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The economy-wide impacts of climate change and irrigation development in the Nile basin: a Computable General Equilibrium approach

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Abstract

A multi-country, multi-sector computable general equilibrium (CGE) model is employed to evaluate the economy-wide impacts of climate change under the IPCC's A2 and B1 scenarios and existing irrigation development plans in the Nile basin. The study reveals that climate change adversely affects mainly downstream Egypt and to a lesser extent Sudan, while it results in a limited impact in the upstream countries Ethiopia and the Equatorial Lakes region, where irrigated agriculture is still limited. The economic consequences for Egypt are especially substantial if the river basin countries pursue a unilateral irrigation development strategy. In order to prevent water use conflicts and ease water scarcity conditions, a cooperative water development strategy is needed as well as economic diversification in favor of less water-intensive sectors, combined with investments in water-saving infrastructure and improved irrigation efficiency.

Key words: Computable general equilibrium, climate change, irrigation development, Nile River Basin

1. Introduction

Agriculture constitutes the backbone of the Nile basin economy. The sector contributes one-third of GDP (FAO, 2013) and provides employment to more than 75 percent of the labor force in the Nile basin countries (Karimi et al., 2012). Since poverty is most severe in rural areas and rural households heavily depend on agriculture for their livelihoods, agricultural development is essential to economic growth and poverty alleviation in the Nile basin countries, as it has been in other regions of the world (e.g. Valdes and Foster, 2010; Christiaensen et al., 2011). Agriculture in the Nile basin is predominantly a rainfed subsistence activity, with the exception of Egypt and Sudan where irrigated agriculture is widely practiced and 97 percent of the 5.6 million hectares of land is currently under irrigation (Bastiaanssen and Perry, 2009; NBI, 2012). In contrast, upstream countries heavily rely on rainfed subsistence agriculture, which is typically characterized by low productivity and high vulnerability to rainfall variability. Temporal and spatial variability of rainfall in many parts of these upstream basin countries has an adverse impact on the productivity of rainfed agriculture and the performance of the economy. For example, economic growth in Ethiopia has been hampered by hydrological variability according to the World Bank (2006), costing the country more than one-third of its growth potential.

Uncertainties related to future climate change pose additional challenges for agriculture in the Nile basin and may have profound repercussions on agricultural production and overall economic conditions. Climate change is expected to affect water resources (Bates et al., 2008) and may hence impose severe constraints on their use in agricultural production. Several studies have hinted at the sensitivity of the Nile basin to climate change (e.g. Yates and Strzepek, 1998; Elshamy et al., 2009; Beyene et al., 2010). While it is not clear how precipitation patterns would change in the basin in the long run (Elshamy et al., 2009), there is consensus that temperature will increase, which will inevitably result in higher evaporation rates and water demand (Conway, 2005). Other impacts include a reduction in agricultural yields as a result of changes in precipitation patterns and temperature, and increasing crop water requirements (Blackmore and Whittington, 2008).

In an attempt to fend off the disruptive impact of rainfall variability, upstream countries plan to make use of the Nile waters for irrigation development. Since “poverty and vulnerability across the basin are linked to access to water through crop and livestock-based livelihoods” (Awulachew, 2010, p.648), water resources development with a view to de-couple economic performance from hydrological variability is instrumental in enhancing economic development and reducing poverty in upstream countries. At the same time, downstream countries are also planning an expansion of their irrigated land. Awulachew et al. (2012) estimated the future irrigation development potential of the entire Nile basin at 10.6 million hectares, which implies an increase in irrigated land in the basin of about 93 percent. Much of the expansion in irrigated land (66%) is envisaged in downstream countries Sudan and Egypt, which already have a huge portion of land under irrigation. Given the current level of irrigation efficiency, this corresponds to a gross irrigation demand of 128 km^3/year (Awulachew, 2012), which is almost 75 percent above the annual natural river flow, so that future irrigation demand in the basin far exceeds water supply.

