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Roberto Roson

Beyond Water Stress: Structural Adjustment and Macroeconomic Consequences of the Emerging Water Scarcity

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This work analyzes some system-wide macroeconomic consequences of lower (sustainable) water availability, when global economic growth is postulated according to the Shared Socio-Economic Pathway 1 (SSP1), for the reference year 2050. After finding that the rather optimistic forecasts of economic development cannot be met in most water scarce macro-regions, we assess what consequences for the structure of the economy, welfare and the terms of trade, the insufficiency of water resources would imply. The analysis is undertaken by means of numerical simulations with a global computable general equilibrium model, under a set of alternative hypotheses. In particular, we consider whether (or not) the regional economic systems have a differentiated capability of adaptation (by means of innovation and modification of economic processes), and whether (or not) the scarce water resources can be allocated among industries, such that more water is assigned where its economic value is greater.

Keywords
Water, Economic Growth, Shared Socio-economic Pathways, Computable General Equilibrium, Virtual Water Trade

JEL Codes
C68, F18, F43, O11, Q01, Q25, Q32, Q56

Address for correspondence:
Roberto Roson
Department of Economics
Ca' Foscari University of Venice
Cannaregio 873, Fondamenta S.Giobbe
30121 Venezia - Italy
Phone: (++39) 041 2349147
Fax: (++39) 041 2349176
e-mail: roson@unive.it

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wp.dse@unive.it

Department of Economics
Ca' Foscari University of Venice
Cannaregio 873, Fondamenta San Giobbe
30121 Venice Italy
Fax: ++39 041 2349210

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1. Introduction

Will economic development be hampered by a lack, or by an unsustainable exploitation, of water resources? For almost all studies addressing the issue of water availability from a macroeconomic perspective (e.g., Rosegrant, Cai and Cline, 2002), the answer is yes. The world will face more frequent and more severe water crises in the future, with negative and serious socio-economic implications, especially for some developing countries, already hit by climate change impacts.

A largely ignored question is, however, how the emerging water scarcity will shape the economy in the medium and long term. In other words: facing an ever increasing (explicit or implicit) cost for water, how the production and consumption processes will change? What the ultimate welfare effects will be? How much economic growth potential will be lost?

Clearly, possible answers to all the issues above are not deterministic. Much depends on public policies, but also on individual choices, as well as on the technological options available. Here we explore some scenarios through numerical simulations with a global computable general equilibrium model, under a set of alternative hypotheses. In particular, we consider whether (or not) the regional economic systems have a differentiated capability of adaptation, and whether (or not) the scarce water resources can be allocated among industries, such that more water is assigned where its economic value is greater.

This research adds to the literature by directly addressing the feedback from water scarcity to the economic system, whereas the conventional approach goes to the opposite direction: a potential water demand is first assessed and then compared with some measure of supply/availability, often by constructing an index of "water stress" (e.g., Alcamo et al., 2003, Arnell, 2004) which, of course, does not inform about how the latent excess of demand for water could be absorbed.

In the following section, the modelling strategy and the design of simulation exercises is illustrated. Results are presented in Section 3, followed by a discussion about the significance and limitations of our findings. After the conclusions, three Appendices (A, B, C) provide additional information on some technical aspects of our methodology.

2. The design of a set of simulation exercises

We base our modeling exercise on the Shared Socio-Economic Scenario 1 (SSP1), referred to the year 2050 (Kriegler et al., 2012; O'Neill et al., 2014), for projections of GDP and population. SSP1 is characterized by the following narrative: "Sustainable development proceeds at a reasonably high pace, inequalities are lessened, technological change is rapid and directed toward environmentally friendly processes, including lower carbon energy sources and high productivity of land".

As in Roson (2016) and Roson and Damania (2017) CGE simulations are conducted to extrapolate the potential water demand, consistent with the economic growth hypotheses of SSP1, as well as to assess the amount of future water deficits (excess demand for water), occurring at a given year. The whole process is described in more detail in the Appendix A.

Our global model considers 14 macro-regions, and we found that potential water demand would exceed "sustainable" levels of aggregate consumption in four of them: Middle East and North Africa (MENA), Central (C_Asia), East (E_Asia) and South Asia (S_Asia), at varying degrees, as shown in Table 1.

Table 1
Percentage of potential water demand exceeding sustainable supply

	SSP1-2050
MENA	-77.1
C_Asia	-4.4
E_Asia	-42.9
S_Asia	-50.2

If water availability will become a constraint for the regional economies, scenarios of economic growth (which is especially sustained in the SSP1), and their associated potential water demand, will turn out to be incompatible with the actual availability of resources.

How the excess demand for water would be absorbed by the economic system? First, efficiency improvements could be achieved by reallocating water consuming activities in time and space, within a region and during the year. This can be obtained through the normal market functioning, driven by the changing relative competitiveness of the various economic units, induced by water scarcity. For instance, sowing times and crops can be changed in agriculture, new energy plants can be built where water supply is sufficient and stable, etc. Where water rights markets are developed, water allocations can be banked and traded. Second, water saving technologies, policies and processes could be introduced, as the corresponding investment would be justified by the rising cost of water. For example, pipelines can be built for water transfer projects, as well as infrastructure for desalination and wastewater recycling.

