Journal of Hydrology 384 (2010) 292–305

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

The economic impact of more sustainable water use in agriculture: A computable general equilibrium analysis

Alvaro Calzadilla [a,b,*], Katrin Rehdanz [a,c,d], Richard S.J. Tol [e,f,g]

[a] Research unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Bundesstraße 55, 20146 Hamburg, Germany
[b] International Max Planck Research School on Earth System Modelling, Bundesstraße 53, 20146 Hamburg, Germany
[c] Christian-Albrechts-University of Kiel, Department of Economics, Olshausenstraße 40, 24118 Kiel, Germany
[d] Kiel Institute for the World Economy, Duesternbrooker Weg 120, 24105 Kiel, Germany
[e] Economic and Social Research Institute, Whitaker Square Sir John Rogerson's Quay, Dublin 2, Ireland
[f] Institute for Environmental Studies, Vrije Universiteit, De Boelelaan 1087, 1081 HV Amsterdam, The Netherlands
[g] Department of Spatial Economics, Vrije Universiteit, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands

ARTICLE INFO

JEL classification:
Q17
D58
Q15
Q25

Keywords:
Agricultural water use
Computable general equilibrium
Irrigation
Sustainable water use

SUMMARY

Agriculture is the largest consumer of freshwater resources – around 70 percent of all freshwater withdrawals are used for food production. These agricultural products are traded internationally. A full understanding of water use is, therefore, impossible without understanding the international market for food and related products, such as textiles. Based on the global general equilibrium model GTAP-W, we offer a method for investigating the role of green (rain) and blue (irrigation) water resources in agriculture and within the context of international trade. We use future projections of allowable water withdrawals for surface water and groundwater to define two alternative water management scenarios. The first scenario explores a deterioration of current trends and policies in the water sector (water crisis scenario). The second scenario assumes an improvement in policies and trends in the water sector and eliminates groundwater overdraft world-wide, increasing water allocation for the environment (sustainable water use scenario). In both scenarios, welfare gains or losses are not only associated with changes in agricultural water consumption. Under the water crisis scenario, welfare not only rises for regions where water consumption increases (China, South East Asia and the USA). Welfare gains are considerable for Japan and South Korea, Southeast Asia and Western Europe as well. These regions benefit from higher levels of irrigated production and lower food prices. Alternatively, under the sustainable water use scenario, welfare losses not only affect regions where overdrafting is occurring. Welfare decreases in other regions as well. These results indicate that, for water use, there is a clear trade-off between economic welfare and environmental sustainability.

Introduction

Water is one of our basic resources, but it is often in short supply. Surface water and groundwater are both important sources not only for human use but also for ecological systems. While in some countries groundwater resources still are abundant and readily available for development, in others depletion due to overdrafting, water-logging, salination as well as pollution cause severe problems. Similarly, overexploitation of surface water resources in some regions is damaging ecosystems by reducing water flows to rivers, lakes and wetlands. Since world-wide use of surface water has remained constant or increased at a slower rate, the increase in global water use in recent years has been based on groundwater (Villholth and Giordano, 2007; Zektser and Everett, 2004). In addition, the uneven distribution of water (and population) among regions has made the adequate supply critical for a growing number of countries. Rapid population growth and an increasing consumption of water per capita have aggravated the problem. This tendency is likely to continue as water consumption for most uses is projected to increase by at least 50 percent by 2025 compared to 1995 level (Rosegrant et al., 2002). One additional reason for concern is (anthropogenic) climate change, which may lead to increased drought in many places (IPCC, 2001).

The agricultural sector is the largest consumer of water. While rainfed agriculture relies on soil moisture generated from rainfall, irrigated agriculture focuses on withdrawals of water from surface

* Corresponding author. Present address: Research unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Bundesstrasse 55 (Pavillion Room 10), 20146 Hamburg, Germany. Tel.: +49 40 42838 4375; fax: +49 40 42838 7009.
E-mail address: alvaro.calzadilla@zmaw.de (A. Calzadilla).

0022-1694/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2009.12.012

and groundwater sources. In many arid and semi-arid regions such as India, Northern China as well as Pakistan groundwater is critical for development and food security. A similar situation is observed in developed arid regions of the world including the USA, Australia and Mexico. In the arid Southern and Eastern rims of the Mediterranean basin, agriculture accounts for 82 percent of the water withdrawals in the region (Plan Bleu, 2009). In other regions of the world the situation is different. Countries in Sub-Saharan Africa, for example, could benefit from more intensive groundwater use for agricultural as well as other uses but are limited in their development due to among others a lack of infrastructure, poor energy access and low investment (Villholth and Giordano, 2007). However, taken together, the more serious problem today is not the development of groundwater but the sustainable management of water (Shah et al., 2000). According to Tsur et al. (2004) the world's major surface irrigation systems lose between half and two-thirds of the water in transit between source and crops.

To ensure a more sustainable management of water resources and groundwater resources in particular, water-use policies need to be established or improved. These could include, for example, incentives to use more water-saving irrigation techniques. Water problems related to water-use management are typically studied at the farm-level, the river-catchment-level or the country-level. About 70 percent of all freshwater withdrawals is used for agriculture (United Nations, 2003), and agricultural products are traded internationally. A full understanding of water use and the effect of more sustainable management of surface and groundwater resources is impossible without understanding the international market for food and related products, such as textiles.

We use the new version of the GTAP-W model to analyze the economy-wide impacts of more sustainable water use in the agricultural sector. The GTAP-W model (Calzadilla et al., 2008) is a global computable general equilibrium (CGE) model that allows for a rich set of economic feedbacks and for a complete assessment of the welfare implications of alternative development pathways. The GTAP-W model is based on the GTAP 6 database and has been calibrated to 2000 and 2025 using information from the IMPACT model (a partial equilibrium agricultural sector model combined with a water simulation model, see Rosegrant et al., 2002). Unlike the predecessor GTAP-W (Berrittella et al., 2007), the new production structure of the model, which introduces a differentiation between rainfed and irrigated crops, allows a better understanding of the use of water resources in agricultural sectors. In fact, the distinction between rainfed and irrigated agriculture in GTAP-W, allows us to model green (rain) and blue (irrigation) water used in crop production.

Efforts towards improving groundwater development as well as the management of water resources, e.g. through more efficient irrigation methods, benefit societies by saving large amounts of water. These would be available for other uses. The aim of our paper is to analyze if improvements in agricultural water management would be economically beneficial for the world as a whole as well as for individual countries and whether and to what extent water savings could be achieved. Problems related to surface and groundwater use, as discussed above, are present today. Since problems related to water availability are becoming more severe in the future, it is important to analyze the impact of different water use options for the future. We use scenario data for 2025 taken from Rosegrant et al. (2002).

Economic models of water use have generally been applied to look at the direct effects of water policies, such as water pricing or quantity regulations, on the allocation of water resources. In order to obtain insights from alternative water policy scenarios on the allocation of water resources, partial and general equilibrium models have been used. While partial equilibrium analysis focuses on the sector affected by a policy measure assuming that the rest of the economy is not affected, general equilibrium models consider other sectors or regions as well to determine the economy-wide effect; partial equilibrium models tend to have more detail. Most of the studies using either of the two approaches analyze pricing of irrigation water only (for an overview of this literature see Johansson et al., 2002). Rosegrant et al. (2002) use the IMPACT model to estimate demand and supply of food and water to 2025. de Fraiture et al. (2004) extend this to include virtual water trade, using cereals as an indicator. Their results suggest that the role of virtual water trade in global water use is very modest. While the IMPACT model covers a wide range of agricultural products and regions, other sectors are excluded; it is a partial equilibrium model. Studies using general equilibrium approaches are generally based on data for a single country or region assuming no interlinkages with the rest of the world regarding policy changes and shocks (e.g. Diao and Roe, 2003; Gómez et al., 2004; Letsoalo et al., 2007).

The remainder of the paper is organized as follows: the next section describes the new GTAP-W model. Section "Simulation scenarios" lays down two simulation scenarios for future agricultural water use in 2025. Section "Results" presents the results and section "Discussion and conclusions" discusses the findings and concludes.

The GTAP-W model

In order to assess the systemic general equilibrium effects of more sustainable water use in agriculture, we use a multi-region world CGE model, called GTAP-W. The model is a further refinement of the GTAP model[1] (Hertel, 1997), and is based on the version modified by Burniaux and Truong (2002)[2] as well as on the previous GTAP-W model introduced by Berrittella et al. (2007).

The new GTAP-W model is based on the GTAP Version 6 database, which represents the global economy in 2001. The model has 16 regions and 22 sectors, seven of which are in agriculture.[3] However, the most significant change and principal characteristic of Version 2 of the GTAP-W model is the new production structure, in which the original land endowment in the value-added nest has been split into pasture land and land for rainfed and for irrigated agriculture. Pasture land is basically the land used in the production of animals and animal products. The last two types of land differ as rainfall is free but irrigation development is costly. As a result, land equipped for irrigation is generally more valuable as yields per hectare are higher. To account for this difference, we split irrigated agriculture further into the value for land and the value for irrigation. The value of irrigation includes the equipment but also the water necessary for agricultural production. In the short-run irrigation equipment is fixed, and yields in irrigated agriculture depend mainly on water availability. The tree diagram in Fig. A1 in "Appendix A" represents the new production structure.

Land as a factor of production in national accounts represents "the ground, including the soil covering and any associated surface waters, over which ownership rights are enforced" (United Nations, 1993). To accomplish this, we split for each region and each

[1] The GTAP model is a standard CGE static model distributed with the GTAP database of the world economy (www.gtap.org). For detailed information see Hertel (1997) and the technical references and papers available on the GTAP website.

[2] Burniaux and Truong (2002) developed a special variant of the model, called GTAP-E. The model is best suited for the analysis of energy markets and environmental policies. There are two main changes in the basic structure. First, energy factors are separated from the set of intermediate inputs and inserted in a nested level of substitution with capital. This allows for more substitution possibilities. Second, database and model are extended to account for CO_2 emissions related to energy consumption.