With irrigated agriculture accounting for 80 percent of water withdrawal in the basin already (Karyabwite, 2000; Bastiaanssen and Perry, 2009; FAO, 2011), further expansion of irrigated agriculture in the basin coupled with future climate change would mean intensified competition for the basin's scarce water resources. In light of this, an important research question is how the interaction between climate change and increasing irrigated agriculture would modify the water and land endowments in the Nile basin countries and impact upon agricultural production and overall economic conditions in these countries. Previous studies focusing on climate change impacts in the Nile basin analyzed primarily the economic effects of infrastructure development in specific parts of the Blue Nile, in particular Ethiopia and Egypt (e.g. Strzepek et al., 2008; Jeuland, 2010a and 2010b; Block and Strzepek, 2010).

The study presented here adopts a computable general equilibrium (CGE) modeling framework, using the revised version of the GTAP-W model (Calzadilla et al., 2010a), with the main aim to analyze the economy-wide impacts of climate change and irrigation development in the Nile basin. CGE models are able to demonstrate how climate change impacts are propagated across sectors and countries (Ginsburgh and Keyzer, 1997) and are best-suited to analyze the direct as well as indirect impacts of policy interventions (Robinsen et al., 2008). A few CGE models have been used to assess the potential impact of climate change and trade liberalization on global agriculture (Calzadilla et al., 2011a) and to analyze alternative adaptation scenarios to climate change in Sub-Sahara Africa (Calzadilla et al., 2013). Findings reveal that climate change would reduce global food production, welfare and GDP and raise food prices over time (Calzadilla et al., 2011a), and enhanced agricultural productivity is expected to yield better outcomes than an expansion in irrigated area alone to cope with the adverse impacts of climate change in Sub-Sahara Africa (Calzadilla et al., 2013). Compared to these previous studies, this study represents the first effort to apply a global CGE model to analyze sustainable water resources management in the Nile basin in a climate change context. It also constitutes the first effort to analyze the interaction between climate change and irrigation development in the basin in a general equilibrium setting.

The remainder of the paper is organized as follows. The next section presents the modeling framework and provides details of the data aggregation procedure. Section 3 introduces the simulation scenarios. Section 4 discusses the results and section 5 concludes.

2. Modeling framework and data

2.1 Modeling framework

The modeling framework applied for the study is the Global Trade Analysis Project (GTAP) model (Hertel, 1997), developed at the Center for Global Trade Analysis, Purdue University, USA. GTAP provides a global modeling framework and a common global database, providing the opportunity to conduct comparable model implementations and policy simulations. It is a static comparative, multi-region, multi-sector CGE model of the world economy that examines all aspects of an economy via its general equilibrium feature. The GTAP model comprises accounting relationships, behavioral equations and global sectors required to complete the model. The accounting relationships of the model ensure the balance of receipts and expenditures for every agent identified in the economy, whereas the behavioral equations specify the behavior of profit and utility optimizing agents in the economy through production and demand functions based on microeconomic theory (Brockmeier, 2001). The GTAP model assumes perfectly competitive markets, constant returns to scale technology, a non-homothetic demand system and a foreign trade structure characterized by the Armington (1969) assumption. Assuming weak separability, the production system is set up as a series of nested constant elasticities of substitution (CES) functions combined through elasticities of substitution (see Appendix A).

The analysis presented here uses the new version of the GTAP-W model (Calzadilla et al., 2010a), which constitutes a refinement of the GTAP-W model introduced by Berrittella et al. (2007). The basic change in the new GTAP-W model is reflected in a new production structure that splits the land endowment in the value-added nest into rainfed land, irrigated land and irrigation water. Unlike the original GTAP-W model which incorporates water into the production structure as a non-substitutable factor of production, the revised GTAP-W model distinguishes between rainfed and irrigated agriculture and implements water as a factor of production directly substitutable in the production process of irrigated agriculture.

