# WATER SCARCITY AND THE IMPACT OF IMPROVED IRRIGATION MANAGEMENT: A COMPUTABLE GENERAL EQUILIBRIUM ANALYSIS

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**Abstract**

We use the new version of the GTAP-W model to analyze the economy-wide impacts of enhanced irrigation efficiency. 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. The results indicate that a water policy directed to improvements in irrigation efficiency in water-stressed regions is not beneficial for all. For water-stressed regions the effects on welfare and demand for water are mostly positive. For non-water scarce regions the results are more mixed and mostly negative. Global water savings are achieved. Not only regions where irrigation efficiency changes are able to save water, but also other regions are pushed to reduce irrigation water use.

**Keywords:** Computable General Equilibrium, Irrigation, Water Policy, Water Scarcity, Irrigation Efficiency

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## 1 Introduction

Aristotle wondered why useless diamonds are expensive, while essential drinking water is free. Any economist since Jevons knows that this is because diamonds are scarce, while water is abundant – at least, when Aristotle lived. Nowadays, water is scarce and therefore should command a price. However, both water management and economics have been slow to adapt to this new reality. This article contributes directly to the latter and indirectly to the former.

Several factors contribute to water scarcity. Average annual precipitation may be low, or it may be highly variable. Moreover, population growth and an increasing consumption of water per capita have resulted in a rapid increase in the demand for water. This tendency is likely to continue as water consumption for most uses is projected to increase by at least 50% by 2025 compared to 1995 level (Rosegrant et al. 2002). Since the annually renewable fresh water available in a particular location is typically constant, water scarcity is increasingly constraining food production.

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 (Seckler et al. 1998; Dinar and Yaron 1992). Since the agricultural sector accounts for about 70 percent of renewable fresh water use worldwide one way to address the problem is to reduce the inefficiencies in irrigation. Irrigated agriculture uses about 18 percent of the total arable land and produces about 33 percent of total agricultural output (Johansson et al. 2002). However, expanding irrigated areas might not be sufficient to ensure future food-security and meet the increasing demand for water in populous but water-scarce regions (Kamara and Sally 2004).

Furthermore, in many regions water is free or subsidized (Rosegrant et al. 2002) and for many countries the average irrigation efficiency is low (Seckler et al. 1998). The current level and structure of water charges mostly do not encourage farmers to use water more efficiently. An increase in water price, for instance by a tax, would lead to the adoption of improved irrigation technology and water savings (e.g. Dinar and Yaron 1992; Tsur et al. 2004; Easter and Liu 2005). The water saved could be used in other sectors, for which the value is much higher. More efficient use would enhance sustainable irrigation with lower environmental impacts including soil degradation (erosion, salination, etc.). However, there are many components of water pricing which make it difficult to determine the marginal value of water (see e.g. Johansson et al. 2002). Furthermore, in their study for northern China, Yang et al. (2003) point out that pricing alone is not enough to encourage water conservation. Water rights need to be clearly defined and legally enforceable, responsibilities for water operators and users identified. Wichelns (2003) discusses the importance of non-

water inputs and farm-level constrains for water use and agricultural productivity. He investigates policies that modify farm-level input and output prices directly, international trade policies, policies that revise regulations on land tenure and sources of investment funds.

An alternative, although limited, strategy to meet the increasing demand for water is the use of non-conventional water resources including desalination of seawater, purification of highly brackish groundwater, harvesting of rainwater, as well as the use of marginal-quality water resources (Ettouney et al. 2002; Zhou and Tol 2005; Qadir et al. 2007). Continued progress in desalination technology has lead to considerably lower costs for water produced. However, costs are still too high for agricultural use. Marginal-quality water contains one or more impurities at levels that might be harmful to human and animal health.

Most of the existing literature related to irrigation water use investigates irrigation management, water productivity and water use efficiency. One strand of literature compares the performance of irrigation systems and irrigation strategies in general (e.g. Pereira 1999; Pereira et al. 2002). Others have a clear regional focus and concentrate on specific crop types. To provide a few examples from this extensive literature; Deng et al. (2006) investigate improvements in agricultural water use efficiency in arid and semiarid areas of China. Bluemling et al. (2007) study wheat-maize cropping pattern in the North China plain. Mailhol et al. (2004) analyze strategies for durum wheat production in Tunisia. Lilienfeld and Asmild (2007) estimate excess water use in irrigated agriculture in western Kansas.

As the above examples indicate, water problems related to irrigation management are typically studied at the farm-level, the river-catchment-level or the country-level. About 70 percent of all water is used for agriculture, and agricultural products are traded internationally. A full understanding of water use and the effect of improved irrigation management 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, based on GTAP 6, to analyze the economy-wide impacts of enhanced irrigation efficiency. The new production structure of the model introduces water as an explicit factor of production and accounts for substitution possibilities between water and other primary factors. The new GTAP-W model differentiates between rainfed and irrigated crops, which allows a better understanding of the use of water resources in agricultural sectors. Efforts towards improving irrigation management, 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 article is to analyze if improvements in irrigation 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. Because the regional and sectoral resolutions are crude, the model cannot be used directly for advice on national let alone local water policy.

The remainder of the article is organized as follows: the next section briefly reviews the literature on economic models of water use. Section 3 presents the new GTAP-W model and the data on water resources and water use. Section 4 lays down the three simulation scenarios with no constraints on water availability. Section 5 discusses the results and section 6 concludes.

## 2 Economic models of water use

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 focus 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 Johannson et al. 2002). Rosegrant et al. (2002) use the IMPACT model to estimate demand and supply of food and water to 2025. 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 is 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 of water use 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. Therefore, none of these studies is able to look at the global impact of improvements in irrigation management. Decaluwé et al. (1999) analyze the effect of water pricing policies on demand and supply of water in Morocco. Diao and Roe (2003) use an intertemporal computable general equilibrium (CGE) model for Morocco focusing on water and trade policies. Diao et al. (2008) extend a general equilibrium-water model to analyze groundwater resources and rural-urban water transfer in Morrocco. 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. Letsoalo et al. (2007)

and van Heerden et al. (forthcoming) study the effects of water charges on water use, economic growth, and the real income of rich and poor households in South Africa. For the Arkansas River Basin, Goodman (2000) shows that temporary water transfers are less costly than building new dams. Strzepek et al. (2008) estimate the economic benefits of the High Aswan Dam. Gómez et al. (2004) analyze the welfare gains by improved allocation of water rights for the Balearic Islands. Feng et al. (2007) use a two-region recursive dynamic general equilibrium approach based on the GREEN model (Lee et al. 1994) to assess the economic implications of the increased capacity of water supply through the Chinese South-to-North Water Transfer (SNWT) project. All of these CGE studies have a limited geographical scope.

Berrittella et al. (2007) are an exception. They use a global CGE model including water resources (GTAP-W, version 1) to analyze 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 actually improve allocative efficiency, as agricultural markets are heavily distorted. The welfare gain from curbing inefficient production may more than offset the welfare losses due to the resource constraint. Berrittella et al. (forthcoming, a) use the same model to investigate the economic implications of water pricing policies. They 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. Like Feng et al. (2007), Berrittella et al. (2006) analyze the economic effects of the Chinese SNWT project. Their analysis offers less regional detail but focuses in particular on the international implications of the project. Berrittella et al. (forthcoming, b) extend the previous papers by looking at the impact of trade liberalization on water use.

In this article we use the new version of the GTAP-W model to analyze the economy-wide impacts of enhanced irrigation management through higher levels of irrigation efficiency. The crucial distinction between version 2 of GTAP-W, used here, and version 1, used by Berrittella et al., is that version 2 distinguishes rainfed and irrigated agriculture while version 1 did not make this distinction.

## 3 The new GTAP-W model

In order to assess the systemic general equilibrium effects of improved irrigation management, 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[2] (2002) 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, 7 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 figure 1 represents the new production structure.

*Figure 1 about here*

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 crop the value of land included in the GTAP social accounting matrix into the value of rainfed

[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 Annex I for the regional, sectoral and factoral aggregation used in GTAP-W.

land and the value of irrigated land using its proportionate contribution to total production (see Annex II, table A1).[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 (see Annex II, table A2).[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 sector. On average, producing rice using irrigation is relatively more productive than using irrigation for growing oil seeds, for example. Regions like South America seems to grow on average relatively more using irrigation instead of rainfed agriculture compared to countries in North Africa or Sub-Saharan Africa.

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).

The GTAP-W model accounts only for water resources used in the agricultural sector, which consumes about 70 percent of the total freshwater resources. Domestic, industrial and environmental water uses are not considered by the model, because the necessary data are missing at a global scale. Therefore, the model does not account for alternative uses of water outside the agricultural sector. Even when water used in municipal and industrial sectors is typically considered to have a higher value than in agriculture.

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

[4] Let us assume 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.

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) (figure 1). 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, 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. 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 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 (figure 1). The procedure how the elasticity of factor substitution between land and irrigation ($\sigma_{LW}$) was

obtained is explained in more detail in Annex III.[6] 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 original elasticity of substitution between primary factors ($\sigma_{VAE}$) is used for the new set of endowments.

