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Modelling Global Water

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Abstract

This paper examines the economic implications of evolving water availability with a twofold objective. Firstly, it provides an overview of the problem of economic modelling of water in a general equilibrium context. To this aim, it presents both a general discussion of key issues and 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 addresses a crucial gap in the research work to date, by developing and implementing a global CGE model that incorporates the economic impacts of both precipitation and total water storage (TWS) – an aggregate measure encompassing soil moisture, surface water, and groundwater. The model also includes the health effects of inadequate water supply and sanitation (WASH). By integrating these key variables, alongside a detailed representation of how water enters in the different value chains, the model provides novel suggestions and a better understanding of how water availability influences economic activity across sectors. Simulation results from the model are then used to provide insights into the question of the "cost of inaction", that is the failure to engage in proactive economic policies under various water-related scenarios, including those driven by climate change.

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.

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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. These 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 debatable 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 geographical location, land use, anthropogenic changes, and the balance between rural and urban areas.[3]

This paper has two objectives. First it provides a broad overview and evaluation of the literature on the economic impacts of water with a particular focus on the contribution of computable general equilibrium (CGE) models. Second, it addresses a gap in this literature by presenting a 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.

2. Modeling Approaches

Empirical research delving into the impacts of rainfall and water availability on economic growth has highlighted the variable effects of climate change on countries' economic performance, 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 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 is 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. Reflecting differences in model structure and assumptions these models generate a wide range of results. A recent meta-analysis (Tol, 2024) reveals that CGE studies correlating economic growth with temperature levels show inconsistent results regarding the direction of the impact. In contrast, studies that consider economic growth as a function of temperature change consistently agree on the direction of the impact but differ significantly in the magnitude of the effect. The former posits that climate change has a permanent effect on economic growth, while the latter suggests that the effect is transient.

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[3] 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%.

While fundamentally rooted in neoclassical economic theory, CGE models exhibit considerable architectural diversity and adopt a wide range of alternative hypotheses with great flexibility. This flexibility allows for the incorporation of deviations from perfect markets, such as involuntary unemployment, imperfect competition, externalities, and various market distortions. Additionally, CGE models can employ different closure rules to examine the effects of exogenous factors like investment shifts, autonomous changes in aggregate demand, productivity enhancements, and technological advancements.

However, while their flexibility has increased the potential of CGEs to analyze the complex interdependencies associated with climate change, the results is a wide and sometimes confusing array of results. 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.

These limitations, however, go hand in hand with an important feature, if only rarely recognized, of static CGEs, and consist in their organic connection with Solow-Ramsey growth models. This connection allows their use to approximate steady-state and growth path dynamics traditionally modeled by Solow-Ramsey frameworks and depends on two main properties. First, the solutions of a static CGE model can be considered steady states of neoclassical growth models, regardless of the specific closures applied. This property depends on CGEs' neoclassical architecture and implies that a static CGE model, even though by definition lacks explicit time dynamics, can mimic the steady-state conditions of Solow-Ramsey models. While not all static equilibrium solutions correspond to steady states of an equivalent dynamic model, all steady states can be rendered by a solution of a static CGE model[4].

In a neoclassical framework, steady states are achieved when capital per worker and output per worker are constant, implying that investment equals depreciation and investment may grow only under the influence of exogenous factors (e.g., productivity increases or other autonomous shocks). Similarly, a static CGE model reaches equilibrium by balancing factor markets (labor and capital) and commodity markets without time variation. Since the equilibrium conditions in CGE

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[4] In general, the solutions of a static computable general equilibrium (CGE) model can be considered steady states of Solow-Ramsey (SR) type growth models regardless of the closures used, because the equilibrium conditions of the static model align with those of the SR models under the assumption of long-term equilibrium. In a SR framework, steady states are achieved when capital per worker and output per worker are constant. Similarly, a static CGE model reaches equilibrium by balancing factor markets (labor and capital) and commodity markets without time variation.

models align with steady-state conditions in Solow-Ramsey models, this property suggests that static CGE models can be used effectively to analyze structural economic responses in a comparable way to growth models, even when the allocation specifics are influenced by the chosen model closures[5].

The second property is that a series of comparative static experiments of a CGE model, projected over time through exogenous changes in population, productivity, or other variables, approximates a steady-state growth path similar to that in a Ramsey-Solow model. In other words, a CGE model can be solved for different dates in the future to provide a sequence of equilibria in response to gradual changes in exogenous variables, such as population growth or technological improvements. Each change in one or more of these variables yields a new static equilibrium, which, when viewed collectively, forms a path mimicking the balanced growth path in Solow-Ramsey models. This property implies that by adjusting exogenous variables or parameters, one can effectively simulate dynamic growth trends as a sequence of steady state equivalent static CGE solutions. This dynamic growth path is quite different from the path provided by dynamic models that generally are used to explore the transitional path to a single steady state. Together, these properties underscore the versatility of CGE models in capturing both equilibrium and growth dynamics traditionally reserved for dynamic growth models. By doing so, they enhance the utility of CGE models in policy analysis, particularly in exploring the long-term impacts of demographic shifts, technological advancements, and other exogenous factors on an economy's steady-state and growth trajectory.

3. Review of the CGE Literature

Modeling climate change 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 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 (5,000 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.

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. To account for the externalities of water a common way of proceeding is to use water as a shifter of the production function, thus resulting in changes in agricultural productivity. Depending upon the research question economic models may legitimately choose to emphasize one of these, without necessarily jeopardizing the usefulness of the model.

An example of the externality assumption is the study by Dudu, Ferrari, and Sartori (2018), who propose using a CES shifter (i.e. sectorial, specifically calibrated total factor productivity), to model

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[5] For example, a closure that fixes the capital stock can be interpreted as a scenario where investment equals depreciation, a condition for a steady state in a Solow-Ramsey model. Similarly, a closure that fixes the savings rate can be interpreted as a specific saving behavior in the Ramsey 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 assumption is that water is a complement rather than a substitute for the other factors and the intermediate goods involved in production. The implication is that large inefficiencies are likely to arise from widespread failure of the market economy to internalize such a pervasive and far-reaching externality.

One of the early examples of modeling water as a production factor in an economy-wide framework is that of Berck et al (1990) which 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. The results indicate that removing water from the Southern San Joaquin Valley results in a rapid decline in cotton and/or grain acreage and in an increase in acreage devoted to livestock. Coincident with this acreage shift is a decrease in Valley GDP, employment, and agricultural income. Common to most CGE model the results indicate that decreases in macroeconomic indicators are much less pronounced than the acreage shift, because the resources released find alternative employment. .

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, 2007). However, each solution appears to have 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; Liu et al., 2019; Luckmann , 2016; Roson and 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 and Winning, 2018, Burniaux and Truong, 2002, Peters, 2016.

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 intricate, making it difficult to isolate and represent the true costs and benefits of individual economic activities. Smajgl et al. (2012) recommend a new more flexible modelling approach that combines the strengths of the bottom up and top-down approaches, while recognizing the distinctive dynamics of water and energy systems and interactions. According to the authors the latter approach would overcome a number of limitations of using the CGE framework to explore the energy water nexus, which are likely to become increasing relevant to policy making as interactions and pressures increase but will temporarily involve a more experimental approach.

Water modelling opportunities and challenges can also be examined from the lens of increased scarcity and deteriorating quality of water and impacts of climate change, leading to distinct approaches that combine the externality and 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 dependence of possible impacts on both theoretical premises and specific circumstances.

They 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. Using a 38-sector, 45-region aggregation of the model, the authors simulate the short-run 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 and 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, water supply constraints could improve allocative efficiency; this welfare gain may more than offset the welfare losses due to the resource constraint. Further work with 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.

Banerjee et al (2015) develop a dynamic computable general equilibrium model linked with a food security module to explore climate change impacts on agriculture and food security for Bangladesh. Although climate change impacts had a relatively small effect on GDP, reducing it by $29,925 million Taka (-0.11%) by 2030, agricultural sector impacts were felt more acutely, reducing output by -1.23%, increasing imports by 1.52%, and reducing total caloric consumption by 17%, with some households remaining underfed due to inequitable food distribution. Evidence generated here can guide policy to ensure that economic growth contributes to meeting national development and food security targets.

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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. They find that, in 2050, climate-change-induced health impacts may increase GDP by 0.08% or reduce it by 0.07% (in the Rest of the World, which includes Africa).