It is extremely difficult to gauge the degree of endogenous efficiency gains potentially achievable in the water stressed macro-regions, at the spatial and temporal scale adopted in our global model. To conduct our simulations experiments, we therefore adopt two sets of assumptions. The first one is a simple benchmark case, consistent with our previous work (Roson and Damania, 2017), were it is assumed that efficiency improvements can cover 75% of the demand gap in all water stressed regions. The remaining 25% is interpreted as cuts in water availability; for instance, the 77.1% excess demand in the MENA region would bring about a reduction in water availability of 19.27%. Alternatively, we consider various factors (economic, technical and institutional) that could ultimately affect the actual degree of "flexibility" or "absorption capacity" in the regional economic systems. Appendix C illustrates how a scenario of regionally differentiated impacts, based on a qualitative index, has been built. In this alternative setting, we assume that the reductions in water availability, expressed as a share of the regional demand gap (25% in the base case), are fixed at 26% for MENA, 34% for C_Asia, 8% for E_Asia, 18% for S_Asia.

The reductions in water availability, determined for the regional aggregate, determine reductions at the finer sectoral level. Again, we use here two settings. The first one is a simple benchmark where sectoral water availability is reduced proportionally across the board. For example, -19.27% water in the MENA region corresponds to -19.27% in all water-using sectors inside the MENA. The second case is a little more elaborated, because sectoral reductions are made sensitive to the relative water efficiency. As in Roson and Damania (2017) sectoral reductions (ρ_{ir}) are increasing functions of the "water per unit of output", or water intensity, coefficients (ω_{ir}):

$$\rho_{ir} = \alpha_r + \left(\frac{\omega_{ir}}{\overline{\omega}_r}\right)^{0.25} \quad (1)$$

where α_r is a constant parameter, determined for each region *r*, set at a level ensuring that the sum of all sectoral reductions matches the one imposed to the regional aggregate, and $\overline{\omega}_r$ is the average water intensity in the region. Roson and Damania (2017) explain how these water intensity coefficients have been estimated. The inverse of the water intensity can be interpreted as the (average) water productivity. Therefore, (1) establishes that sectoral reductions in water availability are larger for those sectors with lower relative water efficiency, typically in agriculture, and vice versa.

Combining the alternative assumptions, we obtain three scenarios for our numerical simulations:

- No regional differentiation in absorption capacity, uniform reduction of water availability in all sectors [NRUS];
- Regional differentiation in absorption capacity, uniform reduction of water availability in all sectors [DRUS];
- Regional differentiation in absorption capacity, non-uniform (efficiency sensitive) reduction of water availability in the various sectors [DRES].

By selecting one of the three cases above, one implicitly determines how large the cuts in water consumption are for each regional industry. These are subsequently translated in terms of changes in (multifactor) industrial productivity. For example, less water in agriculture implies lower yields, *ceteris paribus*. In this study, the water-induced variation in productivity depends on specific characteristics of the different industries, which are captured by a set of "water-output elasticity" parameters. Appendix B illustrates how region and industry specific parameters for the output elasticity and the marginal value of water have been estimated. The mean output elasticity is 0.8. This implies that, on average, a 10% reduction in water usage entails an 8% reduction in the total industrial productivity.

Linking water to productivity allows us to conduct some numerical simulations with the global GTAP CGE model (Hertel and Tsigas, 1997), because productivity parameters are exogenous in that system, in the equilibrium conditions for the various markets. After changing some productivity factors, then, a new counterfactual equilibrium is computed, where variations in endogenous macroeconomic variables, like relative prices, trade flows, production volumes and others can be analyzed. Clearly, the purpose of the simulations is not that of producing forecasts, but to isolate the systemic causal effects of a specific shock (in our case, water-induced productivity variations), from the many factors which could ultimately affect the economic system.

In the following section, some findings corresponding to the three simulation cases are presented and discussed. The results are expressed as relative to a hypothetical reference, where the regional economies grow at the rate imposed by the SSP1, but there is no lack of water resources, thus no effects on productivity related to water availability. Therefore, a negative variation of – for instance – regional income should not be literally interpreted as a reduction, but rather as a growth rate smaller than the one hypothetically set by the SSP1.

3. Results

Variations is water availability for each industry in water stressed macro-regions are defined for the three simulation scenarios (NRUS, DRUS, DRES) and transformed as exogenous productivity shocks in the CGE model. For example, Table 2 shows the productivity variations for MENA in the three cases.

Notice that, when water efficiency is considered in the allocation scheme DRES, a few industries obtain productivity gains. This is because, even if water consumption is reduced in the region as a whole, some individual industries, where relatively little water is used per unit (value) of output, actually get increases in water assignments.

The CGE system computes a global economic equilibrium consistent with the exogenous shocks above, and the model delivers estimates for several macroeconomic variables, like: production volumes, employment, investments, consumption patterns, trade flows, price indexes, GDP deflators, etc. We present here only a limited set of results, to illustrate the key characteristics of the three scenarios.

Table 2

Industrial productivity shocks in the MENA region

	NRUS	DRUS	DRES
Rice	-35.74%	-37.17%	-70.42%
Wheat	-24.03%	-25.00%	-45.26%
Cereals	-24.27%	-25.25%	-47.36%
VegFruit	-30.73%	-31.96%	-40.63%
Oilseeds	-21.67%	-22.54%	-37.89%
Sugar	-22.34%	-23.24%	-34.63%
Oth Crops	-18.06%	-18.78%	-17.20%
Oth Agr.	-36.20%	-37.65%	-35.17%
Extr	-18.82%	-19.57%	-13.10%
P.Food	-14.03%	-14.60%	5.30%
Textiles	-17.29%	-17.98%	7.05%
Light Man	-23.21%	-24.13%	9.63%
Heavy Man	-13.79%	-14.35%	3.75%
Utilities	-13.38%	-13.91%	-7.59%

We start by considering the variations in Real GDP, or national income, relative to the benchmark where water scarcity has no impact on industrial productivity (Table 3).

