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Modelling global water policies*

Pasquale Lucio Scandizzo [a,*], Richard Damania [b]

[a] The University of Rome "Tor Vergata", Italy
[b] World Bank, USA

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Abstract

This article develops an analysis of evolving water availability through a novel global Computable General Equilibrium (CGE) model that moves beyond existing approaches by incorporating both precipitation and total water storage (TWS)– a more comprehensive measure of water availability encompassing surface water, groundwater, and soil moisture. To this aim, the article first provides an overview of the problem of economic modelling of water in a general equilibrium context, through a review of CGE models that have attempted to deal with water as a key economic input and its direct and indirect influence on markets and well-being. Secondly, it includes the health effects of inadequate water supply and sanitation (WASH), capturing a key dimension of water availability and its distributional effects. Third, it provides a granular representation of how water enters in the different value chains, providing novel suggestions and a better understanding of how water widespread influence across sectors may contribute to a more significant impact of climate change than estimated by other studies. Simulations are employed to evaluate the costs associated with policy inaction under various water scenarios, including those influenced by climate change, offering crucial guidance for proactive policy interventions.

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* Corresponding author.
E-mail address: scandizzo@openeconomics.eu (P.L. Scandizzo).

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1. Introduction

Water is ubiquitous and has been described as the bloodstream of the biosphere, since it is essential for life and underpins all economic activity. Managing this essential resource has always remained challenging for a variety of reasons ranging from its uneven distribution and usage as a contended local public good, to the inexorable progression of climate change and its impact on the global water cycle. The intensification of the water cycle with more extreme concentrations of precipitation and droughts leads to higher risks and higher unpredictability, with resulting costly and often inadequate adaptation measures.

Despite these growing risks much of the research on the economic impacts of climate change has neglected or underestimated the role of water on the economy. Most studies typically focus on temperature increases and do not include the impact of the availability or shortage of water. Econometric studies and different economic models also tend to concentrate on the impact of temperature changes as a comprehensive phenomenon, which is deemed to subsume both direct and indirect impacts, including the effects of precipitation changes. An implication is that all of the impacts of precipitation can be proxied through the changes in temperature. This is questionable not least because the timing and impacts of temperature and precipitation changes are very different. Precipitation changes occur gradually and with considerable lags with respect to the temperature increases and the other phenomena associated. Moreover, the distribution of rainfall over space is highly heterogeneous depending on factors such as geographical location, land use, anthropogenic changes, and the balance between rural and urban areas.[1]

This paper makes three main contributions to the understanding of water's economic impact. First it provides a broad overview and evaluation of the literature with a particular focus on the contribution of computable general equilibrium (CGE) models. Second, and more importantly, it breaks new grounds by developing a global model and simulation results that incorporate the economic effects of water availability in novel ways taking account of the economic impacts of precipitation, as well as total water storage using a relatively recent aggregate measure of water that is available in soils, surface water (rivers and lakes) and groundwater. Third, the model offers compelling evidence that implementing moderate water pricing mechanisms, reflecting the scarcity value of water resources, can generate significant economic and social benefits for developing countries. By accounting for these often-overlooked factors, the study generates fresh insights into the economic implications of climate change and evolving water availability, offering valuable guidance for policymakers.

2. Review of the CGE literature

Empirical research delving into the impacts of rainfall and water availability on economic growth has highlighted the variable effects of climate change on countries' productivity and growth. For example, studies by Dell et al., (2012) and Burke et al., (2015) examined the combined influence of rainfall and temperature on economic outcomes, consistently finding negative temperature effects, but inconsistent outcomes of changing rainfall patterns at the country level (Lobell & Asseng, 2017). However, more recent studies have demonstrated that

[1] The study by Khan et al., (2017), found that a decrease in precipitation 1 standard deviation below average rainfall leads to a 1 % reduction in GDP per capita growth while a 1 standard deviation decrease in surface runoff reduces GDP per capita growth by 0.7 %.

spatially aggregated models underestimate the economic impact of rainfall, which is spatially heterogeneous compared to temperature. Globally the within country variation of rainfall is twice as large as that of temperature. Spatially disaggregated estimates find a concave relationship between rainfall and GDP growth, particularly in arid regions (Damania et al., 2020). A similar result is found when examining agricultural productivity (Ortiz-Bobea et al., 2021).

As an alternative to reduced form empirical estimates, computable general equilibrium (CGE) models have been widely used to assess the effects of climate change. However, modeling the economic impacts of water has been challenging for at least three reasons. First, water generates multiple benefits, some in the form of private goods (such as when water is consumed) and some as public goods (such as watershed benefits). Additionally, water use is typified by externalities generated by upstream users on downstream consumers. Finally, the global hydrological cycle determines how water is used and its economic consequences. Globally 65 % of precipitation is held as green water – the moisture in the upper unsaturated layer of the soil (around 70,000 km^3/ year). The remaining 35 % (or 40,000 km^3) is blue water that is held in rivers, lakes, ground water, glaciers and ice. Reflecting its prevalence, green water also provides 75 percent (5000 km^3) of the water consumed in food production. Despite the dominance of green water resources for food production, there is limited research on its contribution to the economy and the role it may play in facilitating adaptation to climate change.

While fundamentally rooted in neoclassical economic theory, CGE models exhibit considerable architectural diversity and adopt a wide range of alternative hypotheses. This flexibility allows for the incorporation of deviations from perfect markets, such as involuntary unemployment, imperfect competition, externalities, and various market distortions. With differences in model structure and assumptions CGE models generate a wide range of results.

As highlighted by Bardazzi and Bosello (2021), two main approaches have been used to account for water in CGE models, one based on water as an externality, and the other based on water as a factor of production. One of the early examples of modeling water as a production factor in an economy-wide framework is that of Berck et al., (1991) who considered water supply constraints in the San Joaquin Valley, USA. An illustrative CGE model of the southern portion of the San Joaquin Valley is constructed and is used to find the effects of reducing water inputs on aggregate Valley gross domestic product (GDP) and on sectoral output, employment, and land use.

Another example is the study by Dudu et al. (2018), who propose using a CES shifter (i.e. sectorial, specifically calibrated total factor productivity), to model such a productivity effect. This choice is in line with a vast literature modelling technological change as a factor-neutral shift in the production function. The implication is that water is a complement rather than a substitute for the other factors and the intermediate goods involved in production and that large inefficiencies are likely to arise from widespread failure of the market economy to appropriately allocate and use such a pervasively used factor of production.