2.2 Data

The GTAP Africa Data Base (ADB), which includes data for most of the Nile Basin countries, is used for the analysis. For the purpose of the present study, the GTAP ADB is aggregated into seven regions: Egypt, Ethiopia, Sudan (pre-2011), the Equatorial Lakes (EQL) region, Rest of North Africa, Rest of Sub-Sahara Africa and Rest of the World (ROW) (see Appendix B for an overview of regions and countries). The four EQL countries covered in the GTAP ADB include the Democratic Republic of Congo, Kenya, Tanzania and Uganda[1]. The regional aggregation reflects the importance of the Eastern Nile region, where the overwhelming proportion of the Nile water resources are generated and used. The 57 sectors in the GTAP ADB are aggregated

[1] Burundi and Rwanda from the EQL region and Eritrea from the Eastern Nile region are not covered in the GTAP ADB.

for the purpose of this study into 17 sectors, of which 8 are agricultural sectors and 9 are non-agricultural sectors (see the overview in Appendix C).

Following Calzadilla *et al*. (2011b), the agricultural land endowment in the standard GTAP database is disaggregated into rainfed land, irrigable land, and irrigation water based on data provided by the International Food Policy Research Institute (IFPRI). The relative share of rainfed and irrigated production in total production is used to split the land rent in the original GTAP database into a value for rainfed land and a value for irrigated land for each crop in each region. In a next step, the ratio of irrigated yield to rainfed yield is used to split the value of irrigated land into the value of irrigable land and the value of irrigation water.

In the GTAP-W model, as in the standard GTAP model, primary factors of production are assumed to substitute for one another according to a constant substitution elasticity parameter. The substitution elasticity parameter, which defines the relationship between changes in the ratio of factor inputs used in the production of a given level of output and the inverse ratio of their marginal products, i.e. their inverse price ratio in equilibrium, describes the flexibility of a production technology to allow for changes in the quantity ratios of factors used in the production of a given level of output as relative factor prices change. Due to a lack of data, the values for the elasticity of substitution between irrigated land and irrigation water used in this study are adapted from Calzadilla et al. (2011b). These values are shown in Appendix D. Sensitivity analysis of the model results with respect to the elasticity parameters is conducted in Section 5 to test how the results change as a result of applying alternative parameter values.

3. Baseline and policy scenarios

Our model examines the economy-wide impacts of climate change in 2050 on the Nile basin economy in the face of extensive irrigation expansion plans of the riparian countries. Climate change occurs in the future and hence impacts the future economy of the Nile basin countries. Climate change impacts are evaluated relative to a future benchmark equilibrium derived assuming a future with no climate change. The dynamic GTAP model (Ianchovichina and McDougall, 2001) is employed to track the path of the world economy over time and obtain the future benchmark equilibrium dataset for the GTAP-W model. In the baseline scenario without climate change, the economies of the Nile basin countries are projected to grow on average between 4 (Egypt and Sudan) and 6 percent (Ethiopia and EQL region) per year over the period 2001-2050 (Poncet, 2006). The analysis considers comparing a future world with and without climate change. Since the future is likely to involve changes in the demand for water, projected values that reflect expected changes in irrigation water demand and hence irrigated land endowments as well as industrial and domestic water demand are used to obtain baseline conditions for water and land endowments in a future with no climate change. The economic effects of future climate change and irrigation development in the Nile basin on water and land supply are then evaluated relative to these future baseline values.