Table 3

Variations in real GDP

	NRUS	DRUS	DRES
N_America	-0.01%	-0.01%	0.00%
C_America	0.05%	0.05%	0.06%
S_America	-0.01%	0.00%	0.01%
W_Europe	0.00%	0.00%	-0.01%
E_Europe	-0.04%	-0.03%	-0.05%
MENA	-8.64%	-8.99%	-3.77%
Sahel	0.21%	0.28%	0.51%
C_Africa	0.26%	0.27%	0.29%
S_Africa	-0.02%	0.00%	0.05%
C_Asia	-0.38%	-0.57%	0.42%
E_Asia	-2.47%	-0.80%	0.42%
S_Asia	-4.17%	-3.36%	0.44%
SE_Asia	-0.03%	0.00%	0.01%
Australasia	-0.02%	-0.01%	0.01%

Drops in (potential) GDP are quite substantial in water stressed macro-regions, most notably in the Middle East and North Africa (MENA). When differences in absorption capacities are taken into account, the picture changes significantly for East Asia (dominated by China), because we are assuming that as much as 92% of the water deficit can be accommodated there, through endogenous efficiency gains and technological progress.

Results for the DRES scenario indicate that the economic impact of water scarcity can be greatly contained when the economic returns per unit of water are considered in the industrial rationing scheme. Interestingly, the negative shock turns positive in the Asian regions, where the aggregate efficiency gains of a better inter-industrial allocation of water resources overrules the direct productivity effect.

To appreciate the impacts on the welfare of households, we employ the Equivalent Variation (EV) concept. The EV is the welfare equivalent reduction in income, virtually obtainable at unchanged relative prices. Therefore, it is the welfare "cost" of an exogenous shock or policy. Table 4 expresses the EV as relative to the benchmark GDP level.

Table 4

EV/ GDP

	NRUS	DRUS	DRES
N_America	-0.03%	-0.02%	0.00%
C_America	0.01%	0.02%	0.02%
S_America	0.01%	0.01%	0.02%
W_Europe	-0.03%	-0.02%	-0.01%
E_Europe	0.01%	0.01%	0.01%
MENA	-1.18%	-1.23%	-0.43%
Sahel	0.07%	0.08%	0.10%
C_Africa	0.16%	0.15%	0.14%
S_Africa	0.02%	0.02%	0.03%
C_Asia	0.09%	0.07%	0.14%
E_Asia	-0.14%	-0.05%	0.01%
S_Asia	-0.25%	-0.21%	0.04%
SE_Asia	0.02%	0.02%	0.02%
Australasia	0.00%	0.00%	0.00%

Table 4 closely mirrors Table 3, but with much smaller figures in absolute value. The reason is that water scarcity affects regions and industries in a differentiated way, so that the representative regional consumer can substitute water-intensive and relatively more expensive goods with cheaper ones, possibly imported from abroad. This endogenous substitution mechanism curbs the overall impact on the welfare of consumers.

Correspondingly, the industrial structure changes in the regions where water gets progressively scarcer. By way of illustration, Table 5 presents the changes in industrial output volumes in the MENA region.

Table 5

Industrial output changes in the MENA region

	NRUS	**DRUS**	**DRES**
Rice	-12.83%	-13.69%	-26.70%
Wheat	-14.31%	-15.20%	-31.37%
Cereals	-9.25%	-9.70%	-15.03%
VegFruit	-6.31%	-6.67%	-8.20%
Oilseeds	-15.67%	-16.61%	-33.38%
Sugar	-6.02%	-6.30%	-4.45%
Fibers	-7.95%	-8.50%	-5.61%
Oth Crops	-13.32%	-14.24%	-26.39%
Oth Agr.	-12.93%	-13.80%	-13.91%
Extraction	-18.32%	-19.26%	-14.40%
P.Food	-6.96%	-7.26%	-4.09%
Textiles	-7.49%	-8.39%	7.73%
Light Man	-18.80%	-19.90%	13.08%
Heavy Man	-12.22%	-12.86%	3.66%
Electricity	-7.96%	-8.30%	-0.92%
GasDis	-8.90%	-9.32%	-3.56%
WaterDis	-5.95%	-6.11%	-2.89%
Construction	-2.76%	-2.65%	-0.48%
TransComm	-2.43%	-2.29%	-0.51%
OthServices	-1.83%	-1.76%	-1.15%

In the Middle East and North Africa, we can see that the industries most vulnerable to reductions in water availability are found in Agriculture, with the addition of Extraction and Manufacturing. However, when water is reallocated on the basis of economic returns, agricultural productions like rice, wheat, oil seeds and others are significantly cut down, whereas the production of textiles and manufactured goods is expanded.

Using terminology from international trade theory, we can say that MENA gets a comparative disadvantage in water-intensive industries, when water gets scarce and affects productivity. In other words, it is not economically efficient to produce water intensive crops like rice or oil seeds, as long as they can be safely imported and paid with exports (e.g., light manufacturing), having a lower impact on water resources.[1]

Another way to highlight the same effect is through the virtual water concept. Since water is needed for the production of goods and services, the water employed is virtually exported as "embodied" into the traded goods. Analogously, importing goods (and services) requiring water in their production processes can be interpreted as virtual water imports.

Since we have data on water utilized in all industries and regions, we can readily estimate regional "virtual water trade balances". A virtual water trade deficit can be interpreted as saved (domestic) water

[1] Another example is Australia, which, during severe droughts, resorts to importing wheat when it normally does not.

resources, because of trade exchanges with the rest of the world. Furthermore, we can assess whether and how much the virtual water balance varies in the three simulation scenarios, when water consumption is reduced in some regions. The variations in the virtual water trade balances are displayed in Table 6.

