{R}^s & if \;\; R_t^s > M^s\bar{R}^s + E\bar{R}^s \\ 0 & if \;\; R_t^s < E\bar{R}^s \end{array} \right\}$$

Green water supply

Green water supply is estimated based on soil moisture (SM) and evapotranspiration (ET) (Pacetti et al., 2021). However, since this study focuses on green water availability for the agricultural sector during the irrigation period, two adjustment factors are applied: the percentage of agricultural area in each LLS (β_A^s) and the number of irrigation months (5). Accordingly, the green water availability indicator is defined as:

$$GWA^s = (ET^s + SM^s) \cdot \beta_A^s \cdot \frac{5}{12} \tag{47}$$

Water stress indicators

a) WEI

The WEI corresponds to the ratio between blue water withdrawals of groundwater and surface water, and the long term natural availability net of the ecological flow (natural ecological supply, ES) (European Environmental Agency, 2005).

$$WEI_t = \frac{\sum_{i=1}^{N} \sum_{k=1}^{2} f_{k,i,t}^{s} \cdot x_i^s}{ES^s} \tag{48}$$

b) WEI⁺

The WEI^+, is an upgraded version of the WEI, which incorporates returns from water uses, therefore taking into account the net water demand (Faergemann, 2012; European Environmental Agency, 2020)

$$WEI_t^+ = \frac{\sum_{i=1}^{N} \sum_{k=1}^{2} (f_{k,i,t}^{s} - r_{k,i,t}^{s}) \cdot x_i^s}{ES^s} \tag{49}$$

c) EWEI

The EWEI indicator is estimated as the extended water demand divided by the feasible supply (Sturla and Rocchi, 2022).

$$EWEI_t = \frac{\sum_{i=1}^{N} \sum_{k=1}^{2} (f_{k,i,t}^{s} - r_{k,i,t}^{s} + w_{k,i,t}^{s}) \cdot x_i^s}{I_t^{s,feas} + R_t^{s,feas}} \tag{50}$$

Water stress indicators

d) EWEI*

The EWEI* indicator corresponds to the EWEI calculated using the natural ecological supply in the year of analysis, rather than in the long term. It is defined as the groundwater recharge and surface runoff, minus the ecological flow. This indicator is proposed in the present study.

$$EWEI_t^{*s} = \frac{\sum_{i=1}^{N}\sum_{k=1}^{2}(f_{k,i,t}^{s} - r_{k,i,t}^{s} + w_{k,i,t}^{s}) \cdot x_i^s}{I_t^s + R_t^s - E\bar{R}^s} \quad (51)$$

e) GWSI

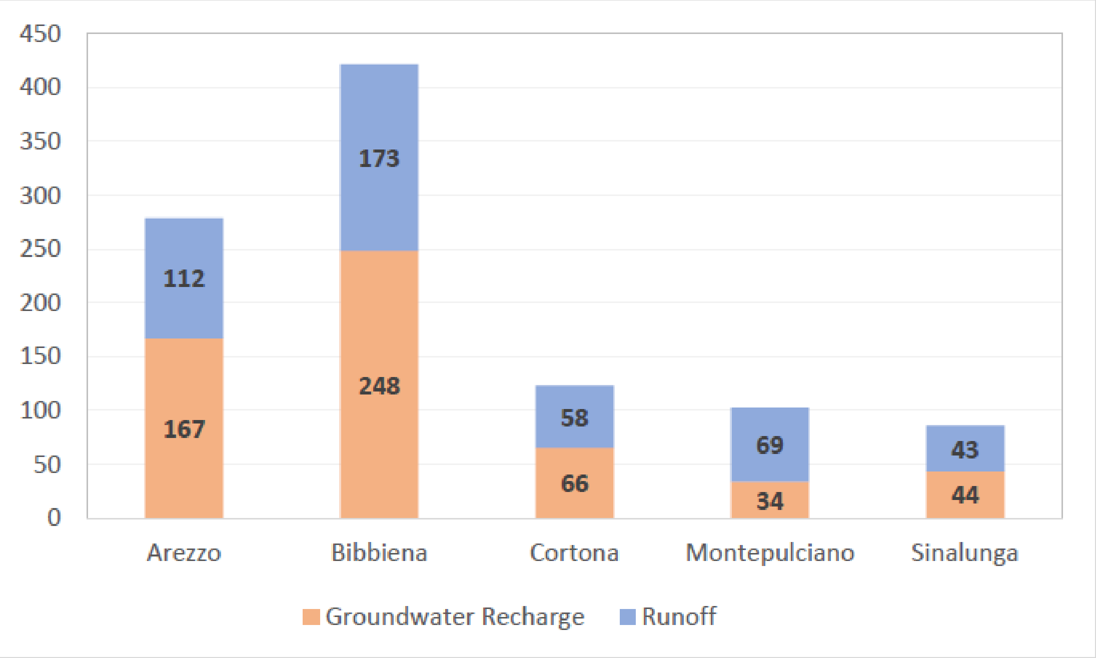
The green water scarcity index (GWSI) is derived based on agricultural soil moisture demand and green water supply. v

