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WATER SCARCITY AND WORLD TRADE: A COMPUTABLE GENERAL EQUILIBRIUM APPROACH

Katrin REHDANZ

Hamburg University
Germany

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THE ECONOMIC IMPACT OF RESTRICTED WATER SUPPLY: A COMPUTABLE GENERAL EQUILIBRIUM ANALYSIS

Maria Berrittella[a], Arjen Y. Hoekstra[b], Katrin Rehdanz[c], Roberto Roson[d,e,f] and Richard S.J. Tol[c,g,h]

[a] *Centro Interdipartimentale di Ricerche sulla Programmazione Informatica dell'Economia e delle Tecnologie (CIRPIET), University of Palermo, Palermo, Italy*

[b] *Department of Water Engineering and Management, University of Twente, Enschede, The Netherlands*

[c] *Research unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, Germany*

[d] *Environmental and Ecological Economics Programme, Abdus Salam International Centre for Theoretical Physics, Trieste, Italy*

[e] *Department of Economics, University Ca' Foscari, Venice, Italy*

[f] *Fondazione Eni Enrico Mattei, Venice, Italy*

[g] *Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands*

[h] *Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA*

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Abstract

Water problems are typically studied at the level of the river catchment. About 70% of all water is used for agriculture, and agricultural products are traded internationally. A full understanding of water use is impossible without understanding the international market for food and related products, such as textiles. The water embedded in commodities is called virtual water. Based on a general equilibrium model, we offer a method for investigating the role of water resources and water scarcity in the context of international trade. We run five alternative scenarios, analysing the effects of water scarcity due to reduced availability of fossil groundwater. This can be a consequence of physical constraints, and of policies curbing water demand. Four scenarios are based on a "market solution", where water owners can capitalize their water rent or taxes are recycled. In the fifth "non-market" scenario, this is not the case; supply restrictions imply productivity losses. Restrictions in water supply would shift trade patterns of agriculture and virtual water. These shifts are larger if the restriction is larger, and if the use of water in production is more rigid. Welfare losses are substantially larger in the non-market situation. Water-constrained agricultural producers lose, but unconstrained agricultural produces gain; industry gains as well. As a result, there are regional winners and losers from water supply constraints. Because of the current distortions of agricultural markets, water supply constraints could improve allocative efficiency; this welfare gain may more than offset the welfare losses due to the resource constraint.

Keywords: Computable General Equilibrium, Sustainable Water Supply, Virtual Water, Water Scarcity

JEL Classification: D58, Q25, Q28

1 Introduction

Water is one of our basic resources, but it is often short. Estimates have shown that the total amount of water available would be sufficient to provide the present world population only with a minimum amount of freshwater required. However, the uneven distribution of water (and population) among regions has made the adequate supply critical for a growing number of countries. A rapid population growth and an increasing consumption of water per capita has aggravated the problem. This tendency is likely to continue as water withdrawal for most uses is projected to increase by at least 50% by 2025 compared to 1995 level (Rosegrant *et al.* 2002). One additional reason for concern is (anthropogenic) climate change. Climate change models predict that geographic differences in rainfall are likely to become more pronounced with increased precipitation in high latitudes, and reduced precipitation in continental interiors. The predictions for temperature indicate that the majority of the warming is expected to occur during winter months and in high latitude countries (IPCC, 1998, 2001).

Water problems are typically defined and studied at the level of the river catchment, if not at a finer spatial scale. This is a valid approach for many applications. Yet, 70% of all water is used for agriculture, and agricultural products are traded internationally. A complete understanding of water use is therefore impossible without understanding the international markets for food and other agriculture related products, such as textiles. This study offers a method of studying the role of water resources and water scarcity in the context of international trade.

Previous studies have introduced the term “virtual water” to indicate the implicit water content of internationally traded commodities. E.g., Chapagain and Hoekstra (2004) calculate a global virtual water flow of 16% of total global water use. However, these studies are descriptive: virtual water flows are estimated, but changes in either water resources or economic circumstances cannot be readily assessed. In contrast, our model allows for the analysis of virtual water flows for many scenarios, within a framework consistent with economic theory. Furthermore, the model belongs to a class of empirical tools (CGE) which has been extensively used for trade liberalization, development, and fiscal policy analysis.

Other studies, notably Rosegrant *et al.* (2002), use partial equilibrium models for scenario studies. Our general equilibrium approach allows for a richer set of economic feedbacks and for a complete assessment of welfare implications. The analysis is based on countries’ total renewable water resources and differences in water productivity. For example, we account for the fact that growing wheat in North African countries requires more water than growing it in the US. Also, different crop types have different water requirements: the production of a ton of rice is more water intensive than the production of a ton of wheat.

In this paper, we present a computable general equilibrium model, especially designed to account for water resources (GTAP-W), and illustrate its potential application for sustainable water supply uses. Section 2 reviews the literature, highlighting the original contribution of our model, which appears to be truly the first global, multi-regional, multi-sectoral trade model with virtual water flows. Section 3 presents the model and the data on water resources and use. The basic model and economic data are derived from the Global Trade and Analysis Project (http://www.gtap.agecon.purdue.edu/). Section 4 discusses five alternative scenarios. Section 5 analyses the results. Section 6 discusses and concludes.