In the benchmark equilibrium, water used for irrigation is supposed to be identical to the volume of 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 SAM information about payments to factors and the volume of water used in irrigation from IMPACT. In this article enhanced irrigation management including more efficient irrigation water use is introduce in the model through higher levels of productivity in irrigated production.

## 4 Design of simulation scenarios

Performance and productivity of irrigated agriculture is commonly measured by the term irrigation efficiency. For a detailed description and evolution of the irrigation efficiency terminology see Burt et al. (1997) and Jensen (2007), respectively. In a finite space and time, FAO (2001) defines irrigation efficiency as the percentage of the irrigation water consumed by crops to the water diverted from the source of supply. It distinguishes between conveyance efficiency, which represents the efficiency of water transport in canals, and the field application efficiency, which represents the efficiency of water application in the field.

In this article, the term irrigation efficiency indicates the ratio between the volume of irrigation water beneficially used by the crop to the volume of irrigation water applied to the crop. In this sense, no distinction is made between conveyance and field application efficiency. Therefore any improvement in irrigation efficiency refers to an improvement in the overall irrigation efficiency.

Figure 2 shows a global map of average irrigation efficiency by country. It is based on the volume of beneficial and non-beneficial irrigation water use provided by the IMPACT baseline dataset. The reported irrigation efficiency clearly indicates that irrigation management in most developing regions is performing poorly, the only exception is water-scarce North Africa, where levels are comparable to those of developed regions. Irrigation

[6] A sensitivity analysis was performed and revealed that the model results are not sensitive to changes in the value of the elasticity of substitution between land and irrigation.

efficiency in Canada and Western Europe is low. However, in those two regions irrigated production is not important relative to total production levels.

*Figure 2 about here*

Certainly, there are differences in performance within regions. Rosegrant et al. (2002) point out that irrigation efficiency ranges between 25 to 40 percent in the Philippines, Thailand, India, Pakistan and Mexico; between 40 to 45 percent in Malaysia and Morocco; and between 50 to 60 percent in Taiwan, Israel and Japan. In our analysis, based on regional averages, these individual effects are averaged out but marked differences between the regions still exist.

Global projections of agriculture-water supply and demand, made by IWMI, FAO and IFPRI reported in World Bank (2003), show that the demand for improved water-use efficiency and hence efforts towards improving irrigation efficiency, would mostly take place in water-scarce areas. Following that proposition, we evaluate the effects on global production and income of enhanced irrigation efficiency through three different scenarios. The scenarios are designed so as to show a gradual convergence to higher levels of irrigation efficiency. The first two scenarios assume that an improvement in irrigation efficiency is more likely in water-scarce regions. In the first scenario irrigation efficiency in water-stressed developing regions improves. We consider a region as water-stressed region if at least for one country within the region water availability is lower than 1,500 cubic meters per person per year.[7] These regions include South Asia (SAS), Southeast Asia (SEA), North Africa (NAF), the Middle East (MDE), Sub-Saharan Africa (SSA) as well as the Rest of the World (ROW). The second scenario improves irrigation efficiency in all water-scarce regions independent of the level of economic development. In addition to the previous scenario Western Europe (WEU), Eastern Europe (EEU) as well as Japan and South Korea (JPK) are added to the list of water-short regions. For the first two scenarios, irrigation efficiency is improved for all irrigated crops in each region to a level of 73 percent. Comparing with figure 2 above, this is the weighted average level of Australia and New Zealand (ANZ), which is close to the maximum achievable efficiency of 75 percent (World Bank 2003). In the third scenario, we improve irrigation efficiency in all 16 regions up to 73 percent.

Our scenarios do not add costs, that is, we assume that higher levels of efficiency are possible with the current technology. Jensen (2007) points out that better irrigation

[7] The water-stressed countries were identified using the current AQUASTAT database.

scheduling practices, controlling timing of irrigation and amounts applied, can improve irrigation efficiency and productivity of water with little additional cost.

## 5 Results

Figure 3 shows irrigated production as share of total agricultural production in the GTAP-W baseline data. Irrigated rice production accounts for 73 percent of the total rice production; the major producers are Japan and South Korea, China, South Asia and Southeast Asia. Around 47 percent of wheat and sugar cane is produced using irrigation. However, the volume of irrigation water used in sugar cane production is less than one-third of what is used in wheat production. In irrigated agriculture major producers of wheat are South Asia, China, North Africa and the USA and for sugar cane South Asia and Western Europe. The share of irrigated production in total production of the other four crops in GTAP-W (cereal grains, oil seeds, vegetables and fruits as well as other agricultural products) varies from 31 to 37 percent. Major producers of cereal grains are the USA and China; for oil seeds are the USA, South Asia and China; for vegetables and fruits are China, the Middle East and Japan and South Korea; and for other agricultural products are the USA and South Asia.

*Figure 3 about here*

The irrigated production of rice and wheat consumes half of the irrigation water used globally, and together with cereal grains and other agricultural products the irrigation water consumption rises to 80 percent. There are three major irrigation water users (South Asia, China and USA). These regions use over 70 percent of the global irrigation water used, just South Asia uses more than one-third.

Table 1 reports the percentage changes in the use of two production factors, irrigated land and irrigation (compare irrigated land-water composite in figure 1) for four of our seven agricultural sectors (rice, wheat, cereal grains as well as vegetables and fruits).[8] These two factors indicate changes in irrigated production. In table 2, the percentage changes in total agricultural production are displayed. Not only regions where irrigation water efficiency changes alter their levels of irrigated and total production in the different sectors, but other regions are affected as well through shifts in competitiveness and international trade. The effects are different for the different scenarios we implemented, as discussed below.

[8] Results for the other three agricultural sectors including oil seeds, sugar cane and sugar beet as well as other agricultural products are excluded for clarity but can be obtained from the authors on request.

Turning to rice production first, the four major rice producers (Japan and South Korea, South Asia, Southeast Asia and China) are affected differently. In Southeast Asia, for example, where irrigation efficiency was lowest, production increases more compared to the other three regions. In general, higher levels of irrigation efficiency lead to increases in irrigated rice production as well as total rice production. However, total rice production within a region increases less if more regions have higher levels of irrigation efficiency (scenarios 2 and 3). Although irrigated production increases, demand for irrigation water decreases in most regions (table 3). After all, the demand for food increases only slightly. An exception is the Middle East where total rice production decreases while irrigated production and water demand increase. The relatively high level of irrigation efficiency leaves little room for further improvements and water savings.

*Tables 1 to 3 about here*

There are seven major wheat-producing regions in the world (South Asia, China, North Africa, USA, Western Europe, Eastern Europe and the former Soviet Union). Within these regions the first four regions are the major producers of irrigated wheat. Comparing the results of table 1 for the different scenarios, higher levels of irrigation efficiency generally lead to increases in irrigated wheat production in these regions. As discussed above, the increase is less pronounced when more regions achieve higher levels of irrigation efficiency (scenarios 2 and 3). Irrigation water demand is affected differently in the different regions. In scenario 3, water demand increases in water-scarce South Asia as well as in the USA and China. In Western and Eastern Europe as well as North Africa higher levels of irrigation efficiency is mostly followed by a decrease in the demand for water. Total wheat production does not necessarily follow the trend of irrigated production. Only in two of the seven regions (South Asia, Eastern Europe and partly China) total production increases with higher levels of irrigation efficiency.

Turning to the rest of the regions, improved irrigation efficiency leads to more irrigated and total wheat production in water-scarce regions. In most of these regions (Japan and South Korea, Southeast Asia, Sub-Saharan Africa and Rest of the World) excluding the Middle East this is followed by an increasing demand for irrigation water. However, production levels are relatively low.

For cereal grains the picture is similar. Major producers (USA, Eastern Europe, former Soviet Union, South America, China and Sub-Saharan Africa) increase their irrigated production with higher levels of irrigation efficiency like all other regions too. In the developing regions as well as the former Soviet Union irrigation water demand is increasing

with higher levels of irrigation efficiency while water demand is decreasing in the USA and Eastern Europe. Total agricultural production increases only in three of the six regions (Eastern Europe, South America and China).

The number of regions that are major vegetable and fruit producers is relatively large (USA, Western Europe, Japan and South Korea, former Soviet Union, Middle East, South Asia, Southeast Asia and China). However, only for China, the Middle East as well as Japan and South Korea irrigated production amounts to a significant share of total production. Comparable to irrigated rice production, irrigated production of vegetable and fruit increases with higher levels of irrigation efficiency. Irrigated production in some regions increases even further when more regions reach higher efficiency levels (an exception is Western Europe). For most of these regions irrigation water demand decreases; exceptions are Western Europe and the former Soviet Union. Comparing results of scenarios 2 and 3, water demand decreases more the lower the number of regions obtaining higher levels of irrigation efficiency. Turning to changes in total production the picture is more mixed. Production levels in the USA, Western Europe and the Middle East decrease and increase in the other regions of major producers.