$$GWSI_t^s = \frac{\sum_{i=1}^{N} f_{sm,i,t}^{s} \cdot x_i^s}{GWA_t^s} \quad (52)$$

III. Results

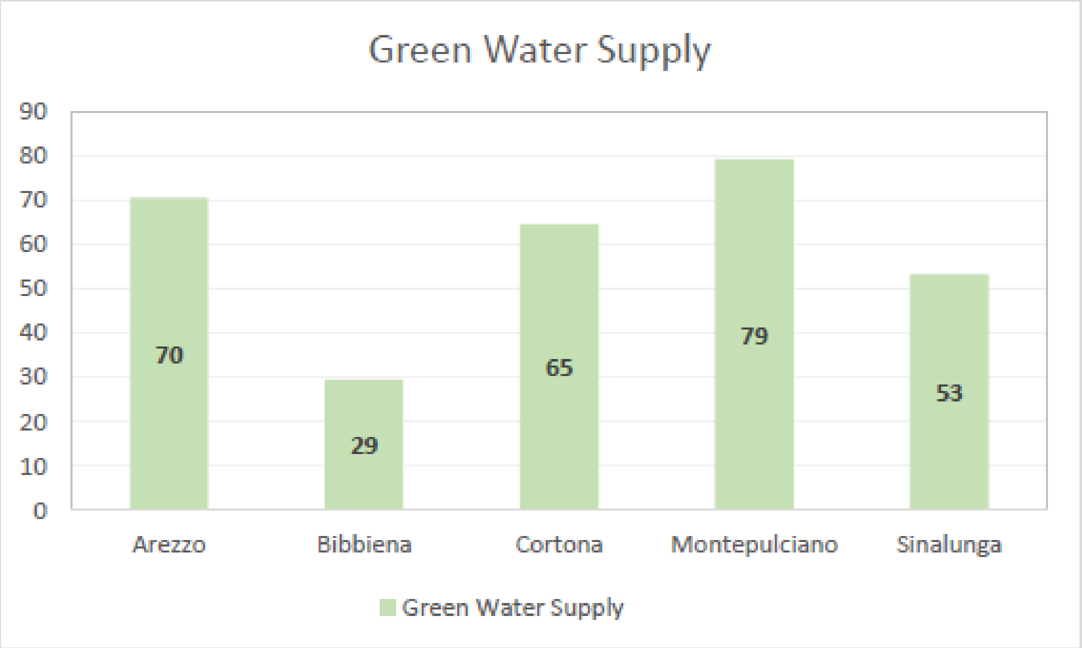
Blue and grey water supply

Figure 5. Natural supply by LLS (blue water)