[3] See Table A1 in "Appendix A" for the regional, sectoral and factoral aggregation used in GTAP-W.

crop the value of land included in the GTAP social accounting matrix into the value of rainfed land and the value of irrigated land using its proportionate contribution to total production.[4] The value of pasture land is derived from the value of land in the livestock breeding sector.

In the next step, we split the value of irrigated land into the value of land and the value of irrigation using the ratio of irrigated yield to rainfed yield. These ratios are based on IMPACT data.[5] The numbers indicate how relatively more valuable irrigated agriculture is compared to rainfed agriculture. The magnitude of additional yield differs not only with respect to the region but also to the crop. On average, producing rice using irrigation is relatively more productive than using irrigation for growing oil seeds, for example.

The procedure we described above to introduce the four new endowments (pasture land, rainfed land, irrigated land and irrigation) allows us to avoid problems related to model calibration. In fact, since the original database is only split and not altered, the original regions' social accounting matrices are balanced and can be used by the GTAP-W model to assign values to the share parameters of the mathematical equations. For detailed information about the social accounting matrix representation of the GTAP database see McDonald et al. (2005).

As in all CGE models, the GTAP-W model makes use of the Walrasian perfect competition paradigm to simulate adjustment processes. Industries are modelled through a representative firm, which maximizes profits in perfectly competitive markets. The production functions are specified via a series of nested constant elasticity of substitution functions (CES) (Fig. A1). Domestic and foreign inputs are not perfect substitutes, according to the so-called "Armington assumption", which accounts for product heterogeneity.[6]

A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, pasture land, rainfed land, irrigated land, irrigation, labour and capital). Capital and labour are perfectly mobile domestically, but immobile internationally. Pasture land, rainfed land, irrigated land, irrigation and natural resources are imperfectly mobile. While perfectly mobile factors earn the same market return regardless of where they are employed, market returns for imperfectly mobile factors may differ across sectors. The national income is allocated between aggregate household consumption, public consumption and savings. The expenditure shares are generally fixed, which amounts to saying that the top level utility function has a Cobb-Douglas specification. Private consumption is split in a series of alternative composite Armington aggregates. The functional specification used at this level is the constant difference in elasticities (CDE) form: a non-homothetic function, which is used to account for possible differences in income elasticities for the various consumption goods.[7] A money metric measure of economic welfare, the equivalent variation, can be computed from the model output.[8]

In the GTAP model and its variants, two industries are not related to any region. International transport is a world industry, which produces the transportation services associated with the movement of goods between origin and destination regions. Transport services are produced by means of factors submitted by all countries, in variable proportions. In a similar way, a hypothetical world bank collects savings from all regions and allocates investments so as to achieve equality of expected future rates of return (macroeconomic closure).

In the original GTAP-E model, land is combined with natural resources, labour and the capital-energy composite in a value-added nest. In our modelling framework, we incorporate the possibility of substitution between land and irrigation in irrigated agricultural production by using a nested constant elasticity of substitution function (Fig. A1). The procedure how the elasticity of factor substitution between land and irrigation (σLW) was obtained is explained in more detail in Calzadilla et al. (2008). Next, the irrigated land–water composite is combined with pasture land, rainfed land, natural resources, labour and the capital-energy composite in a value-added nest through a CES structure.

The IMPACT model provides detailed information on green water use in rainfed production (defined as effective rainfall); and both green and blue water use in irrigated production (blue water or irrigation is defined as the water diverted from water systems).[9] In the GTAP-W benchmark equilibrium, water used for irrigation is supposed to be identical to the volume of blue water used for irrigated agriculture in the IMPACT model. An initial sector and region specific shadow price for irrigation water can be obtained by combining the social accounting matrix information about payments to factors and the volume of water used in irrigation from IMPACT. Contrary to blue water, green water used in rainfed and irrigated crop production has no price. It is modelled exogenously in the GTAP-W model using information from IMPACT.

Simulation scenarios

To model water supply and demand at the basin scale, Rosegrant et al. (2002) introduced the concept of maximum allowable water withdrawal (MAWW), which is the water withdrawal capacity available for agricultural, municipal and industrial water uses. The MAWW constrains the actual water withdrawals and depends on the availability of surface and groundwater; the physical capacity of water withdrawal; instream flow requirements for navigation; hydropower generation; environmental constrains; recreation purposes; and water demand.

Future projections of allowable water withdrawals are presented by Rosegrant et al. (2002) under three alternative scenarios: business as usual, water crisis and sustainable water use. In the business as usual scenario (BAU), MAWW projections are according to current conditions of water withdrawal capacity and physical constrains on pumping; and consider projected growth in water demand and investments in infrastructure. In the water crisis scenario (CRI), MAWW projections reflect a deterioration (from an environmental perspective) of current trends and policies in the water sector. In contrast to the previous scenario, the sustainable water use scenario (SUS) projects improvements in policies and

[4] Let us assume, for example, that 60 percent of total rice production in region *r* is produced on irrigated farms and that the returns to land in rice production are 100 million USD. Thus, we have for region *r* that irrigated land rents in rice production are 60 million USD and rainfed land rents in rice production are 40 million USD.

[5] Let us assume that the ratio of irrigated yield to rainfed yield in rice production in region *r* is 1.5 and that irrigated land rents in rice production in region *r* are 60 million USD. Thus, we have for irrigated agriculture in region *r* that irrigation rents are 20 million USD and land rents are 40 million USD.

[6] The Armington assumption of nationally differentiated products is commonly adopted in global trade models to explain cross-hauling of similar products (when a country appears to import and export the same good in the same period) and to track bilateral trade flows.

[7] A non-homothetic utility function implies that with different income levels a households budget shares spent on various commodities changes.

[8] The equivalent variation measures the welfare impact of a policy change in monetary terms. It is defined as the change in regional household income at constant prices that is equivalent to the proposed change.

[9] Green water used in crop production or effective rainfall is part of the rainfall that is stored in the root zone and can be used by the plants. The effective rainfall depends on the climate, the soil texture, the soil structure and the depth of the root zone. The blue water used in crop production or irrigation is the applied irrigation water diverted from water systems. The blue water used in irrigated areas contributes additionally to the freshwater provided by rainfall (Rosegrant et al., 2002).

Table 1
Annual maximum allowable water withdrawal for surface and groundwater under business as usual, water crisis and sustainable water use scenario, 1995 and 2025 (km^3). *Source*: Rosegrant et al. (2002).

Country/region	Surface (km^3)				Groundwater (km^3)				Total (km^3)			
	1995 Baseline	2025 Projection			1995 Baseline	2025 Projection			1995 Baseline	2025 Projection		
		BAU	CRI	SUS		BAU	CRI	SUS		BAU	CRI	SUS
Asia	1919	2464	2926	2464	478	542	519	389	2397	3006	3445	2853
China	584	764	916	764	138	171	176	137	722	935	1092	901
India	573	735	872	735	237	255	235	163	810	990	1107	898
Southeast Asia	194	286	375	286	22	32	41	32	216	318	416	318
South Asia including India	318	390	444	390	57	58	41	32	375	448	485	422
Latin America	251	358	452	358	65	79	90	79	316	437	542	437
Sub-Saharan Africa	73	141	222	141	63	87	109	90	136	228	331	231
West Asia/North Africa	246	302	348	302	72	74	60	45	318	376	408	347
Developed countries	976	1131	1247	1131	255	278	293	267	1231	1409	1540	1398
Developing countries	2425	3197	3875	3197	670	773	769	594	3095	3970	4644	3791
World	**3401**	**4328**	**5122**	**4328**	**925**	**1051**	**1062**	**861**	**4326**	**5379**	**6184**	**5189**

Note: Business as usual (BAU), water crisis (CRI) and sustainable water use (SUS).

trends in the water sector, with greater environmental water reservation.

Table 1 shows the annual MAWW for surface and groundwater for BAU, CRI and SUS for 1995 and 2025. Compared to 1995 levels, the business as usual projection for 2025 considers a small decline in extraction rates for those countries or regions pumping in excess. Overexploitation of groundwater aquifers is observable particularly in Northern India, Northern China, West Asia and North Africa, and in the Western United States, where extraction rates substantially exceed recharge rates. Alternatively, for those countries or regions underutilizing groundwater relative to the water withdrawal capacity, they assume a gradual increase in the extraction rates (e.g. Sub-Saharan Africa and Southeast Asia).

The water crisis scenario assumes, for countries pumping in excess, the same growth in extraction rates as the business as usual scenario until 2010, followed by a rapid decline in MAWW for groundwater until 2025. The decline in groundwater is more than compensated by additional use of surface water (see e.g. South Asia including India and West Asia as well as North Africa). For regions where overdrafting is not a problem, extraction rates and MAWW for surface and groundwater are higher compared to the business as usual scenario (see e.g. Sub-Saharan Africa and Southeast Asia). Under the water crisis scenario, the world's annual MAWW for surface water increases by 794 cubic kilometres compared to the business as usual scenario. MAWW for groundwater increases only slightly (11 cubic kilometres). Since more water is available for agriculture, the crisis is therefore not a crisis for agriculture, but rather a crisis for the natural environment which would have to make do with less water.

In the sustainable water use scenario, groundwater overdrafting is eliminated gradually until 2025 through a reduction in the extraction rates. Compared to the business as usual scenario, the MAWW for groundwater decreases substantially in all regions except for Sub-Saharan Africa and South Asia where overdrafting is not occurring. The MAWW for surface remains unchanged. Under this scenario the world's annual MAWW for groundwater decreases by 190 cubic kilometres compared to the business as usual scenario. This constrains agriculture, but leaves more water for the natural environment.

