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Water, Poverty, and the Economy

Simulating the Macroeconomic Impact of Future Water Scarcity

Roberto Roson

WORLD BANK GROUP

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Roberto Roson

WORLD BANK GROUP

1818 H Street NW, Washington, DC 20433
Telephone: 202-473-1000; Internet: www.worldbank.org

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Abstract

This paper considers some of the economic implications of climate change scenarios as described in the Shared Socioeconomic Pathways (SSPs). By comparing potential water demand with estimates of (sustainable) water availability in different regions, it identifies regions whose future economic growth potential is likely to be constrained by the scarcity of water resources. The paper assesses the macroeconomic impact of water scarcity under alternative allocation rules, finding that constrained regions can effectively neutralize water-related climate risks and adapt to a changing water environment by assigning more water to sectors in which it has a higher value, shifting production to less water-intensive sectors, and importing more water-intensive goods. However, this adaptation effort is likely to imply some radical changes in water management policies.

Introduction

This paper assesses the macroeconomic implications of possible future water scarcity. In order to do so, the sustainability of a number of economic growth scenarios in terms of water resources are considered. The analysis is based on a comparison between potential demand for water and estimated water availability.

Water supply is calculated using the Global Change Assessment Model (GCAM).[1] Three different climatic Global Circulation Models (GCMs) were used as inputs—CCSM, FIO, and GISS—to feed the complex hydrologic model.[2] The main output of this model is an estimate of runoffs and water inflows for many regions in the world.

In this study, sustainable (renewable) water supply is defined as the total yearly runoff (where necessary, increased by water inflow) within a given region, and scenarios are considered in which this is the only available source of water. Therefore, the possible exploitation of nonrenewable water resources (such as so-called "fossil water") is implicitly ruled out, whereas the adoption of unconventional water supply means (desalination, recycling, harvesting) is indirectly accounted for as improvements in water efficiency (defined as fresh water needed per unit of economic activity).

Because demand for water is mostly an indirect demand, depending on the level of economic activity and income, a global general equilibrium model is used to conduct simulation experiments aimed at assessing changes in economic structure and trade flows, from which the demand for water is obtained.

The economic model considers 14 macro-regions:

1. North America
2. Central America
3. South America
4. Western Europe
5. Eastern Europe
6. Middle East and North Africa
7. Sahel
8. Central Africa
9. Southern Africa
10. Central Asia
11. Eastern Asia
12. South Asia
13. Southeast Asia
14. Australasia[3]

In each region, the model considers the household sector, as well as the following 20 industries:

1. Rice
2. Wheat
3. Cereals
4. Vegetables and fruits
5. Oil seeds
6. Sugar

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7. Fibers
8. Other crops
9. Meat
10. Extraction
11. Processed food
12. Textiles
13. Light manufacturing
14. Heavy manufacturing
15. Electricity
16. Gas
17. Water services
18. Construction
19. Transport and communication
20. Other Services

The analysis shows that although economic growth occurs in all regions, there is significant divergence in future income per capita between scenarios where regions cooperate to mitigate the effects of climate change on water versus scenarios where they take a short-term outlook.

This exercise is conducted for two future reference years, 2050 and 2100, but policy analysis focuses only on 2050. Two Shared Socioeconomic Pathways[4] (SSP; Kriegler et al., 2012) were chosen to represent two plausible, but distinct future economic reference pathways: SSP1, termed *Sustainability*, and SSP3, termed *Regional Rivalry*. 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."[5] By contrast, SSP3 is characterized by the following narrative: "Unmitigated emissions are high due to moderate economic growth, a rapidly growing population, and slow technological change in the energy sector, making mitigation difficult. Investments in human capital are low, inequality is high, a regionalized world leads to reduced trade flows, and institutional development is unfavorable, leaving large numbers of people vulnerable to climate change and many parts of the world with low adaptive capacity."

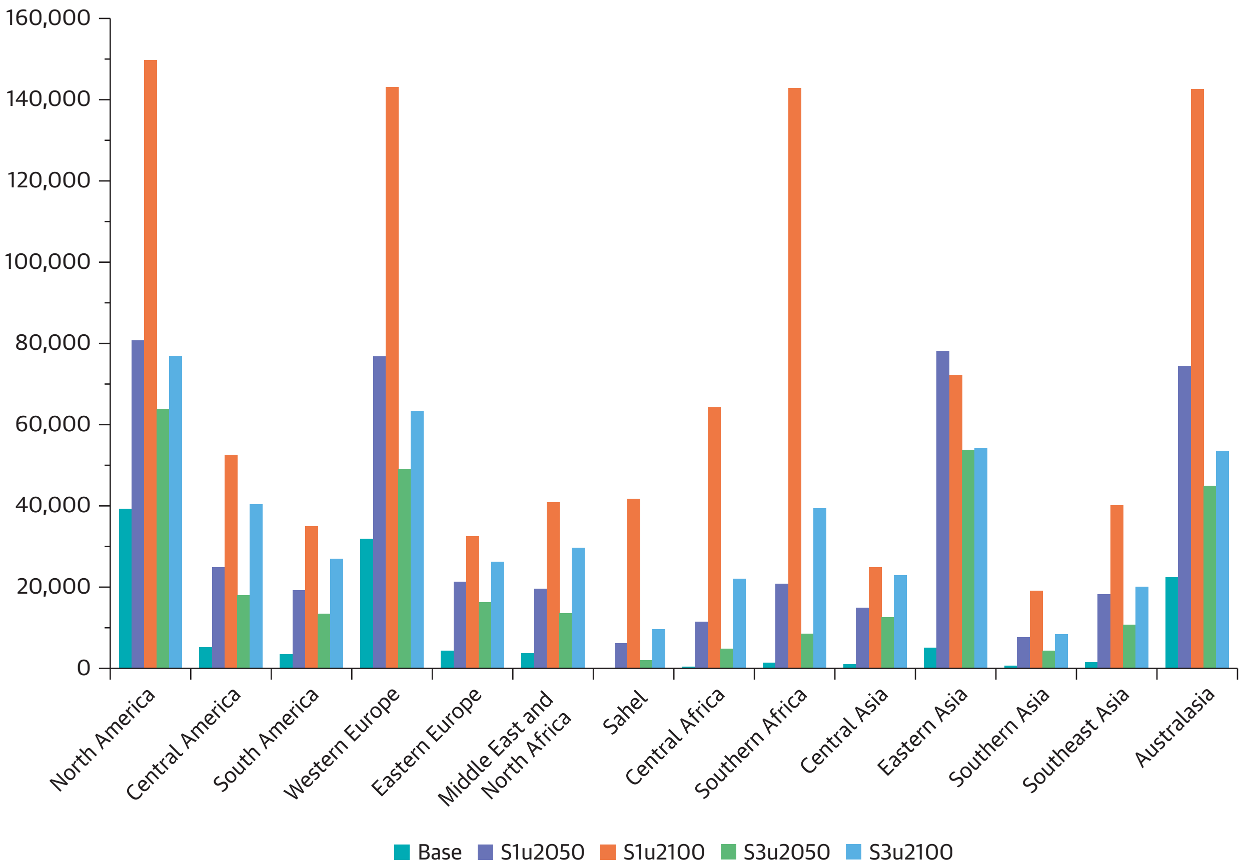
Effects of Water Demand and Water Supply on Economic Growth