One reason to increase the efficiency in irrigation is to save water. Figure 4 compares how much water used in irrigated agriculture could be saved by the different scenarios. The initial water saving shows the reduction in the irrigation water requirements under the improved irrigation efficiency, without considering any adjustment process in food and other markets. The final water saving also considers the additional irrigation water used as a consequence of the increase in irrigated production. At the global level, the final water savings increase as more regions achieve higher levels of irrigation efficiency. At regional level, the tendency is similar except for only slight decreases in Sub-Saharan Africa as well as in Australia and New Zealand. The results show that not only regions where irrigation efficiency changes save water, but also other regions are pushed to reduce irrigation water use. This is evident for the USA and China in scenarios 1 and 2, where total irrigated production decreases. Only in North Africa the final water savings exceed the initial water savings; and the additional irrigation water saved increases more the higher the number of regions improving the irrigation efficiency.

Our estimates of water savings are directly based on the reduction in the irrigation water requirements for crop production. However, if improvements in irrigation efficiency will save water that can be used for other proposes depend on what happen to the drainage

water and the return flow of water (Molden and de Fraiture 2002; Jensen 2007). These features are not considered here.

*Figure 4 about here*

Higher levels of irrigation efficiency lead to a decrease in the production costs of irrigated agriculture. As the production costs of rainfed agriculture remain the same, the result is a shift in production from rainfed to irrigated agriculture. Table 4 reports the percentage changes in rainfed, irrigated and total agricultural production as well as the changes in world market prices. For all agricultural products, the increases in irrigated production and the decreases in rainfed production are more pronounced when more regions reach higher efficiency levels (scenario 2 and 3). In scenario 3, total agricultural production rises by 0.7 percent. This consists of an increase in irrigated production of 24.6 percent and a decline in rainfed production of 15 percent. For individual agricultural products, the shift from rainfed to irrigated production varies widely.

The world market prices for all agricultural products decrease as a consequence of the lower production costs of irrigated agriculture. The world market prices fall more as more regions improve irrigation efficiency. Lower market prices stimulate consumption and total production of all agricultural products increases. In scenario 3, rice has the greatest reduction in prices (13.8 percent) which is accompanied by an increase in total production (1.7 percent). The reduction in the world market price is the smallest for cereals (3.4 percent); total production rises by 0.4 percent.

*Table 4 about here*

Changes in production induce changes in welfare. At the global level, welfare increases as more regions implement strategies to improve irrigation. However, at the regional level, the effects might be less positive for some. Figure 5 compares the changes in welfare for our three different scenarios for the 16 regions. Discussing the bottom panel first, changes in welfare in water-scarce developing regions are mostly positive but the magnitude varies considerably. For water-stressed regions, changes are most pronounced for South Asia followed by Southeast Asia, the Middle East, North Africa and Sub-Saharan Africa. Differences between scenario results 1 and 2 are negligible while the third scenario leads to additional welfare gains. An exception is Sub-Saharan Africa where welfare changes are negative. The gains for food consumers are smaller than the losses incurred by food producers. For non-water stressed developing regions, there are mostly welfare gains, which are marked for China in scenario 3. South America is the exception. As other regions are able to grow more food, South America loses parts of a valuable export.

*Figure 5 about here*

The upper panel of figure 5 indicates that water-stressed developed regions benefit from higher levels of irrigation efficiency, and even more so as efficiency improvement occurs in more regions. This is also true for the non-water stressed former Soviet Union. For food-exporters (USA, Canada, Australia and New Zealand) an opposite effect occurs; the larger the number of regions implementing more efficient irrigation management the greater the loss. This is reversed for the USA in scenario 3, in which the USA itself also benefits from improved irrigation efficiency.

Figure 6 shows, for scenario 3, changes in welfare as a function of the additional irrigation water used in irrigated production, that is, the difference between the initial water savings and the actual water savings (cf. figure 4). There is a clear positive relationship for the major users (Central America, Southeast Asia, China and South Asia). Japan and South Korea are outliers. They show high levels of welfare improvements for small increases in water demand for irrigated agriculture. This is due to a combination of water scarcity and a strong preference for locally produced rice. Welfare gains in Japan and South Korea are mostly associated with improvements in its terms of trade and irrigation efficiency. Japan and South Korea are in line with the rest of the world when changes in welfare are plotted as a function of changes in total agricultural production (figure 7). Changes in welfare are not always associated with higher levels of irrigated production: Western Europe, the Middle East and the former Soviet Union experience welfare increases with an absolute reduction in domestic agricultural production. Figure 6 also shows welfare losses for food-exporting regions that lose their competitive advantage as other regions increase their irrigation efficiency.

*Figure 6 and 7 about here*

Changes in agricultural production modify international trade patterns and generate changes in international flows of virtual water. Virtual water is defined as the volume of water used to produce a commodity (Allan 1992 and 1993). We use the production-site definition, that is, we measure it at the place where the product was actually produced. 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 at the place where the product is consumed (consumption-site definition). The virtual water used in the agricultural sector has two components: effective rainfall (green water) and irrigation water (blue water). Table 5 shows the international flows of irrigation water used associated to the additional agricultural production (blue virtual water). At the global level, depending on the scenario, between 30 to

35 percent of the blue virtual water is traded internationally. At the regional level, the range varies widely.

*Table 5 about here*

In most water-scarce developing regions, the amount of blue virtual water increases with higher levels of irrigation efficiency (table 5, column a). However, it increases less if more regions have higher levels of irrigation efficiency (scenarios 2 and 3). The only exception is North Africa with a negative change in blue virtual water, mainly caused by a reduction in the agricultural exports. In the water-scarce developed regions, initial savings of blue virtual water (scenario 1) vanish when they experience higher levels of irrigation efficiency (scenario 2 and 3). An exception is Western Europe where savings of blue virtual water are observed under all three scenarios.

The largest absolute changes in blue virtual water are in South Asia and Southeast Asia. South Asia exports almost half of its additional blue virtual water; in Southeast Asia on the contrary virtual water exports are modest. Reductions in the agricultural production for exports imply savings of blue virtual water for China, North Africa and the USA. The situation in China and the USA changes under scenario 3, where they achieve higher levels of irrigation efficiency; China substantially increases its blue virtual water use, 43 percent of which is exported.

Western Europe, the Middle East, the USA, Southeast Asia as well as Japan and South Korea substantially increase their blue virtual water imports. Higher levels of irrigation efficiency correspond to higher levels of total use of blue virtual water (table 5, column e). Sub-Saharan Africa is one of the exceptions where the pronounced reduction in the imports of blue virtual water causes a decrease in the total consumption of blue virtual water. Other exceptions, depending on the scenario chosen, are Japan and South Korea, Eastern Europe, and the Rest of the World.

## 6 Discussions and conclusions

In this article, we present a new version of a computable general equilibrium model of the world economy with water as an explicit factor of production. The production structure used in this model allows for substitution between irrigated land, rainfed land, labour, capital, and energy. To our knowledge, this is the first global CGE model that differentiates between rainfed and irrigated crops. 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,[9] which is important as water is implicitly traded in international markets, mainly for agricultural products. In earlier studies by ourselves, we had been unable to separate rainfed and irrigated agriculture.

Efforts towards improving irrigation management, e.g. through more efficient irrigation methods, benefit societies by saving large amounts of water. These would be available for other uses. In this article, we analyze if such a water policy 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. We find that higher levels of irrigation efficiency have, depending on the scenario and the region, a significant effect on crop production, water use and welfare. Water use for some crops and some regions goes up, and it goes down for other crops and regions. This leads to mixed pattern in total water use for some regions.

At the global level, water savings are achieved and the magnitude increases when more regions have higher levels of irrigation efficiency. The same tendency is observed at the regional level, except for only slight decreases in Sub-Saharan Africa as well as in Australia and New Zealand. The results show that not only regions where irrigation efficiency changes are able to save water, but also other regions are pushed to reduce irrigation water use.

We find that welfare tends to increases with the additional irrigation water used in irrigated production. The same positive relationship is observed when changes in welfare are associated with changes in total agricultural production. However, increased water efficiency also affects competitiveness, and hurts rainfed agriculture, so that there are welfare losses as well. Such losses are more than offset, however, by the gains from increased irrigated production and lower food prices.

Several limitations apply to the above results. First, in our analysis water-scarce regions are defined based on country averages. We do not take into account that water might be scarce within countries due to limited availability in water basins. China is an example of such a country. Although on average water is not short, water supply is a problem in Northern China. In fact, we implicitly assume a perfect water market in each region. Second, in our analysis increases in irrigation efficiency are not accompanied by, for example, changes in water prices. We implicitly assume that higher levels of efficiency are possible with the

[9] Although, in a single country CGE, there is either an explicit "Rest of the World" region or the rest of the world is implicitly included in the closure rules.

current technology, at zero cost. Therefore, our scenarios might overestimate the benefits of improved irrigation management. Third, we do not consider individual options for irrigation management. Instead, we use water productivity as a proxy for irrigation efficiency. Fourth, our analysis does not account for alternative uses of water resources outside the agricultural sector. The necessary data on a global basis are missing. These issues should be addressed in future research. Future work will also study other issues, such as changes in water policy, and the effects of climate change on water resources.