Source: Own elaboration

Figure 6. Green water supply by LLS



Source: Own elaboration

Water demand

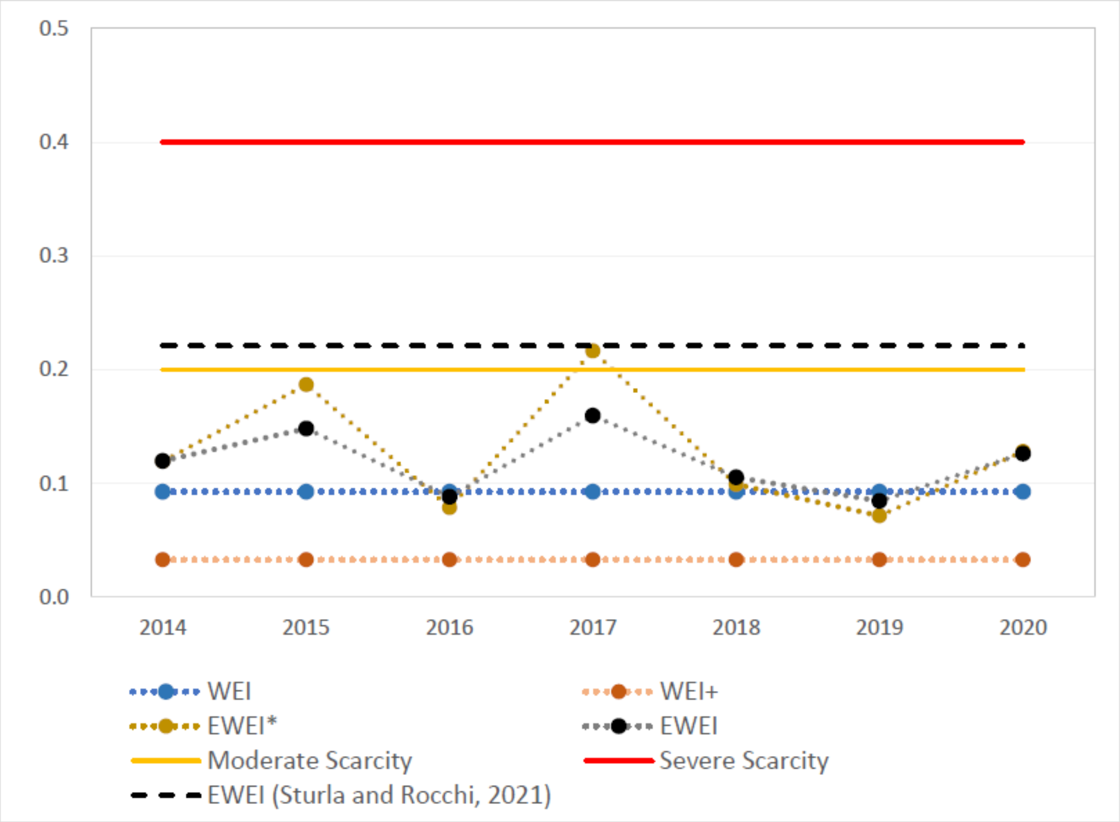
Table 2. Water demand by LLS and year

LLS	Demand Category	2014	2015	2016	2017	2018	2019	2020
Arezzo	WD	12.2	12.2	12.2	12.2	12.2	12.2	12.2
	ND	23.8	23.8	23.8	23.8	23.8	23.8	23.8
	ED	57.9	57.9	57.9	57.9	57.9	57.9	57.9
	GD	30.3	29.7	26.9	29.1	30.3	25.8	30.8
Bibbiena	WD	2.4	2.4	2.4	2.4	2.4	2.4	2.4
	ND	6.4	6.4	6.4	6.4	6.4	6.4	6.4
	ED	26.1	26.1	26.1	26.1	26.1	26.1	26.1
	GD	9.0	9.0	9.2	9.0	8.9	8.0	9.5
Cortona	WD	9.3	14.7	9.4	14.4	12.0	9.8	13.5
	ND	30.2	49.2	30.6	48.3	39.7	32.0	45.1
	ED	65.4	65.4	65.4	65.4	65.4	65.4	65.4
	GD	30.9	47.4	29.9	47.1	37.3	33.0	44.1
Montepulciano	WD	1.4	1.4	1.4	3.3	1.4	1.4	1.4
	ND	6.3	6.3	6.3	16.2	6.3	6.3	6.3
	ED	79.0	79.0	79.0	79.0	79.0	79.0	79.0
	GD	7.5	7.5	7.2	16.3	6.7	6.7	7.5
Sinalunga	WD	4.0	6.6	4.4	7.8	6.0	4.1	4.8
	ND	10.6	23.6	12.4	30.0	20.9	10.9	14.4
	ED	51.9	51.9	51.9	51.9	51.9	51.9	51.9
	GD	12.7	23.5	13.1	28.5	20.0	11.4	15.7