The levels of income per capita (real GDP) in each of the 14 macro-regions considered are depicted in figure 1, in the base year at which parameters of the model are calibrated (2004) and in the four scenarios (SSP1 and SSP3, 2050 and 2100). The figure helps highlight the salient features of the four cases. SSP1/2050 (s1u2050) is characterized by dramatic income growth in East Asia, but also Australasia, where income levels rise to those similar to in North America and Europe. In SSP1/2100 (s1u2100), growth rates are very high all over the world. South Africa is the fastest growing region, whereas income per capita declines in East Asia with respect to 2050. SSP3/2050 (s3u2050) is characterized by a dual world, where developed regions (North America and Western Europe) experience limited growth, but developing regions (most notably East Asia) grow fast. In SSP3/2100 (s3u2100), income distribution is more balanced. North America and Western Europe slow down further after 2050 and East Asia stops growing altogether, whereas Africa and the Middle East accelerate.

Water demand projections are based on water-intensity coefficients: that is, water per unit of output. These are obtained as ratios between sectoral water usage and output in the base calibration year. In turn, sectoral consumption has been estimated by elaborating information from various sources: the WIOD project (Dietzenbacher et al. 2013; Mekonnen and Hoekstra 2011), the European research project WASSERMed (Mielke, Diaz Anadon, and Narayanamurti 2010; Roson and Sartori 2015), and the U.S. Energy Information Administration (2015).[6]

Water-intensity coefficients can be used in principle, to translate the results of any simulation with the numerical economic model (for example, industrial output volumes) in terms of water demand. However, it is necessary to take into consideration that water usage per unit of production (or consumption) does vary over time.

FIGURE 1. **Per Capita Income in the 14 Regions under Four Scenarios, 2050 and 2100 (2005 US$)**



Note: s1u = Sustainability Shared Socioeconomic Pathway; s3u = Regional Rivalry Shared Socioeconomic Pathway.

In this study, it is assumed that efficiency gains are endogenous and dependent on production growth. Specifically, it is assumed that only a fraction *d* of the increase in industrial production volumes in a country, from *q'* to *q"*, translates into higher water consumption *w"*, as specified in the following equation:

$$w'' = i\,[q' + d\,(q'' - q')] = i\,[(1 - d)\,q' + dq''],$$

where *i* is the relevant baseline water-intensity coefficient (water per unit of production), and the value of 0.5, or 50 percent, is assumed for the *d* parameter. Further improvements in water efficiency are posited whenever potential water demand exceeds water availability, as will be better explained in the next section. To guard against exaggerating impacts, the assumptions about technology change err on the side of optimism.

By 2100, excess water demand will exist in nearly every region of the world—with the exceptions of North and South America and Europe—implying that growth expectations for the 21st century will likely not be met if the current water regime persists.

Table 1 shows the crude first stage results obtained for potential water demand (consumption of water resources), which simply mirror the economic growth scenario, and are not affected by any water supply constraint.

TABLE 1. Projections of Sectoral Water Demand

Water demand/usage (millions of m³) and percent

	1 North America	2 Central America	3 South America	4 Western Europe	5 Eastern Europe	6 Middle East and North Africa	7 Sahel	8 Central Africa	9 Southern Africa	10 Central Asia	11 Eastern Asia	12 South Asia	13 Southeast Asia	14 Australasia
Baseline 2004														
Agriculture	1,320,159	462,666	956,679	360,114	838,905	533,776	345,160	496,424	276,015	192,685	1,341,460	1,684,088	1,042,806	182,646
Industrial	509,594	123,345	172,642	172,151	363,591	508,932	6,400	51,398	57,925	48,604	301,802	111,472	111,377	17,777
Municipal	38,677	25,540	17,794	16,250	28,695	29,255	2,788	3,263	6,098	5,228	80,122	63,757	24,215	1,605
Total	**1,868,430**	**611,551**	**1,147,115**	**548,516**	**1,231,191**	**1,071,963**	**354,348**	**551,084**	**340,038**	**246,517**	**1,723,384**	**1,859,318**	**1,178,398**	**202,028**
2050 SSP1														
Agriculture	1,955,926	990,699	2,198,107	468,565	1,828,737	1,280,867	2,737,204	3,083,502	1,051,455	798,891	8,549,132	8,030,985	5,367,159	421,624
	48.16%	114.13%	129.76%	30.12%	117.99%	139.96%	693.02%	521.14%	280.94%	314.61%	537.30%	376.87%	414.68%	130.84%
Industrial	700,836	288,666	497,493	238,685	947,801	1,659,859	86,803	604,495	397,279	344,408	2,443,783	751,185	730,931	38,737
	37.53%	134.03%	188.16%	38.65%	160.68%	226.15%	1256.32%	1076.12%	585.85%	608.60%	709.73%	573.87%	556.27%	117.91%
Municipal	65,660	59,006	43,494	25,683	57,253	82,789	21,782	24,977	32,240	23,383	395,768	285,798	105,966	3,831
	69.77%	131.03%	144.43%	58.04%	99.53%	182.99%	681.26%	665.38%	428.69%	347.24%	393.96%	348.26%	337.60%	138.67%
Total	**2,722,422**	**1,338,371**	**2,739,094**	**732,932**	**2,833,791**	**3,023,515**	**2,845,790**	**3,712,974**	**1,480,974**	**1,166,681**	**11,388,684**	**9,067,968**	**6,204,056**	**464,193**
	45.71%	118.85%	138.78%	33.62%	130.17%	182.05%	703.11%	573.76%	335.53%	373.27%	560.83%	387.70%	426.48%	129.77%
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														
Agriculture	2,576,822	1,347,124	2,941,365	606,135	2,097,823	1,779,373	13,481,650	10,712,068	3,529,485	1,014,491	6,732,773	14,165,877	9,119,300	620,023
	95.19%	191.17%	207.46%	68.32%	150.07%	233.36%	3805.91%	2057.85%	1178.73%	426.50%	401.90%	741.16%	774.50%	239.47%
Industrial	970,751	426,260	730,056	329,211	1,174,845	2,642,777	602,869	3,161,105	2,038,592	532,039	2,017,938	1,685,731	1,459,962	56,300
	90.49%	245.58%	322.87%	91.23%	223.12%	419.28%	9319.96%	6050.29%	3419.34%	994.65%	568.63%	1412.24%	1210.83%	216.71%
Municipal	85,075	80,685	54,438	31,884	63,922	111,587	103,995	100,349	149,064	30,498	301,933	521,091	174,747	5,049
	119.97%	215.91%	205.94%	96.21%	122.77%	281.42%	3629.95%	2975.05%	2344.44%	483.34%	276.84%	717.31%	621.64%	214.52%
Total	**3,632,648**	**1,854,068**	**3,725,858**	**967,231**	**3,336,589**	**4,533,736**	**14,188,515**	**13,973,522**	**5,717,141**	**1,577,028**	**9,052,644**	**16,372,699**	**10,754,008**	**681,373**
	94.42%	203.17%	224.80%	76.34%	171.01%	322.94%	3904.12%	2435.64%	1581.32%	539.72%	425.28%	780.58%	812.60%	237.27%
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%

