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Are we at a watershed? An integrated assessment model for Italy

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Abstract

As global warming intensifies, the availability of water poses an increasing challenge for countries such as Italy. Italy's socioeconomic structure places significant pressure on domestic and international water resources, especially through imports. In 2014, more than half of Italy's total water footprint (WF, 126,453 Mm^3) was sourced from abroad. The agricultural sector is the largest contributor, accounting for 78.6% of the WF—70.9% domestically and 83.7% externally. As climate change concerns grow, efficient water management is crucial, yet research often overlooks the complex interactions between socio-economic factors and water resources.

To address this gap, we extend the EUROGREEN model by integrating a new hydrological module that explores the water-economy nexus. This module evaluates feedback loops and the effects of policy measures on both water and economic outcomes, providing a comprehensive view of their interdependencies. The model introduces an Extended Water Exploitation Index (EWEI), considering variations in water stress by fully accounting

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for grey water demand and supply constraints. We present initial results from a base scenario and several alternatives, analyzing the impact on agricultural productivity, industrial output, and regional water scarcity.

The base scenario suggests that endogenous growth and climate change could exacerbate water stress, underscoring the need for integrated water management strategies to ensure socioeconomic stability.

1 Introduction

Water, unlike fossil resources, is not fully consumed or stored like a traditional stock. It also doesn't fit neatly into the category of renewable resources, as a portion is locked away in nonrenewable aquifers, such as the subterranean lakes beneath the Sahara Desert. Humanity relies primarily on fresh water but also uses saline water. Interestingly, 90% of the global water footprint stems from rain and soil moisture, known as green water, while only 10% comes from aquifers and surface water, classified as blue water (Hoekstra and Mekonnen 2012). However, fresh water constitutes a mere fraction of the 3% of Earth's water that isn't saline. This small share is distributed among glaciers, ice caps, groundwater, soil moisture, and surface water (Roson et al. 2021). Furthermore, just 22% of this fresh water is accessible for human use within socioeconomic systems (Shiklomanov 1993).

Globally, agriculture accounts for roughly 90% of fresh water use and 70% of humanity's total water footprint (Falkenmark and Rockström 2004). The largest part this amount, however, is green water used by rain-fed agriculture: indeed, crops' cultivation is the only production activity able to exploit this component of the global water resources. Despite its ability to inflow in the food supply chain this essential resource that would not be otherwise available, agriculture is also dependent on blue water resources for irrigation (Tamea et al. 2021), when green water scarcity hinders the deployment of the full output potential of crops. The demand for blue water for irrigation competes in the allocation of renewable water resources among different production activities and is likely to exacerbate local conditions of scarcity, contributing to the overexploitation with the consequent adverse effects on ecosystem sustainability and socio-economic development. However, blue water demand has steadily grown over the past century and is projected to rise by 20-30% by 2050, an icrease mainly driven by manufacture and energy sectors and by municipal and domestic uses (UNESCO 2021). In addition to green and blue water, human activities also involve a grey water demand. This refers to the volume of water required to dilute pollutants to a level that restores water quality to acceptable standards within the Earth's water cycle. As pollution increases, so too does the demand for grey water, reflecting the growing burden placed on ecosystems to process and assimilate waste. At the same time, the availability of water is expected to decline, becoming ever more spatially uneven due to climate change, which will significantly impact global food supplies (*The State of Food Security and Nutrition in the*

World 2019 2019). According to UN estimates, about 2 billion people live in water-scarce areas, a number expected to reach 3 billion by 2050. Since water has no viable substitute and is an essential resource, this growing imbalance risks triggering geopolitical tensions and socio-economic instability, underscoring the importance of effective water resource management (Iannucci et al. 2021).

While Europe is better equipped to address water challenges compared to many Global South countries, it has not been immune to the effects of climate change. Over the last three decades, Europe has faced a rising number of droughts, affecting 11% of its territory and 17% of its population. Water scarcity is particularly acute in Southern Europe, with Italy already experiencing mild water stress that is expected to worsen (Lavrnić et al. 2017). Notably, half of Italy's water footprint is external, exerting pressure on the water resources of other countries through virtual water trade (Allan 1998). The three top countries exporting virtual blue and grey water to Italy were China (15.8%), India (4.6%) and USA (4.3%). The production of goods and services consumed in Italy in 2014 required the use of 136,543 Mm3 of water (Sturla, Ciulla, et al. 2023). This amount was composed for the largest part (about 64.3%) of water from precipitation and soil moisture (green water), while renewable groundwater and surface water sources (blue water) provided about the 20% (26,670 Mm3 of which about 50% of internal resources) of total requirements. The exploitation of blue water generated an additional requirement of 22,076 Mm3 (16.2%) to restore the quality of freshwater renewable sources (grey water), for the largest part (about 70%) in other countries. Interestingly, a relevant share of virtual flows imported to support Italian consumptions concern blue and grey water withdrawn in condition of scarcity.

While studies suggest that global water withdrawals will increase to 6,900 billions m3/year by 2030 above the current 4,500 m3/year Young et al. 2015, Distefano and Kelly Distefano and Kelly (2017) show that IPCC scenarios on income growth are not sustainable once integrated limitations due to water scarcity. There is indeed a significant gap in understanding the complex reciprocal interactions and feedback loops between socio-economic variables and water systems, with few studies focusing on a long-term perspective (Tello et al. 2012; Duarte et al. 2014a; Duarte et al. 2014b; Duarte et al. 2019). Much of the existing literature tends to focus on one-way interactions, either from socioeconomic impacts on water resources (Katz 2021) through structural change (Duarte et al. 2021), technical change (Scott et al. 2014) or international trade (Allan 2011) or vice versa (Barbier 2004; Brown et al. 2006; Distefano, Riccaboni, et al. 2018). However, the income-water relationship is bi-directional: economic growth can affect water demand and supply while water availability and quality may reduce income as a result of productivity limitations. This casting doubt on a careless extension of Kuznets curve to water resources and in general on any *a priori* assumption of a single water-income relationship. This study attempts at documenting this context-specific and entangled relationship by focusing on the Italian case using simulation tools.

EUROGREEN combines Post-Keynesian macroeconomics and ecological economics into a dynamic macro-simulation model that enables the assessment of various scenarios and public policies regarding their social, economic, and ecological impacts. Among other applications, it has been utilized in France to evaluate the relative merits of green growth, social equity policies (similar to those of the Green New Deal), and degrowth, focusing on the evolution of key variables (D'Alessandro et al. 2020b). The economy is demand-driven, with factors of production not fully utilized. The investment function depends on the capacity utilization gap, profit rate, depreciation rate, and an autonomous component that does not enhance capacity, which has been identified in the literature as essential for addressing Harrodian instability. The model integrates financial and real sectors through a portfolio model that reflects the demand for financial assets among the population, segmented into 13 groups based on skill levels and occupational status to analyze the distributional impacts of various public policies. Additionally, the model employs input-output methodology using WIOD tables to disaggregate production across ten sectors, specifically modeling the two industries within the energy sector (fossil fuels; electricity and gas). It incorporates endogenous technical change that influences the technical coefficients of each industry.

EUROGREEN is developed to simulate complex dynamics between the social, the economic and the ecological dimensions of a given national economy. In order to study the water-economy nexus, we apply it to Italy and introduce a new module to account for the water footprint of the productive structure. This module assesses an Extended Water Exploitation Index (EWEI) that considers variations in hydric stress (Rocchi et al. 2024; Sturla and Rocchi 2024). Our approach diverges from existing literature in two significant ways. First, building on a suggestion by Guan et al. (2008), it models an extended water demand by sectors, integrating not only green and blue water withdrawals (Garcia-Hernandez et al. 2021), but also discharges (Camara et al. 2020) and, crucially, grey water demand. This grey water represents the volume required by sectors to restore the quality of discharged water. Second, blue water demand endogenously varies in those sectors where water needs depend on the natural variability of hydrological conditions (e.g. blue water for irrigation, grey water for dilution). Finally, we model a *feasible* water supply that acknowledges technical, institutional, and environmental constraints to the natural water supply. Water may be available but not accessible due to technical limitations in capturing and storing water, restrictions on maximum withdrawals based on current concession states, or minimum requirements necessary for maintaining a sustainable state of water bodies (minimum ecological run-off of surface water, non-declining stock of ground water).

In what follows, we discuss the main innovations our study introduces to the original EUROGREEN model calibrated for Italy, as depicted by Fig. 1.