Table 6

Variations in virtual water trade balances

(Millions m^3)

	NRUS	DRUS	DRES
N_America	5657	4365	6951
C_America	1329	1213	1479
S_America	2292	1911	3877
W_Europe	3306	2996	3687
E_Europe	4491	4295	8116
MENA	-23393	-24764	-40979
Sahel	150	54	292
C_Africa	-93	-212	192
S_Africa	1086	1002	1547
C_Asia	407	265	980
E_Asia	2907	6117	6046
S_Asia	-3116	-1410	795
SE_Asia	3924	3420	5024
Australasia	1052	747	1993

Our results suggest that international trade is an important mechanism to alleviate the economic consequences of water scarcity, especially for the MENA. However, there is no simple and direct relationship between virtual water trade and water availability. This is because virtual water trade reflects real trade in tangible goods, especially agricultural products, and the structure of international trade is actually affected by several factors, not just the degree of access to natural resources (Reimer, 2012).

4. Discussion

To correctly interpret the findings above, one should consider the limitations of our analysis, imposed by its geographical and temporal scale. Whereas detailed studies are available, which take into account (usually for a given river basin) several physical and human processes operating at a daily, weekly or monthly period, our global macroeconomic model is based on official national accounts, registering market transactions in a year. Since water is not formally traded in many economies, or its price is significantly distorted, it is not generally possible to ascertain the contribution of water as a production factor in the various industries. Furthermore, we are considering very large macro-regions, and the national boundaries do not overlap with river basins, nor include territories homogeneous in terms of hydrologic, climatic and physical conditions in general.

This means that we are unable to capture and realistically model the many adjustment processes occurring inside an economic system facing rising degrees of water scarcity. On the other hand, our analysis provides a much broader picture of the systemic effects of water scarcity, at a global scale, which simply cannot be offered by more detailed but narrowly focusing studies.

In order to introduce the various adjustment processes and to model the impacts of water scarcity in the economy, we therefore rely on a limited set of data, supplemented by informed guesses and specific assumptions, which are of course subject to debate. This choice was not only imposed by necessity, as we understand that adaptation behavior and policies do not necessarily follow a strictly rational economic logic.[2]

All in all, we come to the rather paradoxical outcome that our analysis, despite being based on a mathematical model providing many detailed numerical results, should be viewed as a qualitative assessment, rather than as a purely quantitative analysis. Indeed, the ultimate purpose of this study is providing an order of magnitude for the effects at play, while highlighting the complex structural adjustment mechanisms, triggered by the emerging water scarcity in some regions of the world.

5. Conclusion

Global modelling scenarios are increasingly taking into account the constraints associated with natural resources availability. This study focuses on water, pointing out that there will be an emerging issue of resource availability in some water scarce (and mostly developing) countries, which, because of this, may not be able to fully reap their economic development potential.

Adaptation to the emerging water scarcity will involve several adjustments in the consumption and production patterns, trade flows, income and welfare levels, not only in the regions and sectors initially affected by the shortage of water resources, but in all interconnected global markets and economies.

The eventual economic impact of water scarcity will depend on several factors, and a number of policy options are available to curb its negative consequences. However, no option will come without a cost (in a broad sense, including political acceptability and effort). The overall flexibility of the economic systems will be very important, as well as the introduction of technologies and processes aimed at improving water efficiency levels.

Our study also reveals that a better allocation of scarce water resources among sectors could play a pivotal role in this respect, suggesting that the issue of water scarcity is not merely a physical but also an economic problem. Accurate estimates of the economic value of water will therefore be essential for a rational allocation of scarce water across locations, uses, users, and time periods (Ward and Michelsen, 2002).

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[22] A beautiful example is provided by the analysis of water scarcity mitigation options in Israel provided by Becker, Lavee and Katz (2010), making clear that innovation in water systems also entails complicated political processes. In addition, learning and knowledge diffusion matter. For instance, rice farmers in Australia were most reluctant to trade water when water reforms first made it possible. But in the drought of 2002-03, they thought it was wonderful that they could sell water for around $300/ML when the average product of water in their production was probably under $250/ML.

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Appendix A – An assessment of future water deficits

Although this study focuses only, as an illustrative case, on the year 2050 and the SSP1 scenario, future potential water deficits were estimated for other years and another scenario (see Roson and Damania, 2017).

The assessment of the future water deficits has been based on a limited set of SSP forecasts of income and population growth, complemented by CGE simulations aimed at enlarging the number of estimated economic variables. The exercise was conducted for two years, 2050 and 2100, and for two SSPs: SSP1, termed “Sustainability”, and SSP3, termed “Regional Rivalry”. For each combination of year and SSP, growth rates in population and GDP have been assumed, using data from the IIASA SSP repository. By shocking the corresponding parameters in the GTAP CGE model (dataset 9.0), several other endogenous variables were obtained, like production volumes by industry and region, household consumption, regional investments, exports and imports, income by source, etc.

Estimates of industrial output are especially relevant because, coupled with some econometrically computed future water intensity coefficients, allow to derive the implied water demand for the years 2050 and 2100. Analogously, municipal water demand was computed by assuming it dependent on population growth, real income levels and a trend of increased water efficiency. Table A1 presents the water demand projections for the four cases (SSP1 and SSP3, 2050 and 2100).

Regional water deficits are defined as the difference between potential water demand and sustainable water supply. In turn, the latter is identified as the sum of water runoff and inflow in a region, estimated by the global hydrologic GCAM model[3], driven by three different Global Circulation Models (CCSM, GISS, FIO ESM). We found that four macro-regions have levels of potential SSP1 demand exceeding sustainable supply in the year 2050, as showed in Table 1.