2 Previous studies

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. For some developing countries, the average irrigation efficiency is far below what is achievable. But even for countries not being short of water there seems to be room for improvement (Seckler *et al.*, 1998). Theoretical and empirical studies have shown that an increase in water price is positively correlated with adoption of improved irrigation technology (Dinar and Yaron, 1992). However, in many regions water is actually subsidized. In urban water systems, water for either domestic or industrial use 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, as the inefficiencies are unevenly spread over regions the potential for savings is generally limited.

An alternative strategy to meet the increasing demand for water is the desalination of brackish or seawater. Continued progress in desalination technology has lead to considerably lower costs of water produced by desalination and thereby rapidly expanding desalination techniques in arid, semi-arid and water-short regions. Today, the costs are competitive with those of long-distance water transport systems, where water is transported from places where it is abundant to places where it is scarce (Ettouney *et al.*, 2002). However, desalination is not a solution for all regions. Zhou and Tol (2005) find that the transportation of desalinated water becomes prohibitively expensive in highlands and continental interiors.

Another possibility to minimize water use in water-short countries is to increase imports of products that require a lot of water in their production. The water embedded in commodities is also called *virtual water* (Allan, 1992, 1993).[1] A recent study by the UNESCO-IHE Institute for Water Education on global virtual water trade, for the period 1997-2001, revealed that in order to produce e.g. one ton of husked rice, on average 3,000 m^3 of virtual water are necessary (see Chapagain and Hoekstra, 2004).[2] For livestock products the numbers are much higher. Due to differences in climate conditions and animal diets, the water use numbers differ significantly between countries. According to Chapagain and Hoekstra (2004), 61% of the global virtual water trade is related to international trade in crops, 17% is related to trade in livestock and livestock products and only 22% is related to trade in industrial products. In total, 16% of water used in the world for agricultural and industrial production is exported as virtual water. Countries like the US, Canada, Australia, Argentina and Thailand are the biggest net exporters of virtual water, whereas Japan, Italy, UK, Germany and South Korea are the biggest net importers. If these figures are weighted against a country’s endowment of water resources the picture is quite different. In relative terms, countries in the Middle East and North Africa import a lot of virtual water. On the other hand, USA, Canada, South America and Australia are exporting a significant share of their water resources.

As the water requirement for food production is large, virtual water might be seen as an additional source of water for water-scarce countries. Indeed, much of the existing literature stresses the political relevance and emphasizes the role of virtual water in providing food security in water-short regions (Bouwer, 2000; Allan and Olmsted, 2003). Some researchers have even argued that virtual water trade could perhaps prevent wars over water (Allan, 1997). Others fear that regions become dependent on global trade and vulnerable to market fluctuations. However, most countries have no explicit strategy for virtual water trade (Yang and Zehnder, 2002). Another branch of the literature has compared the concept of virtual

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[1] We use the production site definition. The virtual water content of a product can also be defined as the volume of water that would have been required to produce the product in the place where it is consumed (consumption site specific definition).

[2] Earlier studies are Hoekstra and Hung (2003, 2005); Chapagain and Hoekstra (2003).

water trade to the economic concept of comparative advantages (see e.g. Wichelns, 2001, 2004; Hakimian, 2003).

Although the concept of virtual water trade is appealing, the number of empirical studies is limited. Two other studies exist that provide estimates on global virtual water trade, one by the World Water Council (WWC), in collaboration with the FAO (Food and Agricultural Organization of the United Nation), and another one by a Japanese research group.[3] Although different in data and methodology, results are close to the ones obtained by the UNESCO-IHE. Others have investigated why the virtual water trade balance is positive for some countries and negative for others. Yang *et al.* (2003) found evidence that virtual water import for cereals increases with decreasing water resources. Hoekstra and Hung (2003, 2005) compared water scarcity and water dependency and found unexpected results for some countries.

One aspect, which has not attracted much attention so far are changes in virtual water trade over time. Yang *et al.* (2003) used population predictions to calculate the annual water deficit for water-scarce countries by 2030.[4] Unsurprisingly, they found an exponential increase. Rosegrant *et al*. (2002) used the IMPACT-WATER model to estimate demand and supply of food and water to 2025.[5] In their most recent paper, they included virtual water trade, using cereals as an indicator (Fraiture *et al*.,2004). Their results suggest that the role of virtual water trade is modest, but these findings have been obtained in a partial equilibrium analysis, in which non-agricultural sectors are mainly excluded.

Studies using general equilibrium approaches typically focus on a single country or region. Decaluwe *et al.* (1999) analyze the effect of water pricing policies on demand and supply of water in Morocco. Daio and Roe (2003) use an intertemporal CGE model for Morocco, analysing water and trade policies. For the Arkansas River Basin, Goodman (2000) shows that temporary water transfers are less costly than building new dams. Gómez *et al*. (2004) analyze the welfare gains of improved allocation of water rights in the Balearic Islands. These studies have an explicit representation of water as a factor of production. Other studies use agricultural productivity (e.g., Horridge *et al*., 2005) or land use as a proxy for water (e.g., Seung *et al*., 2000). Letsoalo *et al.* (2005) treat water as a cost factor only.