Based on the three scenario projections of maximum allowable water withdrawals for surface and groundwater presented by Rosegrant et al. (2002), we evaluate the effects of the water crisis and sustainable water use scenarios on production and income. Both scenarios are compared with the business as usual scenario; assuming that the BAU scenario generates a future baseline with current policies and trends in the water sector (i.e. 2025 baseline).[10]

Table 2
Percentage change in total (surface plus groundwater) maximum allowable water withdrawal used in the agricultural sector, 2025 (percentage change with respect to the business as usual scenario). *Source*: Authors' estimates based on Rosegrant et al. (2002) and the AQUASTAT database.

Regions (according the GTAP-W)	CRI (%)	SUS (%)
United States	3.84	−0.32
Canada	1.09	−0.09
Western Europe	2.33	−0.20
Japan and South Korea	5.13	−0.43
Australia and New Zealand	5.46	−0.46
Eastern Europe	2.80	−0.23
Former Soviet Union	5.11	−0.43
Middle East	6.21	−5.63
Central America	14.46	0.00
South America	17.91	0.00
South Asia	7.82	−5.49
Southeast Asia	22.08	0.00
China	11.37	−2.46
North Africa	6.87	−6.22
Sub-Saharan Africa	29.85	0.87
Rest of the World	7.53	−2.00

Note: Water crisis (CRI) and sustainable water use (SUS).

Table 2 shows for 2025 the percentage change in the total (surface plus groundwater) maximum allowable water withdrawal used in the agricultural sector for the water crisis and sustainable water use scenarios.[11] Under the water crisis scenario, all regions increase the maximum water withdrawal capacity for agriculture compared to the business as usual scenario. In developing regions increases are higher than in developed regions. Under the sustainable water use scenario, water constraints occur in all regions except for those where groundwater is underutilized (Central and South America, Southeast Asia and Sub-Saharan Africa).

[10] Regional mapping between GTAP-W and Rosegrant et al. (2002) is as follows: United States, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Eastern Europe and the former Soviet Union correspond to developed countries; Middle East corresponds to West Asia/North Africa; Central America and South America correspond to Latin America; South Asia corresponds to South Asia including India; Southeast Asia corresponds to Southeast Asia; China corresponds to China; North Africa corresponds to West Asia/North Africa; Sub-Saharan Africa corresponds to Sub-Saharan Africa; and the Rest of the World corresponds to developing countries.

[11] The maximum allowable water withdrawal for surface and groundwater from Rosegrant et al. (2002) presented in Table 1 was updated with information regarding groundwater used by the agricultural sector (AQUASTAT database).

Table 3
Water crisis scenario: percentage change in crop production, green and blue water use and world market price by region and crop type, compared to the 2025 baseline simulation.

Description	Rainfed agriculture		Irrigated agriculture			Total				World market price
	Production	Green water	Production	Green water	Blue water	Production	Green water	Blue water	Total water	
Regions										
United States	−5.33	−6.92	3.09	3.44	3.18	0.54	−0.15	3.18	1.50	
Canada	−3.21	−3.09	1.35	0.96	0.81	−2.83	−2.99	0.81	−2.88	
Western Europe	−1.81	−1.75	2.56	2.24	1.60	−0.65	−1.07	1.60	−0.77	
Japan and South Korea	−12.56	−10.73	4.60	2.04	−0.35	0.13	−0.67	−0.35	−0.65	
Australia and New Zealand	−3.74	−2.66	5.88	5.70	5.72	−0.85	−1.81	5.72	0.41	
Eastern Europe	−0.81	−0.79	2.79	2.76	2.77	−0.06	−0.28	2.77	0.32	
Former Soviet Union	−1.82	−1.59	5.12	5.08	5.09	−0.11	−0.76	5.09	0.52	
Middle East	−8.10	−8.71	5.91	5.28	5.43	−0.67	−3.07	5.43	1.61	
Central America	−9.07	−10.75	13.33	13.44	13.60	1.16	−1.41	13.60	4.29	
South America	−5.54	−4.56	18.21	17.98	17.98	−0.06	−1.98	17.98	0.63	
South Asia	−10.55	−11.70	7.65	7.55	7.74	0.58	−0.70	7.74	2.66	
Southeast Asia	−12.43	−13.79	21.74	21.90	21.88	1.31	−2.99	21.88	−0.16	
China	−11.29	−16.02	11.04	9.65	8.94	1.98	1.91	8.94	3.99	
North Africa	−10.57	−12.94	6.75	6.83	5.98	−0.34	−9.18	5.98	1.60	
Sub-Saharan Africa	−4.73	−3.30	30.00	30.00	30.03	−0.59	−1.95	30.03	0.10	
Rest of the World	−4.51	−3.69	7.43	7.35	7.39	−0.02	−0.37	7.39	1.63	
Total	**−6.69**	**−7.05**	**9.93**	**10.05**	**8.93**	**0.44**	**−1.05**	**8.93**	**1.62**	
Crops										
Rice	−21.63	−21.89	7.75	9.31	7.91	0.64	−2.22	7.91	0.80	−5.08
Wheat	−7.94	−7.30	7.49	7.31	8.05	0.04	−1.96	8.05	2.69	−1.99
Cereal grains	−5.36	−4.77	7.09	9.63	9.18	0.28	−1.36	9.18	1.15	−1.72
Vegetables, fruits, nuts	−4.06	−3.91	9.79	11.61	10.17	0.16	−0.73	10.17	1.26	−1.60
Oil seeds	−3.97	−3.72	6.39	8.91	6.61	0.37	−0.63	6.61	1.05	−1.83
Sugar cane, sugar beet	−8.70	−10.02	12.66	14.40	12.41	0.26	−2.07	12.41	3.14	−2.38
Other agricultural products	−7.44	−5.81	10.46	11.04	9.44	1.33	0.28	9.44	2.17	−1.90
Total	**−6.69**	**−7.05**	**9.93**	**10.05**	**8.93**	**0.44**	**−1.05**	**8.93**	**1.62**	

Projections of future surface and groundwater use in agriculture, according to the water crisis and sustainable water use scenarios, are introduced in the 2025 GTAP-W baseline simulation based on information in Table 2. The baseline dataset and projections out to 2025 on agricultural production as well as green and blue water use are present in "Appendix B". While changes in surface and groundwater use in agriculture modify the use of blue water or irrigation endowment in GTAP-W, changes in green water use driven by changes in rainfed and irrigated crop production is modelled exogenously in the GTAP-W model using information from IMPACT.

Under the water crisis scenario, higher levels of surface and groundwater withdrawal are assumed to expand irrigated agriculture. Irrigated crop area and irrigation are increased in GTAP-W according to Table 2. Under the sustainable water use scenario, constraints in surface and groundwater capacity are assumed to reduce irrigated agriculture (first stage). As a consequence of the decline in agricultural production and income, farmers react and expand rainfed crop areas to offset the initial losses (second stage). In the first stage, irrigated crop area and irrigation are reduced in GTAP-W according to Table 2. In the second stage, rainfed crop area is increased according to the initial reduction in irrigated crop area. That is, total harvested area stays the same, but crop production falls as rainfed agriculture is less productive than irrigated agriculture.

Results

Water crisis scenario: deterioration of current trends and policies in the water sector

Higher surface and groundwater withdrawal capacity increases irrigation water supply, which promotes irrigated crop production and relegates rainfed production. Table 3 shows the percentage changes, with respect to the baseline simulation, in crop production and green and blue water use by region and crop type in 2025. At the global level, global irrigated production increases by 9.9 percent while global rainfed production decreases by 6.7 percent; as a result, total production increases slightly by 0.4 percent.

At the regional level, the tendency is similar. Irrigated crop production increases in all regions, particularly in developing regions where overdrafting in not occurring (Sub-Saharan Africa, Southeast Asia and South America). Contrary to irrigated production, rainfed crop production declines in all regions. The combined effect of changes in irrigated and rainfed agriculture on total crop production is mixed; but total crop production increases mostly in developing regions (China, Southeast Asia and Central America). Reductions in total crop production are considerable in Canada, followed by Australia and New Zealand; the Middle East; and Western Europe.

Green and blue water use changes accordingly. At the global level, total agricultural water consumption increases by 105 cubic kilometres. While blue water use increases by 155 cubic kilometres, green water use decreases by 50 cubic kilometres. At the regional level, total agricultural water consumption decreases only in four regions (Canada; Western Europe; Japan and South Korea; and Southeast Asia) (Fig. 1). Regional blue water use increases more in developing regions where groundwater is underutilized (Sub-Saharan Africa, Southeast Asia, and South and Central America). In developing regions, pumping groundwater in excess, including China, South Asia, North Africa and the Middle East, blue water use increases. Regional green water use in rainfed and irrigated production changes according to the additional crop production.

