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The economic impact of water taxes: a computable general equilibrium analysis with an international data set

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Abstract

Water is scarce in many countries. One instrument for improving the allocation of a scarce resource is (efficient) pricing or taxation. However, water is implicitly traded on international markets, particularly through food and textiles, so that the impacts of water taxes cannot be studied in isolation, but require an analysis of international trade implications. We include water as a production factor in a multi-region, multi-sector computable general equilibrium model (GTAP), to assess a series of water tax policies. We find that water taxes reduce water use and lead to shifts in production, consumption and international trade patterns. Countries that do not levy water taxes are nonetheless affected by other countries' taxes. Taxes on agricultural water use drive most of the economic and welfare impacts. Reductions in water use (welfare losses) are less (more) than linear with the price of water. The results are sensitive to the assumed ability to substitute other production factors for water. A water tax on production would have different effects on water use, production and trade patterns and the size and distribution of welfare losses than would a water tax on final consumption.

Keywords: Computable general equilibrium; Virtual water; Water allocation; Water pricing; Water scarcity

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1. Introduction

Water is one of our basic resources, but it is often in short supply. The total amount of fresh water available would be sufficient to provide the present world population with a minimally required amount of water. However, the uneven distribution of water and people between regions has made the adequate supply critical for a growing number of countries (Seckler *et al.*, 1998). Rapid population growth and increasing consumption of water per capita has aggravated the problem. Water withdrawal for most uses is projected to increase by at least 50% by 2025 compared to the 1995 level (Rosegrant *et al.*, 2002). An additional reason for concern is climate change. Climate change models predict that geographic differences in rainfall are likely to become more pronounced with increased precipitation in high latitudes and decreased rainfall elsewhere. Higher temperatures would imply larger water demand and higher evaporation (IPCC, 2001).

As the supply of water is limited, attempts have been made to economize on the consumption of water, especially in regions where the supply is critical. One way to address the problem is to reduce the inefficiencies in irrigation and urban water systems in existing water uses. In urban water systems, water is wasted through leakage. This is particularly pronounced for large cities in Africa, Asia, Latin America and even in the water-scarce Middle East (Rosegrant *et al.*, 2002). Yet, in 2000 about 70% of all water was used for agriculture[1]. For some developing countries the average irrigation efficiency is far below what is technically possible. The current level and structure of water charges mostly do not encourage farmers to use water more efficiently. For countries that are not short of water there also seems to be room for improvement (Seckler *et al.*, 1998).

An increase in water price, for instance by a tax, would lead to the adoption of improved irrigation technology (e.g. Dinar & Yaron, 1992). The water saved could be used in other sectors, for which the value is much higher. In this paper, we will not consider reallocation of water, but instead look at a reallocation of water-intensive products. National and international markets of agricultural products are affected. A complete understanding of a water pricing policy is therefore impossible without understanding the international markets for food and other agricultural products, such as textiles.

There is strong opposition to higher water prices, especially in water scarce regions. In many regions, water use is even subsidized. This is partly because of the desired aim of food self-sufficiency (Ahmad, 2000). However, food demand could be met by importing more water-intensive food from water-abundant countries and producing and exporting commodities that are less water intensive. The water embedded in commodities is also known as virtual water (Allan, 1992, 1993). So far, few studies provide estimates of the global virtual water trade (see e.g. Chapagain & Hoekstra, 2004). Changes in water prices would affect the virtual water trade. To our knowledge, this has not been investigated in a multi-region, multi-sector general equilibrium model.

Rosegrant *et al.* (2002) and Fraiture *et al.* (2004) use *partial* equilibrium models. Our *general* equilibrium approach allows for a richer set of economic feedbacks and for a complete assessment of the welfare implications. The analysis is based on countries' total renewable water resources and differences in water productivity. Growing wheat in North Africa requires more water than growing it in Germany. Also, different crop types have different crop water requirements and regions grow different crop varieties. The production of a ton of rice is, for example, more water intensive than the production of a

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[1] Data are taken from AQUASTAT.

tonne of wheat. Berrittella *et al.* (2007) use GTAP-W, a computable general equilibrium (CGE) model including water resources, to analyse the economic impact of restricted water supply for water-short regions. In contrast, this study is concerned with demand management, using a *price* rather than *quantity* instrument to regulate water use. In economic theory, under certainty, price and quantities are their duals, and price and quantity instruments have the same effect. However, the politics of prices and quantities are very different. Moreover, quantity instruments are, for all practical purposes, limited to primary production, whereas price instruments can be used at production as well as at consumption levels.