In general, models that treat water as a factor of production are based on either the assumption of Leontief technology, with zero elasticity of substitution, or on a CES function, with positive elasticity of substitution with other components of value added. Berritella et al., (2007), for example, use Leontief functions while CES functions are utilized in other studies (e.g., Calzadilla, Rehdanz, and Tol, 2011). However, each approach brings its own challenges, since water shares both the characteristics of a common good and a private commodity in most circumstances. In part for this reason, studies that include water as a production factor or an intermediate good for sectors other than agriculture appear to be limited, and in many cases confined to quantify the contribution of water to the market economy only in aggregate terms

(Koopman et al., 2017; Luckmann, 2016; Roson & Damania, 2017; Taheripour et al., 2020), or, in some cases, only for the energy sector. These features are common to GTAP based models, such as, for example, Nechifor & Winning, (2018), Burniaux, (2002).

The crucial role played by water and energy combined in all economies constitutes a further challenge to model water as a factor of production. Energy production requires water, but water extraction, processing and distribution requires in turn energy, with a physical and economic connection difficult to extricate and represent as choices and results of economic behavior. This intricate interdependence is not unique and extends for example to mining and other sectors. In the case of water, however, the ensuing web of interdependence is especially pervasive and complex, making it difficult to isolate and represent the true costs and benefits of individual economic activities. Smajgl et al. (2016) recommend a new more flexible modelling approach that combines the strengths of the bottom up and top-down approaches to incorporate the distinctive dynamics of water and energy systems and interactions.

Water modelling opportunities and challenges can also be examined from the lens of increased scarcity, deteriorating quality of water and the impacts of climate change, leading to distinct approaches that combine these externalities with the production function angle. Results from these models (e.g., Horridge et al., 2005; Berrittella et al., 2007; Banerjee et al., 2015) seem to indicate higher impacts on both theoretical premises and in specific circumstances. The results can also be interpreted as second-best outcomes, highly conditioned by the existing distortions and the different externalities associated with the use of water in both national and international markets.

An example of these kind of studies is provided by the work of the Australia's Center of Policy Studies (CoPS), that has investigated issues related to water scarcity, allocation, and pricing over several years utilizing detailed microeconomic statistics through the development of the TERM CGE model (Horridge et al., 2005). TERM - The Enormous Regional Model - is a "bottom-up" CGE model of Australia which treats each region as a separate economy and was created specifically to deal with highly disaggregated regional data while providing a quick solution to simulations. The authors simulate the effects of the Australian drought which endured for 20 years. The effects on some statistical divisions are extreme, with income losses of up to 20 %. Further advances with this modeling framework led to the development of TERM-H2O. This model has considerable irrigation sector detail to explain how changes in relative prices affect water trade and the reallocation of farm factors of production (Wittwer, 2012; Dixon et al., 2011, and Wittwer & Griffith, 2011).

Berrittella et al. (2007) develop an extension to the GTAP model to evaluate groundwater scarcity in the context of international trade. The authors conclude that given the current distortions of agricultural markets, contrary to conventional wisdom the study finds that water supply constraints could improve allocative efficiency. Furthermore, this welfare gain may more than offset the welfare losses due to the resource constraint. Extensions of this model investigates the economics of water pricing (Berrittella et al., 2008) finding that water taxes tend to reduce water use, particularly in agriculture, but their impacts vary across country groups. Because of lower substitution elasticity, high-income countries face significant income losses despite smaller reductions in water use. Low- and middle-income countries see larger water use reductions, with varying economic effects based on dependence on water-intensive sectors. Water taxes also shift production and trade patterns, with global spillover effects on non-taxing countries. Welfare losses are non-linear, with diminishing impacts at higher tax rates.

Wittwer and Banerjee (2015) use a dynamic multi-regional Computable General Equilibrium model of the Australian economy to examine the impacts of developing irrigated agriculture in remote Northwest Queensland. The simulations suggest that on balance clear welfare gains do not arise from irrigation development. Banerjee (2015) also found that investing in irrigation efficiency increased regional output, income, and employment but had a small negative impact due to crowding out of investments.

Damania and Scandizzo (2017) developed a dynamic CGE model for Kenya to study the interaction between conservation and natural resource management. Their results showed that traditional agriculture and mining are more water-intensive than irrigated agriculture, and industrial sectors are less water-intensive than services, indicating that indirect water consumption can be significant. Stated simply, these results indicate that a sector that apparently uses less water than another sector may stimulate other more water-intensive types of economic activity that end up consuming a larger amount of water.

Scandizzo, Cervigni, et al. (2018) use a dynamic CGE model to analyze Mauritius' ocean economy, detailing green and blue water and various ecosystem services. The model extends a social accounting matrix for macro policies and projects. Scandizzo, Cufari, and Pierleoni (2018) create a regional model for Kenya with SEAM, focusing on natural resources, water, parks, and conservation impacts from infrastructure and growth. They also develop a CGE model for Scandizzo and Cufari (2021), incorporating water resources, CO2 emissions, and natural capital to study environmental and economic interactions and poverty among diverse households.

Shan et al. (2023) utilized a CGE model to study water tax reform in Hebei Province, China. Their findings indicate that water taxes can improve water allocation by reducing conventional water use and encouraging the adoption of unconventional water sources. Higher tax rates effectively reduce water consumption in water-intensive industries, balancing efficiency and sustainability.

Finally, a rapidly expanding literature explores the consequences of climate change – though most typically without explicitly accounting for the effects of rainfall variations or changes in freshwater endowments. Examples include Banerjee et al (2015) who develop a dynamic computable general equilibrium model for Bangladesh, uncovering significant impacts on food security. Additionally, Bosello et al (2006) examine how climate change may affect human health, leading to impacts on labor productivity and demand for health care services. They use a standard multi-country world CGE- GTAP model, to estimate the economy-wide effects of the climate-change-induced impacts on health through changes in labor productivity and public and private demand for health care. In another study, Bosello et al. (2012) propose a methodology for assessing climate change impacts on ecosystem services within a CGE approach.

In sum while the flexibility of CGEs has been used to assess a wide range of water and climate related problems, two key issues emerge from the literature:

1.Impact of Closure Rules: The outcomes of CGE models are highly sensitive to the closure rules chosen. However, many studies and meta-analyses report and compare CGE results without adequately discussing or even mentioning the underlying assumptions regarding these closures. This omission can lead to misinterpretations of the findings.

2.Static Model Limitations: Static CGE models provide snapshots of the economy, typically reflecting data from a specific year or an average over several years. The comparative static solutions they offer in response to exogenous shocks represent steady states that the economy may reach after a certain time, depending on the magnitude and nature of the shock. The trajectory leading to this new equilibrium is generally unspecified, and so are the assumptions under which the steady state can be associated with future growth.