Our analysis is different. In this paper, we include water as an endowment in the production structure of the economy. We use a computable general equilibrium model *of the world economy* to analyze the implications of reduced supply of water in water-scarce countries. This always implies an increase in the relative price of water-intensive products, a change in relative competitiveness for all industries and regions and changes in the terms of trade (which benefit water-abundant regions). We consider various scenarios, and study the effects on virtual water flows, international trade, and welfare.

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[3] Results for the first study are reported by Renault (2003) and Zimmer and Renault (2003) and for the second by Oki *et al.* (2003).

[4] Calculations are based on cereal imports.

[5] Scenarios for water demand and supply to 2025 are provided by Seckler *et al.* (1998). A detailed analysis of the world water situation by 2025 is given by Alcamo *et al.* (2000).

3 Modeling framework and data

In order to assess the systemic general equilibrium effects of restricted water supply, we use a multi-region world CGE model, called GTAP-W. The model is a refinement of the GTAP model[6] (Hertel, 1997) in the GTAP-E version modified by Burniaux and Truong[7] (2002). Basically, in the GTAP-W model a finer industrial and regional aggregation level, respectively, 17 sectors and 16 regions, is considered, and water resources, as non-marketed goods, have been modeled.[8] 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 modeled through a representative firm, which maximizes profits in perfectly competitive markets. The production functions are specified via a series of nested CES functions (*figure A1 in Annex*). 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 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 (*figure A2 in Annex*). 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 f.o.b. and 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 modeling framework, water is combined with the value-added-energy nest and the intermediate inputs as displayed in *figure A1 (Annex)*. As in the original GTAP model, there is no substitutability between intermediate inputs and value-added for the production function of tradeable goods and services. In the benchmark equilibrium, water supply is supposed to be unconstrained, so that water demand is lower than 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.[9] Furthermore, water is mobile between the different agricultural sectors. However, water is immobile between agriculture and the water distribution services

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[6] 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.

[7] The GTAP variant developed by Burniaux and Truong (2002) 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.

[8] See *Annex table A1* for the regional, sectoral and factor aggregations used in GTAP-W.

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

sector, because the water treatment and distribution is very different between agricultural and other uses. We change this assumption in a sensitivity analysis.

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.[10] 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 on 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 and Hoekstra (2004).[11] 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 sum of water needed for evapotranspiration, from planting to harvest, and depends on crop type and region. This procedure assumes that water is not short 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.[12]

The mechanism through which water scarcity is introduced into the model is the potential emergence of economic rents associated with water resources. If supply falls short of demand, consumers would be rationed, and willing to pay a price to access to water, because water has an economic value, as it is needed in production. If water resources are privately or collectively owned, the owners receive an economic rent, which becomes a component of available income. The price for water is then set by the market at a level, which makes water demand compatible with supply.[13] Therefore, we introduce a constraint on water amounts, in our model, which entails the creation of a new market and a new exchanged commodity. Finally, we make the link between output levels and water demand sensitive to water prices. In other words, we assume that more expensive water brings about rationalization in usage and substitution with other factors. The actual capability of reducing the relative intensity of water demand is industry-specific, and captured by an industrial water price elasticity (*Table 1*).

Table 1 about here

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

[11] 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.

[12] 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.

[13] In this setting, water supply is assumed to be completely inelastic (vertical). By introducing technologies for "effective" water production, the supply function could, however, be positively sloped.

4. Design of simulation exercises

We run five alternative simulation exercises, all dealing with the economic impacts of restricted water supply.

In particular, we deny the use of fossil groundwater as a source of water. There are two possible, alternative interpretations. First, regulators can decide that groundwater should not be pumped faster than it is replenished. Second, groundwater resources can run dry. Pumping groundwater from aquifers at a rate faster than it replenishes clearly violates sustainability constraints. We subtract the excess use of groundwater from the total amount of available water resources by country (assumed to be equal to water demand in the calibration year), as specified by FAO's AQUASTAT database. Also, we add sustainable water resources per basin, as specified by Rosegrant *et al.* (2002). It turns out that water supply would be restricted in four regions: North Africa (NAF), South Asia (SAS), United States (USA) and China (CHI).

In the first four scenarios, we consider the “market mechanism” to the problem of water scarcity. In the first scenario, NAF is the region with the greatest decrease in water supply, facing a shortage of 10%. For the other regions, the water supply constraints are less substantial. In SAS and USA, water supply decreases by 1.58%, and in CHINA by 3.92%. Scenario 2 can be regarded as an example of what would happen to an economy when sustainable water supply policies are delayed, and unexpected and severe shortages in water availability occur. In this scenario, NAF faces an instantaneous shortage of 44%; (the water supply constraints in the other regions do not change). Scenarios 3 and 4 are both variants of scenario 1. In particular, in scenario 3 we assume that water is specific of any agricultural sector, that is, water is not mobile amongst the agricultural sectors, and in scenario 4 water price elasticities are set equal to zero for all industries.

The main limitation of the market approach is given by the implicit assumption that property rights on water resources can be defined and enforced, which is not always the case. For this reason, in scenario 5, we provide an alternative mechanism that does not require the creation of a competitive market. When water gets scarce, but there is no way of buying more water on the market, the main effect will be a reduction of production for the same level of non-water factor inputs. This is equivalent to a drop in productivity in water demanding industries. The fall in productivity also makes produced goods more expensive, reducing their demand and, indirectly, that for water. This scenario uses the same constraints as in scenario one.