In this paper, we present the GTAP-W model and illustrate its potential application to water pricing policies. We use arbitrary water tax scenarios, as our main concern is methodological. We aim to demonstrate that water tax policies would generate spillover effects for economic activities and water consumption in other industries and regions than those taxed. This analysis complements the one in Berrittella *et al.* (2007), in which we use the same model for different policy simulations.

Section 2 reviews the literature on water pricing. Section 2 also shows that our approach is complementary to what other people have done, as the price of economic comprehensiveness is a lack of detail in production and space. Section 3 presents the model used and the data on water resources and water use. The basic model and the corresponding data can be purchased from the Global Trade and Analysis Project (http://www.gtap.agecon.purdue.edu/). The water data can be downloaded at: http://www.fnu.zmaw.de/GTAP-EF-W.5680.0.html. Section 4 discusses four alternative scenarios. Section 5 presents results. Section 6 concludes.

2. Previous studies

Problems in the water sector are mostly caused by the large difference between the private and the social price of water. The difference is due to policy failures (subsidies), institutional failures (lack of well defined and enforced land and water rights) and market failures (environmental costs that are not internalized). A number of studies investigate the role of water price policies in order to allocate water resources more efficiently, equitably and sustainably. They differ with respect to study area (cross-country, national, regional) and sector analysed (residential, industry, agriculture). Some studies have looked at the implementation and objectives of price policies in the water sector (e.g. Dinar & Subramanian, 1998; Jones, 1998; Ahmad, 2000; Rogers *et al.*, 2002). Other studies have analysed the economic value of water, the costs of its provision and the price of its use (Rogers *et al.*, 1998; Ward & Michelsen, 2002; Young, 2005).

In order to obtain insights from alternative water policy scenarios for 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. Most of the studies using either of the two approaches analyse pricing of irrigation water only (for an overview of this literature see Johannson *et al.*, 2002). Rosegrant *et al.* (2002) use the IMPACT-Water model to estimate demand and supply of food and water up until 2025. Fraiture *et al.* (2004) extend this to include the virtual water trade, using cereals as an indicator. Their results suggest that the role of virtual water trade is modest. While the IMPACT-Water 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 effects for the rest of the world of the implemented policy. Decaluwe *et al.* (1999)

analyse the effect of water pricing policies on demand and supply of water in Morocco. Daio & Roe (2003) use an inter-temporal CGE model for Morocco focusing on water and trade policies. Seung *et al.* (2000) use a dynamic CGE model to estimate the welfare gains of reallocating water from agriculture to recreational use for the Stillwater National Wildlife Refuge in Nevada. For the Arkansas River Basin, Goodman (2000) shows that temporary water transfers are less costly than building new dams. Gómez *et al.* (2004) analyse the welfare gains from improved allocation of water rights for the Balearic Islands. Letsoalo *et al.* (2007) study the effects of tax reform on water use, economic growth and income distribution in South Africa.

Berrittella *et al.* (2007) are an exception, using a multi-country CGE model including water resources (GTAP-W). They analyse the economic impact of restricted water supply for water-short regions. They contrast a market solution, where water owners can capitalize their water rent, to a non-market solution, where supply restrictions imply productivity losses. They show that water supply constraints could improve allocative efficiency, as agricultural markets are heavily distorted. The welfare gain may more than offset the welfare losses caused by the resource constraint. In contrast to Berrittella *et al.* (2007), this study is concerned with demand management (rather than with changes in water supply); this paper investigates the economic implications of water pricing policies.

3. Modeling framework and data

To assess the systemic, general equilibrium effects on water resource demand induced by different policy scenarios, we use a multi-region world CGE model, called GTAP-W. The model is a refinement of the GTAP model[2] (Hertel, 1997) in the version modified by Burniaux & Truong (2002)[3]. Basically, in the GTAP-W model, a finer industrial and regional aggregation level, respectively, 17 sectors and 16 regions, is considered. and water resources have been modelled as non-market goods[4]. Some characteristics are given in (Table A1 in the Annex. The model is based on 1997 data.