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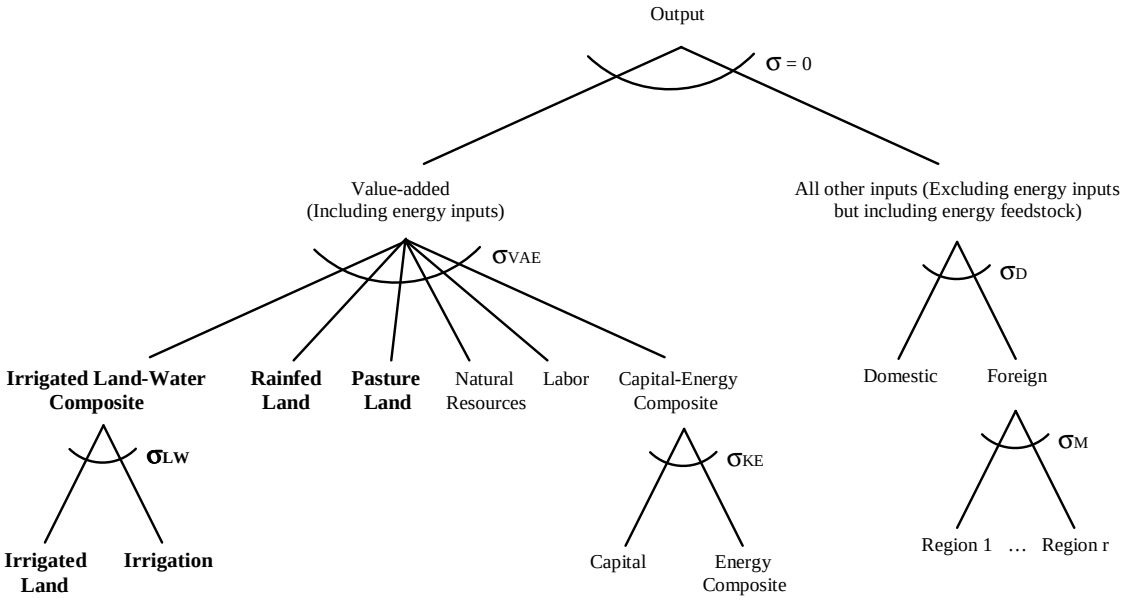


**Figure 1. Nested tree structure for industrial production process in GTAP-W (truncated)**

Note: The original land endowment has been split into pasture land, rainfed land, irrigated land and irrigation (bold letters).

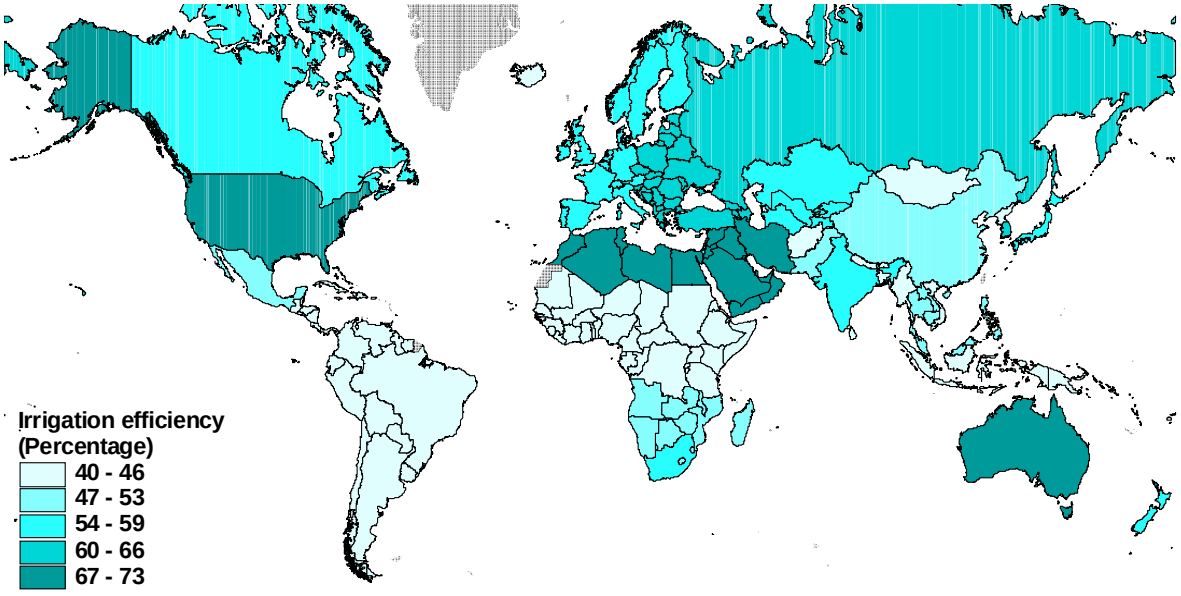


**Figure 2. Average irrigation efficiency, 2001 baseline data**

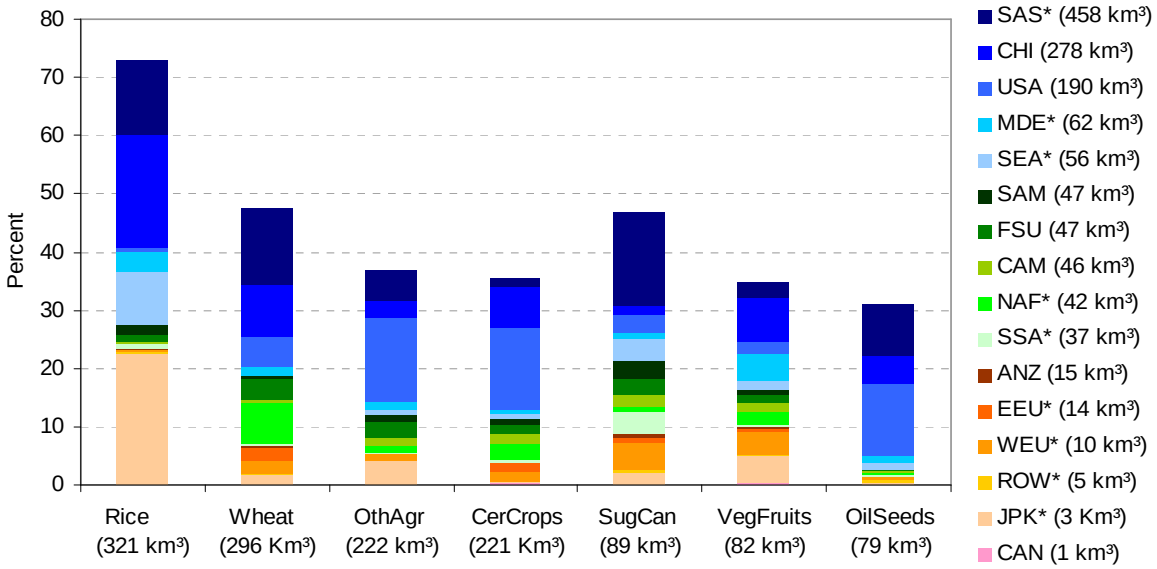


**Figure 3. Share of irrigated production in total production by crop and region, 2001 baseline data**

Note: Irrigation water used in $km^3$ by crop and region is shown in parenthesis. Water-stressed regions are indicated by an asterisk (*).