[3] http://www.globalchange.umd.edu/models/gcam

Table A1

Water demand projections (potential demand consistent with SSP scenarios)

Water Demand/Usage (millions of m3)

Baseline 2004

	1 N_America	2 C_America	3 S_America	4 W_Europe	5 E_Europe	6 MENA	7 Sahel	8 C_Africa	9 S_Africa	10 C_Asia	11 E_Asia	12 S_Asia	13 SE_Asia	14 Australasia
Agriculture	1342925	437391	989677	362819	787372	557957	416269	561212	278599	205749	1722038	1730701	1111081	181193
Industrial	525908	122665	176336	171789	402989	518475	7313	51825	58207	50062	301179	116774	114517	17157
Municipal	38677	25540	17794	16250	28695	29255	2788	3263	6098	5228	80122	63757	24215	1605
Total	***1907509***	***585596***	***1183807***	***550858***	***1219055***	***1105688***	***426371***	***616301***	***342904***	***261038***	***2103339***	***1911232***	***1249813***	***199956***

2050 SSP1

	1 N_America	2 C_America	3 S_America	4 W_Europe	5 E_Europe	6 MENA	7 Sahel	8 C_Africa	9 S_Africa	10 C_Asia	11 E_Asia	12 S_Asia	13 SE_Asia	14 Australasia
Agriculture	1559385	588123	1318522	413177	1052738	772903	778729	1007786	447073	329635	2987297	2885104	1855382	245845
	16.12%	34.46%	33.23%	13.88%	33.70%	38.52%	87.07%	79.57%	60.47%	60.21%	73.47%	66.70%	66.99%	35.68%
Industrial	792478	192757	357243	266391	663366	858813	16133	111071	122626	104255	683424	265696	247127	30111
	50.69%	57.14%	102.59%	55.07%	64.61%	65.64%	120.61%	114.32%	110.67%	108.25%	126.92%	127.53%	115.80%	75.50%
Municipal	65681	58917	43636	25667	57563	82587	21770	24852	32107	23322	395664	284188	105840	3829
	69.82%	130.68%	145.23%	57.95%	100.61%	182.30%	680.80%	661.55%	426.52%	346.08%	393.83%	345.74%	337.09%	138.50%
Total	***2417544***	***839797***	***1719401***	***705235***	***1773667***	***1714303***	***816632***	***1143708***	***601806***	***457212***	***4066385***	***3434988***	***2208350***	***279785***
	26.74%	43.41%	45.24%	28.02%	45.50%	55.04%	91.53%	85.58%	75.50%	75.15%	93.33%	79.73%	76.69%	39.92%
Var. GDP	142.88%	399.98%	456.41%	157.58%	379.45%	484.67%	2160.78%	2085.80%	1341.60%	1204.73%	1426.42%	1175.79%	1151.44%	300.67%

2100 SSP1

	1 N_America	2 C_America	3 S_America	4 W_Europe	5 E_Europe	6 MENA	7 Sahel	8 C_Africa	9 S_Africa	10 C_Asia	11 E_Asia	12 S_Asia	13 SE_Asia	14 Australasia
Agriculture	1722171	647258	1441272	452170	1103106	853525	1141823	1391021	618950	355075	2803403	3392457	2150817	278135
	28.24%	47.98%	45.63%	24.63%	40.10%	52.97%	174.30%	147.86%	122.16%	72.58%	62.80%	96.02%	93.58%	53.50%
Industrial	1358138	270532	648106	453996	931435	1179132	30485	196890	245575	153096	910010	478931	414654	51020
	158.25%	120.55%	267.54%	164.28%	131.13%	127.42%	316.84%	279.91%	321.90%	205.81%	202.15%	310.14%	262.09%	197.37%
Municipal	85112	80628	54555	31871	64662	111016	105150	99913	148520	30323	301866	515882	174344	5046
	120.06%	215.69%	206.60%	96.12%	125.35%	279.47%	3671.37%	2961.71%	2335.53%	479.99%	276.76%	709.14%	619.98%	214.31%
Total	***3165421***	***998419***	***2143934***	***938037***	***2099203***	***2143673***	***1277458***	***1687824***	***1013046***	***538494***	***4015279***	***4387270***	***2739814***	***334201***
	65.95%	70.50%	81.11%	70.29%	72.20%	93.88%	199.61%	173.86%	195.43%	106.29%	90.90%	129.55%	119.22%	67.14%
Var. GDP	334.80%	897.57%	869.69%	360.11%	603.08%	1033.52%	14511.25%	11754.79%	9392.58%	2030.24%	1268.25%	2954.64%	2585.61%	624.45%

2050 SSP3

	1 N_America	2 C_America	3 S_America	4 W_Europe	5 E_Europe	6 MENA	7 Sahel	8 C_Africa	9 S_Africa	10 C_Asia	11 E_Asia	12 S_Asia	13 SE_Asia	14 Australasia
Agriculture	1477989	579230	1275649	372439	1008763	752871	680890	912700	402834	324626	2807859	2651743	1710890	218533
	10.06%	32.43%	28.90%	2.65%	28.12%	34.93%	63.57%	62.63%	44.59%	57.78%	63.05%	53.22%	53.98%	20.61%
Industrial	741811	186999	340903	235325	629419	814546	13645	97230	105442	101546	636978	239965	225081	26347
	41.05%	52.45%	93.33%	36.99%	56.19%	57.10%	86.58%	87.61%	81.15%	102.84%	111.49%	105.50%	96.55%	53.57%
Municipal	50104	60408	42074	17889	48997	76834	13234	16394	21180	21850	292449	202080	77058	2619
	29.55%	136.52%	136.45%	10.09%	70.75%	162.63%	374.67%	402.38%	247.33%	317.92%	265.00%	216.95%	218.22%	63.11%
Total	***2269904***	***826638***	***1658625***	***625654***	***1687179***	***1644251***	***707769***	***1026325***	***529457***	***448022***	***3737286***	***3093788***	***2013028***	***247499***
	19.00%	41.16%	40.11%	13.58%	38.40%	48.71%	66.00%	66.53%	54.40%	71.63%	77.68%	61.87%	61.07%	23.78%
Var. GDP	73.44%	308.59%	331.47%	49.09%	267.02%	347.84%	830.60%	955.50%	568.12%	1020.51%	953.98%	644.31%	669.92%	133.21%