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 CES functions (see Berrittella *et al.*, 2007, for more detailed information). Domestic and foreign inputs are not perfect substitutes, according to the so-called "Armington assumption", which accounts for product heterogeneity.

A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, land, labour and capital). Capital and labour are perfectly mobile

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[2] 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.

[3] Burniaux & Truong (2002) developed a 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.

[4] The 17 sectors are rice; wheat; other cereals and crops; vegetables and fruits; animals; forestry; fishing; coal mining; oil; natural gas extraction; refined oil products; electricity; water collection, purification and distribution services; energy intensive industries; other industry and services; market services; non-market services.

Table A1. Regional characteristics.

	Population	GDP/cap	Renewable water resource*		Water use	Water intensity in agriculture†	Water intensity other‡	Water imports	Water exports
	Million	US$	$10^9 m^3$ per year	m^3/person[§]	$10^9 m^3$ per year	m^3/US$	m^3/US$	$10^9 m^3$	$10^9 m^3$
USA	276	28,786	3,069	11,120	479	2.9	3.7	57	125
CAN	30	20,572	2,902	96,733	46	4.3	5.2	8	51
WEU	388	24,433	2,227	5,740	227	2.6	3.5	256	96
JPK	172	35,603	500	2,907	107	1.4	1.6	82	0
ANZ	22	21,052	819	37,227	26	4.1	1.2	3	30
CEE	121	2,996	494	4,083	60	3.3	13.6	19	6
FSU	291	1,556	4,730	16,254	284	9.1	28.0	27	61
MDE	227	3,150	483	2,128	206	4.9	6.8	35	19
CAM	128	2,938	1,183	9,242	101	5.2	13.6	25	31
LAM	332	4,830	12,246	36,886	164	3.9	5.9	35	68
SAS	1289	416	3,685	2,859	918	9.8	47.5	21	25
SEA	638	4,592	5,266	8,254	279	10.1	12.8	58	35
CHI	1,274	790	2,897	2,274	630	3.6	38.5	33	16
NAF	135	1,284	107	793	95	8.5	39.5	27	4
SSA	605	563	4,175	6,901	113	11.4	6.4	14	132
ROW	42	3,338	2,984	71,048	75	4.7	2.7	6	8

[*] 2001 estimates taken from Aquastat.

[†] Average water intensity covering crop/plant growth and animal production measured in water use/US$ output. Numbers differ considerably between countries and sectors. Note that water use includes the use of different kinds of sources; rain, soil moisture and irrigation water. However, farmers pay for irrigation water only.

[‡] Note that in some countries only a low number of persons is connected to a distribution network. In others a number of self-supplied industries are not connected. However, both are included as users of the services that the water distribution network provides. As a consequence, water use per US$ of output is overstated in the above table.

[§] UN criterion for water resource scarcity degree: slightly scarce (1,700–3,000), middle scarce (1,000–1,700), severe scarcity (500–1,000) and most severe scarcity (<500).

domestically, but immobile internationally. Land (imperfectly mobile) and natural resources are industry specific. The national income is allocated between aggregate household consumption, public consumption and savings (see Berrittella *et al.*, 2007, for more detailed information). 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. A money metric measure of economic welfare, the equivalent variation can be computed from the model output.

In the GTAP model and its variants, two industries are treated in a special way and 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, thereby determining the cost margin between free on board (f.o.b.) and cost insurance and freight (c.i.f.) prices. 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.

In our modelling framework, water is combined with the value-added-energy nest and the intermediate inputs (see Berrittella *et al.*, 2007, for more detailed information). As in the original GTAP model, there is no substitutability between intermediate inputs and value-added for the production function of tradable goods and services. In the benchmark equilibrium, water supply is supposed to be unconstrained, so that water demand is lower or equal to water supply and the price for water is zero. Water is supplied to the agricultural industry, which includes primary crop production and livestock and to the water distribution services sector, which delivers water to the rest of the economic sectors[5].