3. A new modelling approach

Climate change and water pose significant challenges for CGE modeling for two contrasting reasons. On one hand, the dual nature of water as both a public good and private good throughout its lifecycle presents a major hurdle for accurate representation within the confines of traditional CGE frameworks. On the other hand, the heterogeneous nature of climate change, coupled with the local features of water demand and supply, require a granularity that is challenging for any global model. Finding a compromise between the coverage of the model and its regional detail is thus the first target of our global modelling exercise. The model seeks to explore the combined consequences of climate change and water supply on the world economy, as well as the so-called costs of inaction, that is the failure to intervene with appropriate policies on the part of national governments and international authorities.

A second, important objective of our CGE study is to address the question of water supply through the modelling of *water value chains.* Water value chains involve a comprehensive understanding of the different types of water (blue, green, grey, and black water) and their roles in sustaining various economic activities, including international production value chains for agricultural as well as for non-agricultural goods. While each type of water contributes differently to the overall water resource management and its impact on agricultural production, we will focus on green water and blue water as the main components of the international value chains.

A further innovative feature of our approach related to the concept of water value chain, but more specifically linked to the local characteristics of water supply, is modelling the impact of Total Water Storage (TWS). TWS is a critical component of the water value chains that reflects the sum of all water available - blue and green - in a particular area. It is defined as the sum of surface water, groundwater, soil moisture, and ice and snow reserves. Locally, accurate knowledge of TWS enables sustainable planning and usage, crucial for agriculture, industry, and residential needs, particularly in areas prone to drought. Recently available remote sensed data has made available global measures of TWS that have been downscaled to the country level. To our knowledge this paper presents the first attempt to better understand the economic contribution of TWS in a structural economic model.

Finally, we integrate in our modelling scheme the Water, Sanitation and Hygiene (WASH), as key components of the water value chain, especially targeting developing countries. To this end, we estimate key WASH parameters by drawing on diverse data sources, including several detailed World Bank studies. This provides an understanding of the magnitude of WASH related impacts from poor water quality relative to those of other water supply related impediments to progress.

In spite of its lack of explicit dynamics, the model allows us to consider both absolute and relative changes over time, as differences in steady state equilibria, which can be affected by both permanent and transitory shocks. This is especially true under a Keynesian closure, where the emphasis is on determining a stable equilibrium between demand and supply, rather than on long term conditions for growth of potential output. This means that we can use CGE comparative statics to decompose the impact of climate change on the economy into two separate effects: (1) a lasting shock to productive capacity, for example from a permanent increase in the temperature or a permanent decline in rainfall, that degrades the economic system on the supply side, and reduces the natural level of employment on the demand side, thus causing the whole possible trajectories of growth to start from a lower basis; (2) a reduction of the growth rate, which will depend on the slowdown of productivity increase, capital (physical as well as human) capital accumulation and on demand factors such as expectations, households' consumption habits and government interventions.

In sum, the model attempts to expand the channels through which water may impact the economy, accounting for precipitation which has direct impacts on agriculture but may also cause damage when rainfall is excessive, total water storage which includes soil moisture as well as water availability in lakes, rivers and elsewhere with impacts on crop growth, water availability for irrigation, non-agricultural activities and final consumption and water quality through the consequences of inadequate water supply and sanitation (WASH).

4. Results of a global CGE model

The computable general equilibrium (CGE) model developed for this analysis (termed CLIMAWAT), provides a comprehensive representation of the global economy, covering 160 countries and 14 production sectors along with their corresponding commodities. It integrates extensive data from international sources, including GTAP 11, FAO, and the Water Footprint Network, and incorporates information from biophysical models, economic databases, econometric analyses, and climate change projections.

Based on a globally estimated social accounting matrix, the model tracks material and virtual water flows through domestic and international value chains, simulating a global economic system where interconnected markets and jointly determined prices, quantities, and incomes reflect the interactions of all agents. Agents' behavior is assumed to follow standard principles of utility or profit maximization, under limited information, with key parameters given by input-output coefficients, factor income shares and substitution elasticities between capital, labor and land. Different skill levels are recognized for labor, with the possibility of unemployment and institutional wages. Changes in green water are modeled as affecting total productivity in agriculture. Blue water is treated as a primary factor of production and as a commodity produced by extracting, processing and distributing it through specialized activities.

The model's solutions offer a robust foundation for analyzing market responses to exogenous shocks, with comparative static results providing information both as snapshots and as steady state equivalents over time. Accordingly, baseline solutions are projected over 30 years using OECD investment and population forecasts as exogenous inputs. Model simulations under different scenarios can thus be compared with each other and to a benchmark "business as usual" scenario, providing both estimates of level and growth changes. This approach facilitates a long-term analysis of economic impacts and the interactions between various factors within the global economic and environmental landscape.

The core of the CGE model follows Robinson et al. (1999) Logfren et al (2002), reformulated (Damania and Scandizzo, 2017; Cervigni and Scandizzo, 2017; Perali & Scandizzo, 2018) to consider the externalities from climate change and water consumption.[2] Two-level nested CES functions are utilized to define the substitution possibilities between labor, capital, land, water, and intermediate inputs. The corresponding substitution elasticities are initially derived from the literature and subsequently refined through iterative calibration. Each sector produces a composite commodity that can be either exported or produced for the domestic market. All producers for each region are assumed to maximize profits according to a

[2] Further details on the structure of the model and its simulations can be found on the University of Tor Vergata Foundation website: https://fondazionetorvergata.it/water-the-cost-of-inaction/

production function, which uses primary and intermediate inputs, under the assumption (bounded rationality) that the level of use of some of these inputs are fixed by technology or by former uses. Each producer runs a production activity with the end result of supplying one or more commodities with labor, capital land and Natural Resources as primary inputs, which are determined by Constant Elasticity of Substitution (CES) production functions. The demand for intermediate inputs assumes fixed input-output coefficients and the demand for primary factors is given by first order conditions for profit maximization using value-added prices.

The main types of water included in the model are blue water, green water, and, as a derivative of blue water, municipal water.[3] In the baseline equilibrium scenario, it is assumed that water demand does not exceed supply. Green water is set exogenously and provided to agriculture, resulting in an increase in total productivity of this sector. Blue water is a production/ distribution activity that provides water to agriculture and other sectors (e.g., mining, fishing and municipal water). The water distributed by the two service sectors (blue water and a subset of it, municipal water) carries a cost due to the value added created through its delivery process.

