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Toward the full implementation of the water-energy-food nexus in computable general equilibrium modelling: methods and macroeconomic implications

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ABSTRACT

This paper contributes to the advancement of Computable General Equilibrium (CGE) modelling in addressing the Water-Energy-Food (WEF) Nexus. As such, it introduces water resources as a production factor for both the energy sector and irrigated agriculture, as well as their competition for the endowment, aiming to explicitly represent additional components of the WEF with respect to a standard CGE in the literature. Thus, it develops different modelling structures by computing impacts on regional GDP, sectorial prices, and production outputs in response to hypothetical water scarcity scenarios. This analysis allows for the determination of the role of data and modelling assumptions, such as production function, water substitutability with other endowments, water mobility across sectors, and sectorial water intensity, in influencing the results. Finally, the paper develops a dynamic scenario analysis, showing that an enhanced representation of the Nexus can significantly affect the macroeconomic dynamics of the simulations and their regional implications.

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Computable general equilibrium; water-energy-food nexus; water-energy nexus; economic modelling

1. Introduction

Since 2011, the year of its introduction by Hoff (Hoff, 2011) and the World Economic Forum (World Economic Forum, 2011), the Water-Energy-Food (WEF) Nexus (hereafter, the Nexus) has acquired increasing attention in both the academic and policy environments (Bazilian et al., 2011; Bizikova et al., 2013). Accordingly, the Nexus-related ideas of acknowledging sectorial and production interconnections, as well as the importance of adopting a holistic view on all economic relations, are both now deeply rooted in the welfare and environmental economics literature (Credit et al., 2019; Lotze-Campen et al.,

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2008; Lundqvist & Unver, 2018; Raworth, 2017; Visentin & Guilhoto, 2019; Zhang et al., 2018).

Many quantitative methodologies have been adopted to analyse the Nexus. Computable General Equilibrium (CGE) models offer some specific advantages. Indeed, CGEs are intrinsically built to account for input – output linkages between sectors and countries, macroeconomic feedback, and higher-order consequences of economic and policy shocks (Allan et al., 2007; Carrera et al., 2015; Zhou et al., 2018; Zisopoulou et al., 2018). Therefore, these models can be particularly fit to be applied to Nexus investigation (Al-Riffai et al., 2017; Babatunde et al., 2017; Bardazzi & Bosello, 2021; Bergman, 2005; Boulanger & Bréchet, 2005; Dudu et al., 2018; Freire-González, 2018; Nechifor & Winning, 2017; Zisopoulou et al., 2018). Nevertheless, despite their relative advantages, there are still some gaps in the representation of some nodes of the Nexus in the CGE literature. For instance, while modelling the water-food connection with water as a primary production factor for agriculture is quite well-established (Dixon et al., 2010; Koopman et al., 2017; Luckmann et al., 2016; Nechifor & Winning, 2017; Roson & Damania, 2017; van Heerden et al., 2008; Zhong et al., 2015, 2017), the use of water by firms, energy producers, households and the related water competition issues are seldom addressed (Bardazzi & Bosello, 2021). Even some of the most advanced CGEs used for Nexus analysis, (for example, Nechifor & Winning, 2017; Taheripour et al., 2013), still do not account for the full description of some of the Nexus linking mechanisms, in particular the one between overall energy production and water use, as well as the relative macroeconomic implications induced by water competition across sectors and/or the introduction of water markets.

Against this background, this paper (a) proposes a new methodology to represent both the Water-Energy and Water-Food link in a CGE model – i.e. accounts for water uses by both irrigated agriculture and the energy sectors (b) includes water competition across these two sectors, and (c) investigates the implications of this modification in an enriched, although simplified, Nexus analysis. This enables the examination of economic dynamics that are usually poorly investigated: growth implication of water stress due to Nexus uses and competition; specialisation in national-sectorial production driven by comparative advantages induced by water availability; potential energy and food security issues triggered by water scarcity, defined as the higher dependency on imported versus domestic commodities (Mukhopadhyay et al., 2018).

The chosen CGE model is ICES (Intertemporal Computable Equilibrium System) (Bosello et al., 2012; Eboli et al., 2010).[1] ICES is a recursive-dynamic, multi-sector, multi-country CGE model based on the GTAP (Global Trade Analysis Project) databases (Aguiar et al., 2016; T. W. Hertel, 1997), which provides data on domestic and international exchanges with respect to different reference years depending on the database version. As common in a CGE framework, the sectorial supply stems from representative firms aiming to minimise production cost while constrained by technology (elasticity of substitution of inputs in the production function) and taking input prices as given (perfect competition holds in the market). The standard ICES framework accounts for four primary factors: land, labour, capital, and natural resources. This work introduces water as an additional input for both energy production and irrigated agriculture, following a two-step procedure:

[1] The complete bibliography on the structure and the studies developed through ICES can be found at https://www.icesmodel.org/.

(a) implements (some) modifications in the model database and (b) adjusts the production function to include the new input factor.

Although water use concerns many actors, this paper focuses specifically on the Nexus. Households and non-energy industrial water uses are not considered. Notwithstanding this restriction, we acknowledge that agricultural and energy water uses account for roughly 85% of the total global water withdrawals and therefore represent the two main drivers of water competition (FAO, 2021; IEA, 2012). Moreover, the objective of this paper is primarily methodological. Still, the proposed procedure could be easily generalised to other sectors different from the energy ones, as well as domestic uses, though we leave these extensions to future research developments.

2. Materials and methods

2.1. Database modifications

The starting ICES database is the GTAP database version 9, with reference year 2011 (Aguiar et al., 2016). The database can consider 140 countries and 76 sectors in its full extension. Data on water uses for irrigated agriculture are available with extensive country coverage and have been used by GTAP-based CGE models with this high level of detail (Calzadilla et al., 2011; Haqiqi et al., 2016). However, data on water withdrawals[2] by the energy sectors are much coarser. The most disaggregated complete regional data available are provided by the International Energy Agency (IEA) (IEA, 2012). This forces us to consider five macroeconomic sectors: irrigated agriculture, rainfed agriculture, industry, energy production, and services; and ten macro-regions: OECD[3] Europe, OECD America, OECD Asia-Oceania, Other Europe and Eurasia, China, India, Other Asia, Latin America and Caribbean, Africa, and Middle East.

Therefore, the procedure to implement the Water-Energy Link in the model starts by matching the model resolution with that of the available data and then associating km^3 of water withdrawal to energy. Though the spatial detail is low, the description of water withdrawals for energy is rather rich. The IEA (IEA, 2012) reports withdrawal statistics for the production of both primary energy (i.e. coal oil and gas extraction) and several types of electricity generation such as renewables, nuclear and fossils, addressing that different types of energy are characterised by different withdrawal requirements. The lowest level of water withdrawals (i.e. around a mean of 10^2 litres per Megawatt-hour (MWh)) is associated with renewable power generation technologies such as wind, solar and geothermal. The highest, instead, is associated with fossil electricity and nuclear power, even though they show significant differences according to the specific production methods implemented (i.e. cooling towers have lower withdrawals than cooling ponds, while both have lower levels

[2] This variable describes the amount of water extracted from the environment to allow sectorial production. It is, therefore, differentiated from water consumption, which accounts for that part of the water that, due to production, evaporates and is not reintroduced directly into the environment, i.e., the environmental damage related to sectorial production. Nevertheless, this dimension is still subject to caveats: a) agriculture and energy are considered as self-abstracting sectors (Nechifor & Winning, 2018), i.e. they depend directly on the raw material, not accounting for transport and distribution issues b) at this stage of the research, we do not distinguish across withdrawals of different types of water or water "production" technologies, like desalination or wastewater treatment, i.e., water is considered an undifferentiated production factor based on freshwater withdrawals, though the importance of improvements in this direction is acknowledged.