There is an alternative interpretation. Above, we assume that the water supply is constrained. In the market scenarios (1-4), the water users can reap the increase in rent due to the restriction on the resources; the non-market scenario (5), the water users cannot use this rent, for instance because water property rights are implicit and cannot be used as assets on the capital market. In the alternative interpretation, the regulator restricts water supply by imposing a tax. In scenarios 1-4, the tax is recycled to the water users proportional to their water use. In scenario 5, the tax money is not recycled. Economically, and in our model, the two interpretations are equivalent. The interpretation are not the same from an environmental policy perspective; in the first interpretation, the water is not there; in the second interpretation, the water is there but cannot be used by humans.

5 Simulation results

Results for all scenarios described in section 4 are presented in Tables 2 to 7. The tables report values for some key economic variables: water demand, water rent, virtual water trade balance, trade balance, welfare indexes.

In scenario 1, reported in Table 2, we simulate water reductions in NAF, CHI, USA and SAS. The difference in water rent between agriculture and the water distribution services is due to the fact that water distribution is much more responsive to price changes than the agricultural sector (see Table 1). Notice that, although USA and SAS face the same water supply constraint, water prices are higher in the USA. Also, CHI has a significant lower water supply constraint than NAF, but its water rent is higher (3 Cent per m^3) than in NAF (0.5 Cent per m^3). These differences cannot be explained in terms of differences in water price elasticity (as can be easily checked by looking at Table 1). Nonetheless, there are two ways to reduce the amount of water demand: reducing water in water-demanding industries, and reducing demand for goods produced with water. This latter, indirect water demand reduction may be achieved in two ways: substitution in production and consumption with other goods, and substitution with goods of the same type, but produced abroad. Additional imports, however, require an expansion of exports in other industries and/or an increase of foreign direct investments. Results suggest that this indirect demand reduction is the primary determinant of prices in water markets.

Table 2 about here

In terms of virtual water trade, as expected, less water supply leads to an increase in virtual water import in the constrained regions, and to a decrease in virtual water exports. This is due to the relatively more expensive production of water intensive goods and services in the constrained regions. Water-short countries can meet their demand of water-intensive products by importing them (Wichelns, 2004). 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 NAF, SAS and CHI the trade balance improves.

Global welfare falls as production is constrained. Some unconstrained regions gain, however, as their competitive position in agriculture improves. More importantly, agricultural prices increase relative to industrial prices, benefiting industrial sectors and countries. The USA also gain, despite the fact that its water supply is constrained. This is because the loss of agricultural exports is more than offset by its gains in industrial exports. Moreover, the model has the full suite of current market distortions through tariffs and subsidies. Constraints on the US water supply reduce agricultural overproduction, and welfare rises as a result.

Table 3 shows production levels for the water-intensive sectors. In water constrained regions, cereal production and industrial and domestic water use fall; in other regions, the opposite effect occurs, in most cases. The production of vegetable and fruits, and of animals, may go up or down.

Table 3 about here

Table 4 reports the simulation results of scenario 2, where we increase the water constraint for NAF to 44%. Compared to scenario 1, notice that a more severe water reduction in one region, leads not only to a higher water rent in that particular region, but in other constrained regions as well. Water demand in unconstrained regions is also higher, to sustain the increase in imports of water-intensive products in the constrained countries. Furthermore, a higher water supply constraint enforces the effects on the virtual water trade balance. Overall, in scenario 2, NAF is worse off than in scenario 1, both in terms of welfare and real GDP, as expected. Welfare losses increase tenfold, even though the supply constraint goes up by a factor of less than five. Although many other regions are actually better off, because NAF is relatively less competitive, the loss in welfare in NAF substantially decreases the world welfare. This suggests that any country aiming at sustainable water supply should reduce the supply gradually rather than instantaneously. JPK is one of the regions that is better off. Although it pays more for its agricultural imports, its industrial exports increase; the latter effect dominates.

Table 4 about here

In the third scenario, we assume that water is sector specific, that is, water is immobile between agricultural sectors. In addition, as water is nested at the upper level in the production function of the water intensive goods and services, it cannot be substituted with other inputs in the production processes. The difference in the resulting marginal water rents in these sectors is related to their water intensity coefficients. In more water-efficient sectors, such as animal husbandry, the marginal water rents rise more (see Table 5). Animal husbandry need less water per unit of output than do crops. The price increase is particularly pronounced for NAF with a water price of \$63 per m^3 of water for a 10% fall in water supply; this follows from the fact that water is already used very efficiently in this sector and region. In general, NAF, SAS and CHI import more virtual water. Furthermore, they shift their domestic production to water-extensive goods and services, which also increases imports of such goods, leading to gains in the terms of trade. Compared to scenario 1, the restriction of the water mobility increases slightly the competitiveness of the other countries, resulting in a higher GDP. Immobile water resources lead to a *lower* loss of global welfare. This is surprising. The welfare of most regions is lower in scenario 3 than in scenario 1, as one would expect. The two main exceptions are WEU and JPK. Both regions improve their terms of trade, as industrial exports increase. Without water supply constraints, WEU also enjoys a competitive advantage in agriculture. Allocative welfare also improves in both regions, as regional and world prices for agricultural products converge. Note that global welfare in fact *increases* in scenario 3: the current agricultural economy is so distorted that a reduction in production improves welfare.