2100 SSP3

	1 N_America	2 C_America	3 S_America	4 W_Europe	5 E_Europe	6 MENA	7 Sahel	8 C_Africa	9 S_Africa	10 C_Asia	11 E_Asia	12 S_Asia	13 SE_Asia	14 Australasia
Agriculture	1427763	675064	1470544	351690	1107162	878334	931441	1238007	533886	366623	2749694	3034331	1941041	216543
	6.32%	54.34%	48.59%	-3.07%	40.61%	57.42%	123.76%	120.60%	91.63%	78.19%	59.68%	75.32%	74.70%	19.51%
Industrial	1077425	273971	647666	342399	917534	1156536	23347	163255	193165	154116	876965	410323	363042	37648
	104.87%	123.35%	267.29%	99.31%	127.68%	123.06%	219.24%	215.01%	231.86%	207.85%	191.18%	251.38%	217.02%	119.43%
Municipal	43156	96488	62603	14797	62652	119883	35205	46517	56593	32252	250098	292657	108777	2261
	11.58%	277.79%	251.83%	-8.95%	118.34%	309.78%	1162.67%	1325.46%	828.05%	516.87%	212.15%	359.02%	349.21%	40.84%
Total	***2548344***	***1045523***	***2180813***	***708885***	***2087348***	***2154753***	***989992***	***1447779***	***783643***	***552990***	***3876757***	***3737312***	***2412861***	***256452***
	33.60%	78.54%	84.22%	28.69%	71.23%	94.88%	132.19%	134.91%	128.53%	111.84%	84.31%	95.54%	93.06%	28.25%
Var. GDP	82.57%	793.82%	748.21%	63.51%	494.36%	847.50%	3632.63%	4317.64%	2726.50%	1944.13%	937.64%	1293.47%	1292.11%	146.53%

Appendix B – Estimation of the marginal value and output elasticity of water

When water is regarded as a production factor, the Marginal Value of Water (MVW) is the increase in the value of output potentially obtainable when one unit of water (here, one square meter) is added to the process, while keeping all the other production factors unchanged. The concept is strictly linked to that of water pricing and allocation: (a) profit maximization and cost minimization imply that MVW should equate the price of water; (b) water (or any other resource) is efficiently allocated (from an economic viewpoint) when its marginal value is the same across alternative uses.

In principle, estimating the MVW would require specific technical information on the production processes and how water contributes to them. This is simply impossible to get for large aggregate sectors and regions. Instead, we propose here a methodology for a consistent estimation of MVW in 15 industries and 14 macro-regions, based on some available "water intensity coefficients" (WIC - water per value of output) and two calibrated parameters. WIC (indicated in the following as ω) and MVW are related but distinct concepts. Mathematically, WIC is just the ratio of water over output (in value terms), whereas MVW is the partial derivative of output value with respect to water.

The estimation procedure is based on a set of sensible assumptions one could impose on the water elasticity of output (ε). The latter is defined as the relative (percentage) variation of output (x) obtainable through a relative variation in the water input (w), ceteris paribus:

$$\varepsilon = \frac{\delta x/x}{\delta w/w} = \frac{\delta x}{\delta w}\frac{w}{x} = \frac{\delta x}{\delta w}\omega = MVW\omega \qquad \text{(B1)}$$

Consider ε to be a function of ω. Obviously, one would require that $\varepsilon(0) = 0$, because no variation in output would be observed if water is not used at all. A second sensible assumption is:

$$\lim_{\omega \to \infty} \varepsilon(\omega) = 1 \qquad \text{(B2)}$$

meaning that, as water becomes the only relevant factor (enormous amounts of water are employed), the output varies proportionally with water (constant returns to scale). A smooth function with the two properties above would then be characterized by $\varepsilon'(\omega)>0$ and $\varepsilon''(\omega)<0$: the marginal value is positive but decreasing.

One of the simplest mathematical functions that can be adopted to express $\varepsilon(\omega)$ is the powered semi-logistic one:

$$\varepsilon(\omega) = \left(\frac{\alpha\omega}{1+\alpha\omega}\right)^{\beta} \quad \omega \geq 0 \; \beta > 0 \qquad \text{(B3)}$$

By plugging (3) into (1), and solving for the MVW, a relationship linking MVW to WIC (ω) is obtained:

$$MVW = \omega^{-1}\left(\frac{\alpha\omega}{1+\alpha\omega}\right)^{\beta} \qquad \text{(B4)}$$

This allows us to infer the marginal value of water on the basis of the water intensity, once the values of a and β have been set. We calibrated the values for these parameters using some estimates by Moolman, Blignaut and van Eyden (2006), who computed the MVW for five categories of fruits in

South Africa, in the year 2002, and our own estimates of the industrial water intensity for the year 2004 (Roson and Damania, 2017). The beta parameter is calibrated by imposing that MVW equals 1.312 (simple mathematical average of the estimates by Moolman et al., cit.) when WIC (ω) is 0.01039 (our estimated value for Vegetables and Fruits in South Africa). The alpha parameter is simultaneously obtained through numerical optimization, imposing the requirement that the variance of MVW values by Moolman et al. equals the variance of MVW across South-African industries (excluding the outlier Services). The computed values are 0.637 for alpha, 0.855 for beta. Table B1 presents the corresponding MVWs.