	1 North America	2 Central America	3 South America	4 Western Europe	5 Eastern Europe	6 Middle East and North Africa;	7 Sahel	8 Central Africa	9 Southern Africa	10 Central Asia	11 Eastern Asia	12 South Asia	13 Southeast Asia	14 Australasia
2050 SSP3														
Agriculture	1,675,704	950,289	1,951,556	366,545	1,587,041	1,169,091	1,472,979	2,038,368	720,910	749,425	6,372,489	5,644,760	3,763,355	287,768
	26.93%	105.39%	103.99%	1.79%	89.18%	119.02%	326.75%	310.61%	161.19%	288.94%	375.04%	235.18%	260.89%	57.56%
Industrial	594,637	263,415	416,307	178,118	785,532	1,351,739	34,718	298,378	197,637	301,477	1,732,473	467,757	473,415	25,737
	16.69%	113.56%	141.14%	3.47%	116.05%	165.60%	442.47%	480.53%	241.19%	520.28%	474.04%	319.62%	325.06%	44.78%
Municipal	50,095	60,480	41,939	17,899	48,770	76,964	13,269	16,463	21,253	21,887	292,409	202,855	77,095	2,620
	29.52%	136.80%	135.69%	10.15%	69.96%	163.08%	375.93%	404.50%	248.51%	318.62%	264.96%	218.17%	218.38%	63.22%
Total	**2,320,436**	**1,274,184**	**2,409,802**	**562,563**	**2,421,343**	**2,597,794**	**1,520,967**	**2,353,210**	**939,799**	**1,072,788**	**8,397,372**	**6,315,372**	**4,313,866**	**316,126**
	24.19%	108.35%	110.08%	2.56%	96.67%	142.34%	329.23%	327.01%	176.38%	335.18%	387.26%	239.66%	266.08%	56.48%
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														
Agriculture	1,579,208	1,583,227	3,064,792	330,349	2,087,559	1,946,611	4,700,938	6,177,767	1,896,506	1,129,303	5,884,684	8,798,887	5,769,197	281,219
	19.62%	242.20%	220.36%	−8.27%	148.84%	264.69%	1261.96%	1144.46%	587.10%	486.09%	338.68%	422.47%	453.24%	53.97%
Industrial	541,553	444,730	707,642	164,499	1,088,114	2,402,876	136,372	1,186,300	641,149	522,309	1,615,993	822,991	789,906	22,389
	6.27%	260.56%	309.89%	−4.45%	199.27%	372.14%	2030.84%	2208.08%	1006.85%	974.63%	435.45%	638.29%	609.22%	25.94%
Municipal	43,144	96,541	62,444	14,809	62,063	120,288	35,161	46,656	56,783	32,374	250,046	294,545	108,890	2,263
	11.55%	278.00%	250.93%	−8.87%	116.29%	311.17%	1161.10%	1329.70%	831.16%	519.22%	212.08%	361.98%	349.68%	40.94%
Total	**2,163,905**	**2,124,498**	**3,834,878**	**509,657**	**3,237,736**	**4,469,776**	**4,872,471**	**7,410,723**	**2,594,439**	**1,683,986**	**7,750,723**	**9,916,423**	**6,667,992**	**305,870**
	15.81%	247.40%	234.31%	−7.08%	162.98%	316.97%	1275.05%	1244.75%	662.98%	583.11%	349.74%	433.34%	465.85%	51.40%
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%

Note: Water use/demand is measured in millions of m3. Data in percent refers to changes w.r.t. baseline. SSP = Shared Socioeconomic Pathways; SSP1 = sustainability scenario; SSP3 = regional rivalry scenario; var. GDP = variation in gross domestic product.

To estimate the regional "sustainable water supply," results from the GCAM hydrologic model have been used. Water supply in each macro-region is expressed as the sum of yearly runoffs of all countries belonging to the region, averaged for three GCMs climate scenarios. Results are summarized in table 2.

Observe that regional water availability is not expected to change dramatically during the 21st century, whereas (potential) water demand would necessarily follow the underlying assumptions of baseline GDP and population. The emerging regional gap between potential demand and actual "sustainable" water supply is highlighted in tables 3 (SSP1) and 4 (SSP3).

Water consumption in the Middle East—and, to a lesser extent, in South Asia (India and neighboring countries)—already exceeds "sustainable" water consumption in these scenarios. This suggests that in these regions, nonrenewable water resources would need to be exploited, which might include unsustainable abstraction of groundwater.