In estimating the economic impact of climate change in the Nile basin, climate change related effects on (i) water supply, (ii) crop water requirements and crop yields as well as (iii) land use changes in irrigated and rainfed agriculture and (iv) the potential loss of irrigated land induced by sea level rise (SLR) in the Nile delta are taken into consideration. Future climate change impacts on stream flows and irrigation water supply in the Nile basin are based on data provided by Beyene et al. (2010). Using 11 general circulation models (GCMs) and the IPCC's A2 and B1 global emissions scenarios, Beyene et al. (2010) predict the impact of climate change on key climate variables including temperature, precipitation and stream flow for the major sub-basins and the entire Nile basin over three time periods: 2010-2039, 2040-2069, and 2070-2099. They also provide predictions of climate change related changes in irrigation water releases from the High Aswan Dam (HAD). In this study, the impact of climate change on agriculture in the Nile basin is assessed for the two global emissions scenarios A2 and B1 in 2050. The A2 scenario describes a future of high population growth and less rapid economic growth with regionally diverse technological change, while the B1 scenario describes a future with low population growth and rapid change in economic structure and the increased use of clean technologies. The period represents the average for the 30-years centered around the period 2040-2069 in Beyene et al. (2010). Changes in stream flow at HAD and Lake Victoria are used to calculate the changes in water supply for Egypt and the EQL Region, respectively. Changes in irrigation water supply in Ethiopia and Sudan are based on climate induced changes in the Blue Nile flow at the border between Sudan and Ethiopia in El Diem. Climate change related changes in crop water requirements are computed based on data from Nelson et al. (2010) and presented in Table 1. Nelson et al. (2010) provide detailed baseline data for the year 2000 and simulation data until the year 2050 with respect to irrigation water use, crop yields and cropped area, distinguishing between 20 rainfed and irrigated crops and 281 food processing units (FPU) for 115 economies and 126 river basins.

Our estimates of yield responses to climate change in the Nile basin countries presented in Table 2 are based on climate change related changes in temperature and precipitation presented in

Beyene et al. (2010) and their impact on crop yields based on estimates reported by Calzadilla et al. (2010b). The impact of CO_2 fertilization on agriculture in the Nile basin is assessed based on predicted CO_2 concentrations (IPCC, 2013) and yield response ratios for 7 crop types to elevated CO_2 concentration in crop models reported by Tubiello et al. (2006)[2]. Whether experimental free-air carbon dioxide enrichment (FACE) results for crop responses to elevated CO_2 translate into actual field conditions is questioned (Long et al., 2005, 2006). An analysis of experimental FACE studies by Long et al. (2006) demonstrate that CO_2 fertilization effects in the field are about 50 percent of those shown in lab-based experiments. Based on the findings of Long et al. (2006), recent studies such as Calzadilla et al. (2013), assume that no more than half of the positive effects of elevated CO_2 on crop yields reported in Tubiello et al. (2006) can be realized. In this study we assume that the positive effects of elevated CO_2 on crop yields reported in Tubiello et al. (2006) will be effectuated in agriculture in the Nile basin. However, for the sake of comparison, the findings of Long et al. (2006) and the assumption of Calzadilla et al. (2013) are also considered in implementing the yield response to CO_2 fertilization. We expect changes in precipitation, temperature and CO_2 fertilization to affect both rainfed and irrigated yields. Although irrigated farms tend to be less sensitive to high or extreme temperatures, irrigation water supply in the Nile basin is so restricted that we assume the effect to be negligible between rainfed and irrigated agriculture in our model.

[2] These are the so-called C3 and C4 crops. Based on Allen and Prasad (2004), C3 crops in the GTAP-W model comprise rice, wheat, other crops, fruits & vegetables, and oilseeds, while other cereals and sugar cane & sugar beet fall in the category of C4 crops.

Table 1: Percent change in crop water requirements due to climate change in 2050 compared to the baseline year 2000 by crop and Nile region under the two global IPCC emissions scenarios

	Egypt		Ethiopia		Sudan (pre-2011)		EQL Region	
	A2	B1	A2	B1	A2	B1	A2	B1
Rice	15.2	14.4	-	-	15.2	14.4	5.5	9.6
Wheat	6.5	7.8	-	-	6.5	7.8	2.9	5.2
Other cereals	6.3	4.6	16.3	17.9	6.3	4.6	2.9	9.0
Other crops	15.6	16.0	18.6	22.1	15.6	16.0	-	-
Fruits & vegetables	12.9	12.9	12.9	12.9	12.9	12.9	12.9	12.9
Oilseeds	3.7	3.8	-	-	3.7	3.8	2.5	2.5
Sugar cane & sugar beet	12.9	12.9	-	-	12.9	12.9	-	-

Source: Own computations based on data from Nelson et al. (2010).