Table 5 about here

Scenario 4 considers the same case as scenario 1, but the water price elasticity is set to zero in all industries; that is, the water intensity parameters are the same between the base and the policy scenario. This signifies less flexibility at the level of farms and water distribution companies. Water rents are higher than in scenario 1, and the difference is more pronounced in water price sensitive countries such as CHI and SAS, and, for the same reason, in the water distribution industry (see Table 6). Furthermore, as the constrained countries cannot improve their water efficiency in domestic production, they satisfy their demand of water-intensive products by increasing the imports more than in scenario 1, as the results in terms of virtual water trade indicate. NAF, CHI and SAS gain in terms of trade due to their increase of exports of water-extensive products. As the world welfare decreases in scenario 4 more than it does in scenario 1, the world would benefit from a policy, which leads to higher water efficiency.

Table 6 about here

Scenario 5 is based on the “non-market” mechanism, that is, water users cannot reap the increase in resource rents or, equivalently, the water tax is not recycled. In this scenario, productivity is decreased so as to meet the water supply constraints, which are the same as in scenario 1. The resulting productivity change differs between agriculture and water distribution services, and amongst the constrained regions (see Table 7). Productivity decreases faster in less water-efficient sectors. The pattern of variations in the virtual water balance are as in scenario 1, but the absolute changes are greater. The global loss in welfare is considerably larger, even though some regions gain more. In the non-market scenario, each region with a supply constraint, including the USA, loses welfare.

Table 7 about here

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. To an experienced CGE modeller, it should be known how to include an extra production factor – in principle. This paper contributes by doing this – in practice. Previously, this was not possible because the necessary data were missing – at least at the global scale, as water is a non-market good, not reported in national economic accounts. Earlier studies included water resources at the national or smaller scale. These studies necessarily miss the international dimension, which is important as water is implicitly traded in international markets, mainly for agricultural products.

In our model, sector specific water resources are introduced as production factors in the agricultural sectors and the water distribution service sector. Water is mobile between the different agricultural sectors, but immobile between agriculture and the water distribution service sector (which delivers water to the rest of the economic sectors). As water is mainly required for agricultural production, we disaggregated agricultural production into five different sectors. This allows us to gain a wider insight into the implications of different water resource policies. In the model, water use is also country specific, as are water resources. This allows for differentiated responses, in which some countries specialise in water-intensive agricultural products.

We illustrate the new model by studying the implications of increased water scarcity, with a particular focus on groundwater resources. Other applications can be thought of, and we are working on a number of them. The excess use of groundwater resources is an unambiguous example of future reductions in water supply, either through policy or through nature. Computable general equilibrium models are best at analysing structural economic change. In this case, the change is a regionally and sectorally differentiated fall in water supply.

In the base scenario, we restrict water supply in some regions, but not in others. As expected, water use increases in the unconstrained regions as trade patterns shift; unconstrained regions produce and export more water-intensive products. The world as a whole is worse off, as production is constrained. However, some countries gain, as relative prices change. Interestingly, the USA is among the winners even though its water supply is constrained as well. This is partly due to distortionary subsidisation of agricultural production in the USA; water constraints temper the resulting overproduction.

If water constraints are higher, so are welfare gains and losses; however, welfare gains respond less than proportionally, and welfare losses more than proportionally. Shifts in trade patterns are also larger. If water is less mobile, the economy has less ability to adapt, and water constraints have a more negative welfare impact in most regions. At the same time, regional welfare gains are more pronounced as well, so redistribution is amplified. In fact, the positive effects dominate the negative effects, so that global welfare increases; this is a sign that current agricultural markets are severely distorted. If water use is less flexible, the negative effects dominate. If water users cannot reap the higher rents induced by water scarcity (alternatively, if the government does not recycle the water tax), overall welfare losses are much higher, but again, so are the welfare gains in some of the regions that benefit. The USA, however, would be net losers in this scenario. Even though the physical input scenario is identical in 4 out of 5 scenarios, the realignment of agricultural trade is different in all cases; as a result, the actual water use is unique to each scenario.

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. The price is the same for all industries (except agriculture). 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 subregional 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 of the difference is captured by defining sector-specific water, but not all. 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. 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 with 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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Annex