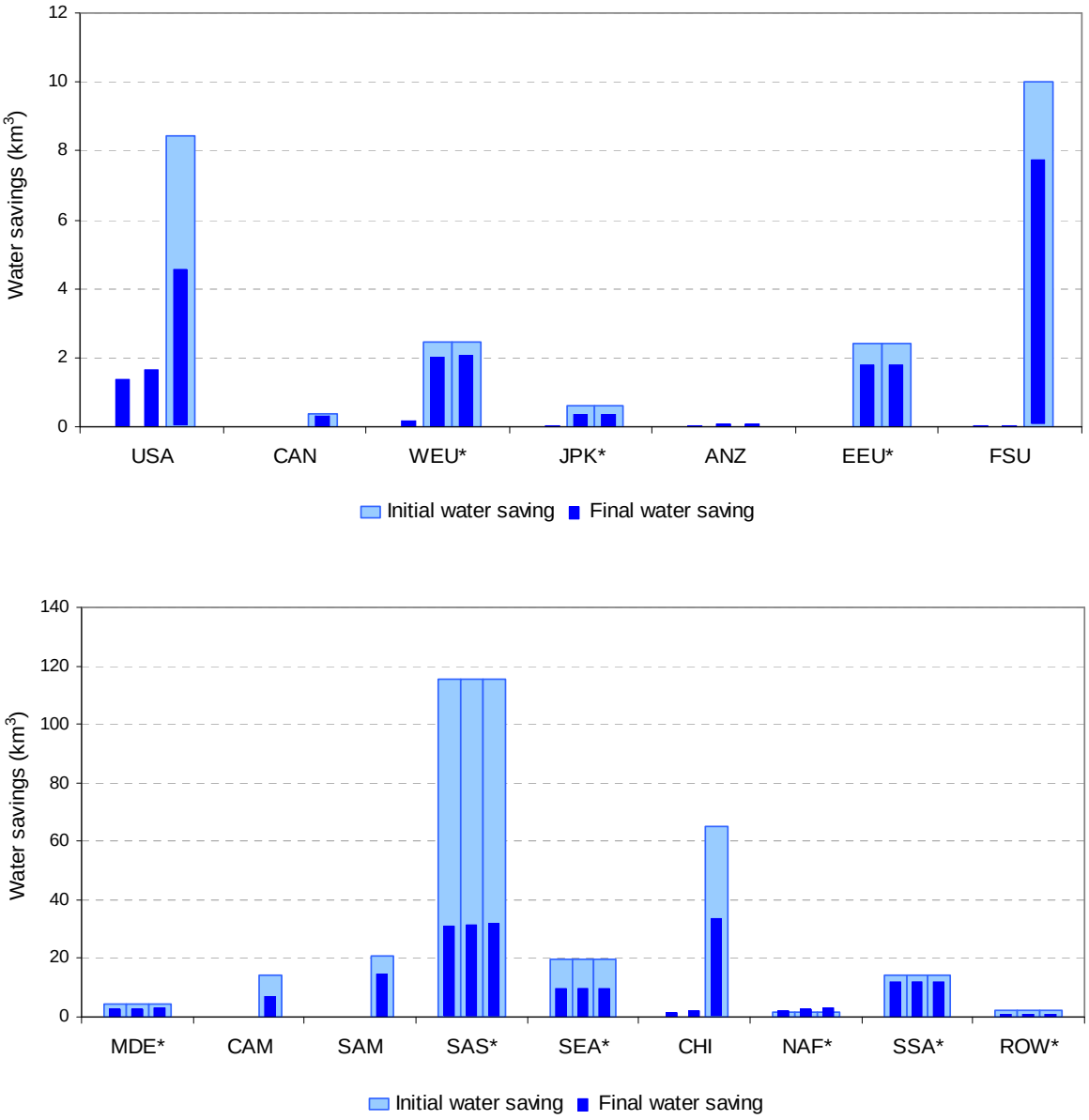


**Figure 4. Initial and final water savings by scenario, 2001**

Note: Developed regions (top panel) and developing regions (bottom panel). Water-stressed regions are indicated by an asterisk (*). The three bars refer to the three scenarios respectively.

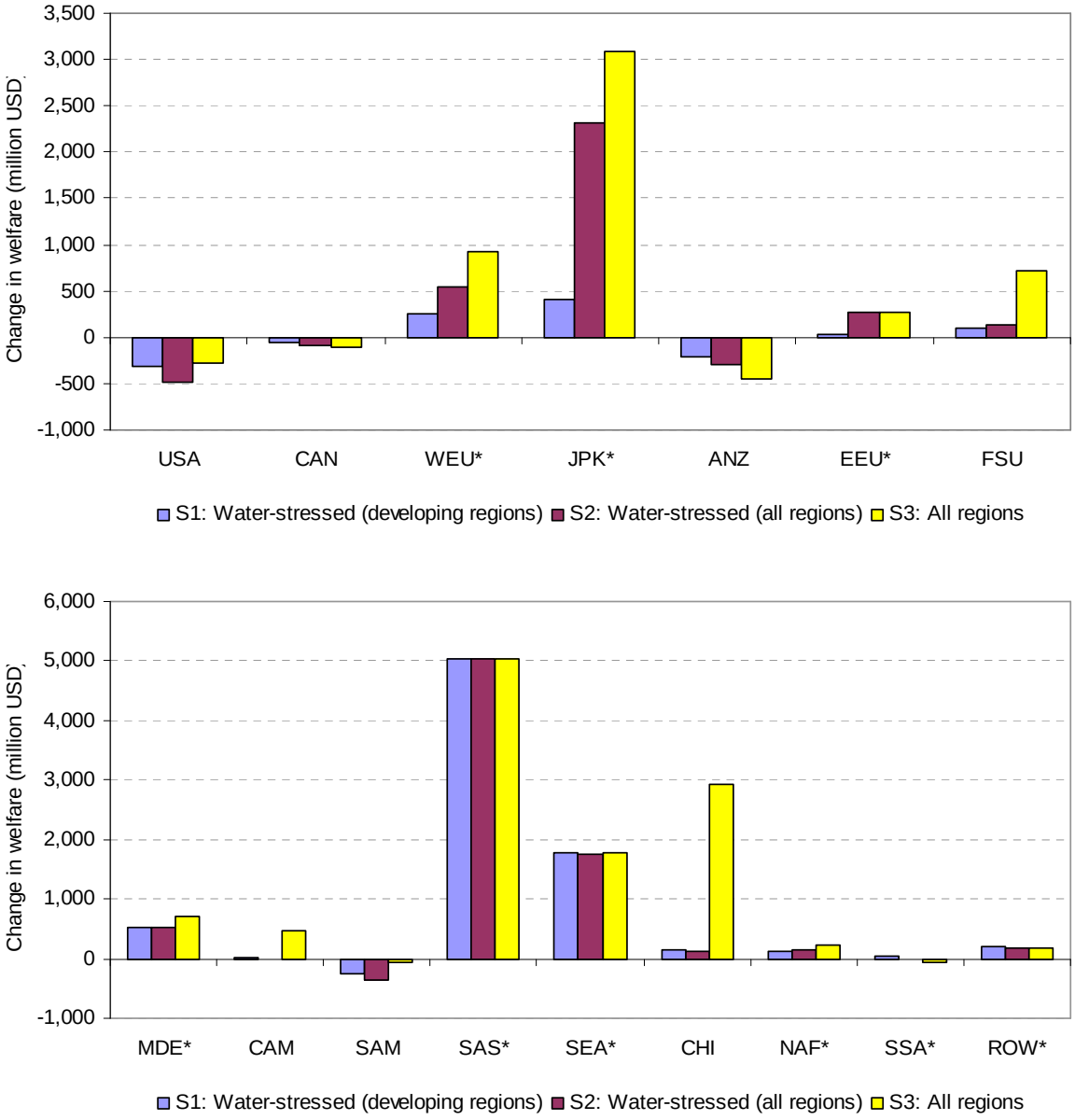


**Figure 5. Changes in regional welfare by scenario (million USD)**

Note: Developed regions (top panel) and developing regions (bottom panel). Water-stressed regions are indicated by an asterisk (*).

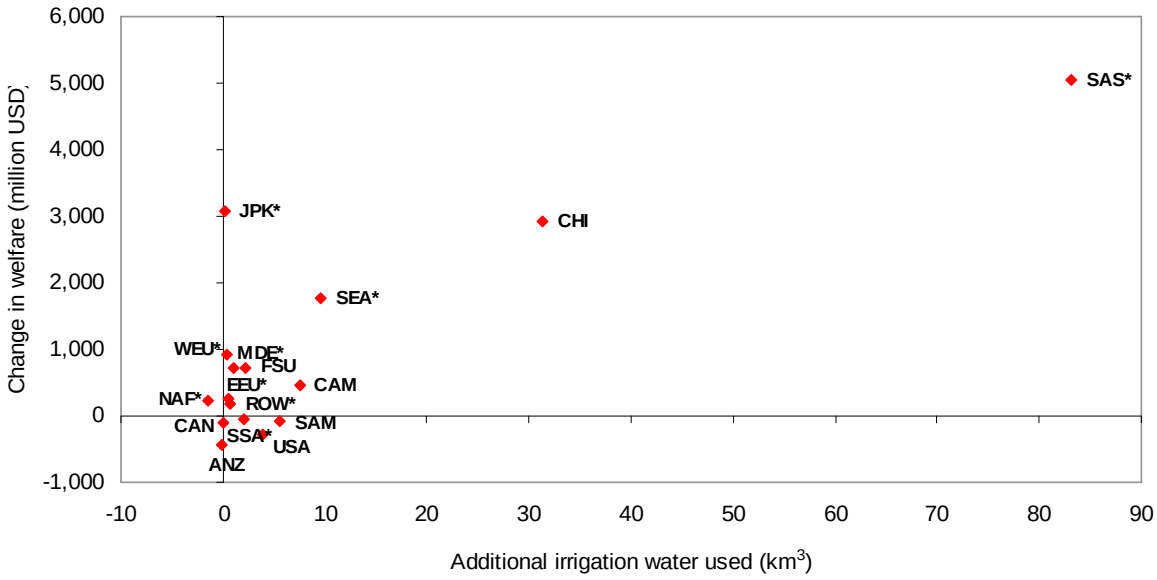


**Figure 6. Changes in welfare as a function of the additional irrigation water used, scenario 3**

Note: Water-stressed regions are indicated by an asterisk (*).