Table 2: Percent change in yield response due to climate change in 2050 compared to the baseline year 2000 by crop and Nile region for the two global IPCC emissions scenarios

	Egypt				Ethiopia				Sudan				EQL Region			
	Rainfed*		Irrigated		Rainfed		Irrigated		Rainfed		Irrigated		Rainfed		Irrigated	
Scenario	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1
Rice	0	0	-25.6	-16.6	0.0	0.0	0.0	0.0	-13.2	-13.2	-22.0	-16.0	2.9	1.4	-6.5	3.8
Wheat	0	0	-26.8	-17.8	-0.3	-0.3	0.0	0.0	-17.6	-17.6	-22.0	-16.0	2.9	1.4	0.0	0.0
Other cereals	0	0	-24.8	-15.8	-7.1	-7.1	-6.7	-7.4	-18.7	-18.7	-22.7	-23.4	5.4	-1.2	-5.7	-2.2
Other crops	0	0	-26.6	-17.6	-6.6	-6.6	-15.6	-9.6	-15.5	-15.5	-21.3	-15.3	2.9	1.4	0.0	0.0
Fruits & vegetables	0	0	-26.6	-17.6	-3.2	-3.2	-14.5	-8.5	-13.6	-13.6	-17.7	-11.7	2.9	1.4	-6.5	3.8
Oilseeds	0	0	-26.6	-17.6	-10.3	-10.3	0.0	0.0	-14.7	-14.7	-22.0	-16.0	2.9	1.4	0.0	0.0
Sugar cane, sugar beet	0	0	-26.3	-17.3	-21.2	-21.2	0.0	0.0	-6.1	-6.1	-26.0	-19.4	5.4	-1.2	0.0	0.0

*Rainfed agriculture hardly exists in Egypt.

Source: Own computations based on data from Beyene et al. (2010), Calzadilla et al. (2010b) and Tubiello et al. (2006).

Climate change poses significant risks in terms of land inundation and submergence of coastal areas around the globe due to SLR (IPCC, 2014). In the Nile basin region, the Nile delta in Egypt is highly vulnerable to the impacts of SLR. Although it constitutes only 2.5 percent of Egypt's land area, the Nile delta region is home to over 65 percent of the population and about 70 percent of the country's commercial and industrial activities (El Raey, 2010). Furthermore it contributes 60 percent to the country's food production (Marriner et al., 2012). Climate change induced SLR in the Nile delta is therefore expected to have far reaching repercussions on Egypt's economy as it will affect several sectors of the economy. The socio-economic repercussions of a range of SLR scenarios on agriculture, tourism and industry in Egypt are documented in several studies (e.g. El Raey et al., 1999; Agrawala et al., 2004; El Raey, 2010). In this study we consider only the agricultural impacts of SLR related to the loss of agricultural land.

According to the IPCC (2007), a global SLR of 0.18 to 0.59 meter is expected by the end of the 21st century. In the Nile delta, the extent of SLR is expected to be more pronounced due to already existing local land subsidence problems. Excessive ground water extraction and reduced silt deposition following the construction of HAD have resulted in an estimated land subsidence rate of 1 to 5 mm per year in the Nile delta (NBI, 2012). Long term land subsidence rates along Egypt's coastal zones of Alexandria, Burullus and Port Said are estimated at 1.6, 1.0 and 2.2 mm per year, respectively (Frihy, 2003). The overall estimate of SLR in the Nile delta consists of the sum of the estimates of the already existing land subsidence problems in the region and the IPCC global estimates of SLR (El Raey, 2010). Based on available estimates (El Raey et al., 1999 and El Raey, 2010), an overall SLR of 0.5 meter in 2050 is assumed in this study. This is likely to cause, among other things, a loss of sizeable fertile irrigated agricultural land in Egypt.