However, in 2050 and 2100, water resources become insufficient in several other regions, all located in Africa and Asia. This implies that for those regions, the strong economic development scenarios are incompatible with the estimated availability of water resources. Equivalently, the analysis highlights that water (or water scarcity) has been neglected in the definition of the Shared Socioeconomic Pathways, suggesting a potential inconsistency.

Policy Scenarios

How can the emerging water demand gap be accommodated in the water-constrained regions? Three complementary ways are envisaged:

- If water is a nonsubstitutable production factor, production should fall in all water-consuming industries by the same percentage of the excess demand gap. Tables 3 and 4 indicate that this gap is generally large, which would imply dramatic and unrealistic drops in production levels. Water is a

TABLE 2. Water Supply Data
billions of m³

Region	Average total runoff			Standard deviation[a]		
	2005	2050	2100	2005	2050	2100
1 North America	5,455	5,252	5,304	210	159	206
2 Central America	2,022	1,971	1,544	111	127	354
3 South America	8,101	8,186	8,519	472	325	1,199
4 Western Europe	1,434	1,456	1,463	19	56	18
5 Eastern Europe	5,797	5,088	5,059	39	123	190
6 Middle East	499	393	362	36	36	28
7 Sahel	1,129	947	953	71	57	79
8 Central Africa	2,642	2,336	2,544	170	69	40
9 Southern Africa	1,275	1,396	1,345	101	210	205
10 Central Asia	532	437	414	76	31	38
11 Eastern Asia	2,539	2,320	2,282	83	115	34
12 S_Asia	1,698	1,711	1,792	240	86	188
13 Southeast Asia	4,822	5,367	5,373	345	225	423
14 Australasia	1,027	1,067	1,085	198	114	20

a. Standard deviation refers to variability among the three reference GSM climate scenarios used for the estimates.

substitutable production factor (in limited ways), so this represents the worst case that is unlikely to prevail. However, at least some part of the demand gap (in this exercise, one-quarter is assumed) translates into production cuts—or, in economics jargon, into reductions of multifactor productivity.

- As water becomes a scarcer resource, its explicit market price or its shadow cost would rise, reducing the relative competitiveness of water-intensive activities. Within each industry in the large macro-regions, activities would then be reallocated in time and space (by specific policies or by market forces), and more efficient water techniques would be adopted. These mechanisms end up reducing the industrial water-intensity coefficients by increasing overall water efficiency. It is assumed here that this effect can cover three-quarters of the demand gap. (Other parameter values have also been used to test robustness, but for brevity are not discussed here.)

- In addition to efficiency-improving reallocations *within* industries, water would be reallocated *between* industries. This either requires establishing water markets or specific policies at the national or regional level. The inverse of the water-intensity coefficient is the value of production per unit of water: that is, the water industrial productivity. Recognizing that perfect reallocations are improbable and unrealistic, policy scenarios are explored in which the cut in water consumption levels is not applied uniformly across all industries, but smaller reductions are applied where water is relatively more valuable (and vice versa). Three cases are discussed here: (1) no water reallocation between industries [NO-WR]; (2) mild [MILD]; and (3) strong [STRONG] water reallocation.

Under business-as-usual scenarios, future global water supply is insufficient to keep up with future global water demand. Nevertheless, smart policies, coupled with increases in water use efficiency, can prevent production shortfalls and avoid reductions of growth in most regions.

TABLE 3. Water Demand Projections for the Sustainability Scenario (SSP1) and Percentage Excess Demand
(billions of m^3)

Region	SSP1			Gap (percent)		
	2005	2050	2100	2005	2050	2100
1 North America	1,868	2,722	3,633	0.0	0.0	0.0
2 Central America	612	1,338	1,854	0.0	0.0	−16.7
3 South America	1,147	2,739	3,726	0.0	0.0	0.0
4 Western Europe	549	733	967	0.0	0.0	0.0
5 Eastern Europe	1,231	2,834	3,337	0.0	0.0	0.0
6 Middle East	1,072	3,024	4,534	−53.5	−87.0	−92.0
7 Sahel	354	2,846	14,189	0.0	−66.7	−93.3
8 Central Africa	551	3,713	13,974	0.0	−37.1	−81.8
9 Southern Africa	340	1,481	5,717	0.0	−5.8	−76.5
10 Central Asia	247	1,167	1,577	0.0	−62.5	−73.8
11 Eastern Asia	1,723	11,389	9,053	0.0	−79.6	−74.8
12 S_Asia	1,859	9,068	16,373	−8.7	−81.1	−89.1
13 Southeast Asia	1,178	6,204	10,754	0.0	−13.5	−50.0
14 Australasia	202	464	681	0.0	0.0	0.0

Note: SSP1 = sustainability scenario. Gap = the emerging regional gap between potential demand and actual “sustainable” water supply.

TABLE 4. Water Demand Projections for the Regional Rivalry Scenario (SSP3) and Percentage Excess Demand
billions of m^3

Region	SSP3			Gap (percent)		
	2005	2050	2100	2005	2050	2100
1 North America	1,868	2,320	2,164	0.0	0.0	0.0
2 Central America	612	1,274	2,124	0.0	0.0	−27.3
3 South America	1,147	2,410	3,835	0.0	0.0	0.0
4 Western Europe	549	563	510	0.0	0.0	0.0
5 Eastern Europe	1,231	2,421	3,238	0.0	0.0	0.0
6 Middle East	1,072	2,598	4,470	−53.5	−84.9	−91.9
7 Sahel	354	1,521	4,872	0.0	−37.7	−80.4
8 Central Africa	551	2,353	7,411	0.0	−0.8	−65.7
9 Southern Africa	340	940	2,594	0.0	0.0	−48.2
10 Central Asia	247	1,073	1,684	0.0	−59.2	−75.4
11 Eastern Asia	1,723	8,397	7,751	0.0	−72.4	−70.6
12 S_Asia	1,859	6,315	9,916	−8.7	−72.9	−81.9
13 Southeast Asia	1,178	4,314	6,668	0.0	0.0	−19.4
14 Australasia	202	316	306	0.0	0.0	0.0

Note: SSP3 = regional rivalry scenario. Gap = the emerging regional gap between potential demand and actual “sustainable” water supply.

Table 5 (SSP1) and Table 6 (SSP3) present estimates of variations in real GDP, for all macro-regions and for the world as a whole, under the three policy scenarios NO-WR, MILD, and STRONG, relative to the 2050 baseline of unconstrained economic growth.