Changes in green and blue water use by crop type are shown in the bottom of Table 3 and in Fig. 2. For most crops, total agricul-

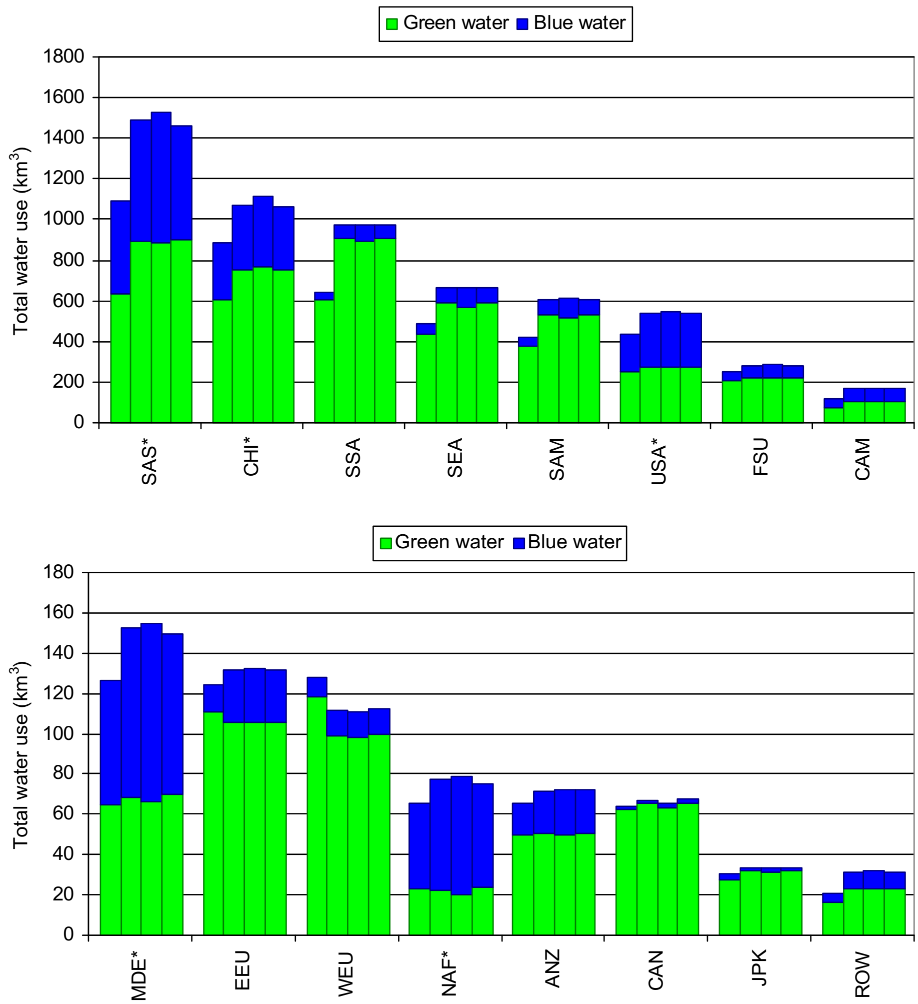

Fig. 1. Green and blue water use by region and scenario (km^3). *Note*: The four bars refer to the 2000 baseline data, the 2025 baseline scenario, the water crisis scenario and the sustainable water use scenario (final result), respectively. Regions where overdrafting of groundwater aquifers occurs are denoted by an asterisk (∗).

tural water use increases as a consequence of higher crop production. Total green water use decreases while blue water use increases for all crops. An exception is "other agricultural products", the crop category with the highest increase in production, for which both green and blue water consumption increases.

Higher surface and groundwater extraction promotes irrigation and improves agricultural yields, which in turn leads to a decrease in the production costs of agricultural products.[12] The last column in Table 3 reports the percentage change in world market prices. For all agricultural products, world market prices decrease as a consequence of lower production costs. Reductions in world market prices are considerable for rice, sugar cane and sugar beet. Lower market prices stimulate consumption and total production of all agricultural products increases. Total production increases particularly for "other agricultural products" as well as for rice and oil seeds production. Lower prices and higher supply of crops promotes non-agricultural activities as well. Market prices for food related products, animal production and meat decline.

Changes in water withdrawal capacity alter competitiveness and induce changes in welfare. At the global level, welfare increase when more water is used in agriculture. However, at the regional level, the results are more mixed. Welfare decreases mainly in food-exporting regions (356 million USD in South America; 326 million USD in Australia and New Zealand; and 234 in Sub-Saharan Africa) (Fig. 3). The competitive advantage of those regions decreases as other regions increase irrigated agriculture. Welfare changes are positive in all other regions, with the exception of Canada (welfare decreases by 85 million USD). Welfare gains are considerable for China and South Asia, developing regions where overdrafting of groundwater is high (welfare increases by 2241 and 2044 million USD, respectively). In Japan and South Korea, Southeast Asia and Western Europe welfare gains are lower (1397; 1104 and 1101 million USD, respectively).

Sustainable water use scenario: improvements in policies and trends in the water sector

Unlike the water crisis scenario, the sustainable water use scenario focuses on the sustainable exploitation of groundwater resources. Under this scenario, no restriction is imposed upon surface water withdrawal; however, groundwater overdrafting is eliminated gradually until 2025. The scenario is divided into two stages, in the first stage restrictions in irrigation water withdrawal constrain irrigated agriculture, which in turn reduce total production and income. In the second stage, farmers react and increase rainfed harvested areas in order to compensate the initial losses in income. Table 4 shows the percentage changes in crop produc-

[12] Higher levels of irrigation usually imply an increase of production costs related to the variable costs of crops. In our analysis we are not able to take that into account.

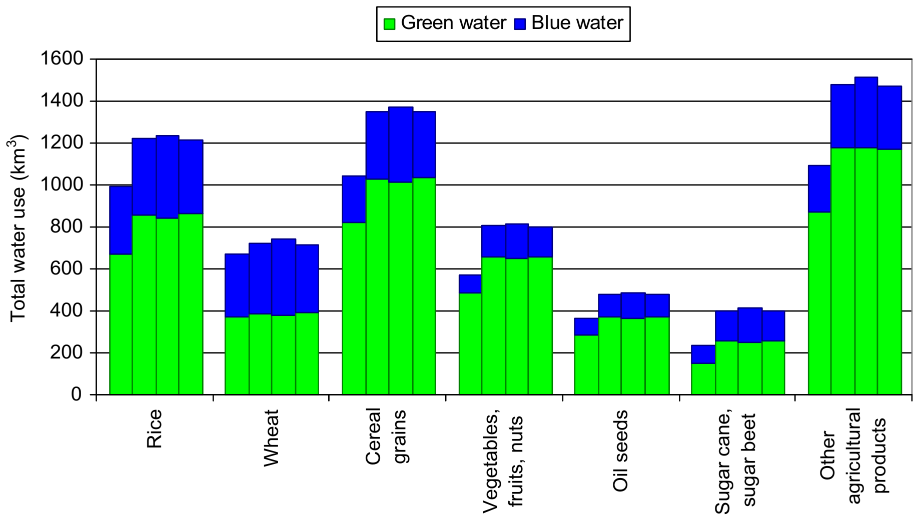

Fig. 2. Green and blue water use by crop and scenario (km^3). *Note*: The four bars refer to the 2000 baseline data, the 2025 baseline scenario, the water crisis scenario and the sustainable water use scenario (final result), respectively.

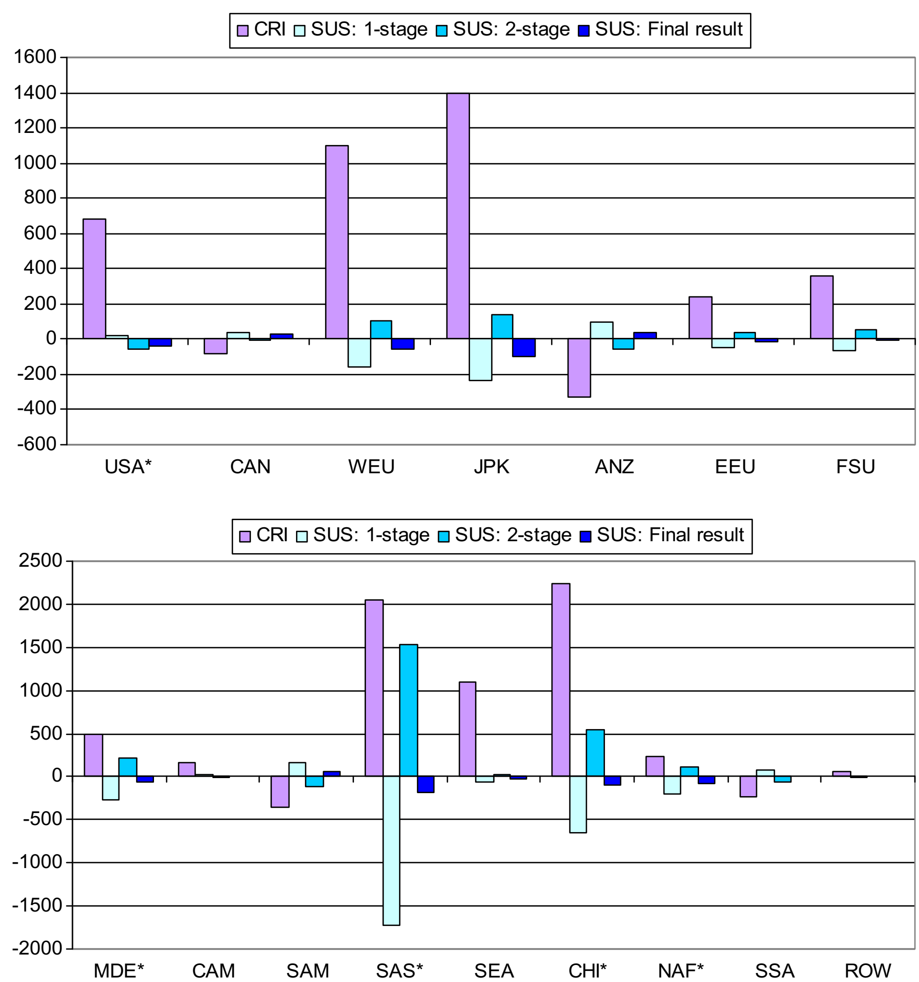

Fig. 3. Changes in regional welfare, water crisis and sustainable water use scenarios (million USD). *Note*: Developed regions (top panel) and developing regions (bottom panel). Regions where overdrafting of groundwater aquifers occurs are denoted by an asterisk (∗).

tion as well as green and blue water use by region in 2025, compared to the baseline simulation. Displayed are the results for both stages as well as the final result. At the global level, total production decreases by 0.13 percent in the first stage and increases by 0.06 percent in the second stage. The final result is a small decrease in total production by 0.07 percent.

Table 4
Sustainable water use scenario: percentage change in crop production and green and blue water use by region, compared to the 2025 baseline simulation.