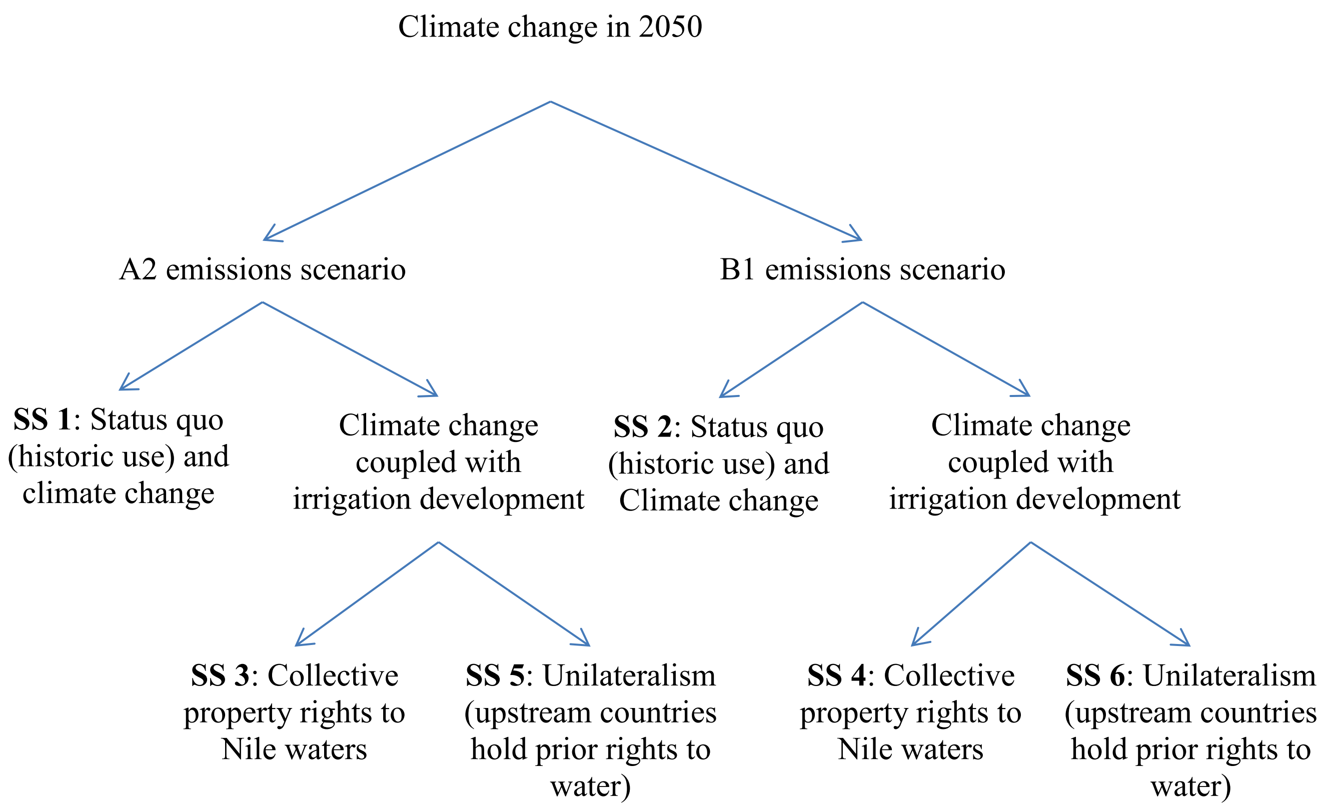
According to FitzGerald et al. (2008), a SLR of 0.5 meter would affect 3.8 million people and result in a loss of 1,800 square kilometers of fertile cropland in the Nile delta. Thus, SLR in the Nile delta would entail a loss of 5.4 percent of the irrigated land in Egypt in 2050. Taking an average annual land subsidence rate of 1.6 mm on Egypt's coastal zones based on the estimates provided by Frihy (2003), land subsidence accounts for about 20 percent of the SLR and the associated agricultural land loss in Egypt. Accordingly, only 4.3 percent (80% of the total) loss in irrigated land in Egypt is considered in implementing the impact of climate change induced SLR on Egypt's agriculture.