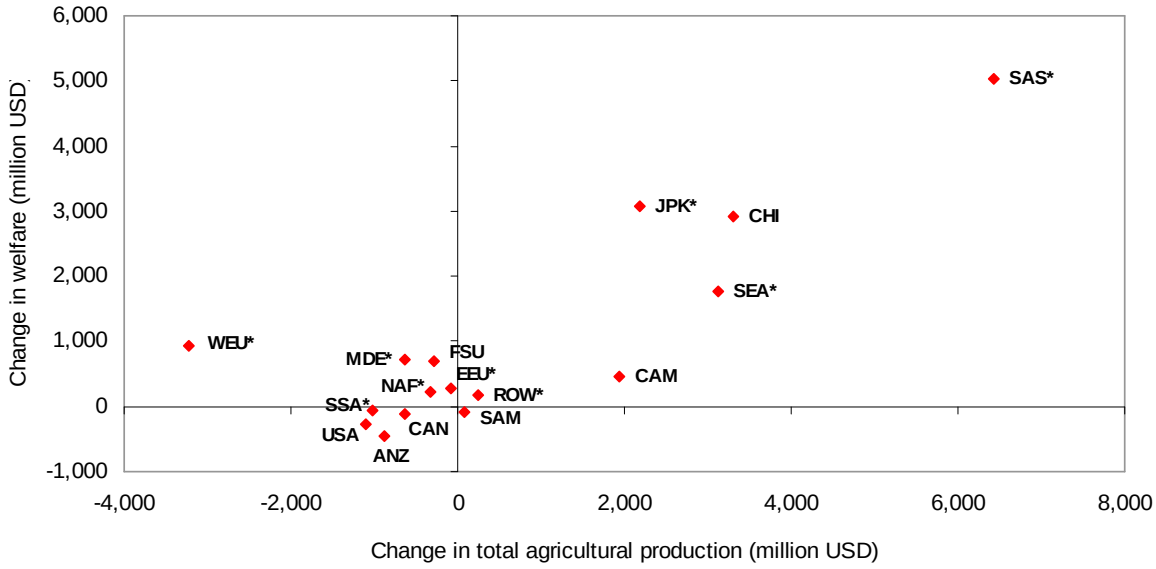


**Figure 7. Changes in welfare as a function of the additional agricultural production, scenario 3 (million USD)**

Note: Water-stressed regions are indicated by an asterisk (*).

**Table 1. Percentage change in irrigated land-water composite as an indicator for changes in irrigated production, results for scenarios 1 to 3 for four agricultural sectors**

| | Rice (%) | | | Wheat (%) | | | Cereal grains (%) | | | Vegetables and fruits (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Region** | **Scen. 1** | **Scen. 2** | **Scen. 3** | **Scen. 1** | **Scen. 2** | **Scen. 3** | **Scen. 1** | **Scen. 2** | **Scen. 3** | **Scen. 1** | **Scen. 2** | **Scen. 3** |
| **USA** | -5.70 | -6.97 | -7.57 | -1.57 | -2.13 | 3.19 | 0.63 | 0.86 | 4.96 | 0.55 | 0.35 | 3.78 |
| **CAN** | 0.00 | 0.00 | 0.00 | -2.56 | -3.45 | 25.54 | 1.11 | 1.50 | 34.67 | -0.01 | -0.06 | 33.20 |
| **WEU*** | -22.87 | 4.13 | 2.36 | -0.52 | 31.91 | 31.30 | 0.83 | 33.17 | 33.86 | 0.67 | 33.76 | 33.67 |
| **JPK*** | -0.62 | 22.99 | 23.05 | -0.12 | 42.78 | 42.00 | 0.67 | 31.75 | 28.97 | 0.64 | 25.93 | 26.43 |
| **ANZ** | -6.10 | -7.51 | -8.11 | -1.86 | -1.98 | -1.32 | 1.35 | 2.02 | 1.38 | 0.50 | 0.47 | 0.89 |
| **EEU*** | -1.04 | 18.89 | 17.67 | -0.17 | 21.69 | 21.61 | 0.06 | 21.45 | 21.53 | 0.10 | 21.90 | 21.93 |
| **FSU** | -0.05 | 0.01 | 26.51 | -0.17 | -0.28 | 26.42 | 0.08 | 0.11 | 27.08 | 0.21 | 0.23 | 25.96 |
| **MDE*** | 7.97 | 8.16 | 8.57 | 6.63 | 6.03 | 4.66 | 8.80 | 8.76 | 8.26 | 10.01 | 10.02 | 10.18 |
| **CAM** | -1.21 | -1.33 | 54.40 | -0.43 | -0.65 | 54.57 | 0.39 | 0.59 | 42.76 | 0.09 | -0.08 | 48.62 |
| **SAM** | -0.79 | -0.59 | 73.99 | -0.72 | -0.64 | 76.81 | 0.38 | 0.55 | 76.81 | 0.45 | 0.29 | 78.26 |
| **SAS*** | 30.54 | 30.47 | 30.55 | 36.36 | 36.25 | 36.15 | 34.59 | 34.71 | 34.93 | 36.08 | 36.11 | 36.20 |
| **SEA*** | 53.32 | 52.37 | 52.91 | 68.47 | 69.19 | 69.06 | 53.70 | 54.63 | 53.92 | 53.00 | 53.56 | 53.86 |
| **CHI** | 0.14 | 0.20 | 29.92 | 0.17 | 0.24 | 29.28 | -0.03 | 0.07 | 30.15 | 0.22 | 0.30 | 34.35 |
| **NAF*** | -5.78 | -8.35 | -13.23 | 4.81 | 4.64 | 4.54 | 4.82 | 4.97 | 5.00 | 4.83 | 4.85 | 5.07 |
| **SSA*** | 61.45 | 63.37 | 63.07 | 57.50 | 58.33 | 56.00 | 61.68 | 63.80 | 63.37 | 63.02 | 64.07 | 63.15 |
| **ROW*** | 76.82 | 76.86 | 71.33 | 98.25 | 95.31 | 94.05 | 77.03 | 72.35 | 72.63 | 71.47 | 69.38 | 73.69 |

Note: Water-stressed regions are indicated by an asterisk (*).

**Table 2. Percentage change in total agricultural production, results for scenarios 1 to 3 for four agricultural sectors**

| Region | Rice (%) | | | Wheat (%) | | | Cereal grains (%) | | | Vegetables and fruits (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Scen. 1 | Scen. 2 | Scen. 3 | Scen. 1 | Scen. 2 | Scen. 3 | Scen. 1 | Scen. 2 | Scen. 3 | Scen. 1 | Scen. 2 | Scen. 3 |
| **USA** | -7.62 | -9.38 | -12.97 | -2.83 | -3.79 | -1.18 | -0.26 | -0.30 | -0.51 | -0.36 | -0.91 | -2.17 |
| **CAN** | -13.89 | -14.27 | -16.73 | -4.64 | -6.30 | -9.56 | -0.30 | -0.48 | -1.36 | -1.65 | -2.33 | -2.07 |
| **WEU*** | -28.14 | -25.86 | -28.34 | -1.95 | -1.26 | -3.03 | -0.33 | -0.19 | -0.81 | -0.53 | 0.69 | -0.67 |
| **JPK*** | -1.50 | 1.80 | 1.10 | -0.92 | 18.97 | 17.35 | 0.00 | 10.88 | 7.38 | -0.08 | 2.38 | 2.11 |
| **ANZ** | -8.53 | -10.75 | -12.44 | -3.56 | -4.31 | -4.59 | 0.21 | 0.37 | -1.47 | -0.83 | -1.51 | -2.13 |
| **EEU*** | -1.44 | -1.16 | -2.65 | -0.39 | 1.09 | 0.76 | -0.13 | 0.27 | 0.11 | -0.08 | 0.74 | 0.52 |
| **FSU** | -0.38 | -0.42 | 0.04 | -0.54 | -0.77 | -0.30 | -0.25 | -0.33 | -0.13 | -0.08 | -0.17 | 0.53 |
| **MDE*** | -0.10 | -0.12 | -0.13 | -2.12 | -3.02 | -5.00 | -0.10 | -0.38 | -1.40 | 0.47 | 0.24 | -0.05 |
| **CAM** | -1.89 | -2.24 | 6.03 | -0.99 | -1.47 | 14.11 | -0.03 | -0.01 | 3.26 | -0.37 | -0.79 | 6.17 |
| **SAM** | -1.62 | -1.68 | 0.52 | -1.47 | -1.67 | -0.30 | -0.22 | -0.32 | 0.07 | -0.12 | -0.58 | 1.40 |
| **SAS*** | 3.71 | 3.53 | 3.30 | 7.16 | 6.92 | 6.47 | 1.37 | 1.37 | 1.29 | 2.61 | 2.53 | 2.34 |
| **SEA*** | 6.08 | 4.79 | 4.75 | 14.56 | 14.54 | 13.93 | 5.63 | 5.82 | 4.84 | 2.79 | 2.71 | 2.53 |
| **CHI** | -0.23 | -0.35 | 1.41 | -0.21 | -0.31 | 2.16 | -0.45 | -0.52 | 2.74 | -0.17 | -0.28 | 0.75 |
| **NAF*** | -11.77 | -14.90 | -20.78 | 0.17 | -0.27 | -0.88 | 0.33 | 0.26 | -0.21 | 0.12 | -0.10 | -0.35 |
| **SSA*** | -0.22 | -0.35 | -0.44 | 1.98 | 0.99 | -0.68 | 0.07 | 0.06 | -0.08 | -0.09 | -0.88 | -1.40 |
| **ROW*** | 5.92 | 5.61 | 2.13 | 20.56 | 19.50 | 18.07 | 0.71 | 0.68 | 0.03 | 3.14 | 2.66 | 2.07 |

Note: Water-stressed regions are indicated by an asterisk (*).