Bosello et al (2012) propose a methodology for assessing climate change impacts on ecosystem services within a CGE approach The analysis captures the role of macroeconomic feedback at the domestic and the international levels in determining the final outcome. Their valuation focuses on the provisioning services provided by European forest and cropland ecosystems and on the carbon sequestration services provided by European forest, cropland and grassland ecosystems. For provisioning services, they show first that agricultural land productivity in the EU is expected to decline in the next 50 years (-6% in the Med EU in 2050 for a temperature increase of 3.1°C with respect to 2000 is the biggest decrease) as a result of soil biodiversity loss, while forest timber productivity may decline in the Mediterranean but increase in other EU areas, in particular the north. In economic terms, this means that the Mediterranean EU may experience a GDP loss ranging in present value (PV) from US$ 9.7 to 32.5 billion and the Eastern EU a loss ranging from US$ 7.2 to 22 billion in the next fifty years depending on the climate scenario. However, climate change has a positive net effect on ecosystem provisioning services in Northern European countries, which may experience a PV - GDP gain ranging from US$ 2 to 5.6 billion. All in all, the total net discounted loss for the three regions ranges from US$ 15 to 49 billion. These results can be interpreted as the general equilibrium costs associated with the decreased ability of forest and agricultural systems to produce provisioning services as a consequence of climate change. The value of EU forest, grassland and cropland carbon sequestration services is assessed by estimating the environmental damage that the world as a whole avoids because of the benefits of those services. According to these estimates, unimpaired ecosystem services could provide a cooling effect of 0.018°C over fifty years. This would imply lower accumulated, discounted (at 3%) GDP losses, ranging from US$ 27 to 85 billion, or from US$ 0.55 to 1.7 billion in annuities.

Along similar lines, Wittwer and Banerjee (2015) applied a dynamic multi-regional Computable General Equilibrium model of the Australian economy to examine the impacts of developing irrigated agriculture in remote Northwest Queensland. A potential investment and operational scenario is implemented using three alternative forecast baselines. The simulations suggest that on balance due to climate change, clear welfare gains do not arise from the potential irrigation development. Banerjee (2015) investigated the returns to investing in irrigation efficiency to return water to the environment for enhanced ecosystem services supply. Results indicate an increase in regional output, income and employment, while at the national level there is a small negative impact resulting from the transfer of resources to the basin and the crowding out of private investment.

Damania and Scandizzo (2016) develop a dynamic CGE model for Kenya, with detailed water accounts to study alternative policies and their interaction with conservation and natural resource management. Using historical data on national accounts and data from a plurality of sources, they estimate detailed SAM accounts for water withdrawn directly and indirectly to sustain the final demand of each sector thus allowing to estimate the water footprints of each sector. These estimates as well as the related CGE simulations lead to the counterintuitive result that (i) traditional agriculture and mining are more water intensive than irrigated agriculture; and (ii) industrial sectors are less water intensive than services. 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 et al (2018) use a dynamic CGE model to model Mauritius ocean economy, with detailed accounts for green and blue water and different types of ecosystem services. The model is based on a detailed social accounting matrix extended to various aspects of the ocean economy and is used to analyze both macropolicies and specific projects. Scandizzo, Cufari and Pierleoni (2018) develop a regional model for Kenya based on a SEAM containing a detailed account of natural resources, water, national parks and conservancies, to study the impact of infrastructure and growth on conservation and wildlife. The same authors (2019) develop a CGE model for Lao including water resources, CO2 emissions and natural capital, as key elements to study the interaction between the environment, the economy and poverty across households of different location and ethnic origin.

Shan et al. (2023) use a CGE model integrating multiple types of water production modules, including surface water, groundwater, and unconventional water, to develop a case study for water tax reform in the China Hebei Province. They found that water taxes improve water allocation by reducing conventional water use and promoting the adoption of unconventional water sources, enhancing long-term sustainability. Higher tax rates are effective in reducing water consumption of water-intensive industries, with a tradeoff between efficiency and sustainability.

4. A New Modelling approach

Climate change and water pose significant challenges for CGE modeling for two contrasting motives. On one hand, the inherent tension between water's public good attributes and its simultaneous role as a 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 effects coupled with the local features of water demand and supply, require a granularity that appears 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, aimed at exploring 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 nonagricultural goods. While each type of water contributes differently to the overall water resource management and its impact on agricultural production,[6] we will focus on green water and blue water as the main components of the international value chains.

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1. [6] Blue water represents freshwater resources in the form of surface water and groundwater. It includes water in rivers, lakes, reservoirs, and aquifers. Blue water is crucial for various purposes, including irrigation, drinking water supply, and industrial use. In the context of water value chains, blue water is directly linked to the production of agricultural goods through irrigation and other water-dependent processes.
2. Green water refers to rainwater that is stored in the soil and used by plants for their growth through evapotranspiration. It plays a significant role in supporting rainfed agriculture and natural ecosystems. Green water is essential in the early stages of crop development and helps sustain vegetation in non-irrigated areas. In water value chains, green water is associated with rainfed agricultural production and its role in supporting agricultural output.
3. Grey water is relatively clean wastewater generated from domestic activities such as bathing, washing dishes, and laundry. It does not contain human waste and is usually diverted from the sewage system. Grey water recycling is an important aspect of water in *urban* value chains, as it can be treated and reused for non-potable purposes, such as irrigation, thereby reducing freshwater demand for certain applications.

Water value chains define the geography of water both in a local and global way. First, the supply of water is impacted by physical endowments and changes both in near and distant regions. For instance, on the supply side blue water flows may be impeded by dams, diversions or biomass loss, while green water fluxes are impacted by upwind vegetation. On the other hand, through virtual water trade, water from one region may be transported to another. International production value chains thus involve the complex network of production, processing, and distribution activities spanning multiple countries to bring products to consumers worldwide. These value chains can have significant implications for water resources, especially when water-intensive commodities are produced in water-scarce regions and transported over long distances.

The three important concepts of virtual water, water footprint and water at a distance are worth recalling in this regard because of their relevance in defining international value chains. Virtual water refers to the hidden water footprint embedded in the production and trade of goods. In the context of agricultural products, it represents the amount of water used in the production process and indirectly transported across borders through exports and imports of these goods. The water footprint of all products of agricultural and industrial processes considers both the direct water use (blue and green water) during cultivation and the indirect water use (virtual water) involved in the supply chains. Understanding the water footprint helps identify the water-intensity of products and their potential impacts on water resources in both water-scarce and water abundant regions The concept of 'virtual water' describes the amount of water embedded within goods and services during their production. This 'hidden' water flow occurs during international trade, where water-scarce regions can import water-intensive products from water-rich regions, effectively 'importing' the water used in their production. Conversely, water-rich regions can export water-intensive products, effectively 'exporting' virtual water to water-scarce regions. This phenomenon extends beyond agricultural products to encompass a wide range of manufactured goods, highlighting the interconnectedness of global water resources through international trade.

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 try to integrate in our modelling scheme the Water, Sanitation and Hygiene (WASH), key components of the water value chain, especially targeting developing countries. To this aim, we estimate key WASH parameters by drawing on diverse data sources, including several

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4. Black water is highly contaminated wastewater from toilets, industry and agriculture. It may contain human waste and other toxins that are especially hazardous to animal, environmental and human health It requires treatment before being released back into the environment. While black water is not directly involved in water value chains for agricultural production, it brings economic costs by reducing available freshwater supplies, impacting human health (labor supply) and impacting environmental health (such as through hypoxia of oceans, freshwater sources and biodiversity).

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 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 an environmental externality 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 models 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, 2016, , Cervigni and Scandizzo, 2017, Perali and Scandizzo, 2018) to consider the externalities from climate change and water consumption. 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 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[7]. 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. Detail are provided in Appendix X. 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, as descriped in Appendix X. 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 factor 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

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[7] 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.

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 good. 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.

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. (further details on the model are provided in the appendix)

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 and Hoekstra, 2011). This data allows for the distinct tracking of green water, which is mainly used by agriculture as soil moisture, and blue water, which is directly consumed as a final good and 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 data base 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)).

Table 1 in the Appendix summarizes the main characteristics of the model.

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. 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 Figures 1-3 below.