Table A1. Aggregations in GTAP-W

A. Regional Aggregation

1. USA - United States

2. CAN - Canada

3. WEU – Western Europe

4. JPK – Japan and Korea

5. ANZ – Australia and New Zealand

6. EEU – Eastern Europe

7. FSU – Former Soviet Union

8. MDE – Middle East

9. CAM – Central America

10. SAM – South America

11. SAS – South Asia

12. SEA – Southeast Asia

13. CHI - China

14. NAF – North Africa

15. SSA – Sub-Saharan Africa

16. ROW – Rest of the world

B. Endowments

1. Land

2. Labour

3. Capital

4. Natural Resource

C. Sectoral Aggregation

1. Rice - Rice

2. Wheat - Wheat

3. CerCrops - Other cereals and crops

4. VegFruits - Vegetable, Fruits

5. Animals - Animals

6. Forestry - Forestry

7. Fishing – Fishing

8. Coal - Coal Mining

9. Oil – Oil

10. Gas - Natural Gas Extraction

11. Oil_Pcts - Refined Oil Products

12. Electricity – Electricity

13. Water - Water collection, purification and distribution services

14. En_Int_ind - Energy Intensive Industries

15. Oth_ind - Other industry and services

16. MServ - Market Services

17. NMServ - Non-Market Services

Figure A1 – Nested tree structure for industrial production process

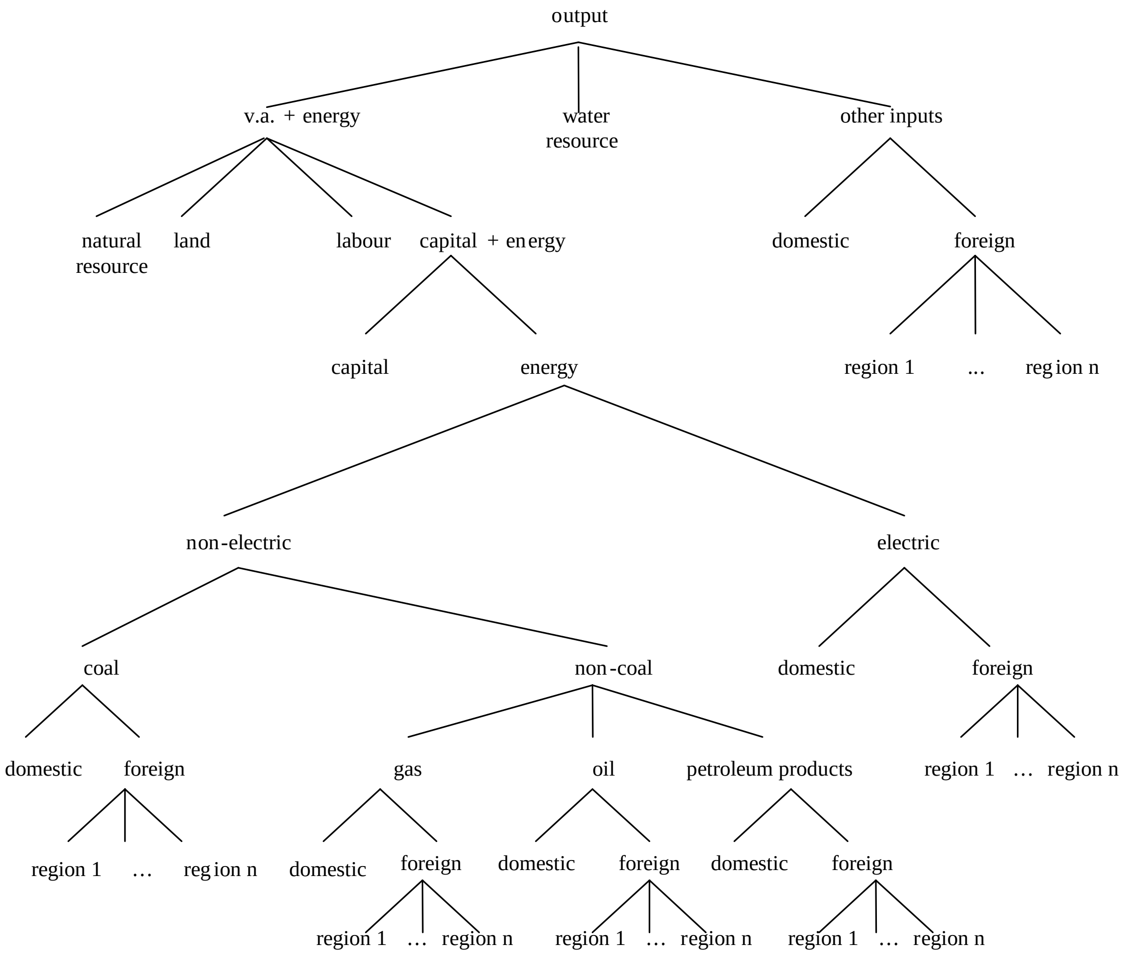
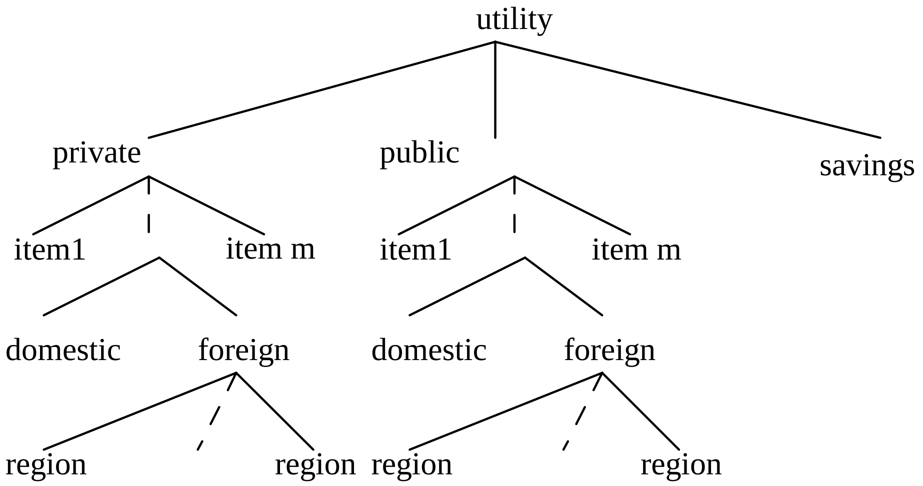