**Table 3. Percentage change in water demand in irrigated agriculture, results for scenarios 1 to 3 for four agricultural sectors**

| Region | Rice (%) | | | Wheat (%) | | | Cereal grains (%) | | | Vegetables and fruits (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Scen. 1 | Scen. 2 | Scen. 3 | Scen. 1 | Scen. 2 | Scen. 3 | Scen. 1 | Scen. 2 | Scen. 3 | Scen. 1 | Scen. 2 | Scen. 3 |
| **USA** | -5.68 | -6.94 | -8.70 | -1.55 | -2.10 | 0.64 | 0.65 | 0.89 | -0.92 | 0.57 | 0.38 | -2.03 |
| **CAN** | 0.00 | 0.00 | 0.00 | -2.56 | -3.45 | -5.43 | 1.11 | 1.50 | 1.45 | -0.02 | -0.06 | 0.34 |
| **WEU*** | -22.86 | -21.51 | -22.84 | -0.50 | -0.48 | -0.94 | 0.86 | 0.47 | 0.98 | 0.69 | 0.91 | 0.84 |
| **JPK*** | -0.63 | -1.45 | -1.43 | -0.13 | 9.83 | 9.20 | 0.66 | 9.51 | 7.18 | 0.63 | -0.38 | -0.01 |
| **ANZ** | -6.11 | -7.53 | -8.16 | -1.88 | -2.00 | -1.38 | 1.34 | 2.00 | 1.32 | 0.49 | 0.45 | 0.83 |
| **EEU*** | -1.04 | -2.30 | -3.31 | -0.17 | -0.01 | -0.07 | 0.06 | -0.21 | -0.14 | 0.10 | 0.17 | 0.19 |
| **FSU** | -0.06 | 0.00 | -2.91 | -0.18 | -0.29 | -0.22 | 0.07 | 0.09 | 0.38 | 0.20 | 0.21 | 1.34 |
| **MDE*** | 1.60 | 1.78 | 2.15 | -0.50 | -1.07 | -2.36 | 0.86 | 0.82 | 0.34 | -0.23 | -0.23 | -0.10 |
| **CAM** | -1.23 | -1.34 | -7.25 | -0.45 | -0.66 | 8.10 | 0.37 | 0.58 | -0.57 | 0.07 | -0.09 | -0.84 |
| **SAM** | -0.78 | -0.59 | -2.12 | -0.71 | -0.64 | -0.09 | 0.38 | 0.54 | 0.65 | 0.46 | 0.29 | 0.67 |
| **SAS*** | -0.18 | -0.24 | -0.18 | 2.78 | 2.70 | 2.61 | -1.60 | -1.51 | -1.36 | -1.23 | -1.21 | -1.15 |
| **SEA*** | -2.07 | -2.65 | -2.33 | -0.15 | 0.31 | 0.20 | 2.98 | 3.64 | 3.12 | -1.19 | -0.80 | -0.65 |
| **CHI** | 0.12 | 0.17 | -3.28 | 0.15 | 0.22 | 2.17 | -0.05 | 0.05 | 3.51 | 0.21 | 0.27 | -0.86 |
| **NAF*** | -9.67 | -12.13 | -16.81 | 0.10 | -0.06 | -0.15 | 0.30 | 0.45 | 0.47 | 0.03 | 0.05 | 0.25 |
| **SSA*** | -1.91 | -0.62 | -0.92 | 6.42 | 7.13 | 5.42 | -0.56 | 0.88 | 0.48 | -2.15 | -1.39 | -2.07 |
| **ROW*** | -1.14 | -0.04 | -3.40 | 10.64 | 9.90 | 9.11 | -0.67 | -2.89 | -2.72 | -4.56 | -4.92 | -1.96 |

Note: Water-stressed regions are indicated by an asterisk (*).

**Table 4. Percentage change in global total, irrigated and rainfed agricultural production and world market prices by scenario**

| Agricultural products | Scenario 1 | | | | Scenario 2 | | | | Scenario 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Agricultural production | | | | Agricultural production | | | | Agricultural production | | | |
| | Total | Irrigated | Rainfed | Price | Total | Irrigated | Rainfed | Price | Total | Irrigated | Rainfed | Price |
| **Rice** | 1.07 | 14.74 | -36.08 | -6.78 | 1.55 | 17.49 | -41.75 | -10.03 | 1.71 | 19.69 | -47.16 | -13.79 |
| **Wheat** | 0.45 | 13.22 | -11.03 | -2.95 | 0.73 | 17.22 | -14.09 | -3.60 | 0.87 | 24.58 | -20.45 | -5.16 |
| **Cereal grains** | 0.07 | 4.35 | -2.29 | -0.95 | 0.13 | 7.34 | -3.84 | -1.34 | 0.38 | 21.94 | -11.49 | -3.44 |
| **Vegetable and fruits** | 0.25 | 7.38 | -3.59 | -1.41 | 0.41 | 15.46 | -7.68 | -2.44 | 0.70 | 29.01 | -14.52 | -4.47 |
| **Oil seeds** | 0.58 | 15.96 | -6.36 | -2.57 | 0.62 | 16.90 | -6.73 | -2.78 | 1.00 | 27.97 | -11.18 | -4.19 |
| **Sugar cane and beet** | 0.76 | 21.52 | -17.59 | -6.26 | 0.80 | 26.69 | -22.09 | -6.87 | 0.90 | 37.49 | -31.45 | -8.25 |
| **Other agri. products** | 0.27 | 8.83 | -4.78 | -1.91 | 0.39 | 12.72 | -6.87 | -2.47 | 0.48 | 21.43 | -11.86 | -3.99 |
| **TOTAL** | **0.35** | **10.02** | **-6.02** | | **0.52** | **14.86** | **-8.93** | | **0.71** | **24.58** | **-15.00** | |

**Table 5. Changes in blue virtual water flows related to the additional agricultural production by scenario, in cubic kilometres ($km^3$)**

| Region | Scenario 1 | | | | | Scenario 2 | | | | | Scenario 3 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Virtual Water | Destination Market | | | Net | Virtual Water | Destination Market | | | Net | Virtual Water | Destination Market | | | Net |
| | | Domestic | Exports | Imports | | | Domestic | Exports | Imports | | | Domestic | Exports | Imports | |
| | (a=b+c) | (b) | (c) | (d) | (e=b+d-c) | (a=b+c) | (b) | (c) | (d) | (e=b+d-c) | (a=b+c) | (b) | (c) | (d) | (e=b+d-c) |
| **USA** | -1.38 | -0.34 | -1.05 | 0.44 | 1.16 | -1.68 | -0.39 | -1.29 | 0.43 | 1.33 | -0.46 | -0.13 | -0.33 | 0.71 | 0.91 |
| **CAN** | 0.00 | 0.00 | 0.00 | 0.03 | 0.03 | 0.00 | 0.00 | 0.00 | 0.02 | 0.03 | 0.00 | 0.00 | 0.00 | 0.07 | 0.07 |
| **WEU*** | -0.19 | -0.11 | -0.07 | 1.48 | 1.44 | -0.09 | -0.05 | -0.03 | 1.37 | 1.35 | -0.12 | -0.08 | -0.05 | 2.57 | 2.54 |
| **JPK*** | -0.04 | -0.01 | -0.03 | 0.41 | 0.42 | 0.06 | 0.06 | 0.00 | -0.34 | -0.29 | 0.04 | 0.04 | 0.00 | 1.13 | 1.17 |
| **ANZ** | -0.06 | -0.02 | -0.04 | 0.03 | 0.05 | -0.08 | -0.02 | -0.05 | 0.02 | 0.05 | -0.08 | -0.01 | -0.07 | 0.04 | 0.10 |
| **EEU*** | -0.01 | 0.00 | 0.00 | 0.17 | 0.17 | 0.08 | 0.04 | 0.04 | 0.07 | 0.08 | 0.05 | 0.03 | 0.02 | -0.24 | -0.23 |
| **FSU** | -0.05 | -0.03 | -0.02 | 0.19 | 0.18 | -0.07 | -0.04 | -0.03 | 0.20 | 0.19 | 0.03 | 0.04 | 0.00 | 0.31 | 0.35 |
| **MDE*** | 0.04 | 0.03 | 0.01 | 1.41 | 1.43 | 0.02 | 0.03 | -0.01 | 1.36 | 1.40 | -0.07 | -0.06 | -0.01 | 1.41 | 1.37 |
| **CAM** | -0.06 | -0.03 | -0.03 | 0.06 | 0.06 | -0.08 | -0.03 | -0.05 | 0.07 | 0.09 | 1.29 | 0.87 | 0.42 | -0.14 | 0.31 |
| **SAM** | -0.15 | -0.03 | -0.12 | 0.07 | 0.16 | -0.16 | -0.03 | -0.13 | 0.07 | 0.18 | 0.11 | 0.08 | 0.03 | 0.06 | 0.11 |
| **SAS*** | 16.41 | 8.70 | 7.72 | -0.08 | 0.90 | 15.89 | 8.62 | 7.27 | -0.08 | 1.27 | 14.85 | 8.43 | 6.42 | 0.39 | 2.41 |
| **SEA*** | 2.21 | 1.81 | 0.40 | 0.83 | 2.24 | 1.95 | 1.57 | 0.37 | 0.66 | 1.86 | 1.84 | 1.54 | 0.30 | 1.44 | 2.68 |
| **CHI** | -1.38 | -0.63 | -0.74 | 0.10 | 0.21 | -1.97 | -0.81 | -1.16 | 0.10 | 0.46 | 7.28 | 4.14 | 3.14 | 0.29 | 1.30 |
| **NAF*** | -0.97 | -0.04 | -0.93 | 0.16 | 1.06 | -1.27 | -0.08 | -1.19 | 0.16 | 1.28 | -1.79 | -0.13 | -1.66 | 0.37 | 1.90 |
| **SSA*** | 0.04 | 0.03 | 0.01 | -0.12 | -0.09 | 0.02 | 0.02 | 0.00 | -0.31 | -0.29 | 0.00 | 0.00 | 0.00 | -0.20 | -0.20 |
| **ROW*** | 0.04 | 0.03 | 0.01 | -0.08 | -0.06 | 0.04 | 0.03 | 0.01 | -0.08 | -0.06 | 0.03 | 0.02 | 0.01 | -0.01 | 0.01 |
| **TOTAL** | **14.45** | **9.36** | **5.10** | **5.10** | **9.36** | **12.66** | **8.92** | **3.73** | **3.73** | **8.92** | **23.00** | **14.79** | **8.21** | **8.21** | **14.79** |