Regions	Rainfed agriculture		Irrigated agriculture			Total			
	Production	Green water	Production	Green water	Blue water	Production	Green water	Blue water	Total water
First stage									
United States	0.77	1.08	−0.25	−0.25	−0.27	0.06	0.21	−0.27	−0.03
Canada	0.93	0.88	−0.14	0.01	0.07	0.84	0.86	0.07	0.84
Western Europe	0.33	0.37	−0.27	−0.14	0.37	0.17	0.28	0.37	0.29
Japan and South Korea	1.61	2.96	−0.44	−0.41	−0.40	0.09	0.31	−0.40	0.27
Australia and New Zealand	0.78	0.79	−0.62	−0.36	−0.43	0.36	0.67	−0.43	0.35
Eastern Europe	0.10	0.11	−0.23	−0.22	−0.22	0.03	0.06	−0.22	0.01
Former Soviet Union	0.24	0.25	−0.44	−0.41	−0.41	0.07	0.16	−0.41	0.04
Middle East	6.17	6.21	−5.58	−5.49	−5.50	−0.05	1.50	−5.50	−2.36
Central America	0.21	0.27	−0.10	−0.08	−0.07	0.07	0.13	−0.07	0.06
South America	0.14	0.26	−0.17	−0.08	−0.06	0.07	0.22	−0.06	0.18
South Asia	6.68	7.36	−5.33	−5.32	−5.47	−0.67	0.12	−5.47	−2.11
Southeast Asia	0.15	0.19	−0.03	0.00	0.00	0.08	0.13	0.00	0.12
China	2.20	3.10	−2.41	−2.12	−1.96	−0.54	−0.55	−1.96	−0.96
North Africa	8.17	9.93	−6.23	−6.27	−6.62	−0.34	6.86	−6.62	−2.73
Sub-Saharan Africa	0.09	0.17	0.78	0.81	0.82	0.17	0.19	0.82	0.23
Rest of the World	1.12	0.88	−1.92	−1.92	−1.93	−0.02	0.04	−1.93	−0.47
Total	**1.41**	**1.51**	**−2.19**	**−2.46**	**−2.76**	**−0.13**	**0.12**	**−2.76**	**−0.65**
Second stage									
United States	0.15	0.12	−0.01	0.00	−0.01	0.04	0.04	−0.01	0.02
Canada	−0.43	−0.35	0.09	0.18	0.13	−0.39	−0.34	0.13	−0.32
Western Europe	−0.18	−0.18	0.01	−0.02	−0.10	−0.13	−0.15	−0.10	−0.15
Japan and South Korea	−0.03	0.08	−0.03	0.01	0.02	−0.03	0.03	0.02	0.03
Australia and New Zealand	−0.22	−0.18	0.17	0.18	0.18	−0.10	−0.15	0.18	−0.05
Eastern Europe	−0.02	−0.03	0.00	0.00	0.00	−0.02	−0.02	0.00	−0.02
Former Soviet Union	−0.06	−0.07	0.01	0.00	0.00	−0.04	−0.06	0.00	−0.05
Middle East	0.34	0.55	0.04	0.19	0.17	0.19	0.39	0.17	0.26
Central America	−0.18	−0.22	0.07	0.06	0.06	−0.07	−0.11	0.06	−0.05
South America	−0.10	−0.21	0.10	0.07	0.05	−0.06	−0.18	0.05	−0.15
South Asia	1.16	1.28	−0.10	−0.03	−0.07	0.43	0.49	−0.07	0.26
Southeast Asia	−0.08	−0.07	0.01	0.03	0.02	−0.04	−0.04	0.02	−0.03
China	0.42	0.52	−0.04	0.01	0.02	0.15	0.16	0.02	0.11
North Africa	0.41	0.48	−0.04	0.02	0.07	0.16	0.38	0.07	0.16
Sub-Saharan Africa	−0.18	−0.17	0.02	0.00	0.01	−0.15	−0.17	0.01	−0.16
Rest of the World	0.07	0.09	−0.02	−0.01	−0.02	0.04	0.06	−0.02	0.04
Total	**0.11**	**0.08**	**−0.02**	**0.00**	**−0.01**	**0.06**	**0.06**	**−0.01**	**0.04**
Final result									
United States	0.93	1.20	−0.27	−0.25	−0.28	0.10	0.26	−0.28	−0.01
Canada	0.50	0.53	−0.05	0.19	0.20	0.45	0.52	0.20	0.51
Western Europe	0.15	0.19	−0.26	−0.16	0.27	0.04	0.13	0.27	0.14
Japan and South Korea	1.58	3.04	−0.47	−0.40	−0.38	0.06	0.33	−0.38	0.29
Australia and New Zealand	0.56	0.60	−0.45	−0.18	−0.25	0.25	0.52	−0.25	0.30
Eastern Europe	0.08	0.08	−0.23	−0.22	−0.22	0.01	0.04	−0.22	−0.01
Former Soviet Union	0.18	0.17	−0.43	−0.41	−0.42	0.03	0.10	−0.42	−0.01
Middle East	6.53	6.72	−5.54	−5.29	−5.32	0.14	1.88	−5.32	−2.09
Central America	0.03	0.05	−0.04	−0.02	−0.01	0.00	0.02	−0.01	0.01
South America	0.04	0.05	−0.07	−0.02	−0.01	0.01	0.05	−0.01	0.04
South Asia	7.92	8.55	−5.42	−5.36	−5.54	−0.24	0.60	−5.54	−1.85
Southeast Asia	0.06	0.12	−0.02	0.02	0.02	0.03	0.09	0.02	0.08
China	2.64	3.61	−2.46	−2.11	−1.94	−0.39	−0.39	−1.94	−0.85
North Africa	8.61	10.37	−6.26	−6.25	−6.54	−0.18	7.21	−6.54	−2.57
Sub-Saharan Africa	−0.09	−0.01	0.80	0.81	0.83	0.01	0.02	0.83	0.08
Rest of the World	1.19	0.97	−1.94	−1.93	−1.95	0.01	0.10	−1.95	−0.43
Total	**1.53**	**1.59**	**−2.21**	**−2.45**	**−2.76**	**−0.07**	**0.17**	**−2.76**	**−0.61**

At regional level, results vary widely. For developing regions where overdrafting is a problem, the results of the first stage show a decrease in irrigated and total crop production (see e.g. South Asia, China, North Africa and the Middle East). In the second stage, rainfed and total crop production increases. However, this increase is insufficient to offset the initial reduction in total production. As a final result, total production declines in these regions. The only exception is the Middle East, where total production increases by 0.14 percent. For the USA, a developed country pumping in excess, total production in both stages increases slightly; as a final result total crop production increases by 0.1 percent.

For regions where overdrafting is not occurring, irrigated production decreases and total production increases in the first stage. An exception is Sub-Saharan Africa, where groundwater is underutilized and irrigated production increases. In the second stage, rainfed and total production decreases. As a final result, total production increases in all these regions, particularly in Canada as well as Australia and New Zealand.

Changes in rainfed and irrigated production have an effect on the demand for green and blue water resources. At the global level, water savings are expected since groundwater is constrained. Total water use decreases by 0.65 percent (42 cubic kilometres) in the first stage and increases slightly by 0.04 percent (3 cubic kilometres) in the second stage. The final result is a decrease in total water use by 0.61 percent (40 cubic kilometres). While blue water use decreases, total green water use increases in both stages.

At the regional level, green and blue water use varies widely. For regions where overdrafting is a problem, blue and total water use decrease in the first stage, particularly in North Africa, the Middle East and South Asia. In the second stage blue as well as total water use increases (exceptions are the USA and South Asia). However, the final result, taken the results of stages 1 and 2 together, blue and total water use decrease (Table 4 and Fig. 1). Together total water savings in all these regions reach 42 cubic kilometres. South Asia accounts for more than two-thirds of the total water savings in these regions. For regions where overdrafting is not occurring, results are less pronounced.

Changes in green and blue water use by crop type are reported in Table 5. In the first stage, when groundwater withdrawal is limited, there is a shift in production from irrigated to rainfed agriculture. Global irrigated production decreases, which implies a reduction in green and blue water use. By contrast, global rainfed production and green water use increases. Rainfed production increases considerably for rice and wheat (5.1 and 3.2 percent, respectively). As a result, global production decreases by 0.1 percent and water savings reach 42 cubic kilometres.

In the second stage, when rainfed areas expand to neutralize production and income losses, global rainfed and total production increases slightly. Taking the results of both stages together, the final results show, at the bottom of Table 5, a decrease in total production for all crops. The sectors "Other agricultural products" and rice have the largest decrease in total production. While blue water use declines for all crops, total green water use increases for all crops except for "other agricultural products" (Fig. 2). The final water savings reach 40 cubic kilometres. Water savings are marked for the crops "other agricultural products", wheat and rice.

The last column in Table 5 shows the changes in world market prices for all crop types. When groundwater use is constrained (first stage), world market prices increase for all crops and for agricultural related products (food products, animal production and meat production). World market prices increase mainly for rice; sugar cane and sugar beet; and wheat. In the second stage, world market prices decrease for all crops when rainfed areas are increased. World market prices decline mainly for oil seeds and vegetables, fruits and nuts. The combined effect of both stages shows a decrease in price for oil seeds and vegetables, fruits and nuts. For all other crops including agricultural related activities, world market prices increase.

Reducing groundwater overdraft world-wide alters the competitiveness of regions and induces changes in welfare. At the global level, welfare declines in the first stage by 2993 million USD and increases by 2490 million USD in the second stage. Taken both results together, welfare declines by 503 million USD (Fig. 3). At the regional level, welfare effects are diverse depending on the region. In the first stage, welfare decreases for most of the regions, but mainly for developing regions where overdrafting is excessive. In South Asia, China and the Middle East welfare decreases by 1721; 643 and 274 million USD, respectively. In this stage, welfare gains are observable mainly in developing regions where groundwater use is underutilized. Welfare increases in South America, Sub-Saharan Africa and Central America by 167, 77 and 20 million USD, respectively. In the second stage, welfare changes for all re-

Table 5
Sustainable water use scenario: percentage change in crop production, green and blue water use and world market price by crop type, compared to the 2025 baseline simulation.