Figure A2 – Nested tree structure for final demand



Figures and Tables

Table 1. Water price elasticities

	Agricultural sectors	Water distribution services
1 USA	-0.14	-0.72
2 CAN	-0.08	-0.53
3 WEU	-0.04	-0.45
4 JPK	-0.06	-0.45
5 ANZ	-0.11	-0.67
6 EEU	-0.06	-0.44
7 FSU	-0.09	-0.67
8 MDE	-0.11	-0.77
9 CAM	-0.08	-0.53
10 SAM	-0.12	-0.80
11 SAS	-0.11	-0.75
12 SEA	-0.12	-0.80
13 CHI	-0.16	-0.80
14 NAF	-0.07	-0.60
15 SSA	-0.15	-0.80
16 ROW	-0.20	-0.85

Source: our elaboration from Rosegrant et al.(2002).

Table 2. Scenario 1: Water supply constraints

	Water demand (%)	Water rent (mln $ per billion m^3 of water)		Virtual water trade balance (change in billion m^3)	GDP (%)	Trade balance (change in mln $)	EV welfare (change in mln $)
		Agricultural sector	Water distribution				
USA	-1.58	9.17	3.80	-5.74	0.002	-885	847
CAN	1.87	0.00	0.00	2.50	-0.001	-167	94
WEU	0.49	0.00	0.00	3.93	0.002	-2611	578
JPK	0.25	0.00	0.00	-0.06	-0.012	-1308	-558
ANZ	3.20	0.00	0.00	2.35	0.003	-115	114
EEU	0.17	0.00	0.00	0.23	0.004	-132	28
FSU	0.41	0.00	0.00	1.11	-0.001	-155	-28
MDE	0.79	0.00	0.00	0.87	-0.010	-201	-226
CAM	0.69	0.00	0.00	1.29	-0.008	-29	-49
SAM	0.46	0.00	0.00	2.51	0.008	-471	294
SAS	-1.58	4.52	0.30	-3.58	-0.010	1009	-243
SEA	0.18	0.00	0.00	1.33	-0.004	55	-156
CHI	-3.92	28.60	1.17	-7.76	0.013	4629	-706
NAF	-10.00	5.45	2.47	-3.71	-0.002	532	-307
SSA	0.59	0.00	0.00	4.31	0.009	-101	160
ROW	0.21	0.00	0.00	0.42	0.002	-49	0

Table 3. Variations in production levels (scenario 1)

	Market solution					
	Rice	**Wheat**	**Other cereals and crops**	**Vegetables and Fruits**	**Animals**	**Water distribution**
USA	-1.10	-3.27	-0.14	-1.59	0.13	-0.57
CAN	3.85	5.07	2.27	0.83	-0.14	0.02
WEU	3.06	0.75	0.84	0.35	0.16	0.06
JPK	0.09	3.46	1.93	0.26	0.08	0.01
ANZ	1.04	6.13	1.89	0.89	0.15	0.04
EEU	1.41	0.30	0.47	0.05	0.10	0.04
FSU	0.08	0.56	1.28	0.41	0.23	0.03
MDE	0.62	1.11	1.39	0.32	0.09	0.02
CAM	0.68	1.35	0.80	0.54	-0.14	0.04
SAM	0.08	0.87	1.22	0.15	0.00	0.02
SAS	-0.44	-2.15	-0.77	-0.39	-0.31	-0.50
SEA	-0.02	2.79	1.67	0.13	0.12	0.07
CHI	-0.14	-4.92	-7.61	-0.87	-1.77	-0.41
NAF	-12.59	-0.46	-13.05	0.11	0.07	-4.58
SSA	-0.09	0.95	1.20	0.34	0.00	0.05
ROW	0.00	0.11	0.62	0.08	0.05	0.03

Table 4. Scenario 2: Sustainable water supply constraints

	Water demand (%)	Water rent (mln $ per billion m^3 of water)		Virtual water trade balance (change in billion m^3)	GDP (%)	Trade balance (change in mln $)	EV welfare (change in mln $)
		Agricultural sector	Water distribution				
USA	-1.58	11.25	3.82	-4.58	0.002	-1271	1270
CAN	2.49	0.00	0.00	3.34	-0.001	-229	124
WEU	0.99	0.00	0.00	7.56	0.004	-3742	1200
JPK	0.30	0.00	0.00	0.12	-0.012	-1922	-424
ANZ	4.01	0.00	0.00	2.91	0.003	-158	150
EEU	0.38	0.00	0.00	0.59	0.006	-155	59
FSU	0.65	0.00	0.00	1.81	-0.005	-181	-105
MDE	1.38	0.00	0.00	1.47	-0.013	-250	-349
CAM	1.02	0.00	0.00	1.84	-0.012	-31	-68
SAM	0.91	0.00	0.00	4.86	0.012	-622	527
SAS	-1.58	4.73	0.31	-3.18	-0.010	1037	-196
SEA	0.24	0.00	0.00	2.14	-0.004	77	-147
CHI	-3.92	29.32	1.17	-7.52	0.011	4703	-711
NAF	-44.00	17.86	14.68	-22.01	-0.882	2932	-3388
SSA	1.36	0.00	0.00	10.05	0.017	-121	282
ROW	0.29	0.00	0.00	0.60	0.004	-66	10