Figure 1. Model Simulations of Baseline GDP by Region

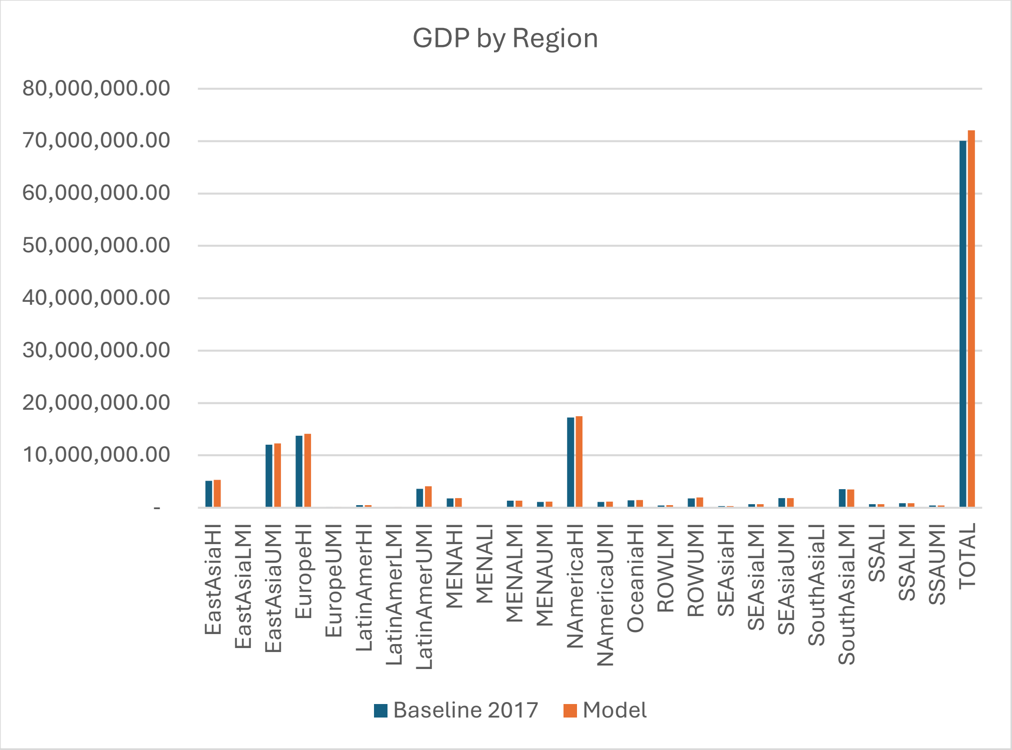


Figure 2. Model simulation of WDI2018 GDP by region

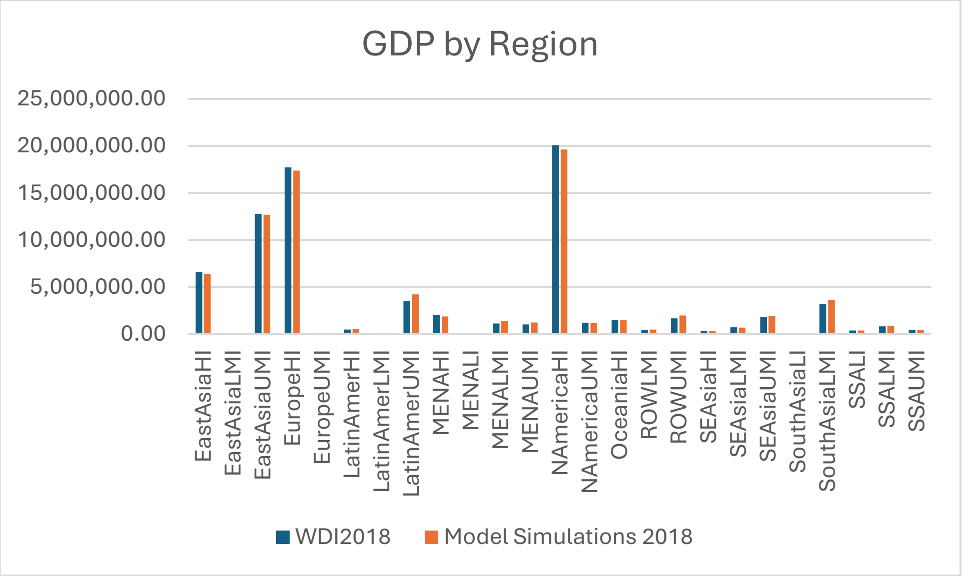
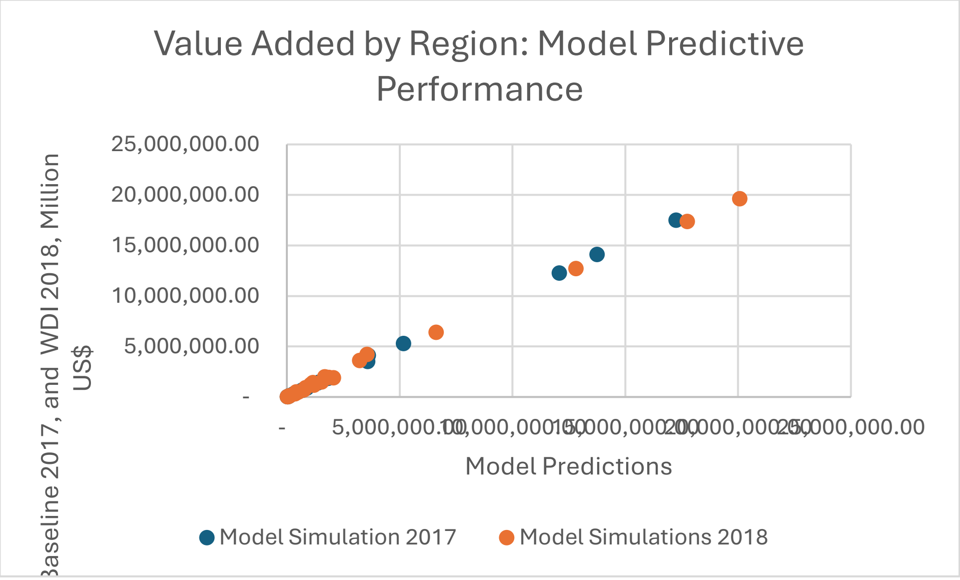


Figure 3. Comparative Model Performance on two Data sets



Figures 1-3 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 Figure 3, 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 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 the 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, described in greater detail in the Appendix.

Climate change only. In the first simulation, the model explores the impacts of climate change on key socio-economic indicators under the mid-range scenario, termed RCP 4.5. RCP 4.5 is a "mid-range scenario where GHG emissions stabilize in 2100". 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 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 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 between 5% to 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.

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 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 essentially unaffected, 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.

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. Agricultural and food production would fall by around 10% or more, when including (WASH) health effects and other human capital-related losses reaching 17% in poor countries.

Overall, these estimates suggest that a deeper deterioration of the international environment may be occurring due to water stresses that 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.

Table 2. 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%

Figure 1

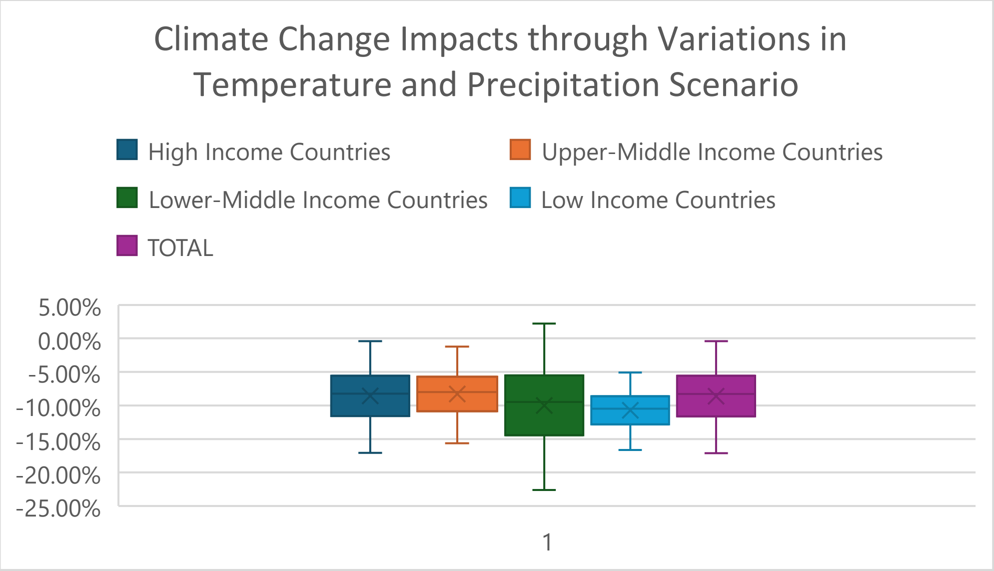


Table 3. Mean Impact of Climate Change through Temperature, Precipitation plus TWS Changes