Crops	Rainfed agriculture		Irrigated agriculture			Total				World market price
	Production	Green water	Production	Green water	Blue water	Production	Green water	Blue water	Total water	
First stage										
Rice	5.11	4.49	−1.95	−2.35	−2.85	−0.24	0.18	−2.85	−0.72	1.50
Wheat	3.19	2.91	−3.15	−2.56	−4.30	−0.09	0.91	−4.30	−1.51	0.84
Cereal grains	0.94	0.84	−1.22	−1.51	−1.38	−0.04	0.28	−1.38	−0.11	0.41
Vegetables, fruits, nuts	0.99	0.75	−2.47	−2.30	−2.91	−0.07	0.13	−2.91	−0.43	0.49
Oil seeds	0.69	0.71	−1.04	−1.63	−1.24	−0.04	0.13	−1.24	−0.18	0.64
Sugar cane, sugar beet	1.24	0.81	−1.93	−1.43	−2.52	−0.09	0.08	−2.52	−0.86	0.98
Other agricultural products	1.88	1.48	−2.67	−3.52	−3.00	−0.35	−0.33	−3.00	−0.88	0.65
Total	**1.41**	**1.51**	**−2.19**	**−2.46**	**−2.76**	**−0.13**	**0.12**	**−2.76**	**−0.65**	
Second stage										
Rice	0.43	0.27	0.02	0.00	0.00	0.13	0.10	0.00	0.07	−0.25
Wheat	0.05	0.01	0.04	0.06	0.05	0.04	0.02	0.05	0.03	−0.24
Cereal grains	0.05	0.05	0.00	−0.03	−0.02	0.02	0.03	−0.02	0.02	−0.28
Vegetables, fruits, nuts	0.14	0.10	−0.09	−0.13	−0.10	0.07	0.05	−0.10	0.02	−0.76
Oil seeds	−0.01	−0.03	0.05	0.05	−0.01	0.02	−0.01	−0.01	−0.01	−0.86
Sugar cane, sugar beet	0.09	0.04	−0.01	0.01	−0.05	0.05	0.03	−0.05	0.00	−0.46
Other agricultural products	0.15	0.10	−0.02	0.04	0.01	0.07	0.08	0.01	0.06	−0.49
Total	**0.11**	**0.08**	**−0.02**	**0.010.**	**−0.01**	**0.06**	**0.06**	**−0.01**	**0.04**	
Final result										
Rice	5.56	4.78	−1.93	−2.36	−2.85	−0.12	0.28	−2.85	−0.65	1.25
Wheat	3.24	2.92	−3.11	−2.51	−4.25	−0.05	0.94	−4.25	−1.48	0.60
Cereal grains	0.99	0.89	−1.22	−1.54	−1.39	−0.02	0.31	−1.39	−0.09	0.12
Vegetables, fruits, nuts	1.12	0.85	−2.55	−2.43	−3.00	0.00	0.18	−3.00	−0.40	−0.27
Oil seeds	0.68	0.68	−0.99	−1.58	−1.25	−0.02	0.13	−1.25	−0.19	−0.22
Sugar cane, sugar beet	1.33	0.84	−1.93	−1.42	−2.56	−0.04	0.11	−2.56	−0.85	0.52
Other agricultural products	2.03	1.58	−2.70	−3.49	−2.99	−0.28	−0.25	−2.99	−0.82	0.15
Total	**1.53**	**1.59**	**−2.21**	**−2.45**	**−2.76**	**−0.07**	**0.17**	**−2.76**	**−0.61**	

gions have an opposite sign than in the first stage. In South Asia, China and the Middle East welfare increases by 1537; 546 and 221 million USD, respectively. In South America, Sub-Saharan Africa and Central America welfare declines by 115, 61 and 12 million USD, respectively.

Regional welfare gains in the second stage are considerably lower or more than offset welfare losses in the first stage. Taken the results of stages 1 and 2 together, final welfare changes are negative for regions with excessive overdraft. Welfare losses are highest for South Asia and China (183 and 96 million USD, respectively). For regions where groundwater use is underutilized, welfare changes are mostly positive. Welfare increases in South America, Sub-Saharan Africa and Central America by 52, 16 and 8 million USD, respectively. The only exception is Southeast Asia, where welfare decreases by 23 million USD. For the rest of the regions where groundwater overdraft is not problematic, welfare changes are mostly negative. The highest decreases in welfare are present in Japan and South Korea; and Western Europe (97 and 59 million USD, respectively). Exceptions are Australia and New Zealand; and Canada, where welfare increases by 40 and 25 million USD, respectively.

Discussion and conclusions

In our analysis, the water crisis and sustainable water use scenarios lead to different patterns in agricultural water consumption. While the water crisis scenario explores a deterioration in current conditions and policies in the water sector, the sustainable water use scenario assumes an improvement and eliminates groundwater overdraft world-wide.

Irrigation water use is promoted under the water crisis scenario. At the global level, total production increases by 1.6 percent. Irrigated production expands suppressing rainfed production. As a result, total agricultural water consumption increases; irrigation water use increases even more, while the use of rain water falls. Higher levels of irrigation increase agricultural yields and allow farmers to obtain more output per unit of input, which in turn reduces production costs and crop prices. World market prices decrease for all crops and for agricultural related products (food products, animal production and meat production). Global welfare would increase by 9 billion USD.

An opposite picture is obtained under the sustainable use scenario. At the global level, total elimination of groundwater overdraft decreases total production moderately. As groundwater use is limited, irrigated production decreases and rainfed production increases. Total water consumption decreases. World market prices increase, but not for all crops. Global welfare falls by 0.5 billion USD.

At the regional level, results vary widely. Under the water crisis scenario, total production increases mainly in China, Southeast Asia and Central America and decreases principally in Canada and Australia and New Zealand. Under the sustainable water use scenario, total production decreases only in China, South Asia and North Africa and increases in all other regions mainly in Canada and Australia and New Zealand.

Under the water crisis scenario, irrigated production increases in all regions but more in developing regions where overdraft is not a problem. Irrigated production increases less in regions with overdraft. Under the sustainable water use scenario, irrigated production decreases in all regions, but mainly in developing regions with overdraft. Irrigated production increases only in Sub-Saharan Africa, where groundwater is underutilized.

Under the water crisis scenario, irrigated and total production increases for all crops, while rainfed production decreases. The opposite occurs under the sustainable water use scenario.

Regional use of green and blue water resources changes according to the additional rainfed and irrigated crop production. In absolute terms, under the water crisis scenario, most of the total water consumption occurs in regions where overdrafting is a problem, mainly in China, South East Asia and the USA. For most regions, total green water use decreases and blue water use increases. In Japan and South Korea, both green and blue water consumption decreases slightly. In China, both green and blue water consumption increases. Under the sustainable water use scenario, water restrictions affect predominantly regions where groundwater resources are on pressure. Total water consumption decrease mainly in South Asia, China and the Middle East.

In both scenarios, welfare changes go beyond changes in agricultural water consumption. Welfare changes in regions where water use changes, but it spills over to other regions too. Under the sustainable water use scenario, global and regional welfare losses could be significant if farmers do not increase rainfed areas to offset initial losses in production and income due to irrigation constraints.

The results reveal a clear trade-off between agricultural production, and hence human welfare as measurable by consumption of market goods on the one hand and nature conservation on the other hand. There is more water available for agriculture in the water crisis scenario than in business as usual scenario, and welfare is higher. The sustainable water use scenario has less water for agriculture, and lower welfare. However, the amount of water available to the natural environment moves in the opposite direction: More water for agriculture means less water for nature. This paper does not quantify the benefits of water to nature. It does, however, quantify the welfare implications of restricting or increasing the human take of total water. In the water crisis scenario, for instance, the human benefits of taking 105 cubic kilometres of water out of nature are some 9 billion USD – less than $1.3 per person. The welfare costs of the policies presumed in the sustainable water use scenario are also very small.

Several limitations apply to the above results. First, our analysis is based on regional averages. We do not differentiate between different regions within a country. China is an example of such a country. Although on average water is not short, water supply is a problem in Northern China, where groundwater overexploitation occurs. In our sustainable water use scenario we try to account for this effect. Second, under the water crisis scenario, expansion of irrigated areas is driven by the availability of water for irrigation, we do not account for possible environmental effects of land use changes. Third, under the water crisis scenario, we do not consider any cost or investment associated with irrigation expansion. Therefore, our results might overestimate the benefits of this scenario. Forth, we implicitly assume, for the sustainable water crisis scenario, availability and accessibility of green water resources when rainfed agriculture expands. In addition, some areas might be more suitable for rainfed agriculture than others. As a consequence, the initial loss in income might not be compensated as much as indicated in our scenario. Fifth, the GTAP-W model considers water quantity and prices but ignores non-market benefits or costs of water use. For instance, the model is unable to predict the direct ecological impact of limiting groundwater use. Sixth, our analysis does not account for surface and groundwater use apart from agriculture, since the necessary data are missing. These issues should be addressed in future research.

Acknowledgements

We had useful discussions about the topics of this article with Holger Hoff and participants at the Global Green–Blue Initiative workshop in Stockholm. This article is supported by the Federal Ministry for Economic Cooperation and Development, Germany under the project "Food and Water Security under Global Change: Developing Adaptive Capacity with a Focus on Rural Africa," which forms part of the CGIAR Challenge Program on Water and Food, and by the Michael Otto Foundation for Environmental Protection.

Appendix A

See Table A1 and Fig. A1.

Table A1
Aggregations in GTAP-W.