Besides climate change, the unilateral irrigation development plans of the Nile basin countries are in the long term expected to intensify water scarcity in the basin. According to Awulachew et al. (2012), these irrigation development plans correspond to an estimated gross irrigation water demand in the Nile basin of 127,660 million m^3/year on 10.64 million hectares of land. Given the wide gap between the demand for and supply of water in the basin, the issue of property rights to the Nile waters has a pivotal role in analyzing water resource management problems in the basin. In this study we consider three options: status quo (historic use right), collective property rights and unilateralism (prior rights to Nile waters held by upstream countries). The first option considers the existing water use where downstream countries Egypt and Sudan claim to have exclusive right to the Nile water which is contested by upstream countries. The 1959 Nile Agreement between the Sudan and Egypt for full Utilization of Nile waters allocated the Nile's annual flow between Egypt (55.5 km3) and the Sudan (18.5 km3), with the remaining 10 km3 of the river's flow assumed to be lost to evaporation and seepage at the Aswan High Dam (Salman, 2013). In this option the Nile waters are considered to be heavily utilized in downstream countries so that there will hardly be any significant expansion in irrigated agriculture in these countries. On the other hand, upstream countries lack rights to the waters to initiate significant irrigation development. Therefore, we assume there will not be new irrigation development that entails water reallocation in the basin under this option. We only consider assessing the impact of climate change in 2050 under the existing water use practices and irrigation development.

In the second option, upstream countries contend for access to the Nile waters and continue to engage upstream countries in the ongoing basin wide dialogue for sustainable development and management of the Nile waters under the auspices of the Nile Basin Initiative (NBI). We assume the Nile riparian countries will eventually subscribe to collective property rights to the Nile waters and adopt cooperative water resource development resulting in water allocation in proportion to the irrigation demand of each riparian country that corresponds to its long term irrigation development plan. In this option, the water use rights and hence the irrigation expansion plans of each country are proportionally divided in such a way that the demand for and the supply of water in the basin match. The third option represents the existing trend towards unilateralism in the basin (Cascao, 2009), exemplified by the vast number of individual countries' irrigation expansion plans (Awulachew et al., 2012). This option represents an extreme case of non-cooperative water development and assumes that each riparian country has property rights to flows in its territory so that only excess water supply is released to a downstream country. The most downstream country Egypt thus relies on the water left after irrigation water demand of the upstream countries has been satisfied. Despite its questionable political feasibility, this option aims to highlight the potential economic consequences of a lack of cooperative solutions to the water resources management challenges in the basin.

Overall, this results in six sets of simulation scenarios (SS1 to SS6 in Figure 1), which were developed to assess the economic impacts of climate change and irrigation development. The scenarios characterize three water rights allocation options (status quo, collective property rights and unilateral water claims based on existing irrigation development plans), for two IPCC climate change scenarios (A2 and B1).

Figure 1: Structure of the climate and water allocation scenarios



Full development of the Blue Nile infrastructure is expected to reduce system-wide reservoir evaporation from 18.8 km^3 to 14.1 km^3 (Blackmore and Whittington, 2008), and hence we assume a 4.7 km^3 increase in the yield of the river system in the long term. We also assume that irrigation development in the basin will be accompanied by a 10 percent improvement in land and water use efficiency. These exogenous improvements in water and land use efficiencies are exclusively related to the expected improvement in the basin’s irrigation technology and not related to water scarcity or climate change. Improved irrigation efficiency increases the effective supply of water and hence slightly eases water scarcity in the basin. Moreover, a 30 percent return flow is assumed in computing irrigation demand in the basin. The effect of climate change and implementation of the long term irrigation development plans in the Nile basin countries on water and land use in the basin's irrigated agriculture for the two water use right options (collective property rights and unilateralism) and two emissions scenarios are presented in Tables 3 and 4, respectively. Irrigation development increases water and land use tremendously in all the Nile countries except Egypt. Unilateral water development decreases irrigation water supply and hence land use in Egypt drastically, aggravating the climate induced decline in water and land use in the country. Compared to the status quo and unilateralism, irrigation expansion in the basin based on proportional water allocation strategy (collective property rights) results in lower adverse effect on Egypt’s net irrigation water supply (Table 4). Although Awulachew et al. (2012) do not put an exact time scale on the long term irrigation development plans, we assume that they are implemented by 2050. Shocks related to these irrigation plans are scaled by the size of irrigated and rainfed agriculture in each country that lies within the basin area.