The key parameter for the determination of regional water use is the water intensity coefficient. This is defined as the amount of water necessary for sector j to produce one unit of commodity[6]. To estimate water intensity coefficients, we first calculated total water use by commodity and country for the year 1997. For the agricultural sector the FAOSTAT database provided information about the production of primary crops and livestock. This includes detailed information on different crop types and animal categories. Information on water requirements for crop growth and animal feeding was taken from Chapagain & Hoekstra (2004)[7]. The water requirement includes both the use of blue water (ground and surface water) as well as green water (moisture stored in soil strata). For crops it is defined as the sum of water needed for evapotranspiration, from planting to harvest and depends on crop type and region. This procedure assumes that water is not in short supply and no water is lost by irrigation inefficiencies. For animals, the virtual water content is mainly the sum of water needed for feeding and drinking. The water intensity parameter for the water distribution sector is based on the country's industrial and domestic water use data provided by AQUASTAT[8].

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[5] Note that *distributed* water can have a price, even if primary water resources are in excess supply.

[6] This refers to water directly used in the production process, not to the water indirectly needed to produce other input factors.

[7] This information is provided as an average over the period from 1997 to 2001. By making use of this data we assume that water requirements are constant at least in the short term.

[8] This information is based on data for 2000. By making use of this data we assume that domestic and industrial water uses in 2000 are the same as in 1997.

We make the link between output levels and water demand sensitive to water prices, by assuming that more expensive water brings about rationalization in usage and substitution with other factors. The actual capability to reduce the relative intensity of water demand is industry specific and captured by an industrial water price elasticity parameter (Table 1).

4. Scenarios

We run four alternative simulation exercises, each dealing with the economic impact of water pricing policies.

In the base scenario (scenario 1), we impose a water charge of US\$10 m per 10^9 m^3 of water for all users. This is equivalent to a price increase of ¢1 per cubic metre of water. The aim of this scenario is to test how much water saving can be achieved and at what economic cost.

As a first sensitivity analysis, in the second scenario (scenario 2), we lower the price to ¢0.5/m^3. The value of water differs not only between countries but also between the various sectors. Prices for agricultural water use are generally lower compared to domestic water use; most expensive is industrial water use (see e.g. Dinar & Subramanian, 1998; Ahmad, 2000). Variable costs for agricultural water use, for example, range between zero and US\$0.39 per m^3. Compared with these numbers, our water taxes are small. There are two reasons for this. First, farmers grow crops with three different sources of water; rain, soil moisture and irrigation water. However, they only pay for irrigation water. The average price for all three uses is, therefore, small. We do not differentiate between water sources because of data limitations. Second, industrial water use is defined as the water use by self-supplied industries, not connected to any distribution network. “Domestic” water use is computed as the total amount of water supplied by public distribution networks and usually includes the withdrawal by industries connected to public networks. However, in the model,

Table 1. Water price elasticities.

	Country region	Agricultural sectors	Water distribution services
USA	United States	−0.14	−0.72
CAN	Canada	−0.08	−0.53
WEU	Western Europe	−0.04	−0.45
JPK	Japan and Korea	−0.06	−0.45
ANZ	Australia and New Zealand	−0.11	−0.67
EEU	Eastern Europe	−0.06	−0.44
FSU	Former Soviet Union	−0.09	−0.67
MDE	Middle East	−0.11	−0.77
CAM	Central America	−0.08	−0.53
SAM	South America	−0.12	−0.80
SAS	South Asia	−0.11	−0.75
SEA	Southeast Asia	−0.12	−0.80
CHI	China	−0.16	−0.80
NAF	North Africa	−0.07	−0.60
SSA	Sub-Saharan Africa	−0.15	−0.80
ROW	Rest of the world	−0.20	−0.85

Q1 Source: Our elaboration from Rosegrant *et al.* (2003).

all industrial and domestic water use, connected to a public network or not, is included as customers of the water distribution network.

Scenario 3 is a variant of scenario 1. Water taxes are introduced in water-short regions only, viz. North Africa (NAF), South Asia (SAS), the United States (USA) and China (CHI). These regions use more groundwater than is recharged (cf. Berrittella *et al.*, 2007).

In scenarios 1–3, water is taxed when used in production. In scenario 4, final consumption is taxed, proportional to the water used in the production of the consumption goods. We apply a water charge of US\$10 m per 10^9m^3 of water.

In all scenarios, the revenue from the water tax is redistributed in a lump sum to the representative household.