A. Regional aggregation	B. Sectoral aggregation
1. *USA* – United States	1. *Rice* – rice
2. *CAN* – Canada	2. *Wheat* – wheat
3. *WEU* – Western Europe	3. *CerCrops* – cereal grains (maize, millet, sorghum and other grains)
4. *JPK* – Japan and South Korea	4. *VegFruits* – vegetable, fruits, nuts
5. *ANZ* – Australia and New Zealand	
6. *EEU* – Eastern Europe	5. *OilSeeds* – oil seeds
7. *FSU* – Former Soviet Union	6. *Sug_Can* – sugar cane, sugar beet
8. *MDE* – Middle East	7. *Oth_Agr* – other agricultural products
9. *CAM* – Central America	8. *Animals* – animals
10. *SAM* – South America	9. *Meat* – meat
11. *SAS* – South Asia	10. *Food_Prod* – food products
12. *SEA* – Southeast Asia	11. *Forestry* – forestry
13. *CHI* – China	12. *Fishing* – fishing
14. *NAF* – North Africa	13. *Coal* – coal
15. *SSA* – Sub-Saharan Africa	14. *Oil* – oil
16. *ROW* – Rest of the World	15. *Gas* – gas
	16. *Oil_Pcts* – oil products
C. Endowments	17. *Electricity* – electricity
Wtr – irrigation	18. *Water* – water
Lnd – irrigated land	19. *En_Int_Ind* – energy intensive industries
RfLand – rainfed land	20. *Oth_Ind* – other industry and services
PsLand – pasture land	21. *Mserv* – market services
Lab – labour	22. *NMServ* – non-market services
Capital – capital	
NatlRes – natural resources	

Appendix B. Future baseline simulation

To obtain a 2025 benchmark equilibrium dataset for the GTAP-W model we use the methodology described by Dixon and Rimmer (2002). This methodology allows us to find a hypothetical general equilibrium state in the future imposing forecasted values for some key economic variables in the initial calibration dataset. In this way, we impose forecasted changes in regional endowments (labour, capital, natural resources, rainfed land, irrigated land and irrigation), in regional factor-specific and multi-factor productivity and in regional population. We use estimates of the regional labour productivity, labour stock and capital stock from the G-Cubed model, a multicountry, multisector intertemporal general equilibrium model of the world economy developed by McKibbin and Wilcoxen (1998). Changes in the allocation of rainfed and irrigated land within a region as well as irrigation and agricultural land productivity are implemented according to the values obtained by the IMPACT model. The information supplied by the IMPACT model (demand and supply of water, demand and supply of food, rainfed and irrigated production and rainfed and irrigated area) provides the GTAP-W model with detailed information for a robust calibration of a new dataset. Finally, we use the medium variant population estimates for 2025 from the Population Division of the United Nations (United Nations, 2004).

Compared to the 2000 baseline data (Table B1), the IMPACT model projects a growth in both harvested crop area as well as crop productivity for 2025 under normal climate conditions (Table B2). The world's crop harvested area is expected to increases by about 1.4 percent between 2000 and 2025. This is equivalent to a total area of 1.3 billion hectares in 2025, 34.4 percent of which is under irrigation. For the same period, green water used (effective rainfall) in rainfed areas is expected to increase by 27.2 percent; and both green and blue water used (water diverted from water systems) in irrigated areas are expected to increase by 33.7 and 32.1 percent, respectively. As a result, total water used in agriculture is expected to rise by 30.4 percent, to 6466 cubic kilometres in 2025.

Farmers in Sub-Saharan Africa and South Asia use around 37 percent of the world's rainfed area in 2025, which accounts for

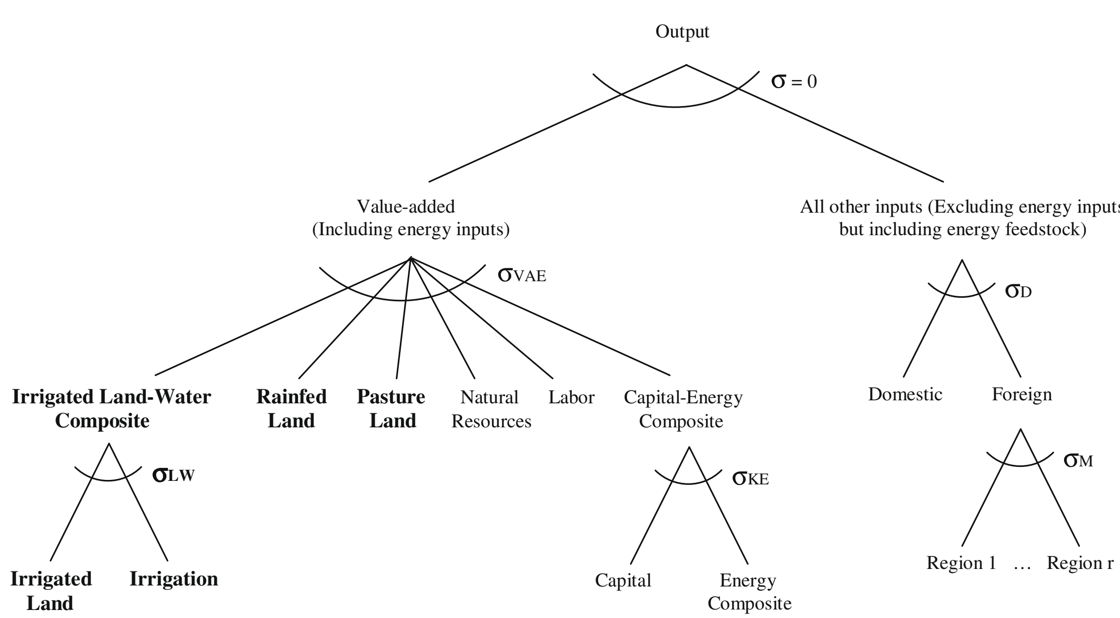

Fig. A1. Nested tree structure for industrial production process in GTAP-W (truncated). *Note*: The original land endowment has been split into pasture land, rainfed land, irrigated land and irrigation (bold letters). σ is the elasticity of substitution between value-added and intermediate inputs, σVAE is the elasticity of substitution between primary factors, σLW is the elasticity of substitution between irrigated land and irrigation, σKE is the elasticity of substitution between capital and the energy composite, σD is the elasticity of substitution between domestic and imported inputs and σM is the elasticity of substitution between imported inputs.

Table B1
2000 Baseline data: crop harvested area and production by region and crop. *Source*: IMPACT, 2000 baseline data.

Regions	Rainfed agriculture			Irrigated agriculture				Total			
	Area (thousand hectares)	Production (thousand metres)	Green water (km^3)	Area (thousand hectares)	Production (thousand metres)	Green water (km^3)	Blue water (km^3)	Area (thousand hectares)	Production (thousand metres)	Green water (km^3)	Blue water (km^3)
United States	35391	209833	89	67112	440470	159	190	102503	650303	248	190
Canada	27267	65253	61	717	6065	2	1	27984	71318	62	1
Western Europe	59494	462341	100	10130	146768	19	10	69624	609108	118	10
Japan and South Korea	1553	23080	6	4909	71056	21	3	6462	94136	27	3
Australia and New Zealand	21196	67204	45	2237	27353	5	15	23433	94557	50	15
Eastern Europe	37977	187468	95	5958	40470	16	14	43935	227939	111	14
Former Soviet Union	85794	235095	182	16793	74762	25	47	102587	309857	208	47
Middle East	29839	135151	40	21450	118989	25	62	51289	254140	65	62
Central America	12970	111615	47	8745	89637	28	46	21715	201252	76	46
South America	79244	649419	335	9897	184304	40	47	89141	833723	375	47
South Asia	137533	491527	313	114425	560349	321	458	251958	1051877	634	458
Southeast Asia	69135	331698	300	27336	191846	134	56	96471	523543	434	56
China	64236	615196	185	123018	907302	419	278	187254	1522498	604	278
North Africa	15587	51056	19	7352	78787	4	42	22938	129843	23	42
Sub-Saharan Africa	171356	439492	588	5994	43283	19	37	177349	482775	608	37
Rest of the World	3810	47466	12	1093	23931	5	5	4903	71397	16	5
World	**852381**	**4122894**	**2417**	**427164**	**3005371**	**1242**	**1310**	**1279545**	**7128265**	**3659**	**1310**
Crops											
Rice	59678	108179	264	93053	294934	408	321	152730	403113	671	321
Wheat	124147	303638	240	90492	285080	133	296	214639	588718	374	296
Cereal grains	225603	504028	637	69402	369526	187.53	221	295005	873554	824	221
Vegetables, fruits, nuts	133756	1374128	394	36275	537730	96.53	82	170031	1911858	489	82
Oil seeds	68847	125480	210	29578	73898	73	79	98425	199379	282	79
Sugar cane, sugar beet	16457	846137	98	9241	664023	49	89	25699	1510161	147	89
Other agricultural products	223894	861303	574	99122	780180	297	222	323017	1641483	871	222
Total	**852381**	**4122894**	**2417**	**427164**	**3005371**	**1242**	**1310**	**1279545**	**7128265**	**3659**	**1310**

Note: 2000 Data are 3-year averages for 1999–2001.

Table B2
2025 Baseline simulation: crop harvested area and production by region and crop. *Source*: IMPACT.