Without reallocation of water resources among sectors, water scarcity imposes a reduction to the world real GDP of −0.37 percent in the SSP1 and −0.49 percent in the SSP3. However, there are large disparities across regions, with a large drop in income for some regions, but small gains in some other regions (such as Central America) due to improved terms of trade and relative competitiveness. In monetary terms, the global welfare impact of water scarcity (equivalent variation) amounts to $762 billion for SSP1 and $712 billion for SSP3, with most of the burden concentrated in East Asia (around 62 percent of the total) and the Middle East (23 percent).

A complete different picture emerges when some redistribution of water resources across sectors is allowed.

TABLE 5. Percentage Variation in Real GDP (SSP1/2050)

Region	NO-WR	MILD	STRONG
1 North America	−0.02	−0.02	0
2 Central America	0.07	0.08	0.14
3 South America	−0.04	−0.02	0.01
4 Western Europe	−0.02	−0.02	−0.01
5 Eastern Europe	0.1	0.08	0.05
6 Middle East	−14	−8.93	−6.02
7 Sahel	−11.7	−10.67	−0.82
8 Central Africa	−7.08	−5.52	−3.09
9 Southern Africa	−0.75	−0.42	0.17
10 Central Asia	−10.72	−7.47	11.5
11 Eastern Asia	−7.05	−3.75	3.32
12 S_Asia	−10.1	−7	1.44
13 Southeast Asia	−1.98	−1.12	1.46
14 Australasia	−0.05	−0.02	0.04
WORLD	−0.37	−0.21	0.08

Note: SSP1 = sustainability scenario; NO-WR = no interindustrial water reallocation.

TABLE 6. Percentage Variation in Real GDP (SSP3/2050)

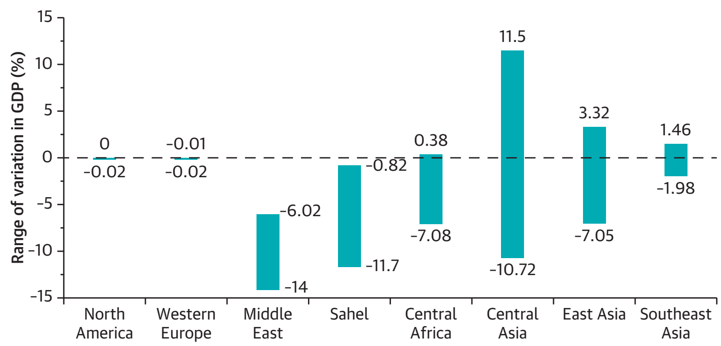
Region	NO-WR	MILD	STRONG
1 North America	−0.02	−0.01	0
2 Central America	0.08	0.09	0.15
3 South America	−0.02	−0.01	0.02
4 Western Europe	−0.01	−0.01	−0.01
5 Eastern Europe	0.07	0.05	0.03
6 Middle East	−13.96	−8.95	−6.21
7 Sahel	−7.21	−6.7	−0.98
8 Central Africa	0.18	0.21	0.38
9 Southern Africa	−0.07	−0.01	0.09
10 Central Asia	−10.3	−7.19	10.98
11 Eastern Asia	−6.44	−3.43	2.95
12 S_Asia	−9.33	−6.51	1.03
13 Southeast Asia	−0.06	−0.04	0.03
14 Australasia	−0.03	−0.01	0.04
WORLD	−0.49	−0.28	0.09

Note: SSP3 = regional rivalry scenario; NO-WR = no interindustrial water reallocation.

Industrial water reallocations are guided by an equation where an elasticity parameter (with values set at 0, 0.1, 0.25 for the three policy scenarios) determines the sensitivity to the relative water productivity. With a limited reallocation of water (MILD), the reduction of global GDP is reduced by 42 percent in both scenarios, whereas regional reductions range from −22 percent to −67 percent.

Furthermore, when the water reallocation is more pronounced (STRONG), it turns out that global real GDP increases. The same applies to regional GDP in many water-constrained regions, although GDP losses are still observed where the water demand gap is very large (as in the Middle East). This is because, with a sufficiently high value for the elasticity parameter, some industries (where water is more valuable) get cuts in water endowments that are more than compensated by improvements in water efficiency, ultimately increasing total

FIGURE 2. Range of Variation in Global GDP in 2050 under SSP1 and SSP3, and at Three Different Policy Levels



productivity. In monetary terms, the welfare equivalent cost of water scarcity becomes a *gain*, of \$214 billion for SSP1 and \$165 billion for SSP3.

This “reversal effect” shown most clearly in figure 2, which displays the range of the effect of water scarcity on global growth, for all four scenarios. The lower bounds in this figure come from the SSP1, no water reallocation [NO-WR] scenario for all regions. The upper bound is from SSP1, strong water reallocation for all regions except for Central Africa, where SSP3, strong water reallocation leads to better growth. However, regardless of which SSP is chosen, the difference between the two policy scenarios can be dramatic in some regions, most notably in Central Asia (which experiences a net increase of GDP of around +22.2 percent from moving from no water reallocation to strong water reallocation). This is due to a combination of factors. First, a region may be characterized by large differences in the industrial water productivity, so that when the allocation scheme becomes more sensitive to productivity differentials, significant variations in water endowments and, consequently, on the overall factor productivity will follow (see table 7). Second, the net aggregate effect also depends on how significant the “winning industries” are in the regional economic structure. For example, in Central Asia when Extraction, Light Manufacturing, Transport, and Communication are allowed to use more water (despite reductions in total regional water consumption), this vastly improves overall industrial productivity. Furthermore, these sectors are already relatively large in the structure of the Central Asian economy, making their impact on regional GDP substantial.

Projected Water Allocations among Industries

Simulations show that with strong water reallocation, water scarcity will lead to a large reduction in agricultural production in water scarce regions, where production will shift to the less intensive manufacturing sector.

To examine water allocations from one industry to another, simulations with the Computable General Equilibrium (CGE) model entail shocking industrial productivity parameters, in a way that is consistent with the underlying hypotheses of water availability and water intensity in each sector. The model computes a counterfactual equilibrium for the world economy and provides a rich set of output in terms of: production and consumption volumes, investments, relative prices, trade flows, and many other economic variables. See box 1 for a more thorough description of the CGE model.

It is not possible to illustrate in detail all the findings of the different simulation exercises in this brief paper. Rather, to show how the economic structure is typically affected, some results for the SSP1/2050 scenario with STRONG water reallocation between industries are described next.