2 Model

Earlier versions of EUROGREEN (Cieplinski et al. 2021; Distefano and D'Alessandro 2023) recognized that "all models are wrong" (Sterman 2002; Saltelli et al. 2014): they can only provide a partial representation of reality. Hence, some assumptions regarding exogenous trends, grounded on historical data, or external shocks must be made, including *international trade*, as the model only includes the rest of the world without considering bilateral trade; *labour force*, aligned with a skill-specific external trend informed by data reflecting shifts in educational attainment; *employment contracts*, based on the assumption that all labour is employed under full-time contracts; and *COVID-19 shocks* which have influenced the economy in 2020, causing a downturn in demand and investments as well as a sudden increase in public spending and associated levels of deficits.[1]

2.1 Water demand

This section presents the formulation of the extended demand in the Input-Output (IO) model developed by Rocchi et al. (2024), modeling changes in extended water demand considering hydrological variability.

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[1] Modelling the impact of the pandemic is beyond the scope of this model; therefore, we only introduce external shocks to the main macroeconomic variables as described in Table A2.2 in Appendix A.1.

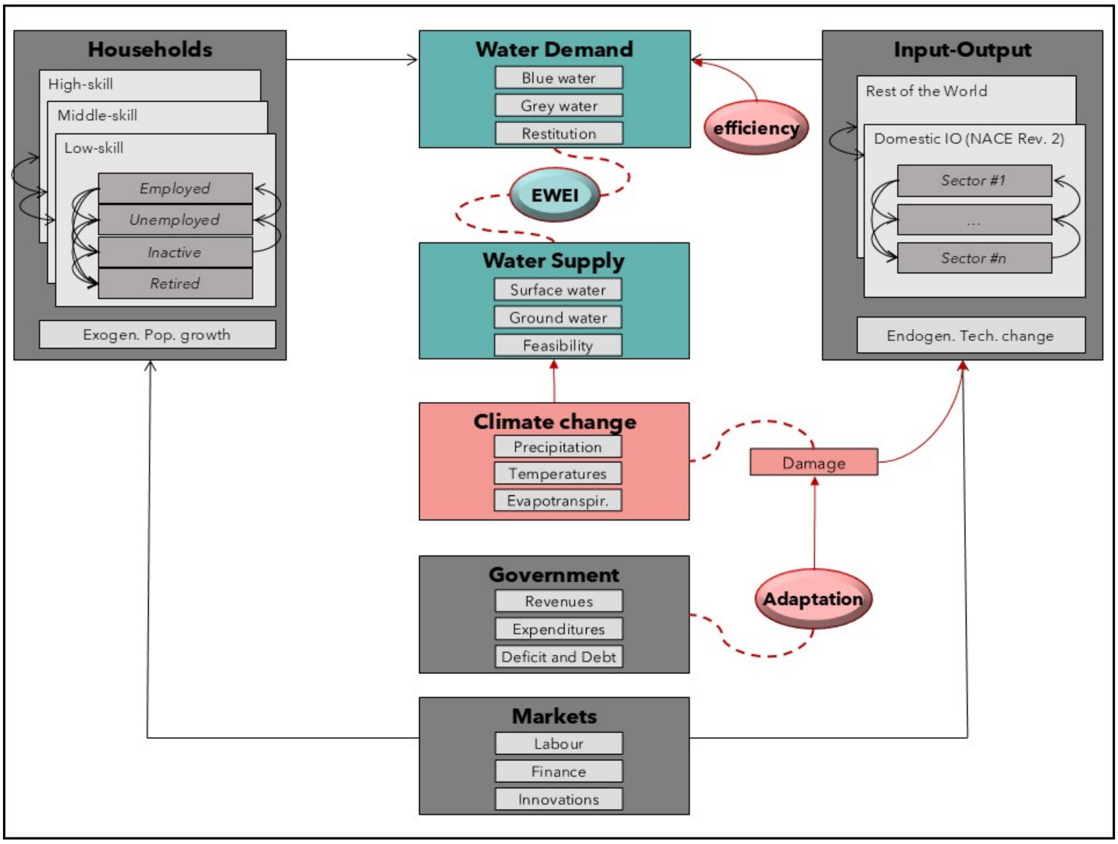

Figure 1: Macroview. The figure shows the key variables and connections of the current extended version of the EUROGREEN model (D'Alessandro et al. 2020a). by including the hydrological module and the impact of climate change (RCP 6.0) on water resources and economic activities.

The extended water sectoral (s) demand vector W_k from water body k (surface water or groundwater) is defined as:

$$W_s^k = (\omega_s^k - \rho_s^k + \xi_s^k) \cdot x_s \tag{1}$$

where ω_s^k, ρ_s^k, ξ_s^k are the vectors of sector coefficients for the water extraction, restitution and dilution, respectively, while x_s is the total sectoral output in monetary terms. This formula estimates extended surface water and groundwater demands for agriculture and other economic sectors (see Table A2.1 in Appendix A.1).

2.1.1 Adjustment of coefficients based on hydrological variability

While blue only represents for 10% of global water footprint, it accounts for 25% of internal water resources used by italian agriculture. In addition, the shares of green and blue components within the agricultural water footprint are highly dependent on hydro-climatic parameters such as precipitations and evapotranspiration, hence temperature (Tamea et al. 2021). When the annual precipitation is less than the average precipitation ($\overline{P}$, from historical series) there is a deficit of green water in agriculture that must be supplied with blue water. In the case that precipitation is higher than average, blue water requirements do not change. On the other hand, when evapotranspiration is greater (less) than the average evapotranspiration, more (less) blue water is required to meet the needs of the crops. These changes are assumed proportional and only affect irrigated agriculture.

Based on the synthetic series of precipitation, temperature and evapotranspiration, it is possible to adjust the water extraction coefficients of irrigated agriculture year by year. If the average extraction coefficients of surface and groundwater in the irrigated agricultural sector are ω^{sw}_{agr} and ω^{gw}_{agr}, respectively, the feasible extraction coefficients for year t (dry) will be:

$$\hat{\omega}^{sw}_{agr}(t) = \begin{cases} \omega^{sw}_{agr} + \pi^{sw}_{agr} \cdot (\frac{\overline{P}-P(t)}{\overline{P}} \cdot \gamma \cdot \hat{\zeta} + \frac{E(t)-\overline{E}}{\overline{E}} \cdot \omega^{sw}_{agr}) & \text{if } P(t) < \overline{P}, \\ \\ \omega^{sw}_{agr} + \pi^{sw}_{agr} \cdot (\frac{E(t)-\overline{E}}{\overline{E}} \cdot \omega^{sw}_{agr}) & else, \end{cases} \tag{2}$$

$$\hat{\omega}^{gw}_{agr}(t) = \begin{cases} \omega^{gw}_{agr} + \pi^{gw}_{agr} \cdot (\frac{\overline{P}-P(t)}{\overline{P}} \cdot \gamma \cdot \hat{\zeta} + \frac{E(t)-\overline{E}}{\overline{E}} \cdot \omega^{gw}_{agr}) & \text{if } P(t) < \overline{P}, \\ \\ \omega^{gw}_{agr} + \pi^{gw}_{agr} \cdot (\frac{E(t)-\overline{E}}{\overline{E}} \cdot \omega^{gw}_{agr}) & else, \end{cases} \tag{3}$$

where $\hat{\zeta}$ corresponds to the green water utilization coefficient of agriculture, π^{k}_{agr} is the proportion of water body k with respect to the total blue water extracted by the agriculture sector, and γ is a factor that expresses the efficiency in the use of water for irrigation.

When precipitation is lower than average, agriculture captures less green water. In this way, the coefficient must also be adjusted as

$$\hat{\zeta} = \begin{cases} \frac{\overline{P}-P(t)}{\overline{P}}\zeta, & \text{if } P(t) < \overline{P}, \\ \\ 0, & else. \end{cases}$$

As blue water withdrawals by irrigated agriculture change, the water restitution coefficients of this sector must also be adjusted. The new coefficient of restitution (surfacewater only) will be:

$$\hat{\rho}^{sw}_{agr}(t) = (\hat{\omega}^{gw}_{agr}(t) + \hat{\omega}^{sw}_{agr}(t)) \cdot \rho^*, \tag{4}$$

$$\tag{5}$$

$$\rho^* = \frac{\rho^{sw}_{agr}}{\omega^{gw}_{agr} + \omega^{gw}_{agr}}. \tag{6}$$

Water efficiency is considered as a cornerstone of green growth strategies. We include an exogenous technological advancements that reduce the water content embedded in final products. Under the case "Δ^{20}_{ω}" we assume a gradual and linear reduction in the water use efficiency coefficient (γ) between 2024 and 2050, achieving total reductions of 20% by the end of the period. This is a "heroic" (Georgescu-Roegen 1971) assumption but enables us to evaluate the practical outcomes of very optimistic water efficiency strategy.