In the CGE modeling framework, water is combined with the value-added nest and the intermediate inputs. Extending the treatment of typical CGE models, both blue water and part of it which is municipal water are assumed to be intermediate goods produced by a corresponding production activity. There is no substitutability between water and other intermediate inputs, while there is a constant elasticity of substitution between water and each value-added component (land, labor and capital) for each production sector. Blue water is an intermediate input, that is produced and distributed by activities, such as water utilities, and a natural resource used as a primary input. In contrast, green water, which stores the bulk of rainfall (65 %) as soil moisture in the root zone of plants, affects the total productivity of agricultural activities.

Production is either for regional domestic market or for trade, according to a Constant Elasticity of Transformation (CET) function, where (i) producers maximize revenue from sales subject to the CET function and (ii) export supply represents the first order condition and is a function of the elasticity of transformation, the share parameter in the function and the relative export price to domestic price. The allocation of imports and domestic production is determined according to CET functions, where import demand represents the first order condition for minimizing the cost of buying a given amount of composite goods. These functional forms (CET and CES) assume imperfect substitution and transformation between imports, exports and domestic goods and imply assumptions about separability and absence of income effects, where the ratios of exports and imports to domestic goods depend only on relative prices.

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[3] We use the following definitions from **Water Footprint Network:**

Green Water The precipitation on land that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation. Eventually, this part of precipitation evaporates or transpires through plants. Green water can be made productive for crop growth (although not all green water can be taken up by crops, because there will always be evaporation from the soil and because not all periods of the year or areas are suitable for crop growth).

Blue Water Fresh surface and groundwater, in other words, the water in freshwater lakes, rivers and aquifers.

Water Withdrawal The volume of freshwater abstraction from surface or groundwater. Part of the freshwater withdrawal will evaporate; another part will return to the catchment where it was withdrawn and yet another part may return to another catchment or the sea.

Municipal Water The water supplied by local authorities (municipalities) to households, businesses, and public facilities within a city or town.

Although the model has a neoclassical structure, in terms of agents' optimization and market equilibrium, these conditions are used as a micro-foundation for the application of Keynesian closure rules to account for unemployment and investment multipliers.

CLIMAWAT, the model, also incorporates modules to simulate the impact of externalities such as morbidity and mortality due to inadequate water supply, hygiene, and sanitation (WASH), based on data from the WHO database. A novel aspect is its incorporation of green and blue water data sourced from the Water Footprint Network (Mekonnen & Hoekstra, 2011). This data allows for the distinct tracking of green water, which is mainly used by agriculture as soil moisture. On the other hand blue water is directly consumed as a final good, utilized as an input in agriculture, as well as in industrial and service sectors. Other water data have been taken from FAO Aquastat database, in particular for what concerns water withdrawal, both for surface-water and groundwater. Data on water requirements and water tariffs are taken from the FAO database and the literature. Data on total water storage is from NASA.

Countries are first divided into 10 subregions, according to geographic location, and then further divided according to World Bank income group classification (Low-income, Lower-Middle Income, Upper-middle Income, High Income). As a result, the model encompasses up to 40 distinct regions along with an aggregate category for the "Rest of the World" (ROW) to ensure comprehensive global coverage. To simulate the impact of climate change to the economy, data from The Potsdam Institute for Climate Impact Research (PIK) are combined with different regression estimates from the literature (Ortiz-Bobea et al. 2021 and Damania et al. 2020).

Thanks to its dynamic calibration, the model can accurately adjust to any base year from 2007 to 2017, meeting researchers' needs for flexibility and preventing excessive results' dependence on a limited calibration basis.[4] This adaptability, facilitated by the panel nature of the GTAP dataset, appears also to improve the model performance in predicting the recent evolution of the global economy, as evidenced by Fig. 1 and 2 below.

Fig. 1 and 2 illustrate the model's predictive performance for value added by region, comparing model simulations with baseline data for 2017 and World Bank WDI data for 2018. In Fig 2, the blue dots represent the 2017 model simulations, while the orange dots correspond to the 2018 model simulations. The alignment of the dots along the diagonal line indicates a strong predictive capability of the model, demonstrating its accuracy in capturing the recent evolution of the global economy. This performance is achieved through dynamic calibration, allowing the model to adjust effectively to various base years within the 2007–2017 period. The close proximity of the dots to the diagonal suggests the model's reliability in forecasting value added across different regions.

5. Simulations and main results

Since water is a ubiquitous input that is used either explicitly or implicitly in all economic activity, there is uncertainty about channels of impacts and how these interact. Additionally, future outcomes of rainfall and temperature also cannot be determined with precision. To

[4] In model calibration and simulations we utilize Keynesian closures, thereby incorporating the interplay between exogenous investment, employment, and output. Compared to the neoclassical closure, this approach provides a more realistic understanding of policy impacts and economic dynamics in the presence of market rigidities and voluntary and involuntary unemployment.

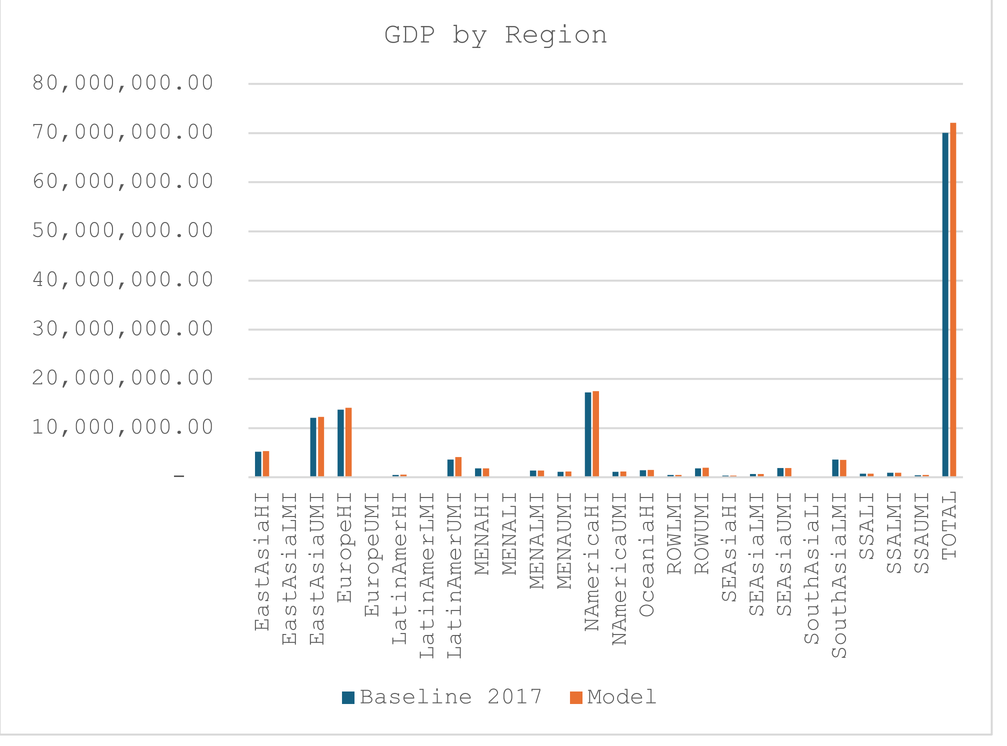

Fig 1. Model Simulations of Baseline GDP by Region.