[3] OECD refers to the Organization for Economic Co-operation and Development (OECD). For a detailed description of the regional and sectorial aggregation of the Database, refer to Table 1 and Table 2 of the Supplementary Information.

of withdrawals than once-though technologies), with withdrawals requirements spanning between 10^4 MWh up to 10^6 litres per MWh. The main water uses related to these types of power generation include, for example, generating steam or hot water, cooling through steam condensing, and pollutant scrubbing. Primary coal oil and gas have a mean water withdrawal level of around 10^4 litres per MWh but still show significant differences according to the production method. For instance, conventional gas has lower requirements than refined oil, but gas-to-liquids have higher withdrawals. In particular, primary oil and gas use water for activities such as drilling, well completion, injection into the reservoir in secondary and enhanced oil recovery, and upgrading and refining oil and gas into products. Primary coal, instead, withdraws water for activities such as cutting and dust suppression in mining and hauling, washing to improve coal quality, and for re-vegetation of surface mines. All these withdrawal values are summed and aggregated into a single 'energy' sectorial statistic, which is then associated with the overall energy sector in ICES through the computation of a proportional economic value.

The functioning of the model is based on a price-accounting system, which requires the economic value of water to be specified 'at market prices' (VFM), 'at agent prices' (EVFA) and 'at agent prices along the supply chain' (EVOA).[4] Given the limited information on both water taxation and water prices, the values for the regional energy sectors are derived from (Calzadilla et al., 2011).[5] This implies transferring the water prices estimated for agriculture to the energy sector. I the absence of better information, we assume that the regional technological/infrastructural, supply sources, availability risks and general costs are comparable across different actors within the same region. Once computed, the value of water used by energy firms has been extracted from the capital value of the energy sector, as suggested by (T. Hertel & Liu, 2019).

The final economic values of water used by the energy sector are reported in Table 1. The overall procedure generally replicates the methodology proposed by the previous studies (Calzadilla et al., 2010, 2011; Haqiqi, 2016; Nechifor & Winning, 2018; Taheripour et al., 2013) to add water as an endowment in a CGE and the values obtained are coherent with the technological dependence on water of the energy sector in the different regions. Indeed, the more water-intensive energy sectors are in OECD America, China and India and OECD Europe, while the water value-added share in Africa, and the Middle East, is negligible.

2.2. Production structure modifications

Concerning the production function, two different specifications have been tested. The first replicates the basic structure of ICES, i.e. water is introduced in the same node of the other primary factors of production, as shown in Figure 1. This is the simplest possible specification, i.e. just one parameter (elasticity of substitution) governs the substitutability in production across all primary factors of production, including water. The elasticity

[4] The differences between these values derive from taxation that can be levied at every transaction phase: a tax on the primary input that firms (in sector j and region r) may have to pay drives a wedge between EVOA and VFM, and a tax on the supply of the endowment that households may have to pay (all primary inputs are by construction owned by households in the model) determines the difference between VFM and EVFA.

[5] Their methodology first computes the economic value of water in irrigated agriculture (VFM water). This value is obtained by splitting the economic value of agricultural land using the shares of irrigated and rainfed land in the different regions. Then, EVFA and EVOA for water in agriculture are calculated by applying the same tax rate of the land endowment in irrigated agriculture. These are the taxation rates also used to compute water taxation for the energy sector.

Table 1. Capital share of energy and water value added extraction.

Region	Energy Water Withdrawal (billion m3)	Economic Value of Water for the Energy Sector			Economic Values of Capital for the Energy Sector			Share of Capital Value directed to Water (%)		
		VFM	EVFA	EVOA	VFM	EVFA	EVOA	VFM	EVFA	EVOA
OECD America	241	11679.1	10268.5	10746.3	299185.5	309022.1	4823449.0	3.9	3.3	0.2
China	106	2993.3	2375.7	2959.8	95477.6	95614.3	2925523.3	3.1	2.5	0.1
India	40	974.1	974.7	938.8	36455.9	36476.5	684071.6	2.7	2.7	0.1
OECD Europe	61	2475.2	2379.5	2282.1	260282.0	265589.3	6401322.5	1.0	0.9	0.0
Other Europe and Eurasia	95	1256.4	1274.6	1188.0	193118.7	196711.0	1151904.3	0.7	0.7	0.1
Latin America	16	487.5	492.1	453.7	128161.7	129287.0	1575094.0	0.4	0.4	0.0
Other Asia	11	165.1	166.1	155.1	92483.1	93151.9	1224403.5	0.2	0.2	0.0
OECD Asia-Oceania	5	158.8	147.5	146.6	91064.7	93576.5	3067511.3	0.2	0.2	0.0
Africa	5	67.7	68.1	57.7	158781.4	160577.1	720084.2	0.0	0.0	0.0
Middle East	3	45.0	45.5	43.6	522909.8	528546.4	1377191.8	0.0	0.0	0.0

Figure 1. ICES's Production Function – CES. Note: QO Production in sector j and region r; QVA Value Added of sector j in region r; QFE use of endowment i in sector j of region r; QF intermediate input i used by sector j of region r; QFD domestic intermediate, QFM imported intermediate input.

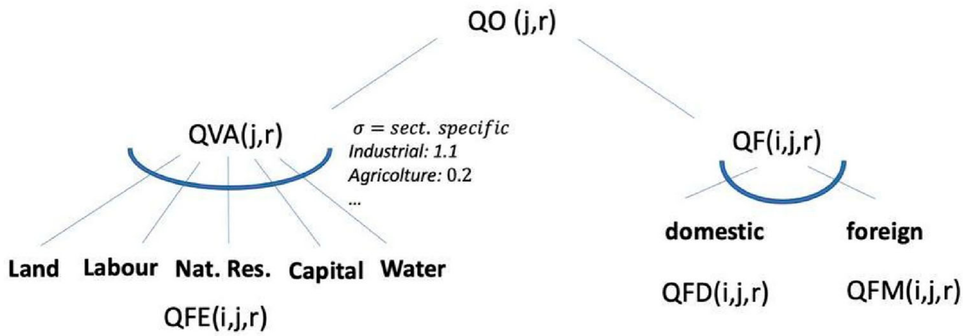
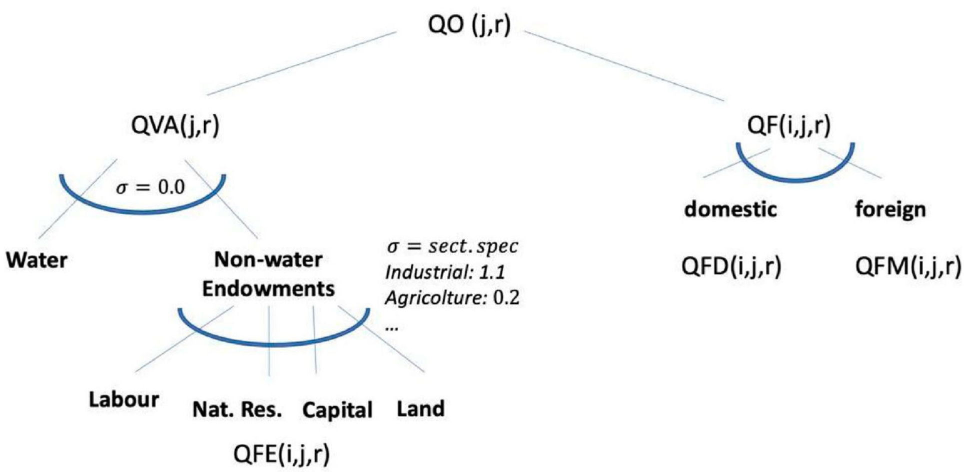