2.1.2 Grey water

The coefficient of dilution water for the sector s, water body k and year t ($w^k_s(t)$) is estimated based on the restitution coefficient and a mixing model of mass balance for COD concentration. Namely

$$w^k_s(t) = \frac{\delta^k_2 \cdot c^k_{p,s} - \hat{c}^k_s(t)}{\delta^k_1 \cdot \hat{c}^k_s - c^k_0(t)} \cdot \rho^k_s(t), \tag{7}$$

where δ^k_1 is the total reaction rate of pollutants after entering the water body k , δ^k_2 is the pollution purification rate before entering the water body k , $\rho^k_s(t)$ is the discharges into the water body k associated with industry s for year t, $c^k_{p,s}$ is the COD concentration in the discharges to the water body k associated with industry s , $\hat{c}^k_s(t)$ is the standard COD concentration in water body k for year t , and $c^k_0(t)$ is the COD concentration in water body k for year t.

In the agricultural sector, the reliance on ρ^* results in a dependence on hydrological variability, influenced by fluctuations in precipitation (P) and evaporation (E). Conversely, within other economic sectors, neither discharges nor extractions exhibit dependence on hydrological variability. The dilution water coefficient is contingent upon runoff (R) and groundwater recharge (I). This relationship, through $c^k_0(t)$, influences the Chemical Oxygen Demand (COD) concentration in aquatic environments. An expression is proposed for this term that accommodates reductions in COD concentration during wetter periods and elevations in COD concentration during drier periods; this proposition is grounded in the premise that the discharge of organic matter is a function of the economic system, which is fixed in this study. To characterize $c^k_0(t)$, a variable is defined, based on hydrological components, as the ratio of the runoff (or groundwater recharge) in year t to the mean runoff (or groundwater recharge). Namely

$$\pi^{gw}(t) \equiv I(t)/\overline{I}, \tag{8}$$

$$\pi^{sw}(t) \equiv R(t)/\overline{R}. \tag{9}$$

A linear model is assumed to represent the relationship between COD concentration in water bodies before discharge and the hydrology. The following linear relation is considered for $c^k_0(t) \in (c^K_{min}, c^K_{max})$:

$$c^k_0(t) = \alpha \cdot \pi^k(t) + b(\alpha), \tag{10}$$

$$\alpha = \frac{c^k_{max} - c^k_{min}}{\pi^k_{min} - \pi^k_{max}}, \tag{11}$$

$$b(\alpha) = \overline{c}^k_0 - \alpha, \tag{12}$$

where c^k_{max} (c^k_{min}) is the maximum (minimum) concentration in water body k , $\overline{c}^k_0$ is the mean concentration in water body k, and π^k_{max} (π^k_{min}) is the ratio of maximum (minimum) volume to average volume in water body k . For concentrations below the minimum and above the maximum, the ratio of the maximum COD concentration to runoff or groundwater recharge is considered constant. Thus, the function representing the COD concentration of water body k in the year t is:

$$c_0^k(t) = \begin{cases} c_{min}^k, & \text{if } \pi^k(t) \leq \pi_{min}^k, \\ \alpha \cdot \pi^k(t) + b(\alpha), & \text{if } \pi_{min}^k < \pi^k(t) < \pi_{max}^k \\ c_{max}, & else. \end{cases} \tag{13}$$

Another endogenous component is $\hat{c}_s^k$, the standard COD concentration in water body k for year t. When COD concentration in water bodies is higher than the standard concentration in average conditions, the standard concentration for the year t is considered to be that of the water body, since in the model the water for dilution comes from the hydrological system. Namely

$$\hat{c}_s^k = \begin{cases} c_s^k, & \text{if } c_0^k \leq c_s^k, \\ c_0^k, & else. \end{cases} \tag{14}$$

The values of the parameters are included in Table A2.3 in the Appendix.

2.2 Water supply

The statistics of total annual temperature (T), precipitation (P) and effective annual evapotranspiration (E) are used considering the period 1951-2022. It is assumed that precipitation follows a normal distribution. From this distribution, synthetic precipitation series are generated, with which evapotranspiration is estimated from a linear relationship. Appendix A.2 provides the details and the values of the parameters used for the econometric estimations.

The equation is as follows:

$$E(P,T) = a_E + \beta_1 \cdot P + \beta_2 \cdot T + \epsilon_E, \tag{15}$$

where $\epsilon_E \sim N(0, \sigma_E^2)$ is a stochastic error.

To determine the annual runoff (R) and the annual groundwater recharge (G), multiple regression is estimated using total precipitation (P) and effective evapotranspiration (E) as explanatory variables. An estimated error term is incorporated based on the regression residuals, which has a normal distribution. The two multiple regressions present good fits to the observed data for the period 1951-2022. Based on these formulas, it is possible to estimate R and I for the historical period (based on the synthetic series of P and E) and for the future period (based on projections of P and E, for climate change). In what follows, the functional relationships and estimated parameters are presented for these two hydrological components.

Namely,

$$R(P,E) = a_R + \beta_3 \cdot P + \beta_4 \cdot E + \epsilon_R, \tag{16}$$

where $\epsilon_R \sim N(0, \sigma_R^2)$ is a stochastic error.

$$G(P,E) = a_G + \beta_5 \cdot P + \beta_6 \cdot E + \epsilon_G, \tag{17}$$

where $\epsilon_G \sim N(0, \sigma_G^2)$ is a stochastic error.

For water supply, the concept of *feasible* supply is considered. This concept, in the case of surface waters, considers environmental (ecological flow, ψ) and technical-institutional (concessions, ϕ) restrictions. In the case of groundwater, the feasible supply corresponds to the long-term average recharge within an admissible extraction range. The formulas for the feasible surface supply is the following:

$$\hat{R}(t) = \begin{cases} R_t - \psi\overline{R} & \text{if } \psi\overline{R} \leq R(t) \leq (\mu+\psi)\cdot\overline{R}, \\ \mu\overline{R} & \text{if } (\mu+\psi)\cdot\overline{R} \leq R(t), \\ 0 & \textit{else}, \end{cases} \tag{18}$$

where $\hat{R}(t)$ is the feasible runoff, μ the maximum volume of concessions as a share of historical average runoff ($\overline{R}$) and $R(t)$ the current volume of runoff in year t.

On the other hand, the feasible groundwater recharge ($\hat{G}(t)$) in year t is given by:

$$\hat{G}(t) = \begin{cases} \overline{G}\cdot(1-\lambda) & \text{if } G(t) \leq \overline{G}\cdot(1-\lambda), \\ \overline{G}\cdot(1+\lambda) & \text{if } G(t) \geq \overline{G}\cdot(1+\lambda), \\ G(t) & \textit{else}, \end{cases} \tag{19}$$

where λ is a parameter defining the range of groundwater feasible availability and $\overline{G}$ the historical average groundwater recharge volume.

The Extended Water Exploitation Index (EWEI) for water body k is then given by the ratio between the extended water demand and feasibly supply.

2.3 Climate change

Since the model only projects national emissions, the evolution of temperatures depends on Representative Concentration Pathways (RCPs), which can be chosen exogenously. The simulations presented henceforth adopt RCP 6.0 which projects global temperature increases between 3 and 3.5ºC by 2100 (IPCC 2007).

2.3.1 Hydrological impact

Climate change is expected to significantly affect precipitation (P), temperature (T), and evapotranspiration (E), with rising temperatures driving higher evapotranspiration and more variable precipitation patterns. These changes are likely to result in more frequent droughts and intense rainfall events, posing risks to water resources, agriculture, and ecosystems worldwide (Legg 2021). In Italy, by 2050, temperatures are projected to rise by 1.5–2.5 °C, with southern regions facing the greatest heatwave intensification. This warming will amplify evapotranspiration, reducing soil moisture and increasing agricultural water stress. Shifts in precipitation patterns will further exacerbate these challenges, threatening the country's water and food security (ISPRA 2021).

Precipitation patterns are projected to change markedly, with southern Italy experiencing a 10–20% annual reduction, while northern regions facing more frequent and intense heavy rainfall. These shifts are expected to cause prolonged droughts in arid areas like Sicily and Puglia, and heightened risks of flooding and soil erosion in the North due to extreme precipitation events. Combined with rising temperatures, these changes would significantly increase evapotranspiration, further reducing water availability in vulnerable regions. Higher evaporation rates would deepen hydrological imbalances, creating serious challenges for water management and agricultural productivity (Ferrari 2022).