account for the combined uncertainty of future climate change and their effects on the economy, projections are based on a range of parameters drawn from literature together with a range of outcomes to assure greater robustness of the projections. The approach accounts for parameter and outcome uncertainty using Monte Carlo methods.[5]

5.1. Climate change only

Our first simulation analyzes the socio-economic impacts of climate change under the RCP 4.5 scenario, a "middle-of-the-road" projection developed by the Intergovernmental Panel on Climate Change (IPCC). In this scenario, greenhouse gas emissions stabilize around the year 2100, leading to moderate climate change. RCP 4.5 envisions a world where climate change concerns are addressed with a balanced approach, integrating economic and urban growth with sustainable energy practices. If water related impacts are found to have troublesome consequences in such a scenario, the predicament is likely much worse in less optimistic futures. To gain understanding of the economic impacts, it is helpful to start by exploring the consequences of changes in temperature and rainfall, without the corresponding projected changes in total

[5] The stochastic simulation methodology involve: (1) estimating parameter distributions for climate-related shocks; (2) defining scenario bounds for these distributions; (3) conducting CGE model simulations for each parameter value; and (4) running Monte Carlo simulations to generate a probabilistic distribution of potential economic impacts.

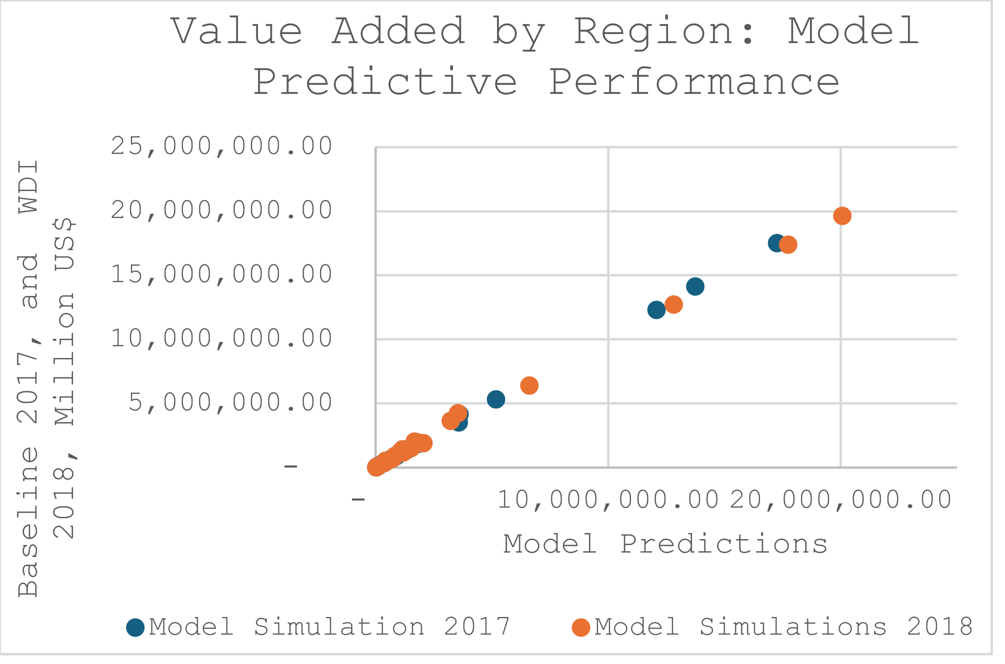

Fig 2. Comparative Model Performance on two Data sets.

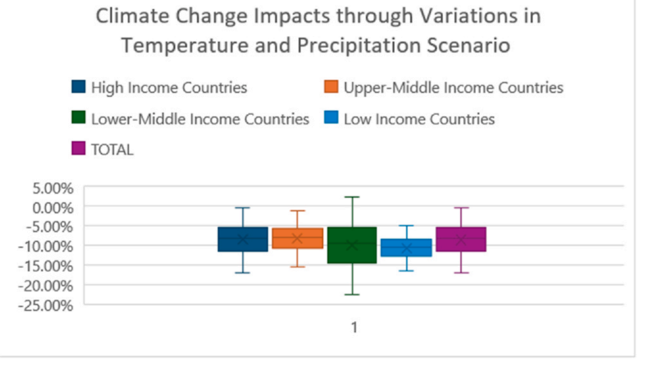

Fig 3. Climate Change Impacts through Variations in Temperature and Precipitation Scenario.

water storage. While this is an artificial exercise, it is nonetheless consistent with all simulation models in the climate change economics literature that focus only on blue water and neglect green water stocks (soil moisture) that are included in the measures of TWS.

The results are in Table 1. Across all parameters considered there is a decline over all economic indicators. On average there is a decline in GDP of 9 % (range of −8 % to −19 %). Reflecting this fall in economic activity, there is a decline in water virtual trade and especially pronounced impacts in agriculture which stands on the front lines of climate change. Across regions the largest relative decline occurs in South Asia and Sub-Saharan Africa and in low-income countries. These results are broadly consistent with previous estimates on the impacts of

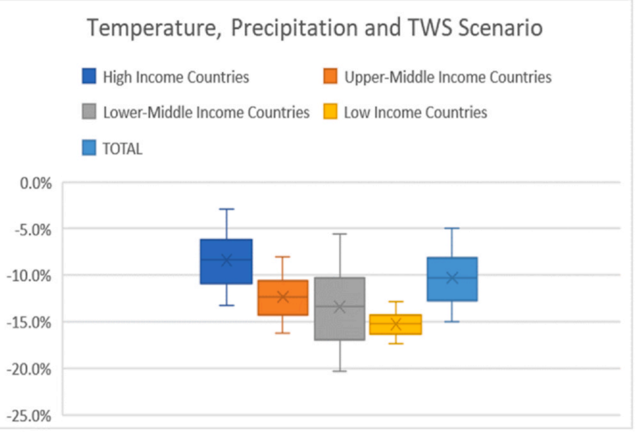

Fig 4. Impact of Climate Change through Temperature, Precipitation plus TWS Changes.

climate change in literature. For instance, the widely-quoted Stern Report on Climate Change found that without action between 2001 and 2200, GDP would decline by Stern et al., (2010) between 5 % and 11 %. But in contrast to much previous work, the projections presented here explicitly include the effects of changes in rainfall and are thus somewhat larger.