	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%**

Figure 3 CHANGE TITLE

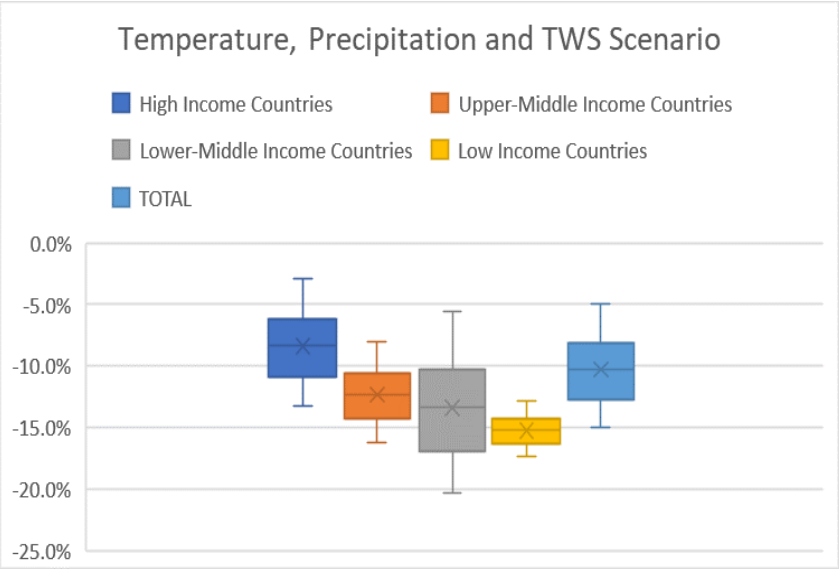
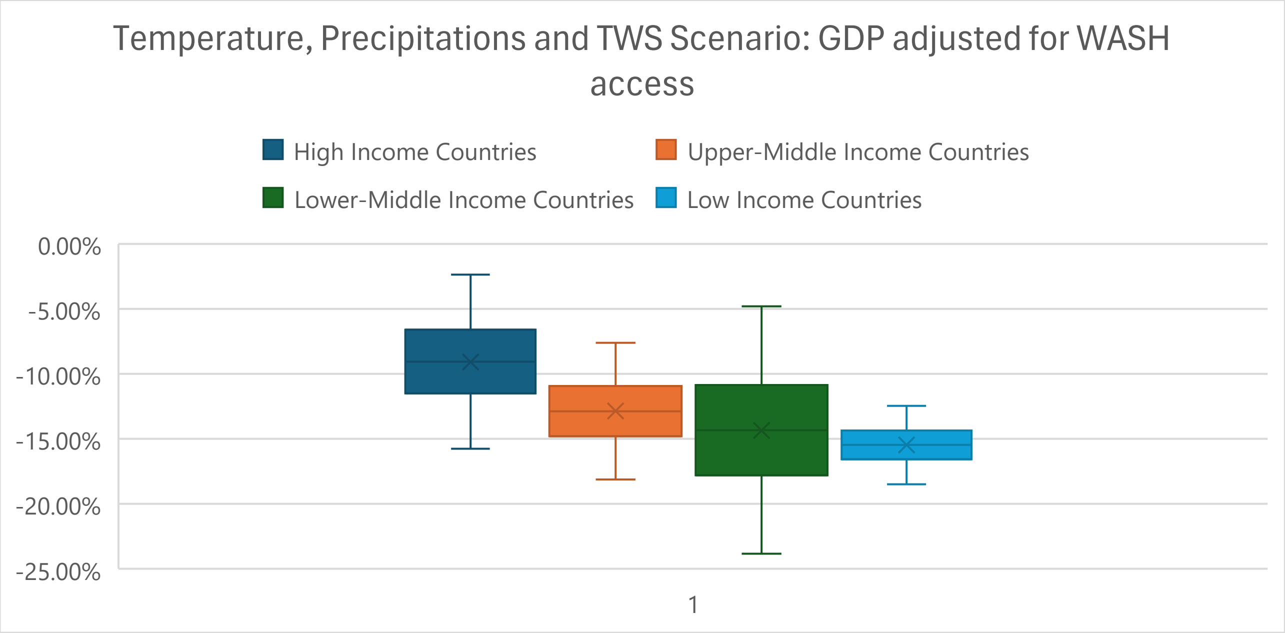


Figure 4.CHANGE TITLE

PERHAPS ONLY SHOW THE IMPACTED INCOME GROUPS? OTHERWISE THE GRAPH MAY MISLEAD?



6. Policy experiments

While climate change appears to importantly impact global economic performance, the model runs are also characterized by substantial divergences between the current values 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 market prices with 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[8] 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, Dinar et al. 2004, Perry,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, 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 simulations to assess how changes in tariff levels influence resource allocation and overall economic health.

Table 4 illustrates the results of these simulations, each testing a different water tariff rate. In each simulation, tariff revenue is redistributed to households as a lump-sum rebate, lessening the existing tax burden. This iterative process, involving a feedback loop from the impacts measured back into model adjustments, indicates that for all, except high income countries, a reasonable tax level is around an average of 22% of the cost of water and beyond this level, the negative effects from the excess tax burden are likely to prevail on the positive effects of the improved resource allocation and the income multiplier.

Table 4. Alternative shadow price proportional tariffs on blue water

Natural Resources Tax				
	Average 7%	**Average 14%**	**Average 22%**	**Average 30%**

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[8] See, for example Bovenberg et al (1996), Fullerton et al (2001), Dinar et al (2004), Perry et al (2009), Holmstead, (2010), Kilimani (2015).

East Asia High Income	11%	22.8%	34%	46%
East Asia Lower-Middle Income	4%	8.6%	13%	17%
East Asia Upper-Middle Income	12%	23.5%	35%	47%
Europe High Income	4%	7.6%	11%	15%
Europe Upper-Middle Income	4%	8.4%	13%	17%
Latin America High Income	5%	9.4%	14%	19%
Latin America Lower-Middle Income	3%	5.7%	9%	11%
Latin America Upper-Middle Income	3%	6.7%	10%	13%
MENA High Income	5%	9.2%	14%	18%
MENA Low Income	18%	36.5%	55%	73%
MENA Lower-Middle Income	9%	18.4%	28%	37%
MENA Upper-Middle Income	5%	10.7%	16%	21%
North America High Income	7%	13.9%	21%	28%
North America Upper-Middle Income	3%	5.8%	9%	12%
Oceania High Income	2%	4.8%	7%	10%
Rest of the World Lower-Middle Income	10%	19.7%	30%	39%
Rest of the World Upper-Middle Income	8%	16.3%	24%	33%
South East Asia High Income	8%	16.4%	25%	33%
South East Asia Lower-Middle Income	6%	12.7%	19%	25%
South East Asia Upper-Middle Income	7%	14.4%	22%	29%
South Asia Low Income	14%	28.8%	43%	58%
South Asia Lower-Middle Income	19%	38.0%	57%	76%
Sub-Saharan Africa Low Income	4%	8.0%	12%	16%
Sub-Saharan Africa Lower-Middle Income	3%	5.7%	9%	11%
Sub-Saharan Africa Upper-Middle Income	8%	15.2%	23%	30%
Average	**7%**	**15%**	**22%**	**29%**

Table 5 and Figure 5-12 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[9].

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 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[10]. 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 (Figure 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 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).

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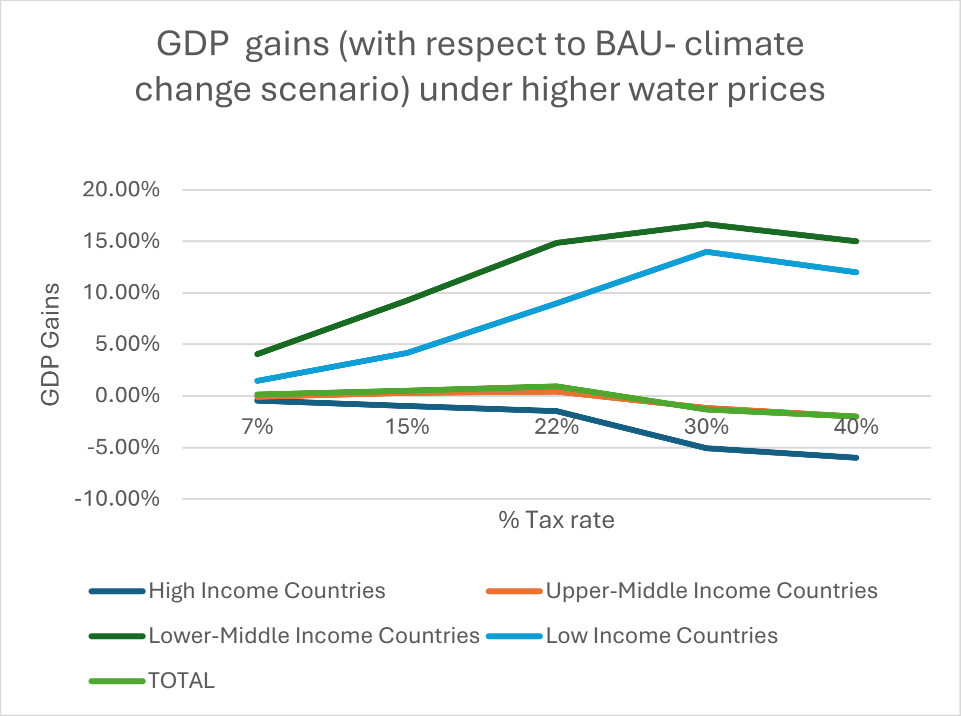
[9] Shan et al. (2023), using a CGE model for China, find a similar result, with an optimal scenario from the perspectives of water quantity, water use efficiency, and economic impact with water resources tax rates of 23% for high water-consuming industries and 18% for general water-consuming industries,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

[10] 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.

Table 5. Impact on GDP of different levels of water pricing

	BAU	**Average increases in water price**			
		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%**

Figure 4. Impact on GDP of different levels of water efficiency pricing



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. Table 2 and Figure 4 show that in lower- and middle-income countries that are mainly water scarce the 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.