Table B1 – Industrial MVW 2004 (US$/M^3)

	N_America	C_America	S_America	W_Europe	E_Europe	MENA	Sahel	C_Africa	S_Africa	C_Asia	E_Asia	S_Asia	SE_Asia	Australasia
Rice	1.247	1.025	1.151	1.494	1.290	1.352	1.165	1.194	1.013	0.847	1.359	1.102	1.163	1.071
Wheat	1.237	1.531	1.344	1.513	1.197	1.375	1.113	1.847	1.449	1.006	1.282	1.224	1.275	1.190
Cereals	1.278	1.303	1.267	1.489	1.267	1.357	0.998	1.375	1.181	1.085	1.238	1.158	1.356	1.165
VegFruit	1.372	1.451	1.199	1.724	1.508	1.553	1.327	1.400	1.312	1.408	1.683	1.413	1.258	1.614
Oilseeds	1.495	1.570	1.582	1.830	1.299	1.413	1.064	1.519	1.236	0.528	1.423	1.309	1.915	1.231
Sugar	1.464	1.282	1.192	1.781	1.390	1.474	1.083	1.670	1.347	1.181	1.379	1.321	1.278	1.286
Oth Crops	1.519	1.490	1.512	2.149	1.468	1.708	1.280	1.403	1.505	1.634	2.096	1.927	1.498	1.568
Oth Agr.	1.912	1.730	1.653	2.303	1.768	1.699	1.181	1.353	1.600	1.498	1.858	1.503	1.436	1.932
Extraction	1.910	1.832	2.063	2.293	1.815	1.843	1.873	1.981	1.816	1.857	2.317	2.044	2.077	2.462
P.Food	3.098	3.425	3.037	3.628	2.442	3.067	2.917	2.917	2.917	2.917	3.436	2.969	3.098	3.650
Textiles	3.036	2.883	2.944	3.472	2.417	3.141	2.719	2.719	2.719	2.719	3.452	3.188	2.975	3.181
Light Man	3.825	3.426	3.343	4.264	2.914	3.158	3.076	3.076	3.076	3.076	3.396	2.655	3.271	4.113
Heavy M.	3.481	3.211	3.027	3.908	2.782	2.845	2.793	2.793	2.793	2.793	3.167	2.591	2.926	3.648
Utilities	2.126	2.040	1.739	2.370	2.059	1.922	1.871	1.871	1.871	1.871	2.243	1.999	1.916	2.293
Services	19.508	18.617	19.970	27.501	19.657	18.041	17.410	17.410	17.410	17.410	25.398	19.973	17.921	25.188

Notice that, the higher the *average* productivity of water (value of output per m^3, the inverse of the WIC), the higher the *marginal* value of water. In this respect, allocating water resources on the basis of the relative industrial water productivity (as it is done in the DRES scenario) is conceptually equivalent to allocating water on the basis of the relative marginal values.

The output elasticity of water is the percentage increase in gross production volumes obtained through higher water utilization. If no adjustment takes place in the production processes and in the use of other factors, then the elasticity is just the product of MVW and WIC. To get more meaningful effects when water availability is varied, we allow in this study some implicit adjustment in complementary factors, by expressing the output elasticity of water (η) as a linear function of the product (ε):

$$\eta = \gamma + \delta\varepsilon \qquad \text{(B5)}$$

where the γ and δ parameter values are set so that the average elasticity is 0.8 and the standard deviation is 0.2. Table B2 shows the elasticities obtained in this way.

Table B2 – Industrial output elasticity of water

	N_Amer	C_Amer	S_Amer	W_Euro	E_Europe	MENA	Sahel	C_Africa	S_Africa	C_Asia	E_Asia	S_Asia	SE_Asia	Austral
Rice	0.9292	1.3853	1.0672	0.7654	0.8851	0.8360	1.0426	0.9968	1.4232	2.2836	0.8316	1.1668	1.0468	1.2464
Wheat	0.9397	0.7534	0.8415	0.7593	0.9933	0.8211	1.1435	0.7009	0.7833	1.4489	0.8925	0.9562	0.8995	1.0026
Cereals	0.8958	0.8737	0.9067	0.7672	0.9068	0.8325	1.4817	0.8215	1.0160	1.2093	0.9392	1.0540	0.8331	1.0428
VegFruit	0.8233	0.7822	0.9902	0.7140	0.7609	0.7474	0.8540	0.8070	0.8657	0.8028	0.7201	0.7998	0.9166	0.7326
Oilseeds	0.7653	0.7429	0.7398	0.7024	0.8768	0.8001	1.2655	0.7572	0.9419	1.6063	0.7950	0.8686	0.6958	0.9469
Sugar	0.7769	0.8922	0.9996	0.7072	0.8123	0.7730	1.2149	0.7221	0.8396	1.0168	0.8191	0.8589	0.8963	0.8886
OthCrop	0.7572	0.7670	0.7595	0.6853	0.7752	0.7163	0.8939	0.8055	0.7617	0.7287	0.6870	0.6951	0.7641	0.7433
Oth Agr.	0.6961	0.7132	0.7251	0.6816	0.7087	0.7176	1.0160	0.8352	0.7357	0.7641	0.7000	0.7624	0.7887	0.6948
Extr	0.6962	0.7022	0.6883	0.6818	0.7037	0.7012	0.6988	0.6920	0.7037	0.7001	0.6814	0.6890	0.6877	0.6793
P.Food	0.6757	0.6751	0.6758	0.6749	0.6795	0.6757	0.6762	0.6762	0.6762	0.6762	0.6751	0.6760	0.6757	0.6749
Textiles	0.6758	0.6763	0.6761	0.6750	0.6799	0.6756	0.6771	0.6771	0.6771	0.6771	0.6751	0.6755	0.6760	0.6755
Light M	0.6748	0.6751	0.6752	0.6746	0.6762	0.6755	0.6757	0.6757	0.6757	0.6757	0.6751	0.6775	0.6753	0.6746
Heavy M	0.6750	0.6754	0.6758	0.6747	0.6768	0.6765	0.6767	0.6767	0.6767	0.6767	0.6755	0.6780	0.6762	0.6749
Utilities	0.6860	0.6892	0.7122	0.6805	0.6884	0.6954	0.6990	0.6990	0.6990	0.6990	0.6829	0.6911	0.6958	0.6818
Constr	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TraspCo	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Serv	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Appendix C – The construction of regionally differentiated impact scenarios