Since precipitation (P) and temperature (T) directly influence groundwater recharge and surface water availability, climate change significantly impacts water supply levels. To address these issues, we adopt projections of P and T distributions from Zollo 2019. For each period, values of P and T are drawn from a normal distribution, with variability reflecting the uncertainty generated by multiple hydrological and climate models. This approach introduces an additional layer of uncertainty, beyond the technological progress already integrated into the EUROGREEN model.

2.3.2 Economic damage

Climate damage is defined as the proportional change in production relative to what it would be without global warming. For each simulation period (year), industry-specific damages are sampled from a Beta distribution, following the approach of (Desmet et al. 2015). These climate-induced damages are applied to the technical coefficients in the input-output tables, effectively increasing the inputs required to produce the same output. Consequently, to satisfy a given level of final demand, industries affected by climate change must raise their demand for intermediate goods, which, in turn, drives an increase in the output of upstream industries.

The change in industry output directly affects employment levels. At the aggregate level, the impact of climate change on unemployment and inequality remains complex and non-linear. However, the increased intermediate demand required to meet the same level of final demand leads to a decline in value-added and profits, assuming relatively rigid wages.

Various other consequences of climate change are not directly addressed here. These include, for example, direct financial losses and shifts in demographic patterns. Nonetheless, many effects are considered indirectly. For instance, since industries encompass the public sector and services, increased public health care costs are integrated into the model via heightened technical coefficients in that sector. Moreover, fluctuations in government spending are influenced by changes in tax revenue—stemming from the dynamics of income, value-added, and profits—and by adjustments in unemployment benefits due to labor market trends.

2.3.3 Adaptation

In the following analysis, the impact of global climate change on the Italian economy is treated as an exogenous factor, independent of Italy's contributions to global emissions. Notably, Italy accounts for less than 2% of global greenhouse gas emissions.

We assume that the government is able to raise the public deficit and debt in order to fund adaptive strategies aimed at mitigating potential economic losses stemming from climate change. Within our model, this is represented by a singular parameter (α), which reflects the efficacy of public spending on adaptation efforts. Essentially, this parameter quantifies the portion of economic damage averted for every euro allocated to adaptation. Thus, we hypothesize that while adaptation measures do not influence the likelihood of extreme events occurring, they help moderate the adverse impacts linked with the escalation of technical coefficients in the input-output framework.

Let us define $a_{i,j}(t)$, the technical coefficient, representing the relation between sector j's output and its input from sector i. Introducing a sectoral climate damage multiplier $(1-\Lambda_j(t)) \in [0,1]$, in every period t we have that the technical coefficient is $\frac{a_{i,j}(t)}{1-\Lambda_j(t)}$. The adaptation policy proportionally reduces the magnitude of $\Lambda_j(t)$ by means of parameter $\alpha(t)$. Thus, the impact of climate change becomes $\frac{a_{i,j}(t)}{1-\alpha(t)\Lambda_j(t)}$, with

$$\alpha(t+1) = \alpha(t) - \beta \cdot S(t), \textit{ or} \tag{20}$$

$$\Delta\alpha(t) = -\beta \cdot S(t), \tag{21}$$

where $S(t)$ is the adaptation expenditure, in billion euros, and β is the effectiveness or efficiency of adaptation expenditure.

We further assume that $\alpha \in [0,1]$ since adaptation can have no effect ($\alpha = 1$) or it can fully recover the productivity in the absence of climate change ($\alpha = 0$), but it cannot increase it beyond that limit.

3 Scenario Settings

To this end, a "sequential scenario" (Nieto et al. 2020) strategy is employed in formulating the narratives, facilitating the isolation of impacts attributable to each distinct hypothesis and appraising their cumulative effects. Specifically, each successive scenario is presumed to encompass all preceding hypotheses in addition to introducing a novel singular condition. The sole distinction, as described below, pertains to the speed of efficiency gain, which is maintained at a higher level in the absence of social policies. This methodological approach allows us to isolate the effects of introducing a single new assumption, thereby precluding spurious interpretations. We delineate five scenarios, summarized in Table 1, in particular:

1. **Business-As-Usual (BAU)**: in the baseline scenario, the Italian economy is pro-

jected to continue along its historical trajectory, with the exception of an exogenous pandemic shock in 2020.

2. **RCP 6.0**: impact of climate change only on hydrological variables.
3. **RCP 6.0 eff**: as above with the addition to exogenous improvements in water use efficiency.
4. **RCP 6.0 damage**: This scenario considers the full economic impact of climate change, under the RCP 6.0 scenario, at the industry level without the introduction of any adaptation policy.
5. **RCP 6.0 adapt eff**: From 2024 to 2026 (3 years), the government plans a new expenditure in adaptation with a budget of €10 billion per year to recover from the climate damages.[2] It also includes exogenous improvements in water efficiency.

Table 1: Summary of the main assumptions for every scenario.

Scenarios	*Climate change*	*Water efficiency*	*Economic damage*	*Adaptation*
BAU				
RCP 6.0	✓			
RCP 6.0 eff	✓	✓		
RCP 6.0 damage	✓		✓	
RCP 6.0 adapt eff	✓	✓	✓	✓

Water efficiency is assumed to represent an external enhancement in water efficiency by 20% by the year 2050 (Δ_{ω}^{20}).

4 Results

For clarity purposes, we present the scenario outcomes in three separate subsections in terms of environmental (4.1), and socio-economic (4.2) effects.

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[2] The budget of €30 billion for the adaptation expenditure is based on the resources that can be mobilized in the next few years stated in the Italian Recovery and Resilience Plan Rapha(Presidenza del Consiglio dei Ministri 2021).

In each case, the BAU (black line) is compared to other scenarios described above, starting from the year 2024 to 2050. We plot the median and the 95% confidence interval out of 500 simulations in order to avoid arbitrary outcomes and to clean out stochastic effects associated with numerical simulations.[3]

Drawing upon publicly accessible data, this study models the Italian economic structure over the period from 2010 to 2022. Employing the system dynamics software Vensim SDD[4], we have calibrated the parameters of our model to approximate the most accurate representation of our socioeconomic system. Nevertheless, the inherent complexity of reality precludes the possibility of an entirely endogenous and perfectly accurate model of the Italian economy. While there remains room for enhancement, the parameters employed are aligned as closely as possible with the typical functioning of our economic, social, and ecological systems.

4.1 Water stress

Under the base scenario, the Italian economy experiments a mild GDP growth up to 2050. It must be stressed that this growth is entirely endogenous to our model. Along this increase in the value of the annual output, the Extended Water Exploitation Index also increases from year to year. Given the current productive structure of the economy for which the input-output table provide a detailed snapshot, the relationships underlying the model suggest that the Italian economy will exhibit an increasing trend of water stress. Furthermore, fluctuations around this upward-trending average are expected to be intensified by climate change. Drier years will reduce water supply, resulting in a higher EWEI, while simultaneously increasing demand for water will exacerbate this effect, further elevating the EWEI. Our model thus indicates an asymmetrical dynamic, with more pronounced effects on the right side of the average compared to the left.

It must be further noted that beyond this average and the variations around the latter, our approach does not permit to assess intra-annual and/or regional evolutions of the EWEI. The sustained but somewhat mild increase of the EWEI in the base scenario is compatible with sharp increases at a more disggragetad level, both in time and space.