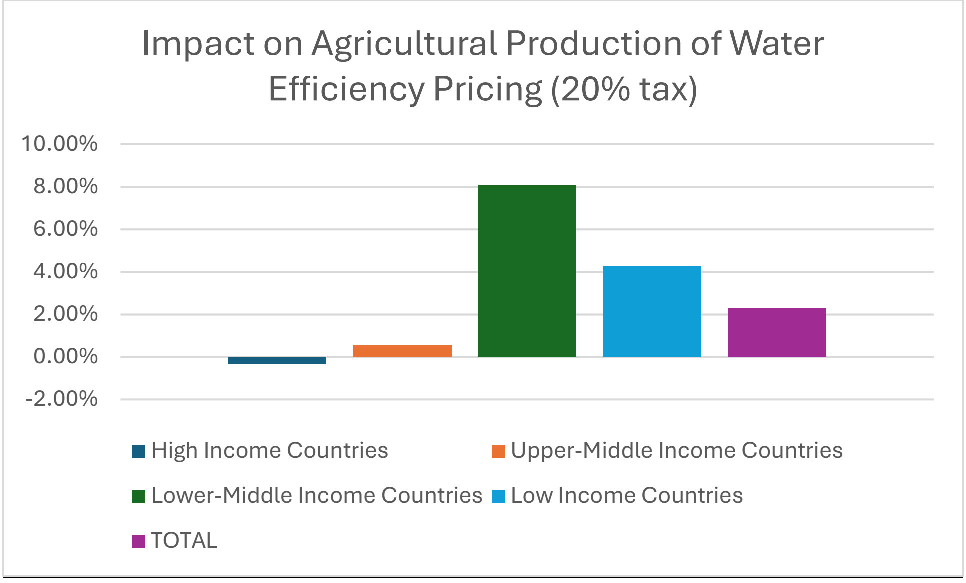


Figure 3. Impact on Agricultural Production of Water Efficiency Pricing

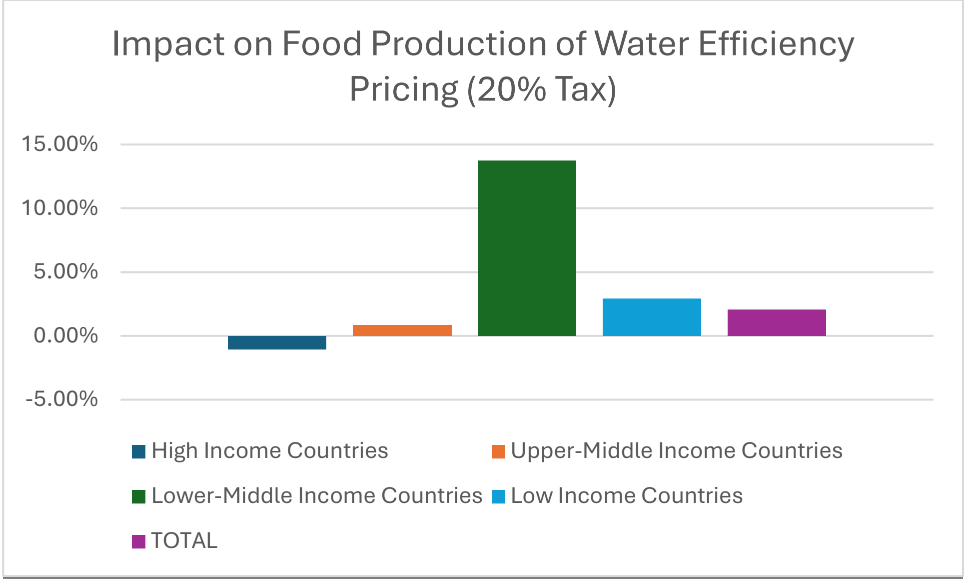


Figure 4. Impact on Food Production of Water Efficiency Pricing

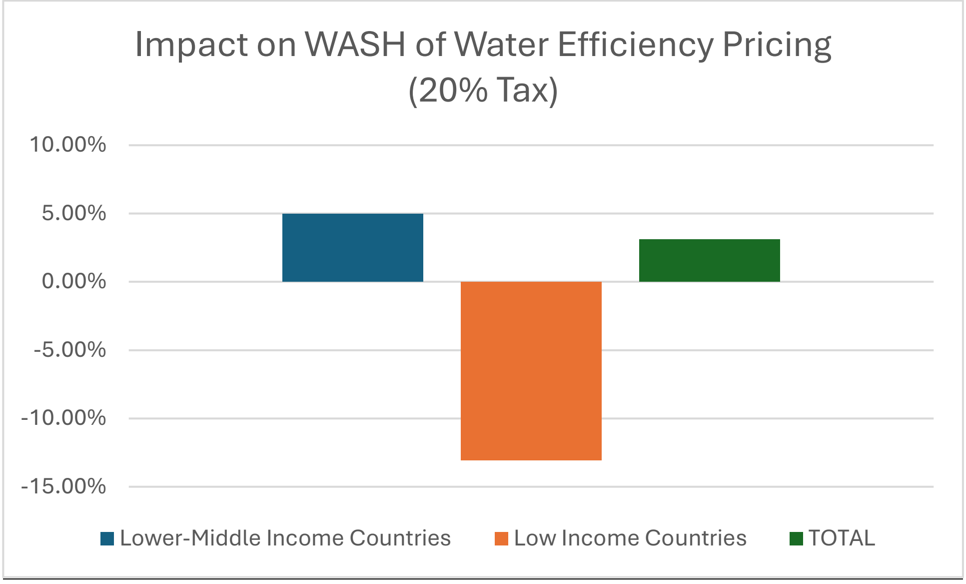


Figure 5. Impact on WASH of Water Efficiency Pricing

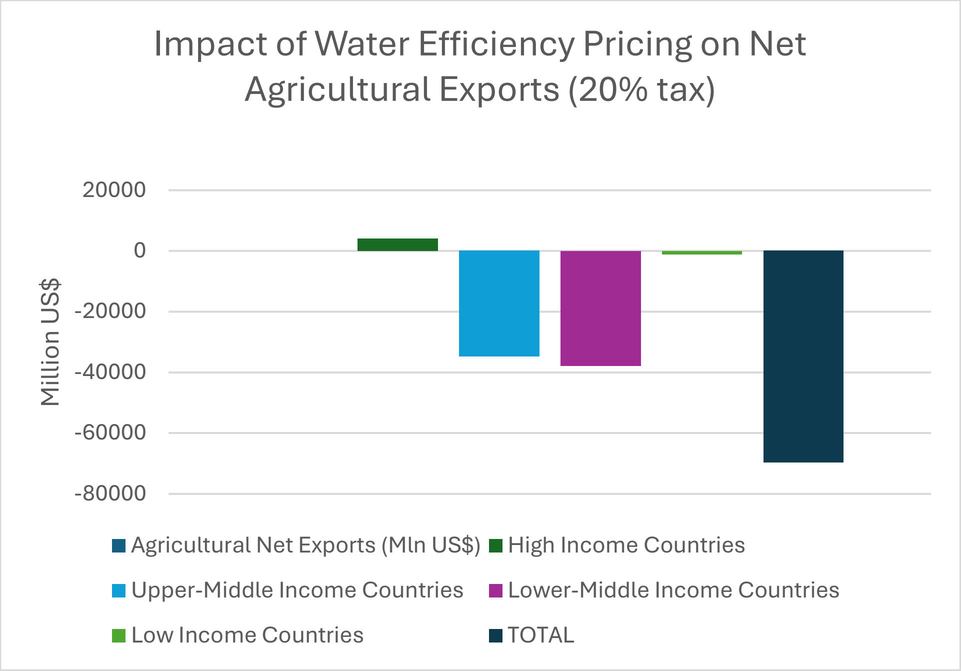


Figure 6. Impact on Agricultural Net Exports of Water Efficiency Pricing

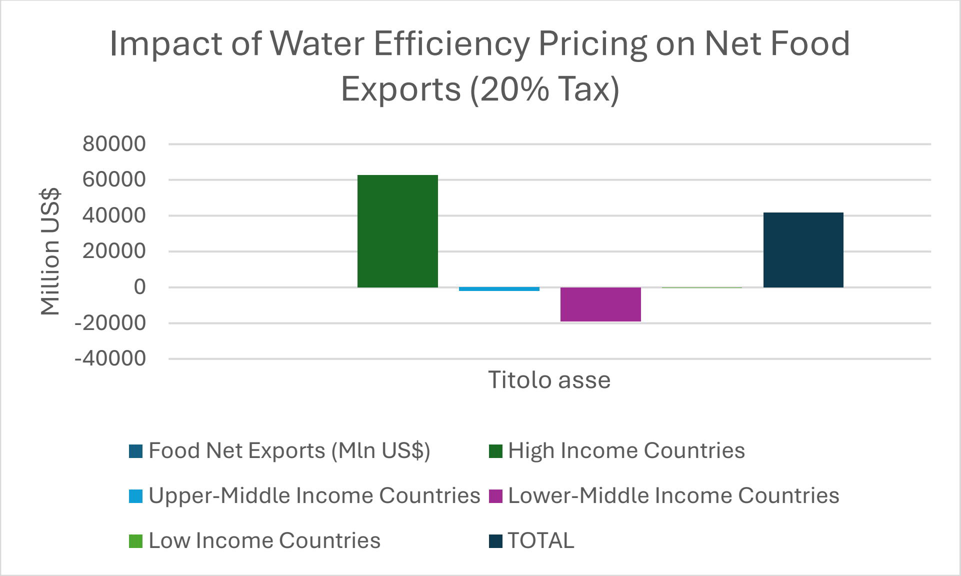


Figure 7. Impact on Net Food Exports of Water Efficiency Pricing

Conclusions

This paper has explored the multifaceted impacts of water on the global economy, emphasizing the critical role of water as both a public good and a production factor. Incorporating green and blue water, as well as total water storage (TWS), has provided a more comprehensive understanding of the economic implications of water resources and suggests that the costs of water mismanagement coupled with the impacts of climate change may be greater than estimated in earlier research.

The findings highlight the substantial economic costs associated with climate change and declining water resources, particularly in lower-income and water-scarce regions. The simulations demonstrate that efficient water pricing, aligned with shadow prices, 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 high income countries, from reallocation that derives from shadow pricing, However, the results also caution against excessively high water pricing, which can lead to economic contractions.