Source: Own elaboration

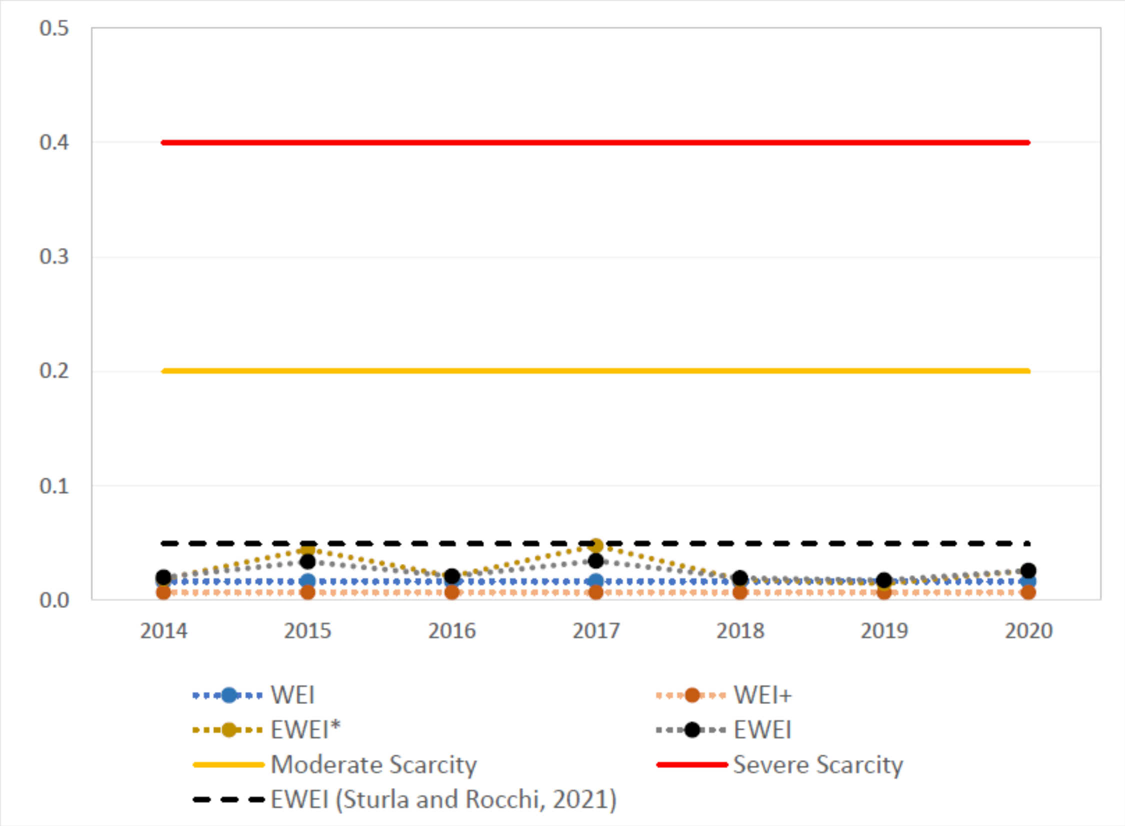
Blue and grey water scarcity indicators

Figure 7. Scarcity indicators (Arezzo)