Figure 2. ICES's Production Function – Quasi-Leontief. Note: QO Production in sector j and region r; QVA Value Added of sector j in region r; QFE use of endowment i in sector j of region r; QF intermediate input i used by sector j of region r; QFD domestic intermediate, QFM imported intermediate input.



of substitution is kept the same as the original model calibration. The second introduces a richer specification consisting of a Quasi-Leontief nest to connect water and other primary production factors (Berrittella et al., 2007; Nechifor & Winning, 2018; van Heerden et al., 2008), i.e. assuming almost perfect complementarity (or very low substitutability) (Leontief, 1970) of water with the other inputs. This implies a two-level framework: in the first water is separated from the bundle of the other primary factors; in the second the substitution across capital, land and labour is specified (Figure 2). This Quasi-Leontief specification allows more realism in the modelling structure as the possibility of technical substitution of water for other factors is considered to be very low (i.e. different from the original value) by most of the literature (Gleick & Palaniappan, 2010; Nechifor & Winning, 2018; Sun et al., 2021).

Furthermore, the two-block framework enables increased modelling flexibility due to the expression of a specific elasticity between our target factor and the other factors, which allows for easier adjustments to test different degrees of substitutability between factors and/or incorporate new information when available. This said, we deem it useful to test and compare both specifications, since the first specification entails a more minor modification of the original model and lower computational challenges which tend to emerge in the presence of low elasticity of substitution. Accordingly, although 'simpler', it can offer important advantages, especially in the scenarios-building phase (see section 2.4). The equations and code used to introduce these functions into the new Water Module of ICES are reported in Section D of the Supplementary Information.

2.3. Endowment mobility across sectors

The primary factors in the models, i.e. land, water, capital, natural resources, and labour, can be perfectly or imperfectly mobile ('sluggish') across sectors. In the latter case, the degree of sluggishness is determined by the elasticity value in a Constant Elasticity of Transformation (CET) function. The standard model setting assumes that capital and labour are perfectly mobile, while land and natural resources are imperfectly mobile, i.e. with some 'friction' across sectors. Nevertheless, introducing water for irrigated agriculture and energy implies introducing additional assumptions on how rainfed land can transform into irrigated land and how water can shift from irrigated agriculture to energy production (and vice-versa). In this exercise, we test alternative specifications where both land and water are sluggish, perfectly mobile, and a combination of the two. This is due to the fact that, in general, the literature assumes low land mobility (transformability) across rainfed and irrigated agriculture, in account of the high investment costs associated with irrigation systems, which are considered a major constraint in shifting from rainfed to irrigated agriculture. However, given that the shocks implemented in our experiments consist of a reduction of water supply for irrigated and not rainfed agriculture,[6] the tests are expected to imply only shifts from irrigated toward rainfed land, following the higher costs/lower availability for irrigated agricultural production. As such, in this specific context, mobility of land could be plausible, and therefore, its implications are tested. The assumption of high water mobility between irrigated agriculture and energy production can be more easily justifiable.[7] The sluggish assumption, however, allows us to compare the presence against the (sluggish) absence of water competition. All in all, the results proved to be quite sensitive to the water mobility assumption but insensitive to assumptions on land mobility. Therefore, for compactness' sake, Section 3 will present only the results relative to the sluggish-in-land-mobility, i.e. the standard literature setting.

2.4. Experiments' design

The behaviour of all the different versions of the modified model is tested under two types of simulations. First, a set of comparative static exercises implementing globally

[6] The water endowment in our model is based on freshwater withdrawals and does not include rain quantities and variations. This assumption is typical in the CGE literature (for example, Calzadilla et al., 2011; Haqiqi et al., 2016; Taheripour et al., 2013), as its provision cannot be controlled, and therefore it cannot have a price, which is crucial for its accounting in the model.

[7] Assuming no institutional or regulatory constraints and the possibility of coordination/cooperation between actors, as remarked in the discussion section.

Table 2. Model specifications.

Version	Water input to irr. agriculture	Water input to energy and irr. agriculture	CES Prod. function (Figure 1)	Quasi-Leontief Prod. function (Figure 2)	Water as 'sluggish' factor of prod.	Water as perfectly mobile factor of prod.
CES_Onesec_SlugW	X		X		X	
CES_Twosec_MobW		X	X			X
CES_Twosec_SlugW		X	X		X	
Quasi-Leontief_Onesec_SlugW	X			X	X	
Quasi-Leontief_Twosec_MobW		X		X		X
Quasi-Leontief_Twosec_SlugW		X		X	X	

uniform water supply reductions, from 10% to 50%,[8] for 120 simulations. These test runs are used to compare how the different model specifications react to the introduction of water as a production factor for the energy sector; the sensitivity of results to the production tree structure (the 'original' Constant Elasticity of Substitution (CES) specification vs the 'Quasi-Leontief'), and the role of water mobility across sectors. Table 2 summarises the different model specifications and their main characteristics.

A second round of analysis focuses on the role of water competition across agriculture and energy in a richer dynamic setting. This is developed by comparing the effects of introducing water as an energy-sector production factor under the different Shared Socio-Economic Pathways (SSPs) (O'Neill et al., 2014; O'Neill et al., 2017; Riahi et al., 2017). These are a set of scenarios that describe five possible socio-economic projections for world population and GDP, detailed at the national level, according to five different narratives. The names of the SSPs (1–5) are, respectively, Sustainability, Middle of the Road, Regional Rivalry, Inequality and Fossil Fueled Development. According to the narratives, different challenges for mitigation and adaptation are posed. For instance, the 'Sustainability' narrative describes a world where both mitigation and adaptation challenges are low, while, on the opposite end, 'Regional Rivalry' with country fragmentation and low international cooperation features high mitigation and adaptation challenges. SSP2, as referenced in its name, concerns medium challenges in both. The model specification adopted for this analysis is the one featuring perfect water mobility across water-using sectors (in our case, energy and irrigated agriculture) and almost zero substitutability of water with the other primary production factors (the Quasi-Leontief specification) due to its higher level of realism and to the possibility of addressing water competition issues.

In detail, the exercise develops this way: in the first step, the ICES model, where water is used just by irrigated agriculture, is calibrated to replicate GDPs and population growth trends in the different SSPs (Crespo Cuaresma, 2017; Samir & Lutz, 2017). This procedure originates a vector of changes in total factor productivities that are the model parameters left free to vary to reproduce the target growth rates for regional GDPs. In the second step, these productivities are kept constant, and water is implemented in the model as an input to both irrigated agriculture and energy production. In these latter runs, the GDP growth rates, as well as prices, sectorial production, etc., will vary due to the presence of the new sector-endowment link and competition issues. These differences, therefore, highlight how

[8] Larger negative shocks proved to be outside the model simulation capacity under some specifications (i.e. Quasi-Leontief-based).

relevant the introduction of the Water-Energy link and Food-Energy competition is. This second set of analysis concerns five baselines (i.e. one for each SSP) and five scenarios.