Overall, this paper underscores the importance of integrating water considerations into economic modeling and policy-making. As climate change continues to alter global water cycles, it is imperative to develop strategies that ensure the sustainable use and management of this vital resource. Future research should further refine CGE models to capture the dynamic interactions between water, climate, and economic systems, providing more robust tools for decision-makers to navigate the challenges of a changing world.

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Appendix

A.1 Level and growth impact in a static CGE model under a Keynesian closure

Except for the calibration runs, model solutions were derived under a Keynesian closure, which offers an integrated view of economic scenarios and policy changes by considering both demand and supply adjustments. This closure incorporates Keynes' views on the autonomy of investment decisions and on the existence of involuntary unemployment. It implies that the model solutions are driven by exogenous changes in investment levels over time, with endogenous labor employment, thus affecting both potential and actual output. Under this closure comparative static experiments can be interpreted as alternative equilibrium states following exogenous shocks of both potential output (supply side adjustments) and actual output (demand side adjustments). This approach contrasts with neoclassical closures, which focus solely on supply-side factors like technology and inputs, assuming that demand automatically meets supply (Say's law). Consequently, the Keynesian closure provides a more comprehensive framework for understanding the broader impacts of policy changes and economic dynamics, integrating the interplay between supply and demand in determining economic outcomes.

Most studies using static CGE models do not differentiate between income levels and growth rates when they use the model to study the impact of exogenous shocks over time. The general consensus seems to be that comparative static experiments may only reveal level adjustments, that is, a change in equilibrium quantities and prices, and that only a dynamic model can show the impact on growth rates. In the case of climate change, this point of view is reinforced by theoretical analyses of the potential impact on optimal growth, in the context of models of both exogenous and endogenous growth (see for example, Fankhauser, S. and Tol, R.S., 2005) In these analyses, the potential impact on growth is examined by discussing the a priori reasons why certain parameters and/or variables of the aggregate neoclassical growth model may be expected to react to the climate change shocks. The presumptive effects are deducted from simple economic principles and reasonable expectations but are not validated by effective mathematical analyses or numerical simulations in a disaggregate growth context. Furthermore, they appear to depend entirely on the concept of marginal productivity of capital from neoclassical production function theory, thus excluding the impact of different combinations of techniques as in Leontief or Von Neuman models.

However, in spite of its lack of explicit dynamics, a static CGE 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 addition to the immediate level effect, the growth rate captures also the dynamic impact of the shock, with new steady state values for key variables such as:

- **Capital Accumulation**: The new equilibrium may reflect a reduced rate of capital accumulation in the form of lower savings and investment rates.

- **Labor Productivity**: Adverse effects on labor productivity could reduce the growth rate of labor input over time.
- **Total Factor Productivity**: The reduction in TFP might cause resources shifts slowing TFP increases over time.

Level and Growth Rate Effects are Distinct but Related

- **The Level Effect** is the immediate impact that causes the economy to move to a new, lower level of GDP due to a CC shock. For example, if the shock consists of a change in temperature from a level T to a higher average level (T+b), the economy will adjust from a previous level $Y(T)$ to a new equilibrium level $Y(T+b)$.
- **The Growth Rate Effect** is the ongoing impact that affects the trajectory of GDP growth. If the temperature increases lead to lower rate of capital accumulation, lower employment rate, and lower productivity, this means that the economy will grow more slowly from the new lower base.

These effects are **distinct** because:

- The level effect refers to the new steady-state level of GDP after the shock.
- The growth rate effect refers to the rate at which GDP grows from that new level.

However, they are **related** in that the level effect sets the new baseline from which the growth rate effect applies, while the reduced growth rate reflects the extent to which the negative effects on resource accumulation and performance of the increase in temperature will persist over time, if the temperature keeps increasing. The reduced growth rate g' will apply to the new lower GDP level $Y(T+b)$.

Since the shock causes not just an immediate drop in GDP but also reduces the economy's growth potential (through factors like lower capital formation, higher rates of unemployment and reduced labor productivity), the economy will grow more slowly in the long term. Over time, the difference in growth rates can lead to a significant divergence in GDP levels between a scenario with the shock and a scenario without it. This means that even if the level effect is a one-time change, the growth rate effect can cause the gap between the two scenarios to widen progressively, leading to more pronounced long-term economic consequences. Moreover, if the temperature continues to rise or if the factors leading to the reduced growth rate persist, the growth rate effect can further exacerbate the level effect, leading to an even lower baseline from which future growth occurs. This creates a feedback loop where lower growth rates perpetuate lower levels of economic activity. The interaction between these effects highlights the long-term economic risks of climate shocks, especially if the conditions leading to slower growth persist.

To what extent a solution of a static CGE model can capture these different effects and how can we distinguish between structural and transient impacts of climate change? As shown in Dietz and Stern (2015), this largely depends on the extent that the model may be interpreted as a means of representing not only level changes, but also endogenous drivers of growth and the potential damage of climate change to these drivers. Moreover, as indicated by Tsigaris and Wood (2019), a major long-term impact on growth from climate change may be due to an increase of the rate of capital depreciation over time, a factor that can be reflected in lower income levels in static solutions. While static CGE models offer limited utility in exploring the complexities associated with economic growth trajectories, they generally provide a more robust machinery for analyzing scenarios that can be approximated as new steady states.

A.2 Results from Stochastic Sensitivity Analysis

This stochastic simulation methodology involves four key steps:

1. Parameter Estimation: Distributions for econometric parameters related to temperature, precipitation, and total water storage (TWS) shocks are generated based on their standard errors. This step quantifies the uncertainty surrounding the estimated impacts of these climate-related factors.
2. Scenario Definition: Upper and lower bounds for these parameter distributions are calculated by adjusting the mean by one standard deviation. These bounds are then adjusted to reflect plausible changes under different climate change scenarios, excluding implausible extreme values.
3. CGE Model Simulations: Separate Computable General Equilibrium (CGE) model simulations are conducted for each of these parameter values (mean, upper bound, and lower bound).
4. Monte Carlo Simulations: The outputs from the CGE model simulations are used as inputs for Monte Carlo simulations. These simulations employ both truncated triangular distributions (representing a range of plausible outcomes with a most likely value) and non-truncated normal distributions. By iteratively feeding these sampled values back into the CGE model (1000 times), the methodology generates a probabilistic distribution of potential economic impacts. This allows for the evaluation of the likelihood and variability of different outcomes, ranging from pessimistic to optimistic scenarios.

Figure 1: Sensitivity to Projected Changes in Temperature. This diagram illustrates the impact on GDP of stochastic simulations of projected thirty-year changes in temperature for different country income groups, showing more pronounced impacts and higher margins of uncertainty in low-income regions.

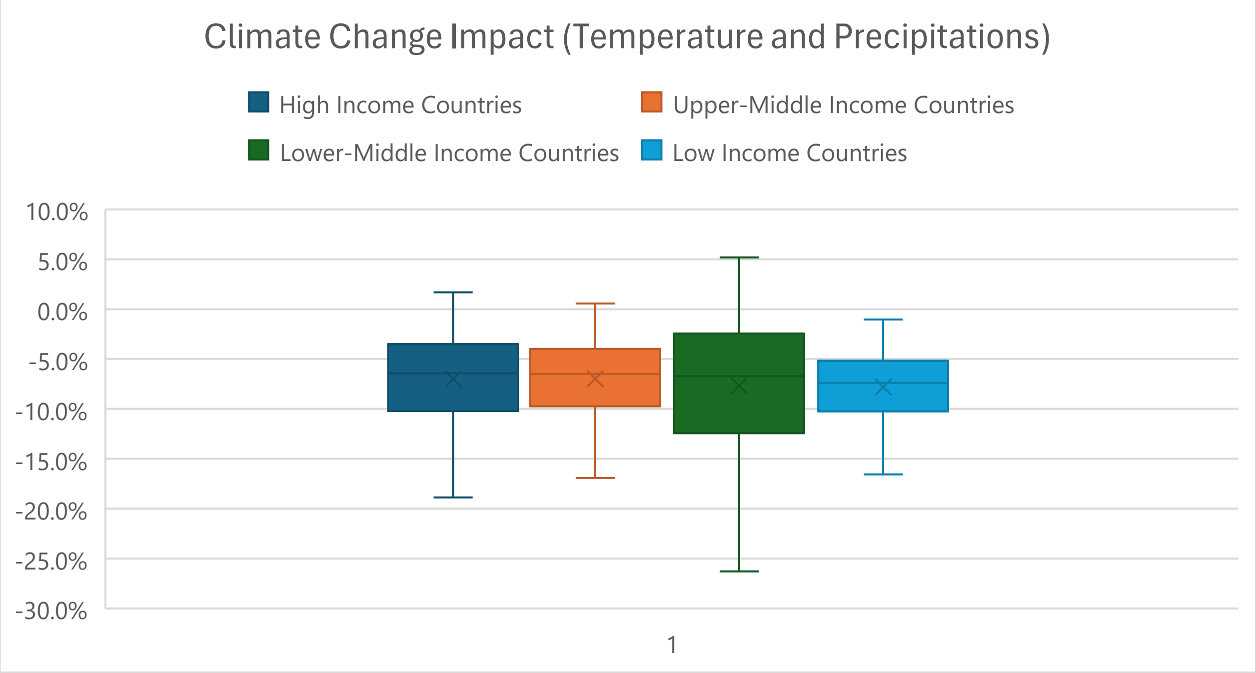

Figure 2: Sensitivity to Projected Changes in Temperature and Precipitations. This diagram illustrates the the impact on GDP of stochastic simulations of projected thirty-year changes in temperature and precipitations for different country income groups. Once precipitations are considered, all country groups are likely to experience negative impacts, still more pronounced impacts in low-income regions, but lower differences across regions and higher uncertainty margins for all.