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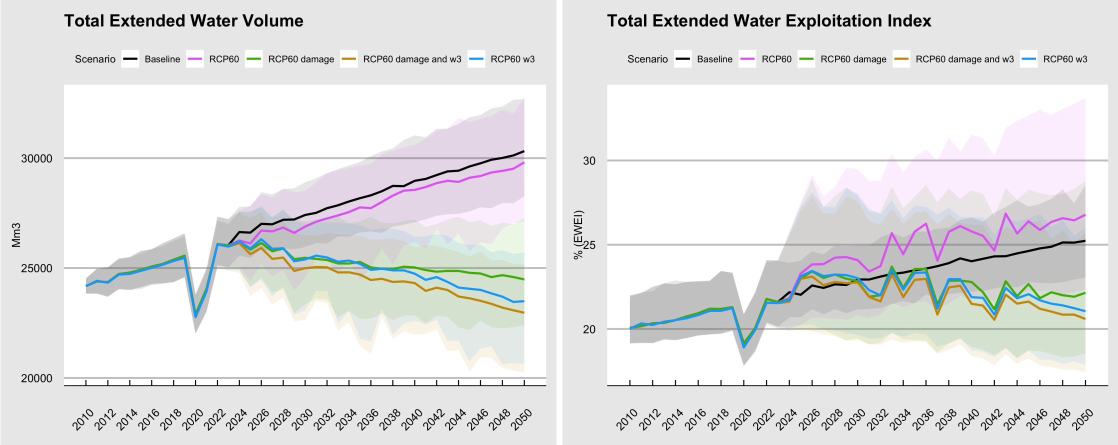
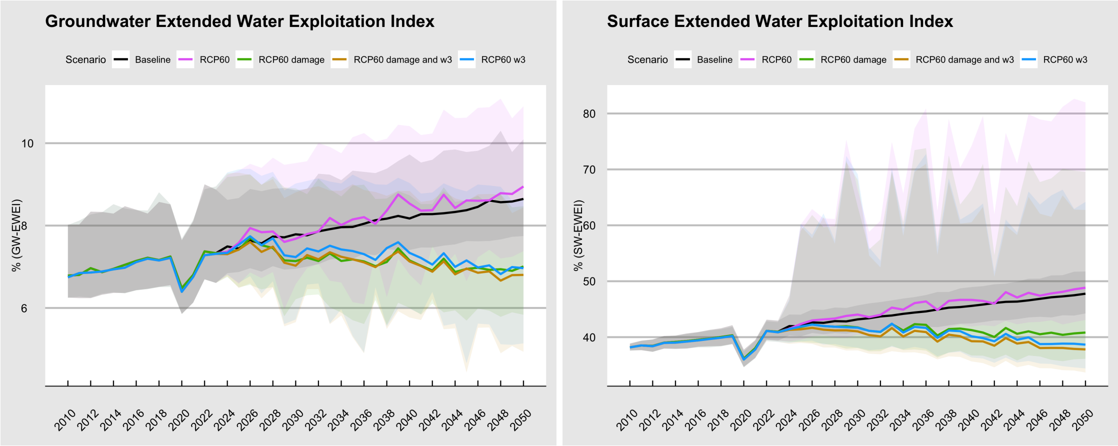
[3] Note that the results are robust to the number of simulations and they look similar even if we increase the trials.

[4] We run a multi-objective parameter optimization mode (which allows to automatize runs performed in simulation mode) as provided by the software Vensim SDD. Technical details can be found here: `https://vensim.com/optimization/#model-calibration`.



(a) Water extended demand (total) **(b)** EWEI (%)



(c) EWEI GW (%) **(d)** EWEI SW (%)

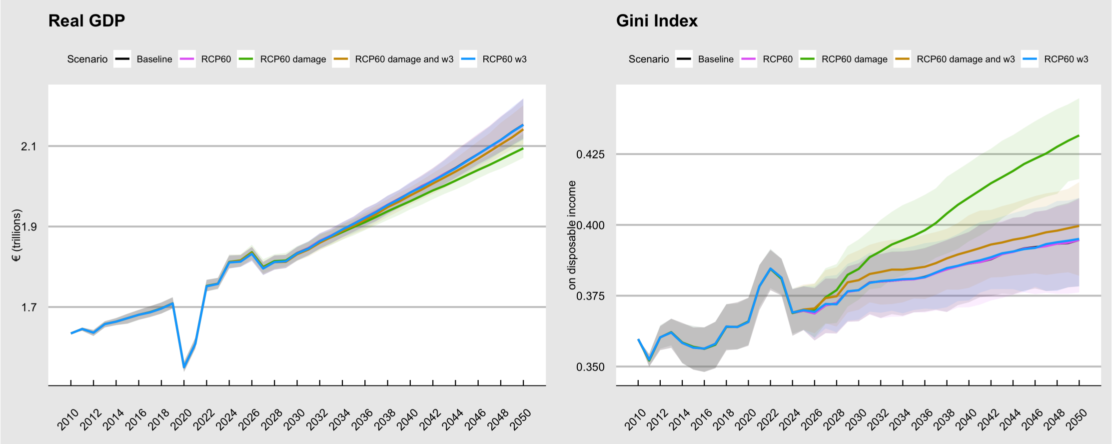
Figure 2: Scenario analysis of environmental indicators. The solid lines and shaded areas around them indicate the medians and 95% confidence intervals, respectively, out of 500 independent simulations.

A fuller assessment should take into account, since local thresholds may thus be reached that further trigger additional feedback loops.

4.2 Economic

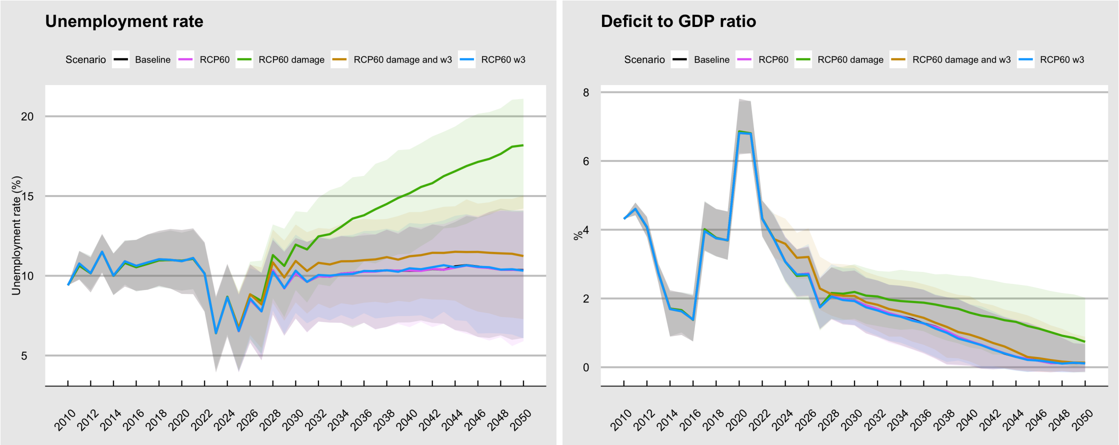
Figure 3 plots the evolution of the main macroeconomic aggregates.

We further explore various scenarios beyond the baseline. These scenarios consider the impacts of climate change, political constraints, or a combination of both. We analyze changes in both the numerator (water demand) and denominator (water supply). We investigate the socio-economic and ecological consequences of changes in the hydrological variability due to climate change and the resulting pattern of water demand across different productive sectors. The model allows to quantify the impact of withdrawals beyond the sustainable limits in terms of water reserve depletion, or the potential impact of water management policies such as changes in the amount of concessions granted for blue water extraction or narrower quality requirements in discharging water after production.



(a) Economic growth

(b) Income inequality



(c) Unemployment rate

(d) Public deficit-to-GDP rate

Figure 3: Scenario analysis of economic and social indicators. The solid lines and shaded areas around them indicate the medians and 95% confidence intervals, respectively, out of 500 independent simulations.

5 Discussion

In the current section, we will outline the main limitations of the present study, suggest future lines of research, and provide key policy recommendations.

5.1 Limitations and future lines of research

Firstly, while endogenous technological progress is modelled in EUROGREEN and affects labour productivity and the technical coefficients, we use exogenous assumptions to represent future water efficiency gains. However, it is important to note that historical data does not exhibit statistically significant trends in water efficiency. Future studies could explore the endogenization of water efficiency gains. Specifically, the total volume of water required in agriculture could be disaggregated into its two main components, each necessitating distinct endogenization approaches: water lost through irrigation system leakages and the remainder effectively distributed to crops.

Water leakage is significantly affected by the type of irrigation technology utilized. Although flood irrigation is generally less costly at the outset, it is substantially less efficient than drip irrigation (Nouri et al. 2019), which, notwithstanding its considerable effectiveness, involves substantial initial expenses. Firm-level data concerning the irrigation systems presently employed by Italian agricultural enterprises can be utilized to assess the potential for advancements in this area. Such analysis may furthermore correlate transformations in irrigation technologies with public investment strategies and, ultimately, incorporate these into EUROGREEN's endogenous technical change module, provided that the costs of alternative irrigation systems are themselves made endogenous. Other approaches might involve modeling reductions in non-beneficial evaporation or enhanced utilization of rainfall (Mekonnen et al. 2014; Hoekstra 2019). Examples include practices like mulching (Chukalla et al. 2015) or rainwater harvesting (Zhuo et al. 2017), which could also influence the distribution between green and blue water resources. On the other hand, the effective volume of water used in agriculture depends, among other factors, on the types of crops cultivated. Modeling shifts toward more sustainable agricultural practices could incorporate changes in the green/blue water distribution, recognizing that different crop species and cultivars exhibit varying preferences for these water types (Tamea et al. 2021). This differentiation is particularly critical given the dual role of blue water: while it can serve as a buffer during drought years, the radical uncertainty surrounding large-scale water availability under climate change emphasizes the need for optimizing green water use, which is not subject to the same scarcity constraints (Tamea et al. 2021). Finally, another avenue for exploration involves modeling changes in the food consumption patterns that could imply a reduction of demand for more water-intensive products such as meat, dairy, and specific crops (Du et al. 2004). Advances in disaggregating and endogenizing consumption patterns using the COICOP classification could make such modeling more feasible.