The dynamic simulations run until the year 2050. Mid-century is a standard choice for this type of analysis: it is sufficiently far into the future to highlight climate impacts, and it is not too far into the future to completely lose the relevance of the baseline calibration. Furthermore, it is a relevant temporal framework also in terms of policies and societal objectives. For instance, the Paris Agreement (Article 4) (UNFCCC, 2015) sets a net zero CO2 emissions objective for the mid-century, and it is also the target year in which the EU aspires to become the world's first climate-neutral continent (Erbach et al., 2022). In addition, it is generally recognised as the year in which the 1.5° threshold will be overshot and the timeframe for the complete decarbonisation of the power sector, both in 1.5°C – and 2° consistent pathways, is expected (IPCC, 2018).

3. Results

3.1. Macroeconomic and sectorial impacts of water scarcity

In general, when cross-sectorial water mobility is not allowed and water supply is restricted, GDP losses are larger if water is a production factor for the energy sector with respect to when water is used only by irrigated agriculture (Table 3). Nevertheless, the entity of this difference is significantly driven by the degree of factor substitution in the production function. Global GDP losses range from – 0.39% to – 0.42% in the two-sector CES specification and from – 16.02% to – 18.63% in the two-sectors Quasi-Leontief one in response to the same 50% water supply reduction. Concerning the price effects, Table 4 shows that the restrictions in water supply lead to increases in the irrigated agricultural price in all the specifications, particularly in the Quasi-Leontief setting.

The energy prices decline when water is not an input to the energy sector, while generally increasing when the Water-Energy Link is 'active'. In the first case, energy prices follow declining macroeconomic activity (GDP) trends. In the second, they are more influenced by the scarcity of the water input. It is worth noticing that when water is mobile between sectors in the Quasi-Leontief specification, energy price increases are larger in OECD Europe, OECD America, and China. This is coherent with the implicit water re-location away from energy production towards irrigated agriculture that emerges in Table 5. Indeed, being water-intensive energy regions, these regions are incentivised to import energy from areas that, being less dependent on water for energy production, have a comparative advantage.

Sectorial production (Table 5) and imports (Table 6) also highlight the emergence of specific regional behaviours under Quasi-Leontief water substitution and water used by both agriculture and energy. In OECD Europe, OECD America, China, and India, the impacts on energy production are lower when water is a sluggish production factor. The sluggishness of the water endowment is therefore positive for the energy sector that would otherwise suffer from water redirection towards agriculture. However, this is not enough to offset the macroeconomic losses, which are higher in this scenario. This effect is particularly evident in OECD Europe and in OECD America, where under the more water-constrained scenario, energy production would decline – 89% and – 92%, respectively, with perfectly mobile water rather than – 34% and – 38% with sluggish water. The

Table 3. Real GDP impacts (% change) across model specifications.

10%	OECDEurope	OECD America	OECD Asia-Oceania	Other Europe Eurasia	Other Asia	China	India	Middle East	Africa	Latin America	Global
CES_Onesec_SlugW	0.00	−0.01	0.00	−0.01	−0.05	−0.02	−0.14	−0.02	−0.02	−0.01	−0.01
CES_Twosec_MobW	−0.01	−0.02	0.00	−0.01	−0.05	−0.02	−0.14	−0.02	−0.02	−0.01	−0.02
CES_Twosec_SlugW	−0.01	−0.02	−0.01	−0.01	−0.05	−0.02	−0.15	−0.02	−0.02	−0.01	−0.02
Q-Leontief_Onesec_SlugW	−0.01	−0.02	−0.02	−0.06	−0.13	−0.07	−0.43	−0.07	−0.10	−0.03	−0.04
Q-Leontief_Twosec_MobW	−0.03	−0.06	−0.01	0.05	−0.12	−0.09	−0.41	−0.02	−0.05	−0.02	−0.05
Q-Leontief_Twosec_SlugW	−0.02	−0.05	−0.02	−0.05	−0.13	−0.09	−0.43	−0.04	−0.07	−0.03	−0.05

50%	OECDEurope	OECD America	OECD Asia-Oceania	Other Europe Eurasia	Other Asia	China	India	Middle East	Africa	Latin America	Global
CES_Onesec_SlugW	−0.09	−0.20	−0.14	−0.33	−1.34	−0.53	−4.31	−0.53	−0.70	−0.36	−0.39
CES_Twosec_MobW	−0.08	−0.23	−0.08	−0.20	−1.10	−0.39	−3.54	−0.35	−0.44	−0.24	−0.32
CES_Twosec_SlugW	−0.11	−0.27	−0.14	−0.35	−1.34	−0.56	−4.37	−0.51	−0.68	−0.37	−0.42
Q-Leontief_Onesec_SlugW	−7.83	−11.91	−10.96	−13.40	−29.03	−35.03	−35.33	−22.66	−28.44	−21.08	−16.02
Q-Leontief_Twosec_MobW	−5.60	−8.11	−4.96	−6.85	−15.62	−29.54	−32.38	−7.31	−13.45	−11.56	−10.67
Q-Leontief_Twosec_SlugW	−10.23	−14.65	−15.53	−20.12	−31.40	−35.46	−36.24	−25.32	−31.14	−22.19	−18.63

Table 4. Prices impacts (% change) of systematic water shocks for different specifications.

Irr. Agri	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Descrip-tion	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)
CES_Onesec_SlugW	2.5	110.7	4.7	178.9	2.4	118.7	4.1	130.6	6.7	226.4	3.1	122.9	8.0	305.6	2.5	96.5	2.3	104.6	4.3	170.0	4.1	156.5
CES_Twosec_MobW	1.7	39.1	3.2	65.5	2.1	61.1	3.2	60.3	6.4	157.7	2.5	58.8	7.4	228.0	2.4	59.5	2.2	56.8	3.6	81.0	3.5	86.8
CES_Twosec_SlugW	2.5	110.5	4.7	178.7	2.4	118.3	4.1	130.3	6.7	225.5	3.1	122.7	8.0	305.0	2.5	96.4	2.3	104.5	4.3	169.6	4.1	156.1
Q-Leontief_Onesec_SlugW	51.6	9009.0	60.7	9810.3	52.5	8071.3	50.9	7647.2	64.0	4248.7	54.8	3918.6	68.8	4064.2	44.5	4688.4	49.8	6649.9	60.7	8884.7	55.8	6699.2
Q-Leontief_Twosec_MobW	38.3	3477.1	45.4	3319.4	41.7	5018.7	42.2	4958.3	54.6	2430.4	43.9	2635.5	63.4	2075.8	36.5	2987.0	39.7	3574.7	47.8	5110.6	45.4	3558.7
Q-Leontief_Twosec_SlugW	51.4	8590.1	60.7	9049.5	52.4	7382.2	50.6	6201.4	63.7	4004.1	55.1	3779.7	70.0	3790.3	44.2	4722.4	49.6	6498.8	60.5	8481.9	55.8	6250.0

(*continued*)