Simulations under the DRES and DRUS scenarios are based on the assumptions that regions, in which potential demand for water exceeds sustainable supply, differ in their capability of absorbing the excess demand (water deficit). The absorption percentages applied in the various cases are based on a mixed qualitative-quantitative analysis of the relevant characteristics, where we keep distinct the potential of technological innovation from the degree of flexibility in the economic structure and trade flows.

Looking first at the innovation side, notice that a number of technologies and management options can be put in place to improve the water efficiency (lowering demand) and/or expanding the water supply. Theoretically, the different options could be ranked in terms of economic efficiency, from the lowest to the highest unit cost, and those whose unit cost (possibly including externalities) falls below the shadow value of water (increasing as the water gets scarcer) should be selected (WRG, 2009). In practice, however, the technological response to the water stress is much more complicated, as a variety of factors (technical, political, institutional, safety, etc.) ultimately affects the choice among the different technology options (Becker, Lavee and Katz, 2010).

We therefore rely on a qualitative index of technology potential for each of the potentially water stressed macro-regions, based on a subjective evaluation of several options and characteristics. Because of the subjective and qualitative nature of this index, the latter should be interpreted as expressing an informed scenario, rather than as a solid scientific appraisal of (future) technical capability in the regions.

We consider three important classes of technology or management options:

1. Desalination
2. Enhanced irrigation techniques and reduced evaporation
3. Water reuse

For each of them, we identify five “facilitating factors”, possibly making the implementation of each option more likely:

1. Physical conditions (e.g., desalination projects will be more effective if most of the urban centres are found along the coast)
2. Factor availability (e.g., access to energy sources for desalination)
3. Institutional capacity (efficient level of government, quality of public institutions)
4. Human and physical capital (relevant for large and complex projects)
5. Demand potential (e.g., enhanced irrigation is primarily targeted to agriculture, therefore its effectiveness depends on the share of agricultural water on total water consumption)

We assign to each factor in each region and for all the three alternatives above a simple scoring system: 1 (poor), 2 (average), 3 (good). A “Technology Potential Index” (Table C1) is quite naturally obtained by simply adding up all the given points. The higher this index, the easier is the expected capability of a region to adjust to water deficits through the introduction of new technologies and more efficient management techniques.

Table C1 – Regional Technology Potential Index

MENA	Sahel	C_Asia	E_Asia	S_Asia
31	28	30	35	31

A second adjustment mechanism is related to the endogenous changes in the regional economic structure. Indeed, when actual water availability turns out to be lower than what would be required for production and consumption purposes, the consumers' utility diminishes and the productivity in water-using industries declines. Even in the absence of a formal market for water resources, scarcity is transmitted as a price signal, and a structural adjustment takes place in the economic system, alleviating the overall impact of the negative shock for the economy. What is maybe less known is that the same process leads to an improvement in the aggregate water efficiency or productivity (water per unit of output), whose magnitude – however – depends on a series of specific characteristics of the economic system under consideration.

Many factors contribute in determining the structural flexibility, and it is not easy to ascertain what economies could respond better and why. To shed some light on this issue, we performed a simple numerical experiment with the global general equilibrium model. In each of the potentially water stressed macro-regions, we simulated a -10% reduction in multi-factor productivity in agriculture, which is the sector where most of the water is utilized. The consequent drop in total agricultural output volume is shown in Table C2.

Table C2 – Agricultural output change

Region	**Var.**
MENA	-8.71%
Sahel	-7.80%
Central Asia	-12.20%
East Asia	-4.22%
South Asia	-5.15%

A CGE model cannot capture all the factors and characteristics affecting the actual degree of flexibility in a certain economy. Nonetheless, a simple experiment like the one above can offer an order of magnitude, or at least can suggest a ranking of the regional economies from the most rigid one (Central Asia) to the most flexible one (East Asia), in terms of absorption of productivity shocks in agriculture, possibly induced by water scarcity.

We combine the ranking provided by Tables C1 and C2 to split the absorption of the excess water demand in the three components: internal structural adjustment, technical and management solutions, and reduction in water delivery. The latter component, which is obtained as a residual, determines the amount of decrease in water delivery (with effects on productivity) in the scenarios DRUS and DRES.

Table C3 – Decomposition of excess water demand absorption

	MENA	Sahel	C_Asia	E_Asia	S_Asia
Internal alloc.	0.42	0.44	0.36	0.52	0.5
Tech solutions	0.32	0.26	0.3	0.4	0.32
Water cuts	0.26	0.3	0.34	0.08	0.18