Secondly, beyond the potential advancements in modeling water demand, a key area for future research involves relaxing a significant assumption about water supply. Our current framework assumes that economic agents adhere strictly to sustainable blue water extraction and ensure adequate dilution of discharged water. This assumption precludes over-exploitation, whether through excessive withdrawals or inadequate quality restoration, which runs counter to observed realities. Research has documented the depletion of groundwater stocks and environmental flows (Falkenmark 2013; Scanlon et al. 2012; Wada 2012; Kummu et al. 2016). Additionally, studies highlight the increasing competition between agriculture and other industries — both energy production and manufacturing . Due to higher profit margins in non agricultural activities, agriculture may face water scarcity, becoming “stranded” in terms of water availability (Rosa, Rulli, et al. 2018; Rosa, Rulli, et al. 2018; Rosa and D’Odorico 2019). Incorporating aspects of the water-energy-food nexus, particularly through differences in yield, could represent a valuable extension of the model. These dynamics may also lead to higher maintenance costs, as water-extracting firms face increased expenses to treat lower-quality input water. Alternatively, overuse could reduce water supply in subsequent periods, as aquifers and rivers dry up due to cumulative feedback effects.

Thirdly, both of the above arguments underscore the need for a more granular understanding of water stress. Our extended water exploitation index could be calculated on an intra-annual basis and at a more localized scale. Localized water overuse—whether caused by limited supply, excessive demand, or both—can lead to extreme water scarcity at specific sites, even when national-level water scarcity appears moderate. Identifying local thresholds and examining how their transgression impacts broader water availability (Hoekstra and Wiedmann 2014) could provide a promising avenue for future research. This is all the more the case that literature on the water-energy-food nexus has had a tendency to focus on sectorial linkages, with few taking into consideration spatial dimensions (Rasul 2015; De Strasser et al. 2016; Yuan et al. 2018) or intra-annual variations (Hoekstra, Mekonnen, and Zhuo 2021).

Fourthly, this study broadens the ecological boundaries traditionally explored in the discourse on water stress indicators by incorporating institutional and technical constraints through the modeling of water extraction concessions. It was deemed unnecessary to model technical constraints independently, as it was postulated that concessions were optimally allocated, considering both the hydrological and technical conditions faced by individual entities. Nevertheless, even under the presumption of ideally granted concessions, non-compliance or insufficient dilution of pollutants by producers could result in feedback mechanisms that jeopardize the hydrological circumstances upon which the original optimality of concessions was founded. Furthermore, in practice, the allocation of concessions frequently reflects various considerations that may diverge from the collective welfare. In such instances, there arises a necessity to model technical constraints separately, potentially utilizing methodologies presented earlier in this section. Hence, there is a compelling argument for the independent modeling of institutional and technical constraints, particularly pertinent when adopting a more detailed spatial and temporal perspective on water scarcity, as discussed in the preceding points.

5.2 Concluding remarks

This study has examined the complex interplay between climate change, water resources, and socio-economic systems, with a particular focus on Italy. Using the EUROGREEN model, we have integrated hydrological dynamics with economic and policy dimensions, providing a novel framework for analyzing the impacts of climate change on water management and socio-economic outcomes.

Our results underscore the importance of considering the dynamic interactions between water resources and socio-economic systems. A key insight from our analysis is that similar Extended Water Exploitation Index (EWEI) values may correspond to different socio-economic configurations. For example, a low EWEI could result from the catastrophic effects of climate change on agricultural production, which would reduce water demand and stress due to economic contraction. Conversely, the same low EWEI could be achieved through proactive public interventions, such as adaptation measures and improvements in water efficiency, which could mitigate water stress while maintaining economic performance and social equity.

This highlights the critical need for water management strategies that go beyond environmental indicators alone. Efforts must focus on achieving reduced environmental impact while also meeting socio-economic desiderata, including good economic performance and social justice. This study aims to contribute to a more informed understanding of water management policies and their broader socio-economic implications, paving the way for more sustainable and equitable resource strategies in Italy and beyond.

Acknowledgment

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A Appendix

A.1 Tables

Table A2.1: List of sectors

Sector no.	Sector name	Nace Rev. 2 code
1	Agriculture, forestry and fishing	A
2	Mining and quarrying	B
3	Manufacturing	C (excl. $C19$)
4	Coke and refined petroleum products	$C19$
5	Electricity, gas, steam and air conditioning supply	D
6	Water supply	E
7	Construction	F
8	Wholesale and retail trade	G
9	Transportation and storage	H
10	Accommodation and food service activities	I
11	Information and communication	J
12	Financial and insurance activities	K
13	Real estate activities	L
14	Professional, scientific, technical, administrative and support service activities	M, N
15	Public administration and defence	O
16	Education	P
17	Human health and social work activities	Q
18	Arts, entertainment and recreation	R
19	Other	S, T, U

Table A2.2: Exogenous shocks from the Covid-19 pandemic from 2019 to 2020.

Covid shocks	Δ%
investments	-12.40
consumption	-8.84
export	-15.4
import	-17.3

Authors' own elaboration. Data are provided by the EUROSTAT GDP and main components.

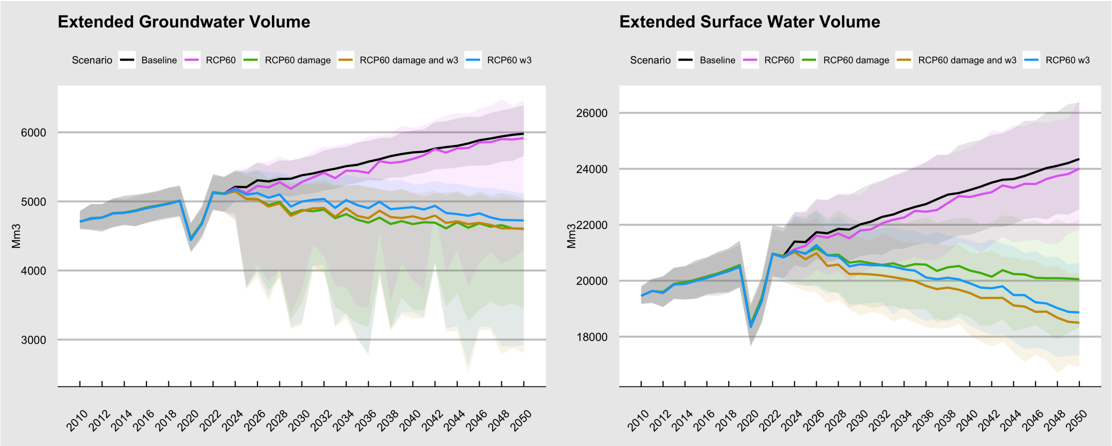
A.2 Hydrological details

All values of the hydrological components in this document are in millimeters. In the case of coefficient adjustment, the units of measurement are not relevant. To determine the water supply, units do matter. To go from millimeters to millions of cubic meters it is necessary to multiply by 302.07 in the case of Italy.

Table A2.3: Parameters values. The parameters for equations 2, 3, 11, 13, 15, 16, 17 and 18 are presented below. Only one parameter is considered for equations 2 and 3 since the others are calculated based on water use coefficients, which are variable in the hydroeconomic model.

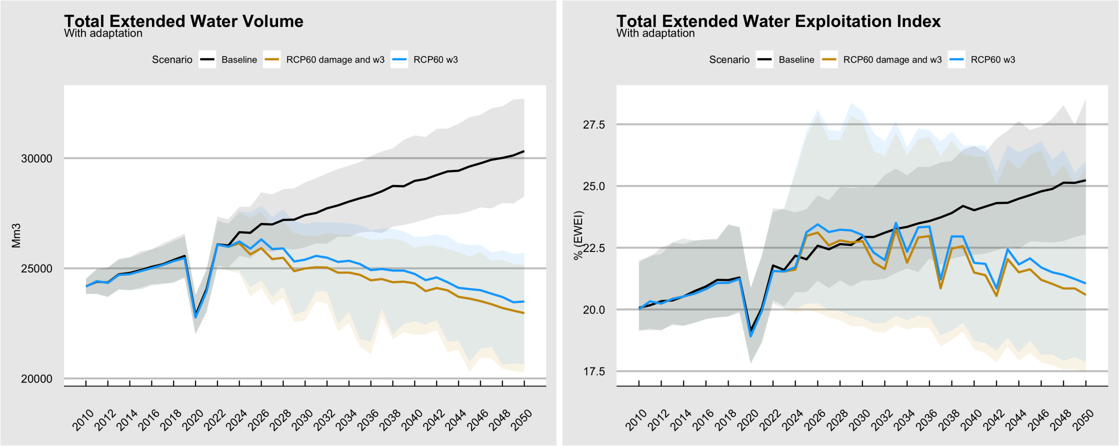
Parameter	**Value**
α_E	56.9671
β_1	0.1764
β_2	21.3139
σ_E	30.1619
μ_E	0
α_R	3.1610
β_3	0.4592
β_4	-0.4023
α_R	100.2310
σ_R	0
μ_E	29.1246
β_5	0.48563
β_6	-0.55675
σ_G	96.5951
μ_G	0
ψ	0.2
ϕ	0.7
λ	0.13
γ	1.428
c_s^k	20 mg/l
c_{min}^k	15 mg/l
c_{max}^k	25 mg/l
$\overline{c}_0^k$	20 mg/l
π_{min}^k	0.5
π_{max}^k	1.5
$\overline{\pi}^k$	1.0