Table 4. Continued

Energy	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)
CES_Onesec_SlugW	0.0	−1.0	0.0	−1.3	0.0	−1.5	0.0	−1.6	−0.1	−4.6	−0.1	−2.7	−0.5	−14.4	−0.1	−2.7	−0.1	−2.4	−0.1	−2.0	−0.1	−3.4
CES_Twosec_MobW	0.1	1.8	0.3	4.1	0.0	0.4	0.1	1.1	0.0	−1.2	0.2	2.1	−0.1	−6.3	0.1	0.5	0.1	1.0	0.1	1.3	0.1	0.5
CES_Twosec_SlugW	0.1	−0.2	0.2	0.7	0.0	−1.0	0.0	−0.8	−0.1	−3.9	0.1	−1.5	−0.3	−12.7	0.0	−1.9	0.0	−1.5	0.1	−1.1	0.0	−2.4
Q-Leontief_Onesec_SlugW	−0.4	−45.3	−0.4	−57.1	−0.6	−60.3	−0.6	−52.4	−1.4	−66.8	−1.1	−53.6	−3.4	−42.7	−0.9	−64.5	−0.9	−64.3	−0.7	−64.4	−1.0	−57.1
Q-Leontief_Twosec_MobW	2.3	204.9	3.8	346.9	0.8	34.9	1.4	60.2	0.4	33.3	2.4	162.8	−0.6	45.7	1.2	52.6	1.5	57.5	1.6	55.8	1.5	105.5
Q-Leontief_Twosec_SlugW	1.2	190.6	2.3	198.8	0.3	157.4	0.9	179.2	−0.1	146.8	1.1	109.4	0.1	87.9	0.5	158.9	0.7	171.6	1.0	173.3	0.8	157.4

(continued)

Table 4. Continued

Rainfed Agr.	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)
CES_Onesec_SlugW	0.0	0.4	0.0	0.6	0.3	6.3	0.0	−0.1	−0.1	−4.4	0.0	−0.2	−0.4	−13.6	0.0	0.0	0.0	−1.0	0.0	−0.3	0.0	−1.2
CES_Twosec_MobW	0.0	0.5	0.0	0.7	0.2	3.3	0.0	0.1	−0.1	−3.7	0.0	0.0	−0.4	−11.6	0.1	0.3	0.0	−0.3	0.0	−0.1	0.0	−1.1
CES_Twosec_SlugW	0.0	0.4	0.0	0.5	0.3	6.3	0.0	−0.1	−0.1	−4.5	0.0	−0.3	−0.4	−13.9	0.1	0.3	0.0	−0.7	0.0	−0.3	0.0	−1.2
Q-Leontief_Onesec_SlugW	−0.2	−26.6	−0.4	−38.9	0.2	−13.0	−0.4	−40.0	−2.3	−58.5	−1.3	−71.4	−4.2	4.0	−0.8	−52.4	−1.2	−39.1	−0.5	−43.5	−1.1	−37.9
Q-Leontief_Twosec_MobW	−0.1	−16.6	−0.5	−24.5	0.1	−16.2	−0.3	−31.8	−2.2	−56.0	−1.2	−73.4	−4.5	−34.1	0.0	8.0	−0.5	−24.1	−0.3	−37.3	−0.9	−30.6
Q-Leontief_Twosec_SlugW	−0.2	−30.5	−0.6	−46.4	0.2	−18.6	−0.5	−56.0	−2.4	−56.8	−1.4	−66.5	−4.9	7.4	−0.3	−43.7	−0.9	−40.4	−0.5	−43.3	−1.1	−39.5

Table 5. Regional production output impacts (% change in real terms) across model specifications.

Irrigated Agriculture	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)
CES_Onesec_SlugW	1.11	9.03	−1.17	−14.51	1.22	11.44	−1.59	−13.77	−1.20	−17.06	0.13	0.69	−1.25	−19.42	0.39	3.71	0.88	10.87	−0.44	−8.57	−0.2	−3.8
CES_Twosec_MobW	1.18	17.61	−0.24	2.41	0.80	5.84	−1.09	−7.76	−1.33	−18.90	0.08	0.45	−1.22	−18.59	0.04	−3.62	0.37	0.95	−0.85	−11.86	−0.2	−3.3
CES_Twosec_SlugW	1.11	9.01	−1.15	−14.49	1.21	11.40	−1.59	−13.79	−1.21	−17.08	0.13	0.69	−1.24	−19.41	0.36	3.58	0.85	10.74	−0.45	−8.60	−0.2	−3.8
Q-Leontief_Onesec_SlugW	0.03	−42.04	−3.59	−44.85	0.76	−41.78	−3.53	−44.38	−4.24	−45.18	−1.01	−42.76	−4.79	−45.76	−0.80	−42.31	0.27	−41.73	−2.71	−44.13	−2.0	−43.5
Q-Leontief_Twosec_MobW	1.86	−9.88	−1.10	−0.31	0.28	−47.87	−5.22	−63.16	−4.62	−47.54	−0.88	−31.43	−5.15	−44.97	−1.44	−43.22	−0.46	−43.82	−3.46	−52.09	−2.0	−38.4
Q-Leontief_Twosec_SlugW	0.03	−42.04	−3.58	−44.85	0.76	−41.77	−3.53	−44.36	−4.25	−45.18	−0.99	−42.76	−4.73	−45.76	−0.87	−42.30	0.22	−41.73	−2.72	−44.13	−2.0	−43.5

(*continued*)

Table 5. Continued

Energy	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)
CES_ Onesec_ SlugW	−0.09	−2.83	−0.06	−2.02	−0.15	−4.61	−0.03	−1.19	0.26	8.57	−0.02	−0.23	0.64	23.05	−0.02	−0.53	−0.01	0.32	−0.04	−1.15	0.0	1.9
CES_ Twosec_ MobW	−0.10	−2.51	−0.45	−6.80	0.05	−0.56	0.01	−0.12	0.39	8.13	−0.19	−3.32	0.24	10.40	0.07	1.06	0.12	2.01	0.08	0.82	0.0	0.9
CES_ Twosec_ SlugW	−0.10	−2.87	−0.34	−4.39	−0.02	−3.50	−0.01	−0.99	0.35	9.29	−0.11	−1.03	0.48	20.15	0.04	−0.03	0.07	1.04	0.04	−0.41	0.0	1.7
Q-Leontief_ Onesec_ SlugW	−0.83	−58.11	−0.74	−23.99	−1.20	−28.28	−0.38	−28.13	2.06	−8.66	0.36	−72.45	4.93	−69.37	0.14	35.00	0.83	90.51	−0.35	38.38	0.5	−12.5
Q-Leontief_ Twosec_ MobW	−2.88	−89.94	−5.00	−92.32	1.14	64.00	0.64	6.12	3.94	135.73	−2.32	−87.68	2.92	−53.67	1.28	35.25	2.31	75.69	1.45	52.99	0.3	4.6
Q-Leontief_ Twosec_ SlugW	−1.42	−34.47	−3.35	−38.54	0.55	−28.09	−0.14	−32.32	2.85	−28.25	−1.21	−36.33	0.09	−37.60	0.99	−16.01	1.94	−22.57	0.29	−31.14	0.1	−30.5

(*continued*)