5.2. Climate change and declining total water storage (TWS)

Agricultural and land use practices, whether induced by climate change, or other factors have significant effects on green and blue water resources. Total water storage (TWS) is a relatively new satellite-based measure of the total water endowment combining soil moisture, surface water, ground water and ice. It captures the interactions and dependencies between blue and green water stocks. For instance, irrigation may lower water tables but increase soil moisture. Conversely, tillage practices can alter the capacity of soils to hold moisture and hence alter green water stocks (i.e., soil moisture), and may also promote greater runoff (blue water) or evaporation. Climate change also influences agricultural practices. With rising temperatures and shifting patterns of rainfall there will be changes in the availability of water and hence the prospects for irrigation. Dryer and hotter regions will likely irrigate more intensively to

Table 1
Mean Impact of Climate change through variations in Temperature and Precipitation.

	Value Added Results (Mln US$)	**Agricultural Production (Mln US$)**	**Agricultural Net Exports (Mln US$)**	**Food Production (Mln US$)**	**Food Net Exports (Mln US$)**
High Income Countries	−8.8 %	−8.3 %	−8.4 %	−11.0 %	−11.0 %
Upper-Middle Income Countries	−8.5 %	−8.5 %	−8.0 %	−12.5 %	−10.9 %
Lower-Middle Income Countries	−10.3 %	−9.8 %	−9.6 %	−14.4 %	−13.9 %
Low Income Countries	−6.2 %	−5.6 %	−5.3 %	−15.4 %	−14.8 %
TOTAL	−8.8 %	−8.7 %	−8.4 %	−12.3 %	−11.4 %

Table 2
Mean Impact of Climate Change through Temperature, Precipitation plus TWS Changes.

	Value Added	Agricultural Production	Agricultural Net Exports	Food Production	Food Net Exports
High Income Countries	−8.7 %	−8.2 %	2.8 %	−7.6 %	−14.7 %
Upper-Middle Income Countries	−13.8 %	−11.5 %	−45.6 %	−12.2 %	−16.9 %
Lower-Middle Income Countries	−12.9 %	−15.0 %	−40.3 %	−12.6 %	8.7 %
Low Income Countries	−12.5 %	−8.8 %	−23.4 %	−11.2 %	3.3 %
TOTAL	**−10.9 %**	**−11.5 %**	**0.0 %**	**−10.6 %**	**0.0 %**

maintain agricultural output, leading to declines in total water storage (TWS). Decreases in TWS, in turn, will increase the costs of water extraction due to declining water tables. The impact will cascade through the economy and increase the costs of other activities.

The model accounts for these effects through supply curves that reflect increasing costs for extracting and distributing water in areas where TWS declines significantly. The biggest declines occur in MENA and some parts of Sub-Saharan countries – regions that are dry and where water is already scarce. Under this scenario (Table 2) global GDP would fall about 11 %, with high income countries experiencing the least severe impact at 8.7%, and a range from and about 12.5 % and 12.9 %, respectively in lower middle income and low-income countries and 13.8 % in higher middle-income countries. Agricultural and food production would fall by around 10 % or more.

5.3. Adding water supply and sanitation (WASH) deficits

When inadequate water supply and sanitation – a developing country problem- is included, the losses decline even further. In low-income countries where access to safe water and sanitation is lowest in the world also exhibit the largest declines in GDP (around 15 %) followed by lower middle income countries where access to safe water and sanitation is also low. These impacts are mediated through changes in human capital that have consequences for labor supply that cascade through impacted economies.

Overall, these estimates suggest that a deeper deterioration of the international environment may be occurring due to water stresses that are suggested in many other studies. For example, the Stern Review forecasts a range of potential welfare costs of unmitigated climate change from 2001 to 2200 that could be equivalent to a 5 % loss in per-capita consumption compared to Business as Usual (BAU) scenarios. By accounting for reductions in total water storage (TWS), and heightened costs of water extraction—factors directly influenced by rising temperatures and shifting rainfall patterns, our simulated scenarios indicate even more concerning impacts that could accelerate these declines (e.g., between –6 and –10 % income per capita fall as compared to BAU before 2050). These changes are likely to exacerbate the economic and environmental pressures of most areas of the world and make especially dramatic the plight of poor countries in arid and semi-arid areas.

6. Policy experiments

While climate change appears to impact global economic performance, the model runs are also characterized by substantial divergences between the current user costs (typically very low) and the shadow prices of water, as well as most goods and services. Aligning these through policies that internalize externalities and correct market failures could, in principle, be effective measures to mitigate the adverse effects of climate change. To explore this option, we used CGE simulations to design and evaluate the impact of a set of policy experiments aimed at improving water allocation efficiency. We assume that the primary goal of these policy interventions would be to internalize the externalities of water usage by setting the prices of blue water, when used as a production factor, to match its opportunity costs, evaluated as shadow prices in the CGE solutions. These prices are calculated in a basic model experiment on the impact of various climate change factors (such as temperature, precipitation, and Total Water Storage trends), and reflect water's value based on its scarcity and the opportunity cost of redirecting it from its most valuable application. While enforcing shadow prices should improve efficiency, we should expect such effects to be somewhat limited in a second-best scenario where the economy is plagued with distortions like taxes, subsidies, regulations, and monopolies that influence resource allocation.

To simulate the implementation of efficiency pricing, we create a CGE scenario where an equivalent tax (or tariff) is imposed on water consumption to align water costs with its shadow prices, thereby ensuring that economic agents are motivated to internalize the externalities from water uses. The use of the tax receipts, however, has significant economic implications. For example, if tax revenue is used to fund public services, infrastructure, or to reduce existing distortive taxes (a revenue-neutral approach), it can stimulate economic activity or offset the economic burden of the tax. If the revenue is used to pay down national debt or to develop a government surplus, it can reduce future interest obligations and improve the government's fiscal position. More generally, if revenues are directly returned to consumers or businesses, such as lump-sum rebates or reductions in other taxes, they can mitigate the regressive impacts of the original tax and boost consumer spending. In a CGE model, shadow prices are calculated endogenously and express the value of one good or resource relative to another within the model. They reflect the opportunity costs of utilizing a resource and are relative to an arbitrary numeraire, rather than to money. In the case of the Keynesian closure used in our model, the numeraire is assumed to be unskilled labor, whose shadow price is fixed at unity, and whose supply is assumed to be unlimited.