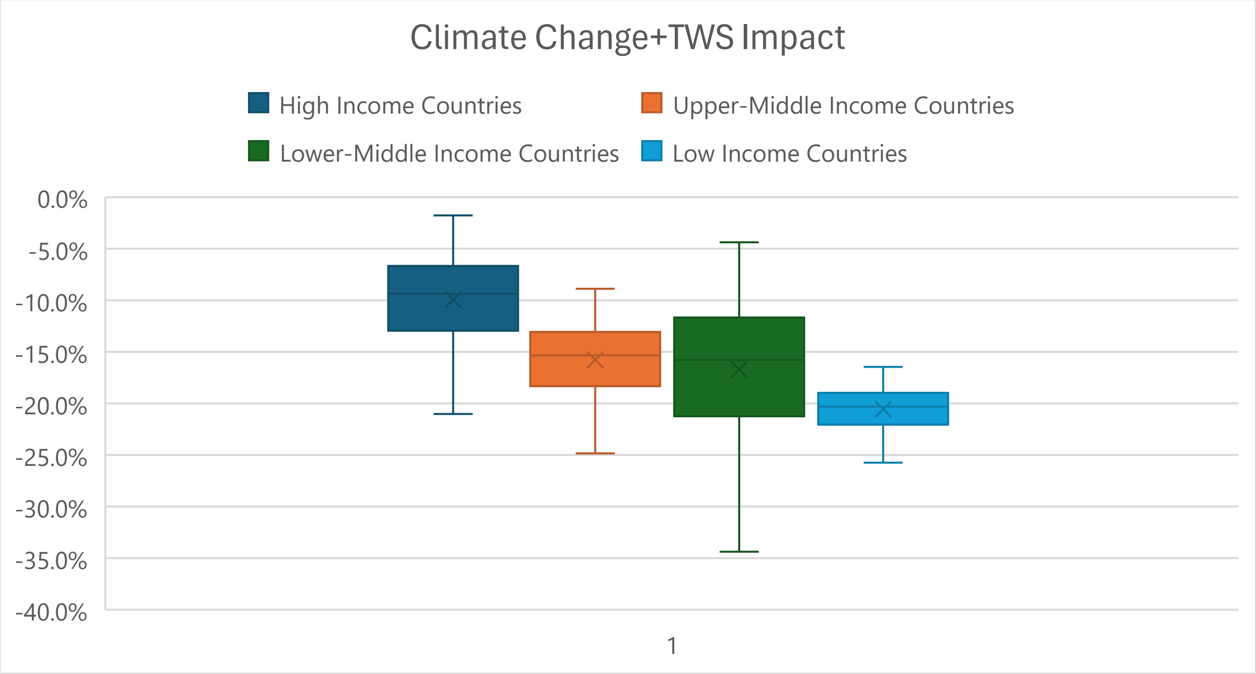

Figure 3: Sensitivity to Projected Changes in Temperature, Precipitations and TWS. This diagram illustrates the the impact on GDP of stochastic simulations of projected thirty-

year changes in temperature, precipitations and TWS for different country income groups. Once TWS is considered, all country groups appear to experience negative impacts, again with more pronounced impacts in low-income regions (see sensitivity analysis below), but lower differences across regions and higher uncertainty margins for Lower-Middle Income Countries

A.3. Sensitivity Analysis for the impact of TWS on Blue Water Consumption

In order to conduct a sensitivity analysis of the impact of Total Water Storage (TWS) trends, several regression models were estimated. Each model estimates served to simulate water consumption levels and use them as inputs to Monte Carlo simulations within the CGE model. This combined approach aims to quantify the economic impact of TWS changes more robustly.

Regression Models and Their Roles

1. **V25 (Initial OLS Model)**:
    - **Model**: Ordinary Least Squares (OLS)
    - **Dependent Variable**: LOG(totalwaterconsumption)
    - **Independent Variables**: LOG(Watertablechange in cm)
    - **Notes**:
        - Unweighted aggregation of predicted percentage changes
            - Only predicted decreases in consumption considered in the simulations.
    - **Purpose**: This initial model establishes a baseline, focusing on the direct relationship between water table changes and water consumption.
2. **V41 and V43 (TSLS Models)**:
    - **Model**: Two-Stage Least Squares (TSLS)
    - **Dependent Variable**: LOG(totalwaterconsumption)
    - **Independent Variables**: Average temperature; LOG(backwardTWSchange)
    - **Instruments**: First difference of average temperature and first difference of average precipitation
    - **Notes**:
        - Unweighted aggregation of predicted percentage changes
        - Predictions based on the assumption of 20% reduction of TWS impact
        - Only predicted consumption decreases are used in V41
    - **Purpose**: These models address potential endogeneity by using instrumental variables to reduce the simultaneity bias between TWS changes and water consumption.
3. **V45 and V48 (OLS Models)**:
    - **Model**: Ordinary Least Squares (OLS)
    - **Dependent Variable**: LOG(totalwaterconsumption)
    - **Independent Variables**:
        - LOG (backwardTWSchange)
        - Agricultural greenwater consumption
        - Dummy variables for regions (Oceania, high-income, upper-middle-income)

        - Average temperature
        - Cultivated area
        - Livestock greenwater consumption
        - First difference of average precipitation
    - **Notes**:
        - Unweighted aggregation of predicted percentage changes
    - **Purpose**: These models incorporate a broader range of variables, offering a more comprehensive view of factors influencing water consumption.

Monte Carlo Simulation with CGE Model

Purpose of Monte Carlo Simulation

Monte Carlo simulations are employed to handle the uncertainty and variability in the regression results. By integrating these results into a CGE model, the analysis aims to:

- **Quantify Economic Impacts**: Assess how changes in TWS influence GDP and other economic indicators.
- **Capture Uncertainty**: Reflect the range of possible outcomes based on the variability in regression coefficients and model parameters.
- **Enhance Robustness**: Provide more reliable estimates by considering numerous scenarios and their probabilities.

Process

1. **Regression Results**: The coefficients from each regression model are used to obtain predictions of reductions of water consumption levels as inputs for the simulation. These reductions are modeled as results of leftward shifts in water supply functions.
2. **Monte Carlo Simulation**: Multiple iterations are run, each time randomly sampling from the distribution of predicted water consumption levels. This simulates a wide range of possible outcomes.
3. **CGE Model Integration**: Each set of sampled predictions is fed into the CGE model, which simulates the economy's response to changes in water consumption driven by TWS variations.
4. **Results Analysis**: The simulation produces a distribution of economic outcomes (e.g., changes in GDP) reflecting the uncertainty in the impact of TWS changes. The results are then analyzed to determine the most likely impacts and their associated probabilities.

Table 2. Details of the Different Models Used

Equation	Model	Dependent Variable	Independent Variables	Instruments	Notes
V25-Reg1	OLS	LOG(totalwaterconsumption)	LOG(Watertablechange in cm)	None	First regression tried, Unweighted Regional Aggregatio

					n. Only negative values of TWS considered in the simulations.
V41-Reg2	TSLS	LOG(totalwaterconsumption)	Average temperature; LOG(backward TWSchange)	First difference average temperature; first difference average precipitation	Unweighted Regional Aggregation. Only negative values of TWS considered in the simulations.
V43-Reg2	TSLS	LOG(totalwaterconsumption)	Average temperature; LOG(backwardTWSchange)	First difference average temperature; first difference average precipitation	Unweighted Regional Aggregation.
V45-Reg3	OLS	LOG(totalwaterconsumption)	LOG(backwardTWSchange); agricultural greenwater consumption; dummy Oceania; dummy high income; average temperature; cultivated area; dummy upper middle income; livestock greenwater consumption; first difference average precipitation	None	Weighted Regional Aggregation.
V48-Reg4	OLS	LOG(totalwaterconsumption)	LOG(backwardTWSchange); agricultural greenwater consumption; dummy Oceania; dummy high income; average temperature; cultivated	None	Weighted Regional Aggregation.

			area; dummy upper middle income; livestock greenwater consumption; first difference average precipitation		