Table 5. Continued

Rainfed Agriculture	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)
CES_Onesec_SlugW	−0.03	−1.39	−0.05	−2.63	−0.30	−8.48	0.02	−0.26	−0.04	−0.52	−0.04	−1.10	−0.03	−0.06	−0.07	−2.33	−0.04	−0.93	−0.01	−0.69	−0.1	−1.8
CES_Twosec_MobW	−0.04	−1.14	−0.05	−2.27	−0.25	−4.94	−0.01	−0.59	−0.04	−0.04	−0.03	−0.72	−0.01	0.38	−0.15	−2.45	−0.04	−0.64	−0.02	−0.49	−0.1	−1.3
CES_Twosec_SlugW	−0.04	−1.41	−0.02	−2.34	−0.31	−8.55	0.01	−0.37	−0.05	−0.57	−0.04	−1.08	−0.02	0.02	−0.14	−2.93	−0.05	−1.03	−0.03	−0.89	−0.1	−1.9
Q-Leontief_Onesec_SlugW	−0.73	−33.14	−1.03	−29.77	−1.57	−56.40	−0.20	−2.39	0.37	−24.60	0.14	0.94	0.47	−49.48	−0.53	−23.23	−0.03	−24.77	−0.54	−35.39	−0.4	−27.8
Q-Leontief_Twosec_MobW	−0.51	−36.28	−0.41	−38.10	−1.47	−47.12	−0.51	−18.92	0.27	−10.38	0.24	60.07	0.67	−43.30	−1.88	−69.06	−0.25	−17.42	−0.84	−24.95	−0.5	−24.5
Q-Leontief_Twosec_SlugW	−0.71	−31.28	−0.67	−16.24	−1.74	−55.59	−0.31	20.16	0.30	−32.03	0.22	−23.78	0.80	−52.65	−1.64	−39.51	−0.20	−16.64	−0.78	−38.10	−0.5	−28.6

Table 6. Import impacts (% change in real terms) across model specifications.

Irrigated Agricul-ture	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Descrip-tion	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)
CES_Onesec_SlugW	−0.95	−2.74	2.34	41.95	−3.24	−19.4	2.84	32.69	5.97	110.6	−2.27	−21	11.4	313.8	−1.56	−12.41	−3.01	−24.4	0.86	21.88	1.23	44.11
CES_Twosec_MobW	−1.05	−9.97	1.13	16.65	−1.68	4.58	2.04	23.39	6.69	163.1	−1.38	−5.29	12	519.9	−0.63	4.96	−1.42	−0.16	1.89	36.35	1.75	75.36
CES_Twosec_SlugW	−0.95	−2.75	2.33	42.07	−3.23	−19.5	2.81	32.26	5.94	109.8	−2.26	−20.9	11.3	313	−1.52	−12.51	−2.98	−24.5	0.87	21.63	1.23	43.86
Q-Leontief_Onesec_SlugW	2.35	50.55	19.43	79.39	0.98	93.82	10.75	74.56	17.23	−72.4	3.81	−87	27.9	−79.87	−3.4	−49.9	−3.05	−62	12.44	−12.88	8.85	−6.57
Q-Leontief_Twosec_MobW	0.43	13.72	14.75	45.39	3.05	193.4	11.81	84.57	19.16	−55	5.66	−45.8	45.3	−82.58	−1.85	−19.36	−1.7	−35.9	13.19	130.26	10.98	22.87
Q-Leontief_Twosec_SlugW	2.36	51.22	19.62	68.53	0.61	72.57	10.26	−11.05	16.39	−72.3	4.44	−85	30.8	−82.09	−3.85	−39.07	−3.62	−52.6	12.11	−7.84	8.91	−15.76

(*continued*)

Table 6. Continued

Energy	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)
CES_Onesec_SlugW	0.05	1.88	0.05	2.03	0.01	0.53	0.01	0.57	−0.27	−8.18	−0.03	−1.21	−0.73	−26.96	−0.04	−0.89	−0.09	−2.77	−0.03	−0.79	−0.11	−3.58
CES_Twosec_MobW	0.04	1.35	0.45	7.38	−0.04	−0.4	−0.04	−0.47	−0.3	−6.13	0.25	4.36	−0.4	−15.47	−0.08	−1.16	−0.07	−1.1	−0.02	−0.18	−0.02	−1.18
CES_Twosec_SlugW	0.04	1.83	0.34	4.68	−0.03	0.12	−0.02	0.25	−0.3	−8.36	0.1	0.02	−0.61	−25.23	−0.07	−1.12	−0.09	−2.79	−0.04	−0.88	−0.07	−3.15
Q-Leontief_Onesec_SlugW	0.55	83.96	0.66	42.18	0.12	−7.39	0.17	89.98	−2.11	−81.2	−0.77	−29.6	−4.88	−62.77	−0.22	−15.65	−0.94	−74.9	−0.16	−48.18	−0.76	−10.35
Q-Leontief_Twosec_MobW	1.41	116.5	5.52	261.9	−0.58	−5.56	−0.6	−8.25	−2.54	−60.2	3.71	81.81	−3.11	−64.48	−0.95	−14.7	−0.83	−49.4	−0.49	−15.71	0.15	24.19
Q-Leontief_Twosec_SlugW	0.74	31.43	3.52	33.37	−0.45	−16.4	−0.19	−25.68	−2.25	−75.8	1.8	−76.8	−1.05	−87.11	−0.71	−36.23	−1.06	−68.3	−0.08	−34.03	0.03	−35.55

(*continued*)

Table 6. Continued

Rainfed Agriculture	1 OECD Europe		2 OECD America		3 OECD Asia-Oceania		4 Other Europe and Eurasia		5 Other Asia		6 China		7 India		8 Middle East		9 Africa		10 Latin America		Mean % change	
Model Description	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)	Min (−10%)	Max (−50%)
CES_Onesec_SlugW	0.02	1.19	0.04	1.74	0.22	5.65	−0.01	1.61	−0.24	−8.15	0.03	1.07	−0.97	−30.68	−0.03	−0.47	−0.1	−3.46	−0.04	−1.27	−0.11	−3.28
CES_Twosec_MobW	0.03	0.94	0.05	1.7	0.15	2.73	−0.04	0.46	−0.27	−6.52	0.03	1.06	−1.04	−26.58	−0.04	−0.65	−0.05	−1.79	−0.06	−1.06	−0.12	−2.97
CES_Twosec_SlugW	0.02	1.18	0.03	1.66	0.21	5.63	−0.04	1.31	−0.25	−8.17	0.03	1.05	−1.04	−31.18	−0.03	−0.44	−0.06	−3.07	−0.04	−1.23	−0.12	−3.33
Q-Leontief_Onesec_SlugW	0.47	35.35	0.33	12.5	0.64	34.92	0.54	37.35	−3.05	−64.4	−1.12	−89.3	−7.53	291	−0.7	−49.44	−2	−35	−0.24	−34.87	−1.27	13.8
Q-Leontief_Twosec_MobW	0.46	45.59	0.27	46.87	0.44	32.87	−0.26	12.66	−2.97	−51.7	−0.89	−89.2	−8.58	11.68	−0.49	24.75	−0.76	3.07	−0.17	−17.9	−1.29	1.87
Q-Leontief_Twosec_SlugW	0.49	35.65	0.26	−8.22	0.6	23.88	0.08	−44.23	−3.06	−64.7	−1.12	−82.8	−9.17	278.6	−0.6	−28.21	−1.34	−16.5	−0.17	−28.9	−1.4	6.45

reverse happens for irrigated agriculture in these areas: production declines are larger than 40% in the sluggish case rather than the maximum of 10% in OECD Europe in the mobile scenario. These trends are mirrored by energy imports that would increase by 116% and 261% when water is mobile, instead of 31% and 33% when water is sluggish. Regions with lower water intensity in their energy sectors show opposite trends.