Source: Own elaboration

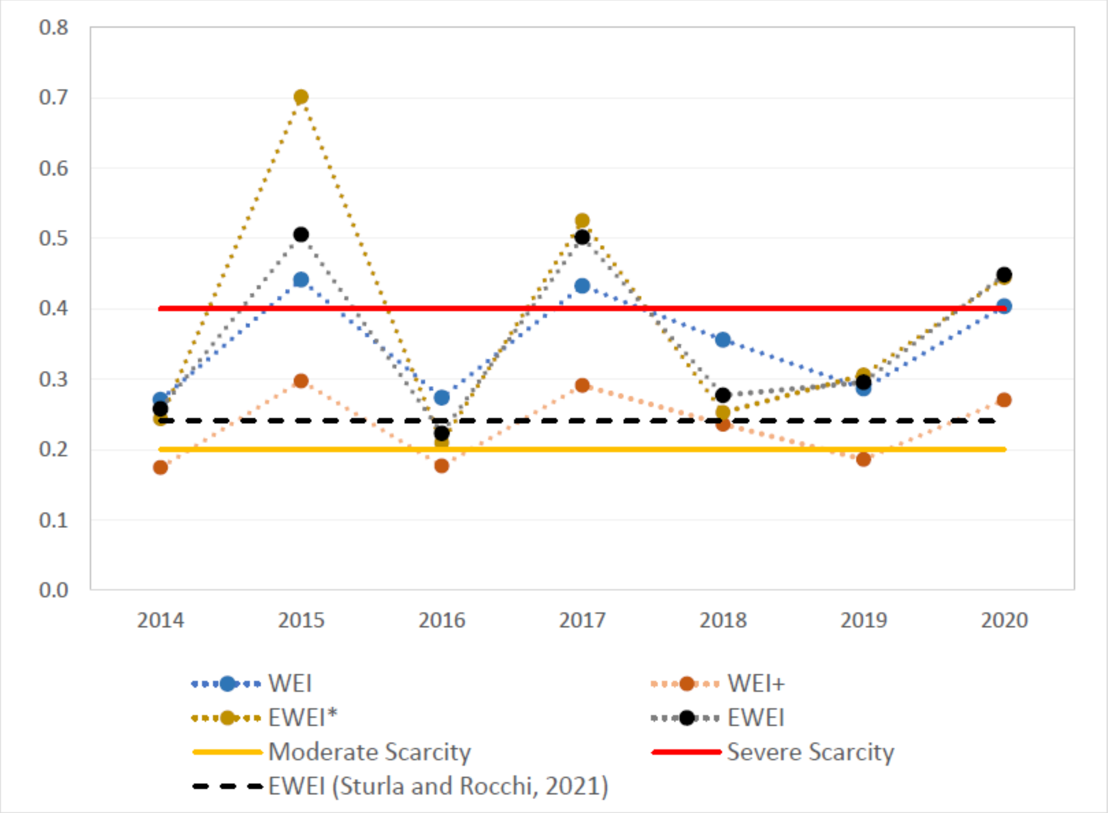
Figure 8. Blue and grey water scarcity indicators (Bibbiena)