5. Simulation results

Results for all scenarios described in Section 4 are presented in Tables 2–5, reporting water demand, virtual water trade balance, GDP, trade balance and welfare. The virtual water trade balance reports, similar to the trade balance, the difference between a region's exports and its imports measured in water quantities.

In scenario 1, reported in Table 2, we simulate a water tax of US\$10 m per 10^9 m^3 for water. The increase in water prices leads to a decrease in water demand in all regions, except in Western Europe. This region has a low-water intensity and shows little sensitivity to changes in prices for water. Consequently, although water prices increase, agricultural production is raised and water-intensive products are exported to other regions. The virtual water trade balance is positive for Western Europe. North Africa exhibits the highest reduction in water demand. This is because the water intensity of this

Table 2. Scenario 1: Uniform change in the regional water rent (US\$10 m per 10^9 m^3 of water).

	Water demand (%)	Virtual water trade balance (change in 10^9 m^3)	GDP (%)	Trade balance (change in million US\$)	EV welfare (change in million US\$)
USA	−1.45	4.31	−0.003	−4719	1766
CAN	−3.69	−1.99	0.016	−72	449
WEU	0.45	24.78	0.011	−4863	1135
JPK	−0.19	4.97	0.001	−3961	816
ANZ	−1.23	−0.47	0.008	−197	394
EEU	−3.54	2.27	−0.028	663	−280
FSU	−12.20	−6.85	−0.024	1092	−712
MDE	−6.63	−0.89	−0.024	1913	−1448
CAM	−4.10	−1.78	0.012	57	102
SAM	−0.62	4.02	0.004	93	583
SAS	−5.25	−5.01	−0.069	2644	−842
SEA	−2.73	3.49	−0.029	1862	−781
CHI	−7.58	2.37	−0.011	2006	−365
NAF	−19.25	−3.72	−0.119	1097	−1123
SSA	−6.85	−25.58	−0.115	2278	−428
ROW	−1.73	0.07	−0.004	106	−112

Table 3. Scenario 2: Uniform change in the regional water rent (US$5 m per 10^9 m^3 of water).

	Water demand (%)	Virtual water trade balance (change in 10^9 m^3)	GDP (%)	Trade balance (change in million US$)	EV welfare (change in million US$)
USA	−0.76	1.97	−0.001	−2247	830
CAN	−1.84	−0.97	0.009	−29	222
WEU	0.19	12.29	0.005	−2278	477
JPK	−0.10	2.53	0.000	−1873	372
ANZ	−0.72	−0.30	0.004	−93	187
EEU	−1.86	1.12	−0.013	330	−139
FSU	−6.50	−3.40	−0.007	522	−307
MDE	−3.33	−0.44	−0.008	911	−661
CAM	−2.04	−0.86	0.008	26	63
SAM	−0.34	1.89	0.002	62	266
SAS	−2.75	−2.33	−0.020	1235	−320
SEA	−1.35	1.69	−0.012	874	−355
CHI	−4.31	1.16	−0.004	995	−173
NAF	−8.90	−1.54	−0.013	474	−407
SSA	−3.35	−12.86	−0.040	1039	−127
ROW	−0.86	0.03	−0.002	53	−53

region is high. The water tax leads to a net increase in virtual water imports in regions that are relatively water intensive, such as North Africa, sub-Saharan Africa and South Asia. These are also the regions with limited water resource availability. Water-short countries partly meet their demand for water-intensive products by importing them. Global welfare falls owing to the increase in water prices and the restriction of a scarce resource. However, welfare losses are not universal; some regions gain as their competitive position improves, such as the USA and Western Europe.

Table 4. Scenario 3: Uniform change in regional water rent for water short countries (US$10 m per 10^9 m^3).

	Water demand (%)	Virtual water trade balance (change in 10^9 m^3)	GDP (%)	Trade balance (change in million US$)	EV welfare (change in million US$)
USA	−2.56	−6.22	0.002	−518	782
CAN	1.87	2.54	−0.001	−179	101
WEU	0.61	5.12	0.003	−2817	780
JPK	0.19	0.57	−0.005	−1567	−66
ANZ	4.76	3.36	0.003	−125	152
EEU	0.24	0.30	0.005	−141	35
FSU	0.49	1.22	−0.001	−166	−38
MDE	0.95	1.27	−0.011	−203	−261
CAM	0.74	1.38	−0.009	−30	−58
SAM	0.54	2.89	0.008	−499	320
SAS	−5.62	−9.68	−0.069	2831	−951
SEA	0.15	1.51	−0.003	−6	−117
CHI	−8.04	−1.72	−0.001	2360	−416
NAF	−21.09	−8.10	−0.099	1222	−818
SSA	0.69	5.15	0.010	−101	132
ROW	0.19	0.42	0.002	−61	12

Table 5. Scenario 4: Water taxation on consumption (US$10 m per 10^9 m^3 of water).