Concerning the impacts on rainfed agriculture, in the simulations, this sector is not affected directly by water scarcity shocks. Although relatively unrealistic, it remains interesting to examine the indirect feedback on rainfed agricultural production, given this sector's linkages with irrigated agriculture and the possibility of land shifts between the two sectors. Prices and production of rainfed agriculture depict mostly negative trends, especially in the Quasi-Leontief specifications. Thus, in this context, they are dominated by the macroeconomic and demand declining trends rather than by a substitution effect that could shift demand and production away from irrigated agriculture.[9]

3.2. Water competition under water scarcity

After examining the macroeconomic and sectorial impacts of water scarcity, this section focuses on the dynamics triggered by sectorial water demand. Given the general agreement in the literature on the limited substitutability between water and the remaining factors of production (Berrittella et al., 2007; Dixon et al., 2010; Nechifor & Winning, 2018; van Heerden et al., 2008), we focus on and develop this scrutiny just in the Quasi-Leontief setting. When water is a sluggish factor of production between sectors, sectorial water demand is constrained to follow precisely the water supply (Table 7). This does not hold when water is mobile, being sectorial water demand influenced by cross-sectorial substitution and regional production specialisation effects. In this mobile setting, regions like OECD Asia-Oceania, Africa, and Latin America, notwithstanding the 50% water supply reduction, increase energy production and, accordingly, water demand by that sector. Consequently, in the same regions, the water demand for irrigated agriculture declines as water is shifted toward energy production. These production choices are reflected in the changes in the share of water used by the different sectors in the different regions reported in Table 8, highlighting how the water intensity of the regional energy sector is strongly interlinked with the production and macroeconomic results.

3.3. Modelling nexus implications in a dynamic setting

Lastly, this study tests the effects of implementing the Water-Energy link in the dynamic setting represented by the SSP2,[10] i.e. the Middle of the Road scenario. For compactness,

[9] To be noted, due to the overall testing objective (i.e. testing the model responses to an expansion of the detail in the representation of the water endowment), these are results based on simplified systematic shocks on water withdrawals and, therefore, directly affect only irrigated agriculture. Furthermore, the irrigated and rainfed agriculture sectors aggregate (exactly) the same agricultural goods (e.g. wheat, paddy rice, etc.) which were included in the GTAP database of Version 9 (Aguiar et al., 2016), just differentiated according to production method, i.e. divided by proportion of land type (rainfed or irrigated) and water uses as in GTAP-W (Calzadilla et al., 2011; Haqiqi et al., 2016). Thus, there is no consideration of what types of crops are currently (or are able to be) grown with and without irrigation in different regions and for what use (food or non-food), which would, though, be necessary for more realistic assessment scenarios such as impacts of climate change pathways.

[10] In detail, the shocks entail a GDP/Total Factor Productivity and a Population/Labour trend calibration coherent with the different SSPs. As such, it needs to be noted that no explicit assumptions on sectorial-specific technological changes and innovation trends are made in this context.

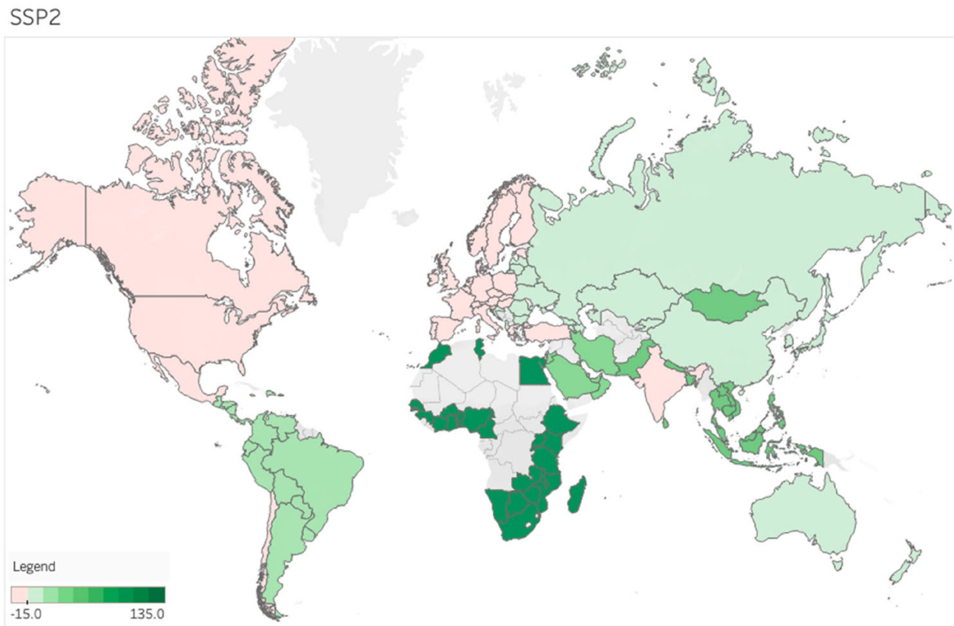
Table 7. Sectorial water demand (% change).

	Irrigated Agriculture				Energy			
	Perfect water mobility across sectors		'Sluggish' water mobility across sectors		Perfect water mobility across sectors		'Sluggish' water mobility across sectors	
Water supply reduction	10%	50%	10%	50%	10%	50%	10%	50%
1 OECD Europe	−7.59	−22.21	−10	−50	−13.66	−92.30	−10	−50
2 OECD America	−7.15	−9.57	−10	−50	−13.09	−93.74	−10	−50
3 OECD Asia-Oceania	−9.89	−55.22	−10	−50	−11.39	16.35	−10	−50
4 Other Europe and Eurasia	−11.21	−66.88	−10	−50	−7.85	−20.06	−10	−50
5 Other Asia	−10.08	−52.14	−10	−50	−4.70	84.05	−10	−50
6 China	−9.37	−40.10	−10	−50	−12.58	−90.33	−10	−50
7 India	−10.24	−49.27	−10	−50	−5.69	−62.88	−10	−50
8 Middle East	−10.01	−50.73	−10	−50	−9.36	−0.53	−10	−50
9 Africa	−10.01	−51.76	−10	−50	−9.35	27.83	−10	−50
10 Latin America	−10.21	−57.11	−10	−50	−8.10	13.51	−10	−50

Table 8. Percentage Share of water used by sector in different scenarios (mobile water).

Irrig. Ag.	Initial	10	20	30	40	50	Energy	Initial	10	20	30	40	50
1 OECD Europe	60.35	61.96	66.66	74.74	85.00	93.90		39.65	38.04	33.34	25.26	15.00	6.10
2 OECD America	51.97	53.62	62.44	75.92	86.63	93.99		48.03	46.38	37.56	24.08	13.37	6.01
3 OECD Asia-Oceania	92.71	92.82	92.15	89.73	85.86	83.03		7.29	7.18	7.85	10.27	14.14	16.97
4 Other Europe and Eurasia	63.94	63.08	60.56	54.88	47.84	42.35		36.06	36.92	39.44	45.12	52.16	57.65
5 Other Asia	98.43	98.34	97.92	96.95	95.65	94.22		1.57	1.66	2.08	3.05	4.35	5.78
6 China	80.29	80.86	83.24	89.58	94.99	96.19		19.71	19.14	16.76	10.42	5.01	3.81
7 India	94.66	94.41	93.64	93.09	93.89	96.04		5.34	5.59	6.36	6.91	6.11	3.96
8 Middle East	98.54	98.53	98.40	98.08	97.66	97.10		1.46	1.47	1.60	1.92	2.34	2.90
9 Africa	97.78	97.77	97.44	96.69	95.64	94.34		2.22	2.23	2.56	3.31	4.36	5.66
10 Latin America	89.93	89.72	88.61	85.91	81.82	77.13		10.07	10.28	11.39	14.09	18.18	22.87
World	77.73	78.27	80.95	85.48	89.32	91.77		22.27	21.73	19.05	14.52	10.68	8.23

Figure 3. Difference in real GDP % change 2011–2050 between impact and baseline scenarios in SSP2.



the results for the other SSPs are reported in the Supplementary Information. This part is developed under the Quasi-Leontief mobile water framework. Figure 3 shows that when water competition across energy and agriculture is introduced, the regions featuring the more water-intensive energy sectors cannot reach, with the total factor productivities originally calibrated, the overall multi-decadal GDP growth targets associated with the SSP. OECD Europe and OECD America show a cumulative GDP of around 5% lower than the goal, and India shows a GDP contraction of 5.6%. On the contrary, Other Asia and African regions show a higher GDP than the target. As from the results on water competition, similar trends on the role of water intensity of the countries emerge.