Source: Own elaboration

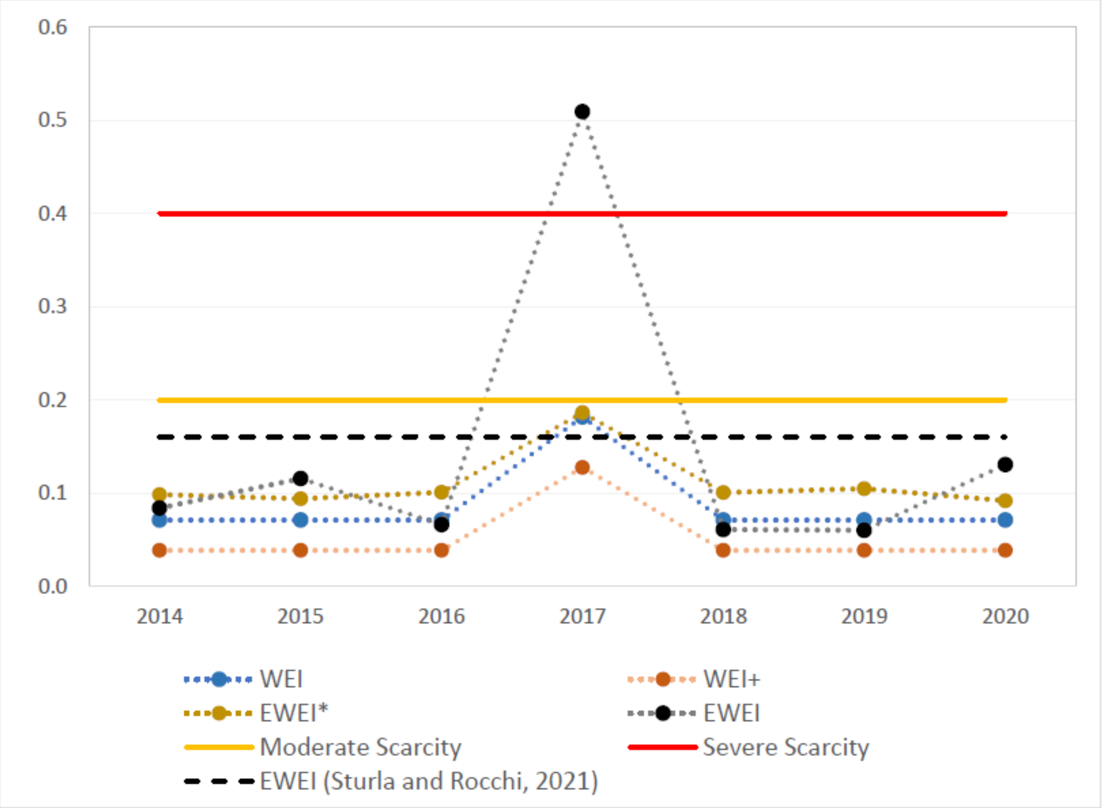
Blue and grey water scarcity indicators

Figure 9. Blue and grey water scarcity indicators (Cortona)



Source: Own elaboration

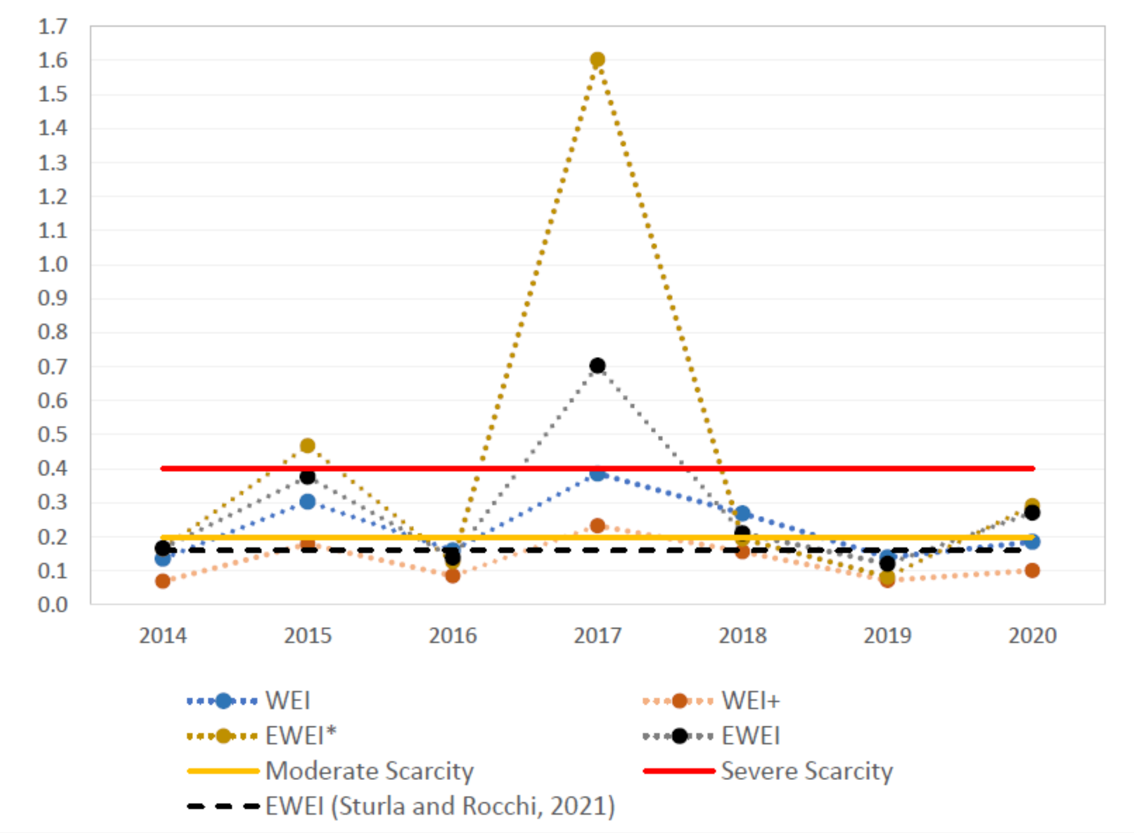
Figure 10. Blue and grey water scarcity indicators (Montepulciano)