By shifting production to less water-intensive sectors, and importing more water-intensive goods, water scarce regions can adapt to a changing water environment

Table 7 shows how the multi-factor productivity changes in the water-consuming industries of the various regions. Industries in regions that are not water constrained are unaffected. In the other cases, there can be both increases and decreases in productivity. This is because water is reduced, by different amounts (depending on relative water returns), but all industries improve in terms of water efficiency. When improvements in water efficiency more than compensate for the cuts in water availability, industrial productivity rises. This generally implies a shift in the economic structure away from agricultural production, to the benefit of manufacturing and food processing.

Shifting Patterns of Imported and Exported Water

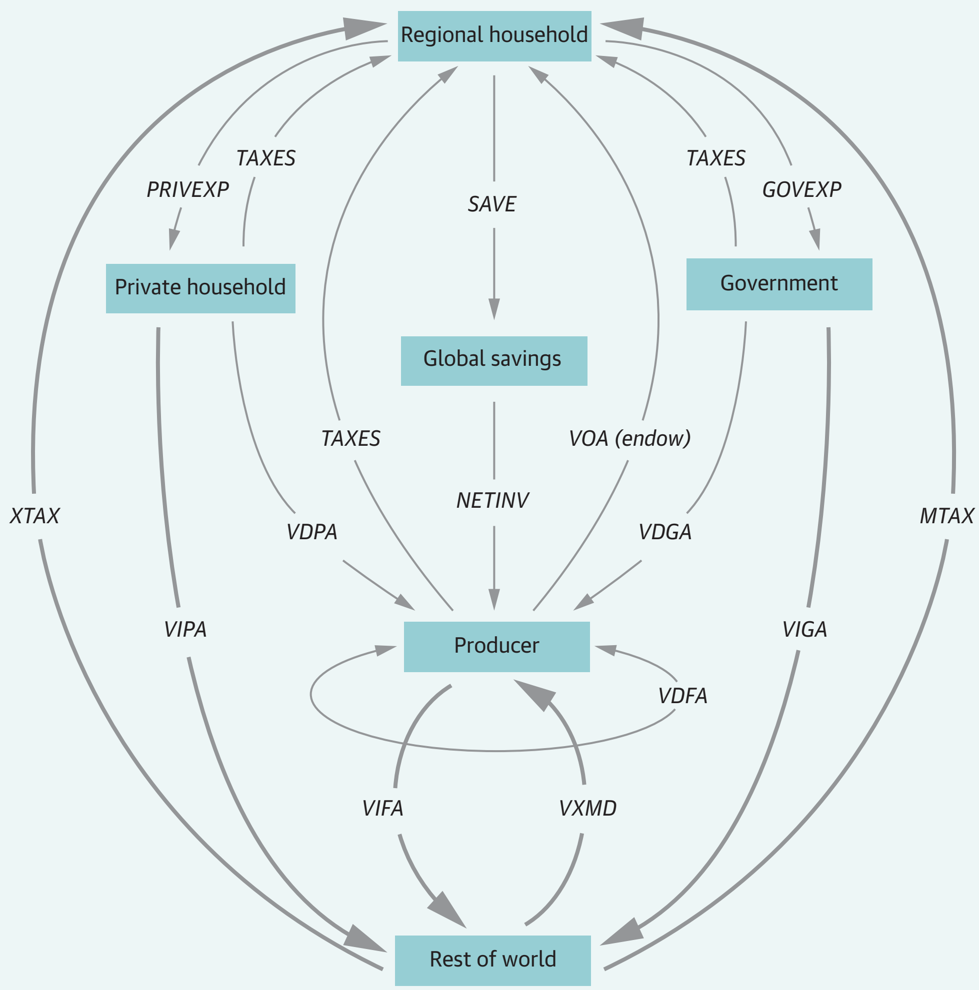
Another interesting way to look at the changes in the economic structure is by analyzing the variations in virtual water trade flows. Virtual water trade refers to the implicit content of water in import and export flows. The water-intensity coefficients can be employed to estimate the amount of water that was used to produce goods that have been subsequently transferred abroad, which can be interpreted as a virtual export of water. Table 8 presents the changes in virtual water flows (in billions m^3) among the 14 macro-regions, again for the scenario SSP1/2050/STRONG.

The reduction in agricultural production and other water-consuming activities in water-constrained regions implies a substitution of domestic water-consuming goods with imports: that is, an increase in virtual water imports. The difference between row and column totals gives the changes in the "virtual water trade balance" for each region. These differences are summed and presented in figure 3. As a consequence of market mechanisms affecting regional economic structures, the most water-constrained region, the Middle East, increases its net imports of virtual water by about 478 billion m^3. Other water-constrained regions also increase net imports of virtual water: Sahel by 210 billion m^3; Central Asia by 164 billion m^3; and Central Africa by 98 billion m^3. The global virtual water trade balance must equal zero, implying that regions that are not water constrained will expand their exports of virtual water.

BOX 1. **A Brief Description of the GTAP Model**

The Global Trade Analysis Project (GTAP) is an international network that builds, updates, and distributes a comprehensive and detailed database of trade transactions among different industries and regions in the world, framed as a Social Accounting Matrix (SAM). The SAM is typically used to calibrate parameters for a Computable General Equilibrium (CGE) model. The GTAP database is accompanied by a relatively standard CGE model and its software. The model structure is quite complex and is fully described in Hertel and Tsigas (1997). For brevity, summaries of the meaning of the main equations of the model are presented, and a graphical representation of income flows in the model is shown in figure B1.1.

FIGURE B1.1. **Income Flows in the GTAP Model**



Source: Brockmeier 2001.
Note: GTAP = Global Trade Analysis Project.

box continues next page

BOX 1. continued

Equation and identities in the model include the following conditions:

Production of industry *i* in region *r* equals intermediate domestic consumption, final demand (private consumption, public consumption, demand for investment goods), and exports to all other regions.