Note: Water-stressed regions are indicated by an asterisk (*).

**Annex I: Aggregations in GTAP-W**

***A. Regional Aggregation***

**1. USA -** United States
**2. CAN -** Canada
**3. WEU -** Western Europe
**4. JPK -** Japan and South 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

***C. Endowments***

**Wtr -** Irrigation
**Lnd -** Irrigated land
**RfLand -** Rainfed land
**PsLand -** Pasture land
**Lab -** Labour
**Capital -** Capital
**NatlRes -** Natural resources

***B. Sectoral Aggregation***

**1. Rice -** Rice
**2. Wheat -** Wheat
**3. CerCrops -** Cereal grains (maize, millet, sorghum and other grains)
**4. VegFruits -** Vegetable, fruits, nuts
**5. OilSeeds -** Oil seeds
**6. Sug_Can -** Sugar cane, sugar beet
**7. Oth_Agr -** Other agricultural products
**8. Animals -** Animals
**9. Meat -** Meat
**10. Food_Prod -** Food products
**11. Forestry -** Forestry
**12. Fishing -** Fishing
**13. Coal -** Coal
**14. Oil -** Oil
**15. Gas -** Gas
**16. Oil_Pcts -** Oil products
**17. Electricity -** Electricity
**18. Water -** Water
**19. En_Int_Ind -** Energy intensive industries
**20. Oth_Ind -** Other industry and services
**21. Mserv -** Market services
**22. NMServ -** Non-market services

**Annex II:**

**Table A1. Share of irrigated production in total production by region and crop (percentages)**

| Region | Rice | Wheat | CerCrops | VegFruits | OilSeeds | Sug_Can | Oth_Agr | Total |
|---|---|---|---|---|---|---|---|---|
| **USA** | 51.01 | 78.93 | 70.25 | 34.20 | 68.45 | 48.00 | 100.00 | **67.73** |
| **CAN** | 0.00 | 1.92 | 10.36 | 34.72 | 3.33 | 44.08 | 0.00 | **8.50** |
| **WEU** | 48.77 | 19.56 | 16.28 | 35.32 | 5.69 | 40.28 | 5.03 | **24.10** |
| **JPK** | 93.71 | 79.66 | 65.26 | 66.26 | 32.10 | 56.64 | 81.50 | **75.48** |
| **ANZ** | 48.10 | 12.82 | 17.94 | 33.66 | 11.66 | 48.34 | 9.30 | **28.93** |
| **CEE** | 48.50 | 30.30 | 18.81 | 19.01 | 5.82 | 28.97 | 0.00 | **17.75** |
| **FSU** | 49.40 | 20.76 | 9.67 | 28.31 | 6.18 | 40.22 | 24.57 | **24.13** |
| **MDE** | 55.82 | 45.36 | 29.59 | 51.77 | 47.07 | 49.60 | 44.45 | **46.82** |
| **CAM** | 46.82 | 55.43 | 49.03 | 47.34 | 56.54 | 41.98 | 43.73 | **44.54** |
| **SAM** | 63.32 | 9.71 | 12.39 | 20.53 | 0.66 | 27.80 | 17.57 | **22.11** |
| **SAS** | 70.32 | 75.46 | 31.05 | 33.55 | 31.53 | 62.55 | 41.47 | **53.27** |
| **SEA** | 48.59 | 49.43 | 30.67 | 25.16 | 45.26 | 51.96 | 24.62 | **36.64** |
| **CHI** | 100.00 | 85.91 | 73.32 | 26.99 | 46.83 | 41.74 | 82.65 | **59.59** |
| **NAF** | 82.09 | 63.92 | 76.49 | 56.02 | 46.76 | 49.65 | 65.34 | **60.68** |
| **SSA** | 20.80 | 28.95 | 4.75 | 4.20 | 5.92 | 42.06 | 1.07 | **8.97** |
| **SIS** | 49.46 | 49.75 | 10.78 | 25.41 | 56.09 | 39.33 | 22.38 | **33.52** |
| **Total** | **73.16** | **48.42** | **42.30** | **28.13** | **37.06** | **43.97** | **47.53** | **42.16** |

Source: Own calculations based on IMPACT baseline data.

**Table A2. Ratio of irrigated yield to rainfed yield by region and crop**

| Region | Rice | Wheat | CerCrops | VegFruits | OilSeeds | Sug_Can | Oth_Agr |
|---|---|---|---|---|---|---|---|
| **USA** | 1.42 | 1.42 | 1.42 | 1.41 | 1.35 | 1.42 | 1.31* |
| **CAN** | -- | 1.36 | 1.38 | 1.39 | 1.30 | 1.41 | 1.31* |
| **WEU** | 1.42 | 1.36 | 1.36 | 1.39 | 1.30 | 1.39 | 1.26 |
| **JPK** | 1.39 | 1.37 | 1.36 | 1.42 | 1.35 | 1.43 | 1.33 |
| **ANZ** | 1.41 | 1.39 | 1.38 | 1.39 | 1.32 | 1.43 | 1.33 |
| **CEE** | 1.41 | 1.37 | 1.36 | 1.36 | 1.32 | 1.38 | 1.31* |
| **FSU** | 1.42 | 1.38 | 1.38 | 1.40 | 1.33 | 1.40 | 1.32 |
| **MDE** | 1.33 | 1.36 | 1.36 | 1.38 | 1.37 | 1.36 | 1.29 |
| **CAM** | 1.43 | 1.41 | 1.40 | 1.40 | 1.33 | 1.39 | 1.30 |
| **SAM** | 1.44 | 1.54 | 1.36 | 1.36 | 1.33 | 1.47 | 1.30 |
| **SAS** | 1.43 | 1.41 | 1.38 | 1.40 | 1.39 | 1.41 | 1.32 |
| **SEA** | 1.42 | 1.40 | 1.35 | 1.36 | 1.34 | 1.41 | 1.31 |
| **CHI** | 1.40* | 1.42 | 1.42 | 1.38 | 1.40 | 1.44 | 1.32 |
| **NAF** | 1.33 | 1.37 | 1.33 | 1.34 | 1.33 | 1.34 | 1.31 |
| **SSA** | 1.37 | 1.36 | 1.34 | 1.36 | 1.34 | 1.34 | 1.32 |
| **SIS** | 1.39 | 1.41 | 1.34 | 1.34 | 1.33 | 1.39 | 1.31 |

Source: Own calculations based on IMPACT baseline data.

* World average.

**Annex III: The substitution elasticity of water**

Let us assume that there is a production

$$A = f(X, W) \tag{1}$$

where $A$ is output, $W$ is water input, and $X$ is all other input. The cost of production

$$C = pX + tW \tag{2}$$

where t is the price of water and p is the composite price of other inputs. Production efficiency implies

$$\frac{A_X}{A_W} = \frac{p}{t} \tag{3}$$

Let us assume that (1) is CES

$$A = \left( X^{-\rho} + W^{-\rho} \right)^{-1/\rho} \tag{1'}$$

This implies

$$\frac{A_X}{A_W} = \frac{W^{\rho+1}}{X^{\rho+1}} = \frac{p}{t} \tag{3'}$$

From Rosegrant et al. (2002), we know the price elasticity of water use, $\eta$. Thus, we have

$$\begin{aligned} &\frac{W_1^{\rho+1}}{X^{\rho+1}} = \frac{p}{t} \wedge \frac{W_2^{\rho+1}}{X^{\rho+1}} = \frac{p}{t(1+\delta)} \Rightarrow W_1^{\rho+1} = W_2^{\rho+1}(1+\delta) \\ &W_1 = W_2(1+\eta\delta) \end{aligned} \tag{4}$$

That is, the price elasticity $\eta$ implies the substitution elasticity $\rho$, for any price change $\delta$:

$$\rho = \frac{\ln(1+\delta)}{\ln(1+\eta\delta)} - 1 \tag{5}$$

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