Source: Own elaboration

Blue and grey water scarcity indicators

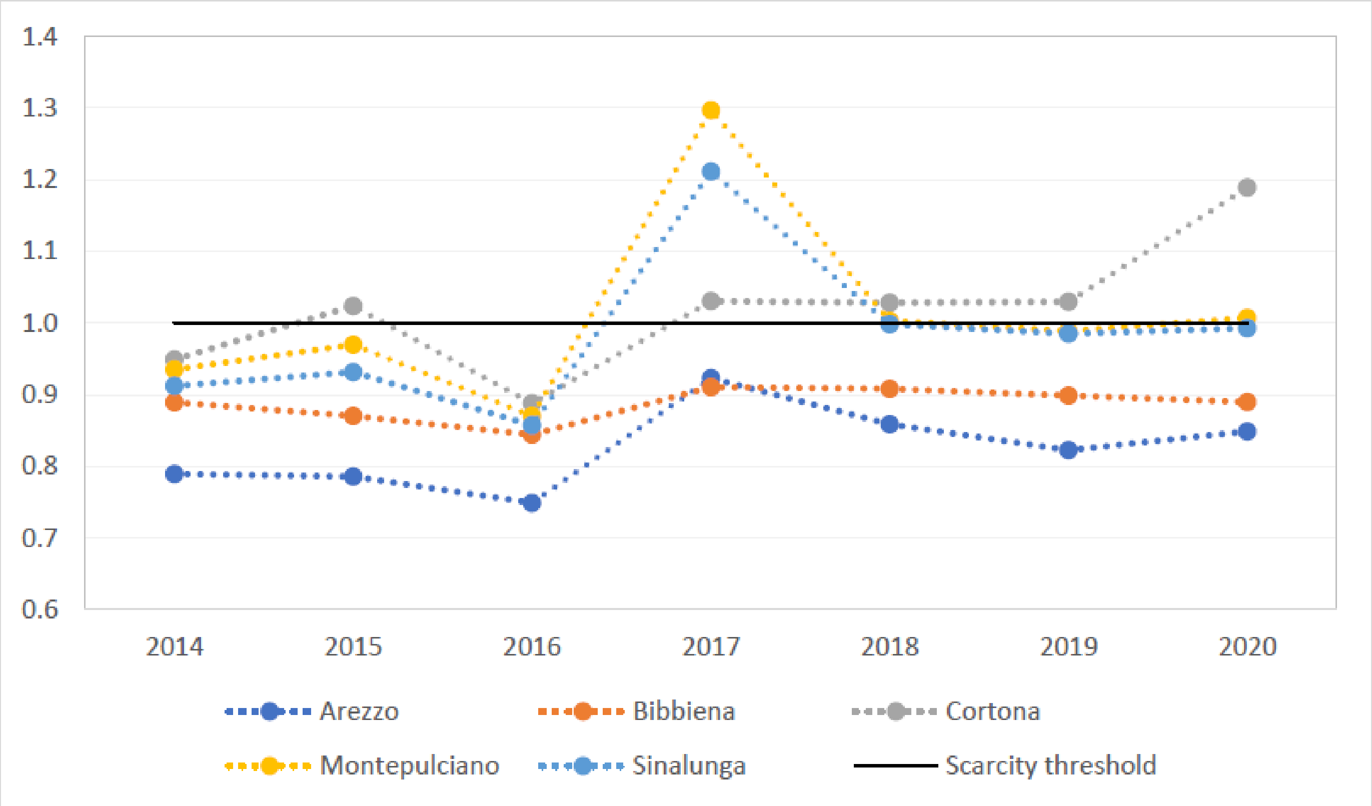
Figure 11. Blue and grey water scarcity indicators (Sinalunga)



Source: Own elaboration

Green water scarcity indicator

Figure 12. Green water scarcity indicator (All LLS)



Source: Own elaboration

IV. Conclusiones

Conclusions

- The integrated hydro-economic model allows a realistic simulation of green-to-blue water substitution, improving upon previous models by explicitly estimating soil moisture scarcity rather than using precipitation as a proxy.
- New indicators (EWEI and GWSI) offer a more nuanced assessment of water scarcity*, capturing dynamics like reduced dilution capacity and the difference between ecological and feasible water supply.
- The model reveals that some local economies face severe water scarcity, especially under dry conditions, while others show minimal stress—highlighting the importance of spatially detailed assessments.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