Table 5. Scenario 3: Water sector specific

	Water demand (%)	Water rent (mln $ per billion m^3 of water)						Virtual water trade balance (change in billion m^3)	GDP (%)	Trade balance (change in mln $)	EV welfare (change in mln $)
		Rice	Wheat	Other cereals and crops	Vegetables and fruits	Animals	Water distribution				
USA	-1.58	11.08	8.04	10.48	9.97	597.23	3.81	-4.74	0.002	-1086	900
CAN	2.39	0.00	0.00	0.00	0.00	0.00	0.00	2.87	-0.001	-312	154
WEU	0.71	0.00	0.00	0.00	0.00	0.00	0.00	4.47	0.007	-5252	1639
JPK	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.31	-0.003	-3166	389
ANZ	2.95	0.00	0.00	0.00	0.00	0.00	0.00	2.00	0.005	-230	170
EEU	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.009	-275	74
FSU	0.58	0.00	0.00	0.00	0.00	0.00	0.00	2.01	-0.004	-279	-87
MDE	1.09	0.00	0.00	0.00	0.00	0.00	0.00	1.68	-0.012	-463	-338
CAM	0.64	0.00	0.00	0.00	0.00	0.00	0.00	1.13	-0.009	-141	-48
SAM	0.48	0.00	0.00	0.00	0.00	0.00	0.00	2.66	0.011	-923	416
SAS	-1.58	5.71	2.37	5.08	8.37	20.35	0.33	-3.75	-0.016	1484	-289
SEA	0.29	0.00	0.00	0.00	0.00	0.00	0.00	1.13	-0.002	-140	-74
CHI	-3.92	62.57	18.08	12.44	54.89	53.65	1.18	-5.57	-0.008	7998	-1601
NAF	-10.00	6.38	31.10	4.45	100.85	63585.53	2.58	-9.82	-0.136	3110	-1311
SSA	0.60	0.00	0.00	0.00	0.00	0.00	0.00	4.96	0.013	-204	219
ROW	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.006	-121	30

Table 6. Scenario 4: No water price elasticities

	Water demand (%)	Water rent (mln $ per billion m^3 of water)		Virtual water trade balance (change in billion m^3)	GDP (%)	Trade balance (change in mln $)	EV welfare (change in mln $)
		Agricultural sector	Water distribution				
USA	-1.58	12.78	10.40	-7.20	0.002	-1408	1242
CAN	2.83	0.00	0.00	3.75	-0.001	-272	153
WEU	0.73	0.00	0.00	5.51	0.004	-4304	991
JPK	0.38	0.00	0.00	-0.58	-0.017	-2243	-768
ANZ	5.23	0.00	0.00	3.86	0.004	-190	188
EEU	0.27	0.00	0.00	0.31	0.007	-226	49
FSU	0.62	0.00	0.00	1.60	0.000	-270	-29
MDE	1.15	0.00	0.00	1.22	-0.014	-357	-336
CAM	1.01	0.00	0.00	1.76	-0.012	-71	-67
SAM	0.67	0.00	0.00	3.57	0.012	-777	452
SAS	-1.58	7.79	0.76	-6.73	-0.030	1868	-530
SEA	0.27	0.00	0.00	1.75	-0.005	47	-231
CHI	-3.92	41.43	6.86	-11.57	0.001	7863	-1418
NAF	-10.00	6.00	5.22	-4.07	-0.012	596	-395
SSA	0.86	0.00	0.00	6.22	0.014	-171	252
ROW	0.32	0.00	0.00	0.60	0.004	-85	5

Table 7. Scenario 5: Non-market solution

	Water demand (%)	Technical augmenting change (%)		Virtual water trade balance (change in billion m^3)	GDP (%)	Trade balance (change in mln $)	EV welfare (change in mln $)
		Agricultural sector	Water distribution				
USA	-1.58	-3.08	-4.15	-8.74	-0.131	-816	-9439
CAN	3.42	0.00	0.00	4.02	-0.004	-369	170
WEU	1.06	0.00	0.00	6.88	0.005	-5642	1193
JPK	0.40	0.00	0.00	-0.21	-0.013	-3180	-415
ANZ	4.28	0.00	0.00	2.97	0.003	-230	193
EEU	0.40	0.00	0.00	0.39	0.007	-239	57
FSU	0.99	0.00	0.00	3.29	-0.005	-263	-146
MDE	1.73	0.00	0.00	2.10	-0.027	-264	-756
CAM	1.23	0.00	0.00	2.08	-0.017	-51	-105
SAM	0.85	0.00	0.00	4.54	0.014	-970	550
SAS	-1.58	-4.96	-1.93	-7.22	-1.796	2171	-9782
SEA	0.48	0.00	0.00	2.07	-0.007	91	-342
CHI	-3.92	-9.02	-29.58	-13.18	-2.533	8621	-26292
NAF	-10.00	-14.22	-13.99	-8.35	-3.462	1418	-7688
SSA	1.08	0.00	0.00	8.53	0.014	-191	263
ROW	0.44	0.00	0.00	0.83	0.004	-87	2

Working Papers

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