A.3 Other results

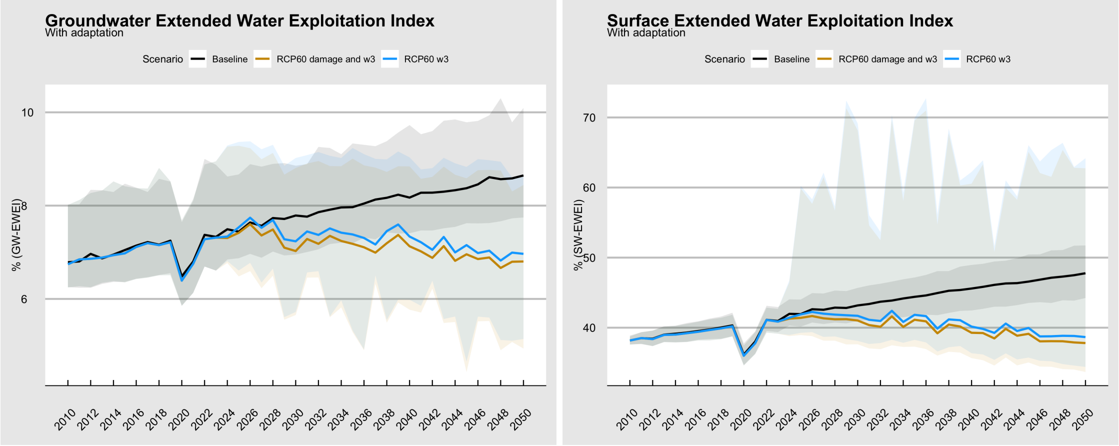


(a) Groundwater demand **(b)** Surface water demand

Figure A.1: Additional water indicators (all scenarii). The solid lines and shaded areas around them indicate the medians and 95% confidence intervals, respectively, out of 500 independent simulations.

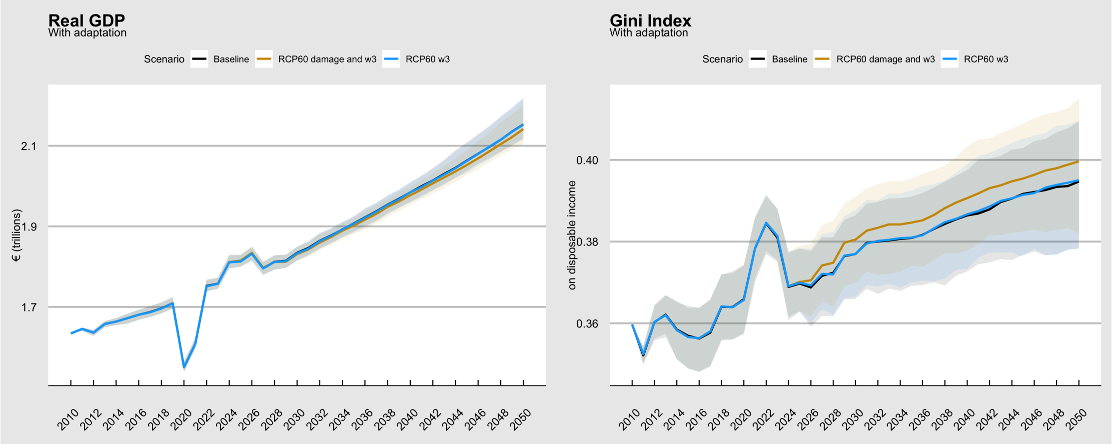


(a) Water extended demand (total) **(b)** EWEI (%)

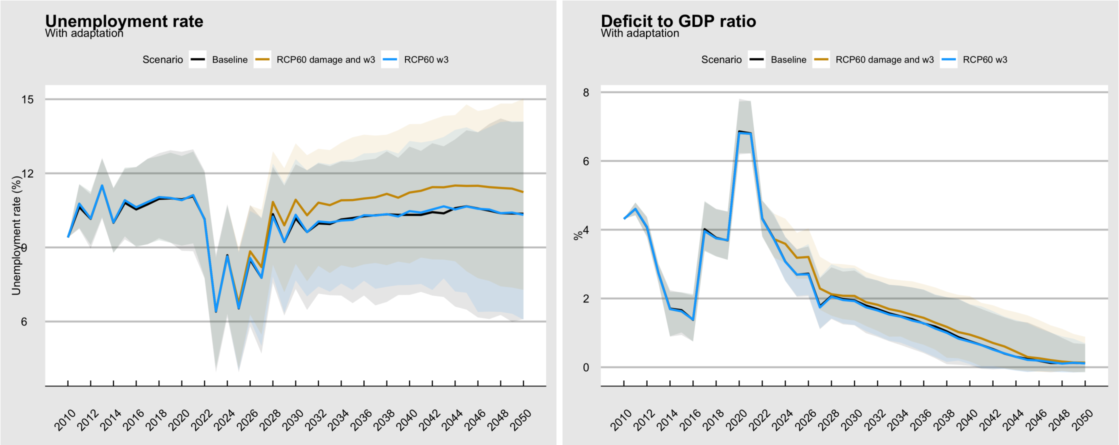


(c) EWEI GW (%) **(d)** EWEI SW (%)

Figure A.2: Scenario analysis of environmental indicators (scenarii with adaptation). The solid lines and shaded areas around them indicate the medians and 95% confidence intervals, respectively, out of 500 independent simulations.

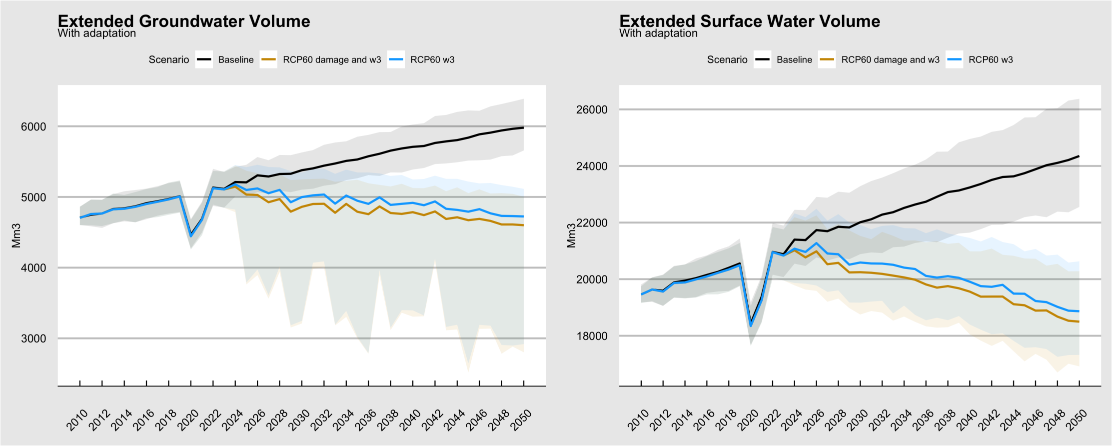


(a) Economic growth **(b)** Income inequality



(c) Unemployment rate **(d)** Public deficit-to-GDP rate

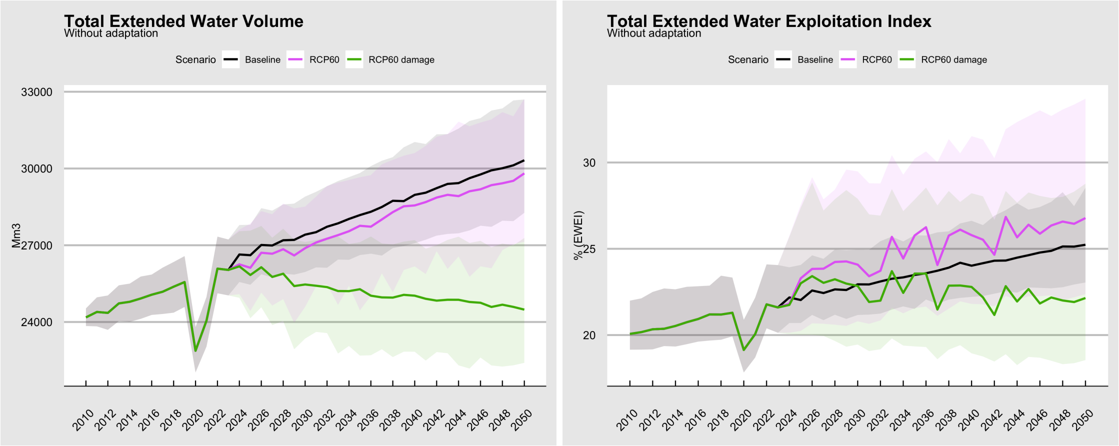
Figure A.3: Scenario analysis of economic and social indicators (scenarii with adaptation). The solid lines and shaded areas around them indicate the medians and 95% confidence intervals, respectively, out of 500 independent simulations.