4. Discussion

The outcomes of our simulations, although, at this stage, our research is mainly meant to test the modelling methodology developed, already highlight some interesting implications. First, the implementation of a sluggish water endowment for different sectors has a detectable effect both on GDP and sectorial production in the presence of changes in water supply. In our case, decreases in water supply lead to higher GDP losses when agricultural and energy water uses are considered, compared to when only the former is modelled. Despite being apparently trivial, this hints that the analyses performed without considering this aspect can be biased.

Second, GDP responses to water supply reductions are non-linear, with the losses growing exponentially after the homogeneous 30% water decline (see Table 3). This outcome, especially the 30% threshold, is clearly dependent upon the current model calibration and description of the economic relations, as well as on the simple structure of the shocks (homogeneous decrease). Nonetheless, it is interesting to note that our economic setup allows for the detection of potential discontinuities and significant losses induced by water scarcity.

Third, the GDP losses in two water user settings are lower when sectorial water mobility is allowed, even with respect to the only agriculture setting. Thus, the simulations suggest that the existence of a 'water market'[11] granting/regulating water access to different users could be a critical feature in adapting to water scarcity and mitigating its overall negative impacts.

Fourth, water mobility can trigger international specialisation effects driven by the relative regional water intensity of agriculture and energy production. In our simulations, water scarcity induces regions with lower water-intensive energy sectors to specialise in energy production and regions with higher water-intensive energy sectors to specialise in food production from irrigated agriculture. As a direct consequence, our analysis also confirms that food security issues are more likely to emerge in developing areas like Asian and African countries, while energy security issues might arise in developed areas like the OECD Europe and the OECD America. Be noted that the share of total water used by agriculture increases significantly in many regions and at the global level, but the number of regions with potential food security issues is still higher than the ones at risk of energy insecurity. This suggests that water is less compressible for agriculture than for the energy sector. This said, although smaller, contractions in production of the energy sector are far from negligible and water scarcity can induce higher dependency on imported energy commodities in water-intensive energy-sector countries. Among these, we find that OECD Europe is already a heavy net energy importer and, accordingly, already sensitive to concerns for its energy security.

A final insight can be derived from the results of the dynamic simulations. It is shown that developed (developing) regions can expect lower (higher) growth due to food-energy water competition. To be noted, higher growth does not necessarily imply the absence of downsides. Indeed, this does not exclude the possibility of food security issues, especially if higher GDP growth is induced by acute specialisation in the production of energy.

All in all, these findings, albeit purely explorative, confirm the importance of explicitly considering the competing uses of water across sectors. The Nexus analysis can highlight tensions in achieving given development targets that would remain hidden otherwise. It also suggests the need to reconsider, from a Nexus perspective, the quantitative assessment of sustainability, planetary boundaries, and economic growth scenarios. These reflections can be directly extended to energy and climate policy analyses, whose cost and effectiveness can be better assessed with a proper description of the water dimension.

5. Conclusions

Given the methodological focus of the paper, the proposed simulations have been developed primarily to test the behaviour of the improved model structure and its sensitivity to different parameterisations. Accordingly, it has been possible to verify that,

[11] The presence of a water market must be intended as a hypothetical institutionalised platform that allows the exchange of information/coordination between actors and the possibility to allocate resources between different sectors, maximising economic efficiency.

among all the tested factors, the degree of water substitutability with the other factors of production and water mobility across sectors are the most important drivers of model responses.

Lower emphasis was put on the realism of the simulations, though we are aware of real-life complexities and the limited representativeness of our simplified tests. For instance, when addressing water competition across sectors, regulatory and institutional constraints can be much more important than purely economic efficiency considerations. Furthermore, in the presence of water scarcity, water use by households or agriculture cannot be easily compressed. If some rationing is necessary, it will be decided by water authorities after careful evaluations and not by 'free market' mechanisms. Similarly, international specialisation, which in this study is driven exclusively by comparative advantages, is also mediated by geopolitical strategies. Indeed, it is difficult to believe that Europe, which is already facing energy security issues due to its dependence on foreign energy imports, would increase this dependence as a response to water scarcity pressures, even though this could be economically efficient.

Our analysis presents some further limitations. First, we acknowledge the rather narrow scope of a Nexus analysis that considers just agricultural and energy water uses, neglecting other sectorial and domestic ones. Secondly, with the current structure, the model does not allow for the accounting of technological innovations after the reference year of calibration. Moreover, the model features just one aggregated energy sector and therefore it cannot capture the specificities of water uses across different energy types. Consequently, it is not possible to account for substitution between different energy technologies within a region in response to water scarcity (e.g. substitution of thermoelectric power plants for a less water-intense electricity generation technology such as solar or wind-based). Similarly, the structure and model settings do not account for the issue of electricity losses across long distances.

Another limitation of this work is the regional dimension of the analysis, centred on large geo-political blocks. This choice driven by data availability, prevents capturing local water scarcity issues, failing to highlight potential hot spots for energy or agricultural production declines at the sub-national or basin level. Finally, the current study does not include different water types and water generation technologies. Similarly to the limit highlighted for the representation of the energy sector, this analysis just considers water as an undifferentiated production factor. Therefore, it does not account for any difference in the availability and use of freshwater or groundwater. Furthermore, the possibility of compensating for water shortages with non-conventional water production technologies, like desalination or wastewater treatment, is not examined.

Still, the enriched Nexus analysis that can be conducted with our improved framework highlights adjustments usually neglected in the current macroeconomic analyses which can lead to biased scenario projections and misleading policy recommendations. This work marks the first step towards a complete Nexus analysis, which opens the path to many research developments. Potential steps forward include tackling the policy dimension, examining, for instance, if climate change mitigation can be more or less effective and/or costly in the presence of sectorial water competition.

In essence, the improvements to the nexus analysis suggested in this paper can be useful in supporting the advancement of both academic research and policy action. Its relevance for academia is mainly methodological. As such, it provides a detailed description of the implementation of so-far neglected features of the Water-Energy nexus, like water sectorial competition mechanisms in a global Computable General Equilibrium Model (CGE). Moreover, it tests and discusses the current water-modelling assumptions and key parameterisation in the literature in a replicable way while offering the starting point for future expansions.

Concerning the relevance of this work for policymaking, this paper provides an improved tool to evaluate the macroeconomic and sectorial consequences of water scarcity on food and energy security, international trade and, potentially, climate policies. Finally, this paper can also contribute to the current debate on the sustainable use of resources as it improves the quantitative assessment of the Nexus dynamics, which involve basic human needs and, as such, are foundational for the well-being of human societies.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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