- Endowments of primary factors (such as labor and capital) matches demand from domestic industries.
- Unit prices for goods and services equals average production costs, including taxes.
- Representative firms in each regional industry allocate factors on the basis of cost minimization.
- Available national income equals returns on primary factors owned by domestic agents.
- National income is allocated to private consumption, public consumption, and savings.
- Savings are virtually pooled by a world bank and redistributed as regional investments, on the basis of expected future returns on capital;
- The structure of private consumption is set on the basis of utility maximization under the budget constraint.
- Intermediate and final demand are split according to the source of production: first between domestic production and imports, and then the imports among the various trading partners. Allocation is based on relative market prices, including transportation, distribution, and tax margins. Goods in the same industry but produced in different places are regarded as imperfect substitutes.
- There is perfect domestic mobility for labor and capital (single regional price), but no international mobility.
- There is imperfect domestic mobility for land (industry-specific price), but no international mobility. Land allocation is driven by relative returns.

From a mathematical point of view, the model is a very large nonlinear system of equations. Structural parameters are set so that the model replicates observational data in a base year. Simulations entail changing some exogenous variables or parameters, bringing about the determination of a counterfactual equilibrium. The partition between endogenous and exogenous variables, as well as the regional and industrial disaggregation level, is not fixed but depends on the scope of the simulation exercise.

TABLE 7. Changes in Multifactor Productivity (SSP1/2050/STRONG)

(percent)

	North America	Central America	South America	Western Europe	Eastern Europe	Middle East	Sahel	Central Africa	Southern Africa	Central Asia	Eastern Asia	S_Asia	Southeast Asia	Australasia
Rice	0.00	0.00	0.00	0.00	0.00	−42.30	−15.92	−17.10	−4.01	−42.47	−37.12	−40.21	−6.00	0.00
Wheat	0.00	0.00	0.00	0.00	0.00	−40.47	−20.23	−0.98	−1.32	−25.34	−44.20	−28.34	−4.19	0.00
Cereals	0.00	0.00	0.00	0.00	0.00	−41.89	−31.20	−10.70	−2.72	−18.23	−48.74	−34.41	−3.08	0.00
VegFruit	0.00	0.00	0.00	0.00	0.00	−28.74	−4.92	−9.96	−1.95	2.57	−15.86	−14.37	−4.43	0.00
Oilseeds	0.00	0.00	0.00	0.00	0.00	−37.66	−24.66	−6.87	−2.38	−84.58	−31.88	−21.49	1.43	0.00
Sugar	0.00	0.00	0.00	0.00	0.00	−33.51	−22.90	−3.78	−1.78	−10.71	−35.44	−20.61	−4.14	0.00
Other crops	0.00	0.00	0.00	0.00	0.00	−21.01	−7.76	−9.88	−1.10	11.42	−0.57	6.91	−1.52	0.00
Other Agr.	0.00	0.00	0.00	0.00	0.00	−21.41	−14.66	−11.35	−0.78	6.53	−8.26	−9.25	−2.15	0.00
Extr	0.00	0.00	0.00	0.00	0.00	−15.64	15.74	0.71	−0.21	17.46	4.72	9.86	2.16	0.00
P.Food	0.00	0.00	0.00	0.00	0.00	6.81	29.57	7.12	1.11	30.82	18.57	22.97	4.61	0.00
Textiles	0.00	0.00	0.00	0.00	0.00	7.45	28.02	6.25	0.98	29.37	18.68	24.65	4.43	0.00
L. Man.	0.00	0.00	0.00	0.00	0.00	7.59	30.63	7.72	1.21	31.82	18.27	19.89	4.83	0.00
H. Man.	0.00	0.00	0.00	0.00	0.00	4.60	28.63	6.60	1.03	29.94	16.42	19.13	4.35	0.00
Utilities	0.00	0.00	0.00	0.00	0.00	−12.96	15.68	−0.66	−0.09	17.78	3.10	8.79	1.43	0.00

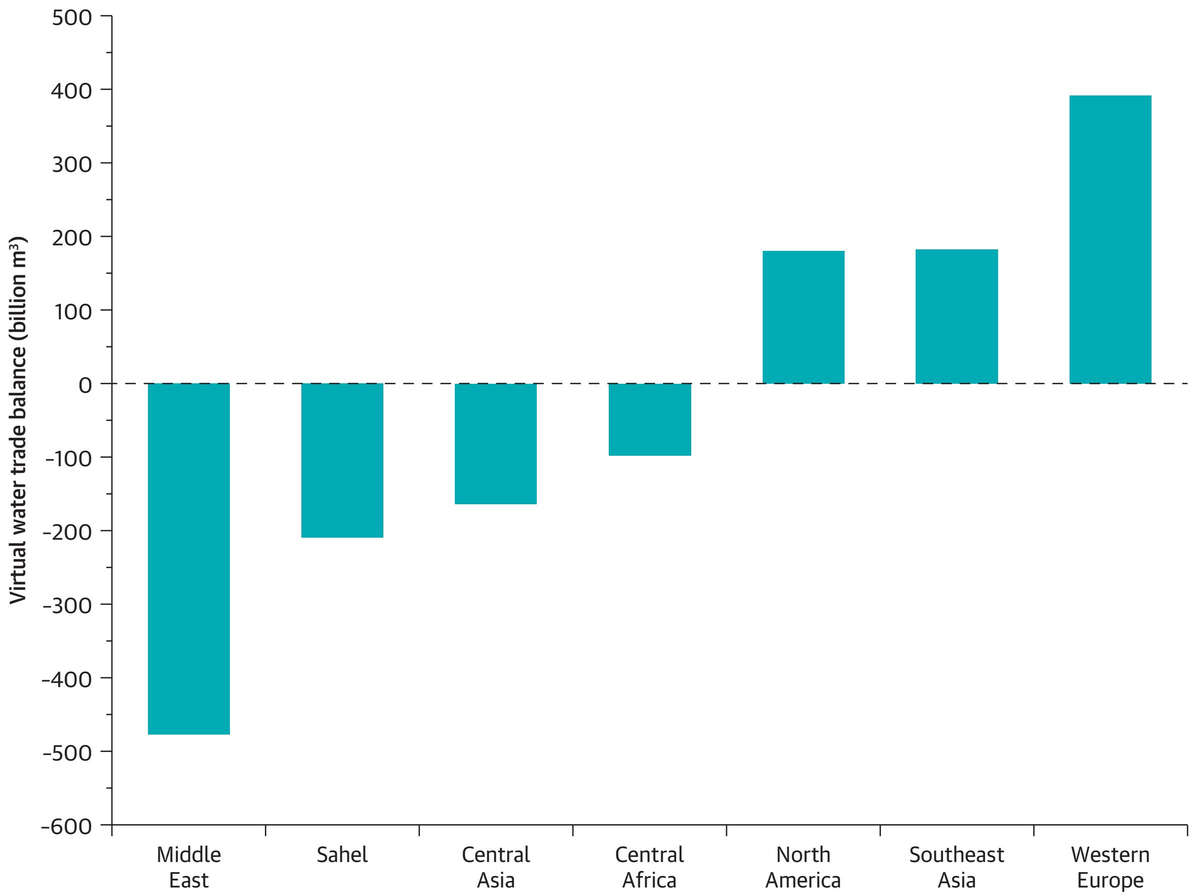
Note: L. Man = light manufacutring; H. Man = heavy manufacturing; SSP1 = sustainability scenario; STONG = strong water reallocation.