Regions	Rainfed agriculture			Irrigated agriculture				Total			
	Area (thousand hectares)	Production (thousand metres)	Green water (km^3)	Area (thousand hectares)	Production (thousand metres)	Green water (km^3)	Blue water (km^3)	Area (thousand hectares)	Production (thousand metres)	Green water (km^3)	Blue water (km^3)
United States	33561	282634	95	68312	649118	178	269	101873	931752	272	269
Canada	24547	84579	64	668	7816	2	2	25216	92395	65	2
Western Europe	49655	471745	82	9206	170610	17	13	58861	642355	99	13
Japan and South Korea	1330	25507	7	4339	72386	25	2	5669	97893	32	2
Australia and New Zealand	20574	87458	45	2211	37586	5	21	22785	125044	50	21
Eastern Europe	33620	214995	91	5411	56306	15	26	39031	271301	106	26
Former Soviet Union	83041	327597	194	16850	107271	28	62	99890	434868	222	62
Middle East	30330	171058	41	22838	192787	28	84	53169	363844	69	84
Central America	13197	177760	63	9543	149400	40	63	22740	327161	103	63
South America	89653	1305413	468	11725	391766	60	79	101378	1697179	528	79
South Asia	117502	567087	384	129479	893522	511	594	246981	1460609	895	594
Southeast Asia	73223	457800	409	27488	307826	178	76	100711	765626	587	76
China	61143	710893	227	120294	1041731	526	316	181436	1752624	753	316
North Africa	16117	79552	18	7820	114835	4	55	23937	194388	22	55
Sub-Saharan Africa	200093	727357	873	8311	98412	37	62	208404	825769	910	62
Rest of the World	4122	78566	16	1260	47376	7	8	5382	125941	23	8
Total	**851709**	**5770002**	**3075**	**445754**	**4338747**	**1660**	**1730**	**1297463**	**10108749**	**4736**	**1730**
Crops											
Rice	52329	107187	318	91357	335710	542	365	143686	442897	860	365
Wheat	115502	370764	245	88649	397007	141	336	204150	767771	387	336
Cereal grains	221740	682485	787	74630	566363	244	322	296370	1248848	1031	322
Vegetables, fruits, nuts	142260	1838783	523	41014	806515	135	147	183274	2645298	658	147
Oil seeds	71325	137662	278	30735	99416	90	111	102060	237078	368	111
Sugar cane, sugar beet	21827	1662782	173	11997	1202418	84	144	33823	2865200	257	144
Other agricultural products	226726	970340	751	107373	931317	425	305	334099	1901657	1175	305
Total	**851709**	**5770002**	**3075**	**445754**	**4338747**	**1660**	**1730**	**1297463**	**10108749**	**4736**	**1730**

Note: Linear interpolation from IMPACT 2050 simulation with no climate change.

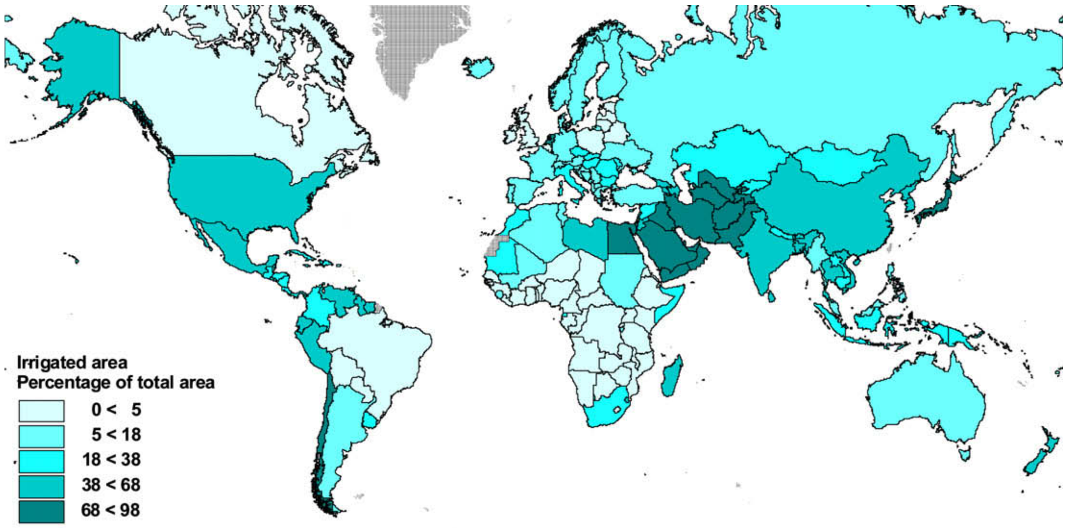

Fig. B1. Irrigated harvested area as a share of total crop harvested area, 2025 baseline simulation. *Source*: IMPACT.

about 24 percent of the world's crop area (Table B2). Similarly, 62 percent of the world's irrigated area in 2025 is in Asia, which accounts for about 21 percent of the world's crop area. Sub-Saharan Africa, South Asia and China use more than half of total green water used world-wide. Principal users of blue water are South Asia, China and the United States, using almost 70 percent of the total. On the crop level, rainfed production of "cereal grains" and "other agricultural product" consumes about half of the total green water used in dry farms. Similarly, irrigated production of "rice" and "other agricultural products" uses around half of the total green and blue water used in irrigated agriculture.

Fig. B1 shows for the 2025 baseline simulation a global map of irrigated harvested area as a share of total crop area by country. Most of the farming land in the Middle East region is nowadays highly irrigated and this situation is projected to persist in the future. Irrigated crop area in Iraq is expected to account for 92 percent of the total crop area. In Saudi Arabia and Iran, the share of irrigated area to total area is projected to be 84 and 73 percent, respectively. In the USA, approximately 67 percent of the total harvested area is expected to be under irrigation in 2025. In Asia, irrigated farming is expected to account for more than half of the total crop area in the region. By contrast, irrigated agriculture in Sub-Saharan Africa is small, only 4 percent of the total crop harvested area is expected to be irrigated by 2025. Most of the countries in Sub-Saharan Africa are expected to continue to use irrigation on less than 5 percent of crop land. Madagascar and Swaziland are exceptions expected to be irrigating around 55 percent of their total crop area. The numbers for Somalia and South Africa are much lower (34 and 22 percent, respectively).

References

AQUASTAT Online Database. <http://www.fao.org/nr/water/aquastat/data/query/index.html>.

Berrittella, M., Hoekstra, A.Y., Rehdanz, K., Roson, R., Tol, R.S.J., 2007. The economic impact of restricted water supply: a computable general equilibrium analysis. Water Research 41, 1799–1813.

Burniaux, J.M., Truong, T.P., 2002. GTAP-E: An Energy Environmental Version of the GTAP Model. GTAP Technical Paper No. 16.

Calzadilla, A., Rehdanz, K., Tol, R.S.J., 2008. Water Scarcity and the Impact of Improved Irrigation Management: A CGE Analysis. Research unit Sustainability and Global Change FNU-160, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg.

de Fraiture, C., Cai, X., Amarasinghe, U., Rosegrant, M., Molden, D., 2004. Does International Cereal Trade Save Water? The Impact of Virtual Water Trade on Global Water Use. Comprehensive Assessment Research Report 4, Colombo, Sri Lanka.

Diao, X., Roe, T., 2003. Can a water market avert the "double-whammy" of trade reform and lead to a "win–win" outcome? Journal of Environmental Economics and Management 45, 708–723.

Dixon, P., Rimmer, M., 2002. Dynamic General Equilibrium Modelling for Forecasting and Policy, North Holland.

Gómez, C.M., Tirado, D., Rey-Maquieira, J., 2004. Water exchange versus water work: insights from a computable general equilibrium model for the Balearic Islands. Water Resources Research 42, W10502. doi:10.1029/2004WR003235.

Hertel, T.W., 1997. Global Trade Analysis: Modeling and Applications. Cambridge University Press, Cambridge.

IPCC, 2001.In: McCarthy, J., Canziani, O., Leary, N., Dokken, D., White, K., Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Johansson, R.C., Tsur, Y., Roe, T.L., Doukkali, R., Dinar, A., 2002. Pricing irrigation water: a review of theory and practice. Water Policy 4 (2), 173–199.

Letsoalo, A., Blignaut, J., de Wet, T., de Wit, M., Hess, S., Tol, R.S.J., van Heerden, J., 2007. Triple dividends of water consumption charges in South Africa. Water Resources Research 43, W05412.

McDonald, S., Robinson, S., Thierfelder, K., 2005. A SAM Based Global CGE Model Using GTAP Data. Sheffield Economics Research Paper 2005:001. The University of Sheffield.

McKibbin, W.J., Wilcoxen, P.J., 1998. The theoretical and empirical structure of the G-Cubed model. Economic Modelling 16 (1), 123–148.

Plan Bleu, 2009. The Mediterranean has to take up Three Major Challenges to Ensure Sustainable Management of its Endangered Water Resources. Blue Plan Notes No. 11. United Nations Environment Programme, Mediterranean Action Plan, Plan Bleu, Regional Activity Centre, Valbonne.

Rosegrant, M.W., Cai, X., Cline, S.A., 2002. World Water and Food to 2025: Dealing with Scarcity. International Food Policy Research Institute, Washington, DC.

Shah, T., Molden, D., Sakthivadievel, R., Seckler, D., 2000. Global Groundwater Situation: Opportunities and Challenges. International Water Management Institute (IWMI), Colombo, Sri Lanka. ISBN 92-9090-402-X.

Tsur, Y., Roe, T., Doukkali, R., Dinar, A., 2004. Pricing Irrigation Water: Principles and Cases from Developing Countries. Resources for the Future, Washington, DC.

United Nations, 1993. The System of National Accounts (SNA93). United Nations, New York.

United Nations, 2003. Water for People, Water for Life. The United Nations World Water Development Report, UNESCO-World Water Assessment Programme and Berghahn Books, Paris.

United Nations, 2004. World Population to 2300. Population Division, Department of Economic and Social Affairs, United Nations, New York.

Villholth, K., Giordano, M., 2007. Groundwater use in a global perspective – can it be managed? In: Giordano, M., Villholth, K. (Eds.), The Agricultural Groundwater Revolution: Opportunities and Threats to Development. International Water Management Institute, Colombo, Sri Lanka, pp. 393–402.

Zektser, I.S., Everett, L.G. (Eds.), 2004. Groundwater Resources of the World and Their Use. UNESCO IHP-VI, Series on Groundwater No. 6, Paris.