A growing body of literature[6] suggests that finding an optimal Pigouvian tax for water is exceptionally challenging due to the presence of multiple market distortions, spatial and temporal variability, and the likelihood of non-linear responses. The impacts of water taxes can vary significantly depending on the specific context, and poorly designed taxes can lead to unintended negative consequences, such as shifting production across sectors or exacerbating inefficiencies elsewhere. Several studies (e.g, Tsur et al., 2004; Perry et al., 2009) also suggest that the level of effective water taxation required to achieve greater efficiency and conservation would have to be too high to be politically feasible.

In order to address these concerns, in our policy experiments, we calibrate the tariff rates using the observed degree of inefficiency in water allocation. To this aim, we examine the effects of implementing water tariffs as a percentage of the market price (or the equivalent current cost), based on the relative shadow price, rather than converting shadow prices to absolute values. We also test various tariff levels to observe their economic impact, by conducting

[6] See, for example Bovenberg & Goulder, (1996), Fullerton et al (2001), Tsur et al (2004), Perry et al. (2009), Kilimani (2015).

Table 3
Impact on GDP of different levels of water pricing.

	BAU	**Average water price tax rates**			
		7 %	**15 %**	**22 %**	**30 %**
	Impact on GDP of climate change	**Impact on GDP of water price changes (Differences from BAU)**			
High Income Countries	−8.7 %	−0.45 %	−0.97 %	−1.47 %	−5.08 %
Upper-Middle Income Countries	−13.8 %	−0.07 %	0.29 %	0.42 %	−1.17 %
Lower-Middle Income Countries	−12.9 %	4.06 %	9.27 %	14.86 %	16.67 %
Low Income Countries	−12.5 %	1.46 %	4.16 %	8.98 %	13.99 %
TOTAL	**−10.9 %**	**0.14 %**	**0.52 %**	**0.93 %**	**−1.33 %**

simulations to assess how changes in tariff levels influence resource allocation and overall economic health.

Table 3 and Fig 6 show the impact of various levels of water pricing on GDP across the income and regional country groups, set against a baseline that includes the impacts of climate change and Total Water Storage (TWS) variations. The table shows GDP impacts at different incremental water pricing levels (7 %, 15 %, 22 %, 30 %) with each subsequent percentage representing an increased level of water pricing, proportional to shadow price levels and intended to reflect a progressively stricter water resource management or conservation policy. Importantly, these results do not necessarily imply that similar GDP impacts could be achieved in the absence of climate change but demonstrate that these policies enhance the economy's capacity to buffer against the negative impacts of climate change.

For high-income countries, water taxation provides no apparent advantage. The already significant negative effects of climate change (-8.7 %) worsen nearly proportionally with water price increases until a threshold of 22 % is reached. Beyond this point, the negative impacts of the tax become even more pronounced. For lower- and middle-income countries, these simulations suggest an inverted-U pattern, indicating that while the tariff initially mitigates the negative economic impacts of climate change by promoting more efficient water use and internalizing externalities, beyond a certain point, the costs, such as reduced consumer welfare and economic output, begin to dominate. The turning point identifies the tariff rate beyond which these negative impacts outweigh the benefits of climate change mitigation.[7]

The varying impacts suggest differences in how water pricing affects economies based on their income levels and their economic structure and adaptation capacity. In general, while moderate water pricing appears to be beneficial, the weight of the excess tax burden tends to become prevalent as higher levels are approached with a significant risk of economic contractions. However, the results should be interpreted with caution, since they refer only to the response to adverse climate change conditions and are thus an indication of the tax inducing greater resiliency, rather than necessarily best absolute performance. Moreover, the relationship

[7] Shan et al. (2023), using a CGE model for China, find a similar result, with an optimal scenario from the perspectives of water quantity, water use efficiency, and economic impact with water resources tax rates of 23 % for high water-consuming industries and 18 % for general water-consuming industries, coupled with tax refunds and subsidies for sectors.

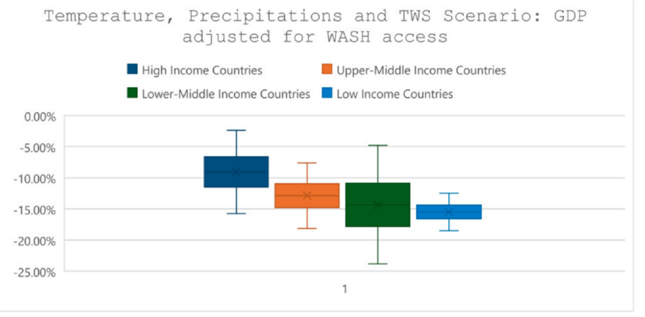

Fig 5. Impact of Climate Change through Temperature, Precipitation plus TWS Changes, plus WASH access deficits.

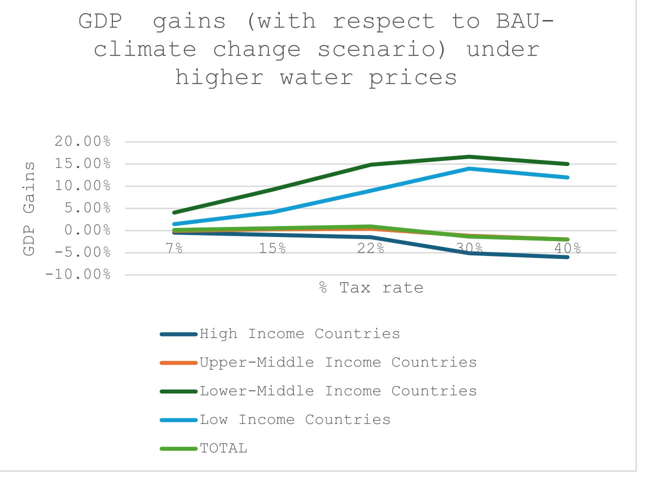

Fig 6. Impact on GDP of different levels of water efficiency pricing.

between the size of the tax and the economic impact appears clearly U shaped only for the case of lower middle income and low-income economies.[8] Only for these countries, in spite of the general second-best conditions and other market distortions, the policy experiments suggest an optimal Pigouvian tax level, that maximizes economic welfare, with any deviation from this level resulting in lower overall economic output. In this case, however, the WASH effects appear especially dramatic and call for supportive measures for the most vulnerable population groups in low-income countries (Fig 5). In higher income settings, policy measures to mitigate negative impacts at higher pricing levels might also be necessary, such as subsidies for water-saving technologies or assistance for industries heavily dependent on water.

Higher water prices appear to improve WASH outcomes in lower-middle-income countries by reducing water wastage and promoting efficient use. Since the model redistributes the tax

[8] Our results confirm some earlier CGE studies, such as, for example Berrittella et al. (2008), which highlighted that water taxes can promote conservation and efficiency, with positive spillovers and gains for lower income countries, but possible negative consequences in high-income nations.