Table 2. TWS. Regression Output

Reg. Method	**OLS**	**2SLS**	**OLS**	**OLS**
DepVar: logwaterconsumption	**REG1**	**REG2**	**REG3**	**REG4**
Logtws	4.11282***	3.937434***	4.749756***	
	(0.062555)	(0.1443066)	(0.196704)	
logtws_nocc				4.645462***
				(0.1912687)
avgtemperature*avgprecipitation		-0.0000204	-	-
		(0.000133)		
greenwatercons_crops			0.000008***	8.02E-06***
			(0.000002)	(2.18E-06)
greenwatercons_livestock			3.13E-05**	0.0000313**
			(1.32E-05)	(0.0000132)
cultivatedarea			0.000158**	0.0001728***
			(0.000158)	(0.0000627)
avgtemperature1850-2014			-0.094215***	-0.082738***
			(0.018785)	(0.0182679)
diffavgprecipitation1850-2014			0.18712*	0.1538129
			(0.099626)	(0.0989942)
dy_oceania			-2.225114***	-2.224536***
			(0.499105)	(0.4968593)
dy_highincome			-1.726727***	-1.824066***
			(0.334893)	(0.3356218)

dy_uppermiddleincome			-0.941784***	-0.975182***
			(0.332083)	(0.3310457)
N.	184	184	184	184
R^2	0.97		0.5	0.96

Table 3. Sensitivity of TWS Impact on GDP

	TWS V25	**TWS V41**	**TWS V43**	**TWS V45**	**TWS V48**
High Income Countries	-3.00%	-2.31%	-2.87%	-3.89%	-3.91%
Upper-Middle Income Countries	-7.09%	-8.07%	-7.06%	-8.97%	-9.41%
Lower-Middle Income Countries	-8.28%	-6.30%	-5.86%	-6.75%	-6.58%
Low Income Countries	-10.76%	-9.23%	-9.64%	-12.08%	-12.36%
TOTAL	-4.98%	-4.72%	-4.65%	-5.97%	-6.11%

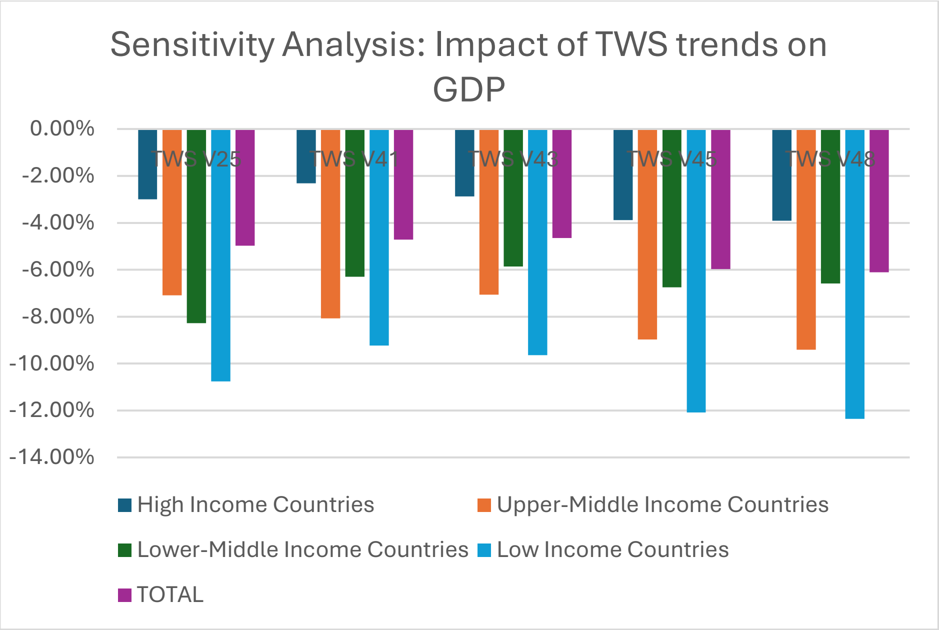

Figure 3. Sensitivity Analysis: Impact of TWS trends on GDP

A.4 Details of the CGE Water Module

Model Components

1. **Commodity Outputs (Fixed Yield Coefficients):**

   (1) $Q_i = \alpha_i A_i$

   for all i

   Where:

   - Q_i= Quantity of output i
   - α_i= Fixed yield coefficient for output i
   - A_i = Activity level for output i

2. **Activity Level (CES/Leontief Function):**

   (2) $A_i = f(\sum_j \beta_{ij} Z_{ij}, \gamma_i G_i)$

   Where:

   - Z_{ij}= Intermediate input j used in the production of i
   - β_{ij} = Share coefficient for intermediate input j in the production of i
   - G_i = Greenwater externality associated with activity i
   - γ_i= Sensitivity of activity i to the greenwater level

3. **Value-Added (CES Function):**

(3) $V_i = \sum_k \delta_{ik} L_{ik}^{\rho}$

   Where:

   - V_i = Value-added in the production of i
   - L_{ik}= Primary factor k used in production of i
   - δ_{ik} = Share coefficient for primary factor k in production of i
   - ρ = Substitution parameter between primary factors

4. **Intermediate Inputs (Leontief Function):**

$Z_{ij} = \min(\frac{X_{ij}}{\gamma_j}, \frac{B_i}{\beta_{ij}})$

Where:

- X_{ij} = Quantity of intermediate input j used in production of i
- γ_j = Leontief coefficient for intermediate input j in the production of i
- B_i = Blue water used as an intermediate input in production of i
- β_{ij} = Blue water share coefficient for production of i

5. **Composite Commodities:**

(4) $X_j = \text{ϕj}X_j, \text{imported} + (1 - \text{ϕj})X_j, \text{domestic}$

Where:

- Xj = Composite commodity j
- ϕj = Share of imported commodity j
- X_j, imported = Imported quantity of commodity j
- Xj, domestic== Domestic quantity of commodity j

Integration of Municipal (Blue) Water as a Factor of Production

For water companies and utilities (blue) water is also considered as a primary factor:

(5) $L_{ik} = B_i$ for water-related activities

Where:

- B_i = Blue water input used as a primary factor in water companies/utilities

Greenwater impact

Greenwater affects the activity level through its influence on the production process, and can be represented as a modifier to the activity function:

$$dA_i = \frac{\partial f}{\partial G_i} f(\sum_j \beta_{ij} Z_{ij}, \gamma_i G_i) dG_i$$

In sum, the model combines CES and Leontief production functions to capture the different relationships between inputs and outputs in the production process. The introduction of greenwater as an externality modifies the activity level directly, while blue water serves as both an intermediate input and a factor of production for certain activities (e.g., water companies and utilities).

Table 1. CLIMAWAT main characteristics

Aspect	**Characteristics**	**Strengths**	**Weaknesses**
Geographic Scope	Covers 160 countries.	Broad global coverage allows for comprehensive analysis across diverse economies and regions.	Regional heterogeneity might be oversimplified due to aggregation.
Sectoral Scope	14 production sectors with corresponding commodities.	Detailed sectoral breakdown enables sector-specific insights.	Limited sectoral detail could miss nuances within broader categories.
Data Sources	Integrates GTAP 11, FAO, Water Footprint Network, and additional biophysical, economic, and climate data.	Utilizes a diverse data set, enhancing the model's accuracy and applicability to economic-environmental contexts.	Relies on the accuracy and availability of external data sources, which may have inconsistencies or limitations.
Economic Agents	Includes consumers, producers, and governments operating in interconnected markets.	Allows for dynamic market interactions and detailed policy analysis.	Complexity in modeling may increase computational requirements and interpretation complexity.
Endogenous Variables	Joint determination of prices and quantities within markets.	Reflects real-world economic dependencies and equilibrium outcomes.	May be limited in capturing non-market influences (e.g., policy interventions).
Key Features and Parameters	Production and utility functions, input-output coefficients, income shares, substitution elasticities across resources (land, labor, capital, water).	Flexibility in parameterization allows for diverse scenario analysis.	Sensitive to parameter assumptions, which can impact model reliability.
Water Resources	Models green water's impact on agricultural productivity and treats blue water as a primary production input and as a commodity.	Recognizes the critical role of water in economic production, particularly agriculture, allowing for water resource-specific policy analysis.	Simplified assumptions on water usage may not capture complex regional water dynamics or scarcity impacts.
Labor Market Dynamics	Accounts for unemployment and distinguishes between high/low income and skill levels.	Enables nuanced labor market analysis, including income distribution effects and labor allocation.	Income and skill categorizations may be broad, potentially overlooking finer distinctions.
Comparative Static Analysis	Provides comparative static-steady state equivalents,	Facilitates insights into long-term equilibrium adjustments to shocks, allowing policy	Limited in capturing short-term dynamic adjustments and

		comparison against a steady-state benchmark.	transitional economic responses.
Projection Horizon	Uses a 30-year timeline based on OECD investment and population forecasts.	Enables examination of long-term impacts, valuable for understanding enduring effects of structural changes.	Long-term projections may be subject to uncertainties in assumptions and exogenous data (e.g., OECD forecasts).
Climate and Environmental Data	Incorporates climate change projections and biophysical inputs.	Enables assessment of economic-environmental interactions and impacts of climate change on production and resources.	Climate projections depend heavily on external models and assumptions, potentially affecting the accuracy of economic-climate linkages.
	Complex CGE model structure with extensive data integration.	Provides a comprehensive, multi-dimensional view of economic systems under environmental constraints.	High computational demands may limit usability for routine analysis or require simplifications that could affect model accuracy.

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