	Water demand (%)	Virtual water trade balance (change in 10^9 m^3)	GDP (%)	Trade balance (change in million US$)	EV welfare (change in million US$)
USA	−2.10	−2.19	0.000	−3919	671
CAN	−3.08	−1.54	0.007	44	29
WEU	−0.83	−3.81	0.015	−4609	2629
JPK	−0.53	−0.13	0.009	−4354	1998
ANZ	−2.67	−1.36	−0.001	−46	−96
EEU	−3.37	−0.15	−0.017	431	−105
FSU	−7.44	0.01	−0.015	1182	−537
MDE	−1.72	0.39	−0.032	1584	−1092
CAM	−1.96	0.00	0.000	173	−90
SAM	−1.32	−0.81	−0.009	357	−392
SAS	−3.76	2.40	−0.067	2602	−755
SEA	−2.02	1.77	−0.031	1963	−453
CHI	−6.29	−0.15	−0.004	1585	−201
NAF	−3.16	0.59	−0.015	555	−253
SSA	−3.12	4.99	−0.079	2317	−1049
ROW	−1.50	0.01	−0.005	136	−118

Applying the water tax only to agricultural sectors (results not shown), total water demand is higher than in the first scenario, because there is no change in the water charge for the water distribution services sector. The more water-intensive are the agricultural sectors, the higher is the deficit in terms of virtual water trade balance. Overall, taxing agricultural water use only is a reasonably effective policy. It deviates from the optimum of taxing all water use, but the welfare loss is limited.

The scenario results depend to some extent on water price elasticity (results not shown). If there is no flexibility in water intensity at the level of farms and water distribution companies, countries cannot improve their water efficiency in domestic production. The global water demand is higher (decreases less) than in scenario 1. On the regional level the change in demand differs; demand decreases less, increases rather than decreases, or increases more depending on the regions' water price elasticity as well as the water-intensity coefficient. Global welfare decreases more, because the resource constraint is more stringent. Although the regional pattern is the same as in scenario 1, regions with higher price elasticities suffer more if they cannot improve their water efficiency in domestic production.

Table 3 reports the simulation results of scenario 2, where water is taxed at US$5 m per 10^9 m^3. As expected, water demand falls, but less so than in scenario 1. Comparing the two sets of results, the reduction in water demand is slightly less than linear for the water tax. Water price increase is half the amount of scenario 1, but water demand decreases more than 50% for most regions. Welfare falls in the more water-intensive countries, such as North Africa and the Middle East, but less so than in scenario 1. The opposite occurs for more water efficient regions, such as Western Europe and the USA. At world level, welfare falls, but a factor 7 less so than in scenario 1 (−US$125 m compared to −US$846 m).

In scenario 3, we increase the water charges only for water-short regions, viz. North Africa, China, the USA and South Asia (see Table 4). The water demand decreases in these four regions, more so in the less water efficient ones, such as North Africa. In terms of the virtual water trade, as expected, an increase in the water price leads to an increase in virtual water imports in the constrained regions and to a decrease in virtual water exports. On the other hand, a deficit in terms of virtual water trade is not always accompanied by a negative variation in the trade balance. For example, in North Africa, South Asia and China, the trade balance improves. The USA, South Asia and China lose in terms of welfare, relative to scenario 1. On the other hand, North Africa gains because the increase in the imports of water-intensive goods is less expensive than in scenario 1. Global welfare decreases in scenario 3, but less so than in scenario 1, as water prices increase in some regions only. Increasing water charges in four regions reduces the world welfare by half the amount an increase in water rent for all 16 regions would lead to. Furthermore, excluding the USA from the list of water-restricted countries affects water savings only slightly (from 2.7–2.6%), but reduces the world welfare loss substantially, from a welfare loss of US$413 m to a welfare loss of US$281 m (results not shown).