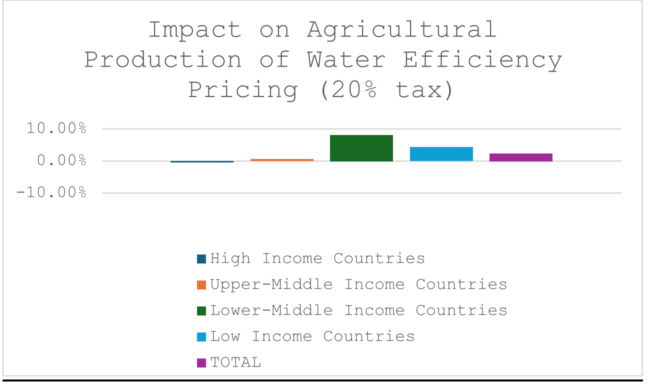

Fig 7. Impact on Agricultural Production of Water Efficiency Pricing.

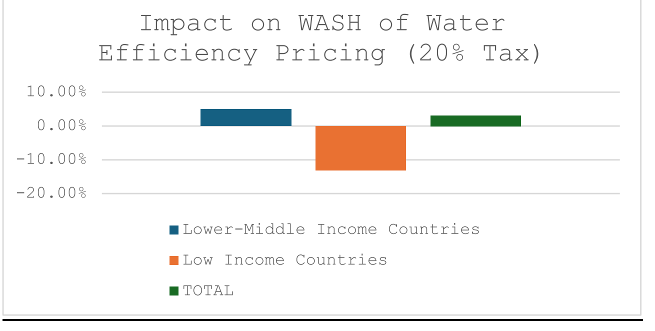

Fig 8. Impact on WASH of Water Efficiency Pricing.

proceedings according with historical shares, some of the additional revenue from the tax is invested in WASH infrastructure and services, improving access to clean water and sanitation. The redistribution of tax proceedings also includes subsidies for vulnerable populations that can promote more equitable access and provide better funding for maintenance and expansion of supply systems. More generally, water price increases appear to encourage water-saving behaviors, which in turn is linked to positive impacts on enhancement of hygiene and reducing waterborne diseases (Shan et al., 2023). Fig 6

Making water prices closer to CGE shadow prices can be interpreted as a partial correction of market failures, with two main effects. First it improves allocative efficiency. Especially in countries where water is both scarce and allocated inefficiently, the economic gains from improved management and allocation of blue water are likely to be substantial. In addition, changing relative prices also alters the relative comparative advantages of water intensive commodities and hence trade patterns of these goods (Fig 9). In general, in lower- and middle-income countries that are mainly water scarce allocative efficiency gains are substantial and hence their GDP suffers comparatively lower reductions from climate change. In higher income countries the impacts are more muted and almost zero, reflecting the fact that water is more abundant in these countries and is often used in higher value-added sectors of the economy. This is shown in Fig. 7, 8 and 9 below for a 20 % tariff on water. Fig 9

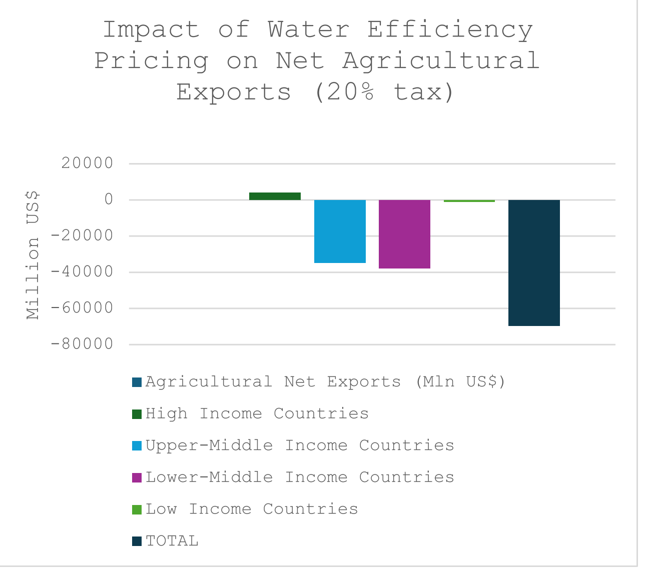

Fig 9. Impact on Agricultural Net Exports of Water Efficiency Pricing.

7. Conclusions

This paper has explored the complex and multiple impacts of water on the global economy, emphasizing its critical role of water as both a public good and a production factor. By focusing on the water value chains and by explicitly incorporating green and blue water, as well as total water storage (TWS) in a global CGE model, the study provides a more comprehensive understanding of the economic implications of water resources. Key results suggest that the costs of water mismanagement coupled with the impacts of climate change may be greater than estimated in earlier research, with potential losses reaching over 10 % of GDP by 2050, particularly in lower-income and water-scarce regions.

The findings highlight the substantial economic costs associated with climate change and declining water resources, particularly in lower-income and water-scarce regions. Model simulations indicate that implementing efficient water pricing mechanisms aligned with shadow prices, such as tiered tariffs or volumetric charges, can mitigate some of these adverse effects by promoting better resource allocation and encouraging sustainable practices. A key finding is that low- and middle-income countries with their greater dependence on water intensive sectors such as agriculture exhibit greater gains, than higher income countries, from resource reallocation that may derive from improved water management practices. While these policies may be difficult to implement and imply undesirable social consequences, in lower-income countries, the potential economic gains from better water pricing appear so significant that they could effectively counter the projected losses from climate change, highlighting the transformative impact of such policies. At the same time, the results also caution against excessively high-water pricing, which can lead to economic contractions and adverse social consequences.

Overall, this paper addresses the problem of global water management and climate change within economic modeling and policymaking. As anthropogenic impacts on the environment continue to alter global water cycles, it becomes crucial to develop and quantify economic strategies that mitigate negative changes and ensure sustainable use and management of this vital resource. CGE models are one increasingly informative and accurate tool that can be used for this purpose, but present several limitations, including estimation problems, as well the imperfections of a schematic representation of a very complex reality. Our model attempts to take a small step in removing some of these limitations and in so doing paving the way for future research advancements in this field.

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Data base used

GTAP11: https://www.gtap.agecon.purdue.edu/databases/v11/GTAP
AQUASTAT (FAO): http://www.fao.org/aquastat/en/
Water Footprint Network: https://www.waterfootprint.org/
NASA GRACE/GRACE-FO: https://grace.jpl.nasa.gov/
WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP): https://washdata.org/
OECD: https://www.oecd.org/

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