TABLE 8. **Changes in Virtual Water Trade Flows (SSP1/2050/STRONG)**

(billions m³)

From\to	North America	Central America	South America	Western Europe	Eastern Europe	Middle East	Sahel	Central Africa	Southern Africa	Central Asia	Eastern Asia	S_Asia	Southeast Asia	Australasia	Total
North America	0	−2,280	−288	−581	1	2,867	−63	−66	−60	2	4,271	83	82	12	**3,982**
Central America	68	0	6	231	23	248	1	8	1	0	430	−21	7	4	**1,005**
South America	35	19	0	626	227	4,404	32	161	−29	19	2,014	37	140	14	**7,699**
Western Europe	−42	−4	−2	0	−17	559	12	32	−12	0	−3	−77	−11	0	**435**
Eastern Europe	91	−27	−2	−2,035	0	9,263	−107	10	−29	13	487	90	206	6	**7,966**
Middle East	−29,405	−1,157	−3,579	−74,484	−6,055	0	−576	−2,170	−12,783	−416	−373,879	−50,614	−78,477	−2,021	**−635,615**
Sahel	−8,976	−1,783	−1,712	−43,556	−2,211	−26,877	0	−25,440	−3,719	−24	−78,762	−8,492	−14,663	−456	**−216,669**
Central Africa	−24,641	−1,094	−5,374	−68,558	−3,746	−4,582	−2,038	0	−4,930	−243	−62,724	−24,279	−6,567	−396	**−209,170**
Southern Africa	−417	−76	−80	−3,971	−220	−46	−52	−385	0	−19	−4,871	−130	−653	−30	**−10,947**
Central Asia	−2,660	−2,724	−586	−22,522	−86,955	−21,663	−21	−60	−283	0	−25,800	−1,858	−646	−100	**−165,879**
Eastern Asia	−45,054	−6,324	−3,242	−52,678	−9,300	−10,402	−1,049	−2,907	−3,871	−827	0	−3,219	−46,907	−3,327	**−189,104**
S_Asia	−53,602	−8,264	−2,393	−99,100	−9,193	−115,817	−1,990	−75,700	−23,714	−736	−108,192	0	−128,967	−2,882	**−630,550**
Southeast Asia	−11,803	−1,504	−965	−24,063	−1,847	2,591	−1,035	−4,737	−2,324	−32	−43,591	−2,306	0	−2,691	**−94,306**
Australasia	13	−21	−12	−255	0	1,515	−33	−54	−213	0	27	121	−49	0	**1,040**
Total	**−176,393**	**−25,239**	**−18,227**	**−390,945**	**−119,293**	**−157,940**	**−6,919**	**−111,306**	**−51,966**	**−2,261**	**−690,591**	**−90,665**	**−276,505**	**−11,866**	

FIGURE 3. Virtual Water Trade Balance



Conclusion

This paper presents findings of some numerical simulation exercises aimed at assessing the macroeconomic consequences of a possible future scarcity of water. It is important to emphasize that models are not designed to forecast the future. As with all modeling exercises, the analysis is based upon a litany of assumptions and cannot be interpreted as predictions of future changes in GDP. Instead, the exercise serves to improve understanding of the magnitude and direction of changes and how alternative policies can either accentuate or mitigate the adverse impacts.

The results demonstrate that water remains a significant obstacle to growth and development in the context of a changing climate. It also forcefully illustrates that prudent management of water resources is likely to be sufficient to neutralize some of the undesirable impacts.

The analysis introduces several assumptions, which are all more or less questionable. Nevertheless, the main results are robust to alternative conjectures, and three main messages emerge from the analysis.

First, scenarios of economic development that have been recently proposed to support the scientific analyses of climate change have ignored water availability. The underlying assumptions of sustained economic growth, especially for developing countries, would imply an excessive consumption of water, even when substantial improvements in water efficiency are envisaged.

Second, and related to the previous point, the emerging water scarcity will mainly affect developing countries in Africa and Asia, hampering their prospects of economic growth. This means that water scarcity will increase economic inequality around the world.

Third, an intelligent reallocation of scarce water resources toward sectors where the economic return per unit of water is higher can be a very effective policy response to the emerging water scarcity and its consequences. The analysis reveals that with a STRONG reallocation of water (implying aggressive policies in many countries), it would be possible to mitigate the macroeconomic impacts (measured by GDP) due to water resources scarcity. Of course, the model says nothing about how this reallocation could be implemented in practice. The introduction of water markets (through efficient water pricing) or a more market-oriented planning of water infrastructure could be part of the solution. These are issues that have been widely discussed in the water management literature and are beyond the scope of this modeling exercise.

Notes

1. The Global Change Assessment Model (GCAM) is a dynamic-recursive model with technology-rich representations of the economy, energy sector, land use and water linked to a climate model, developed at the Joint Global Change Research Institute of the University of Maryland. For more information, visit http://www.globalchange.umd.edu/models/gcam.

2. CCSM (the Community Climate System Model) is a Global Circulation Models (GCM) developed by the University Corporation for Atmospheric Research. GISS (the Goddard Institute for Space Studies) model is primarily aimed at the development of coupled atmosphere-ocean models for simulating Earth's climate system. FIO-ESM is an Earth System Model (ESM) developed by the First Institute of Oceanography (FIO) in China.

3. Australasia consists of Australia, New Zealand, and Pacific small island states.

4. SSPs are reference pathways describing plausible alternative as trends in the evolution of society and ecosystems over a century timescale, in the absence of climate change or climate policies (O'Neill et al., 2014).

5. O'Neill et al. (2014).

6. WIOD = World Input-Output Database; WASSERMed = Water Availability and Security in Southern Europe.

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