In scenario 4, final consumption of water-intensive commodities and services is taxed instead of taxating factor inputs. Taxing water in this way leads to a decrease in the demand for water in all regions. In this scenario, the reductions in water resource uses are more uniform amongst regions than in scenario 1 and global water demand changes less. Furthermore, changes in virtual water trade are substantially lower. Unlike in any other scenario, global welfare increases. Particularly, Western Europe, Japan and South Korea gain more, while the Middle East and sub-Saharan Africa are the main losers. However, compared to scenario 1, welfare changes are generally less negative in many regions. The more a region imports water-intensive commodities, the more that region gains compared to the first scenario. This shows that it matters how the costs of water resources use are internalized, as this determines the options for substituting away from water, as well as the distribution of the burden.

6. Discussion and conclusion

In this paper, we present a computable general equilibrium model of the world economy with water as an explicit factor of production. We use the model to test water taxes under different scenarios. In the base scenario, we simulate a water charge of US$10 m per 10^9 m^3 of water. As expected, the water demand decreases in many regions, but some regions find it profitable to raise the production of water-intensive commodities in order to export them. The world as a whole is worse off, although some countries gain as their competitive position improves. Water demand falls are less than linear in the water tax; welfare losses are more than linear in the water tax. The impact of a water tax is more pronounced if it is harder to improve water efficiency. Furthermore, any water price policy should take into account who and what is taxed. Water taxes in agriculture drive most of the effects and virtually all of the trade effects. A tax in water-scarce regions only would lead to a shift in agricultural trade and an increase in water demand elsewhere. A water tax in some countries, particularly the USA, contributes little to water savings but substantially to welfare losses. There is a clear trade-off between water savings and welfare change. A tax on the final consumption of water rather than on the use of water in production would be less effective in reducing water use, but would be less costly; while the distributional and trade effects are very different.

For some world regions, the water supply is already critical. Rapid population growth and increasing consumption per capita has further aggregated the problem. An additional reason for concern is climate change. Today, most problems in the water sector are caused by large differences between the private and the social price of water. Although an optimal policy would include all water-using sectors, a water tax on agriculture, the main water user, has a significant impact on water savings already. Such a policy would considerably reduce the gap between the private and the social cost of water. For water-short countries, it would be beneficial if water is not taxed abroad. Water taxes in water-rich countries would further increase market prices for agricultural goods and raise the price of imported water-intensive products. To limit the negative impact of rising world market prices for water-intensive products, a water tax should be accompanied by policies promoting the substitutes for water-intensive products, improved irrigation, limiting water leakage and improved efficiency. Another important issue is the crop mix. A different mix with less water-demanding crops, which are perhaps also more adapted to heat, might reduce water demand further. Trade liberalization might help as well, as it stimulates substitution.

The analysis establishes two things. First, domestic policies to conserve water, here implemented by a water tax, have ramifications for international trade. As a result, national water policies are interconnected and should, at the least, not be set in ignorance of other countries' water policies. Second, the effects of water policy on national economies and international trade can gainfully be studied with a computable general equilibrium model. The data used in this paper to extend the GTAP-CGE, are in the public domain.

This analysis needs to be extended in several ways and a number of limitations apply. First, we have not been able to allocate industrial water use to its different users. We rather used a simplifying assumption that water for domestic and industry use is supplied by the water service sector. Second, we consider regional water supply, implicitly assuming that there is a perfect water market and costless water transport within each region. Sector-specific water resources allow for sub-regional differentiation of water resources, but only to a limited extent. Third, we were not able to differentiate between the different qualities of water supplied. Some, but not all, of the difference is captured by defining sector-specific water. Fourth, in our model we assume that water is used efficiently and no water is wasted. The water intensity coefficient captures some differences, but these differences do not respond to price or other signals, except to the price of water. Fifth, for the agricultural sector, we used irrigation water plus rainfall, without distinction; water use is gross water use, ignoring evapotranspiration by crops. Sixth, we nested water at the upper level in the production function of the water intensive goods and services, so that water cannot be substituted by specific inputs in the production processes. Seventh, we used a single data set for water use and water resources, ignoring the uncertainties in the data. All this is deferred to future research.

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