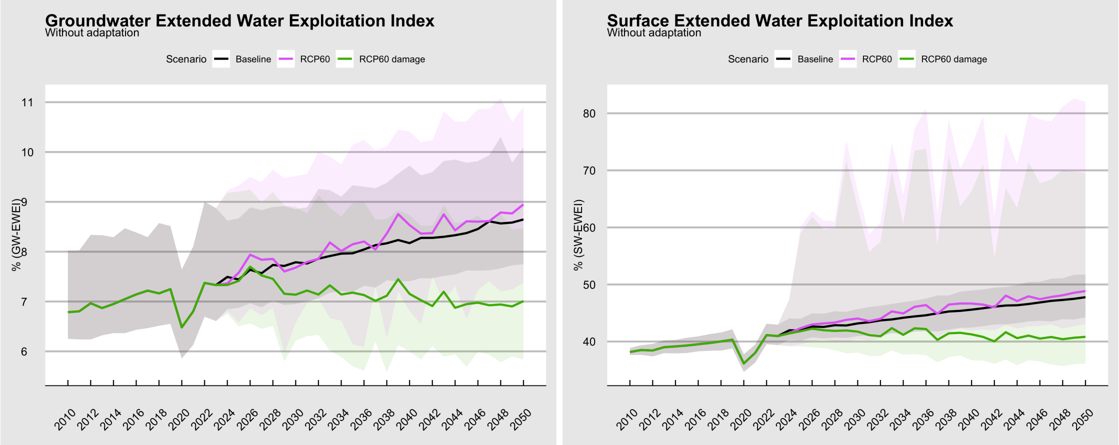
(a) Groundwater demand

(b) Surface water demand

Figure A.4: Additional water indicators (scenarii with adaptation). The solid lines and shaded areas around them indicate the medians and 95% confidence intervals, respectively, out of 500 independent simulations.

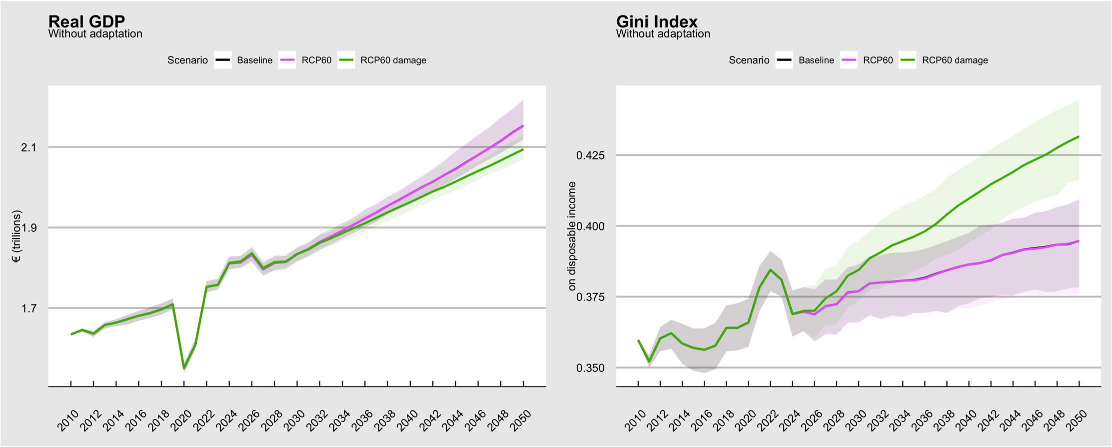


(a) Water extended demand (total) **(b)** EWEI (%)



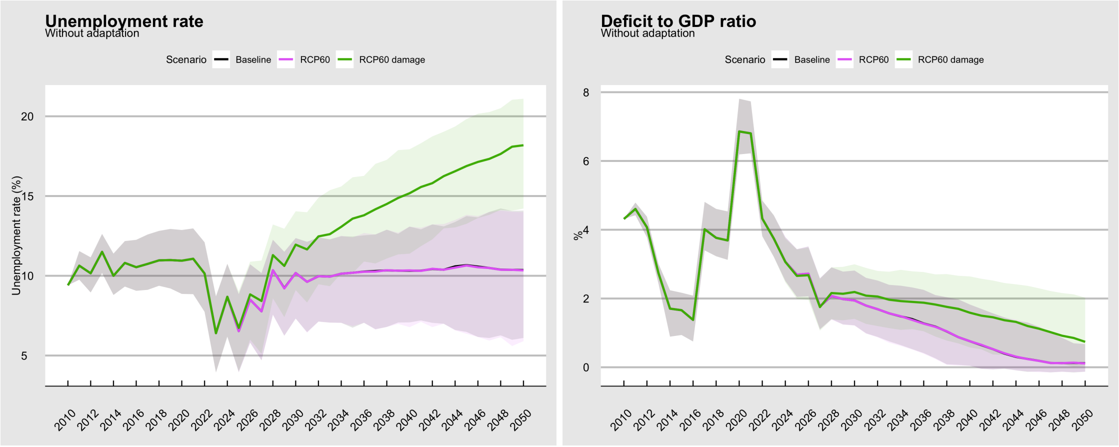
(c) EWEI GW (%) **(d)** EWEI SW (%)

Figure A.5: Scenario analysis of environmental indicators (scenarii without adaptation). The solid lines and shaded areas around them indicate the medians and 95% confidence intervals, respectively, out of 500 independent simulations.



(a) Economic growth

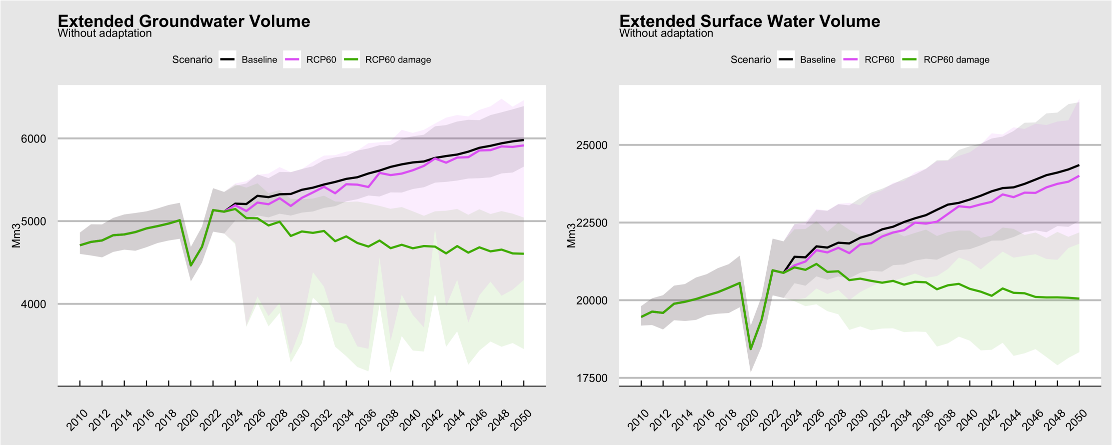
(b) Income inequality



(c) Unemployment rate

(d) Public deficit-to-GDP rate

Figure A.6: Scenario analysis of economic and social indicators (scenarii without adaptation. The solid lines and shaded areas around them indicate the medians and 95% confidence intervals, respectively, out of 500 independent simulations.



(a) Groundwater demand

(b) Surface water demand

Figure A.7: Additional water indicators (scenarii without adaptation. The solid lines and shaded areas around them indicate the medians and 95% confidence intervals, respectively, out of 500 independent simulations.