Table 3: Change in irrigated land use due to climate change and irrigation development in 2050 compared to the baseline year 2000

	Climate change only[1]				Climate change coupled with irrigation development[2]							
	Status quo (historic water use)				Collective property rights				Unilateralism			
	A2 scenario		B1 scenario		A2 scenario		B1 scenario		A2 scenario		B1 scenario	
	10^3 ha	%	10^3 ha	%	10^3 ha	%	10^3 ha	%	10^3 ha	%	10^3 ha	%
Egypt	-439.5	-7.3	-400.0	-6.7	-405.3	-6.8	-332.8	-5.6	-983	-16.4	-910	-15.2
Ethiopia	-0.8	-1.1	-0.5	-0.7	762.0	1035.2	763.4	1037.1	796	1081.4	797	1083.4
Sudan (pre-2011)	-109.7	-6.3	-67.0	-3.8	109.5	6.3	157.8	9.0	653	37.3	701	40.1
EQL Region	-0.4	-0.2	2.2	1.2	191.8	108.3	222.3	125.5	205	115.8	236	133.1

Sources:

[1] Own computations based on data from Beyene et al. (2010).

[2] Own computations based on Awulachew et al. (2012) and Beyene et al. (2010).

Table 4: Change in irrigation water use due to climate change and irrigation development in 2050 compared to the baseline year 2000

	Climate change only[1]				Climate change coupled with irrigation development[2]							
	Status quo (historic water use)				Collective property rights				Unilateralism			
	A2 scenario		B1 scenario		A2 scenario		B1 scenario		A2 scenario		B1 scenario	
	km^3/yr	%	km^3/yr	%	km^3/yr	%	km^3/yr	%	km^3/yr	%	km^3/yr	%
Egypt	-7.05	-12.7	-6.11	-11.0	-3.4	-6.1	-2.5	-4.4	-10.91	-19.7	-9.96	-18.0
Ethiopia	-0.04	-7.2	-0.02	-4.4	7.8	1478.8	7.8	1481.6	8.12	1544.9	8.13	1547.7
Sudan (pre-2011)	-1.30	-7.2	-0.81	-4.4	1.2	6.3	1.7	9.1	7.00	37.8	7.51	40.6
EQL Region	-0.05	-3.9	0.25	20.7	1.9	154.7	2.2	179.3	2.00	165.5	2.30	190.1

Sources:

[1] Own computations based on data from Beyene et al. (2010).

[2] Own computations based on Awulachew et al. (2012) and Beyene et al. (2010).

4. Simulation results

This section presents the results of the simulations to assess the economic effects of future climate change and irrigation development on the Nile basin economies. We use changes in water allocation across crops, municipal and domestic water use, agricultural production, market prices of agricultural products, and economic growth (change in real GDP) relative to the projected 2050 benchmark equilibrium without climate change as indicators of the economic implications of climate change and irrigation expansion in the basin. Because of the expected significance of the impacts on especially the most downstream located river basin country Egypt, these will be detailed separately where appropriate. We furthermore zoom in on the 7 arable farming sectors most affected by climate change and irrigation development and omit the results for the livestock and meat sector and the non-agricultural sectors.

Climate change and irrigation development modify the water and land endowments of the Nile basin countries and induce changes in water allocation across sectors. In Egypt, a decline in water supply due to climate change and new irrigation development in the basin results in a large reduction in water use across sectors (Table 5). The adverse impacts on water use related to climate change combined with the status quo (historic water use) (SS1 and SS2) are substantial and most pronounced for the IPCC's A2 scenario. Climate change coupled with irrigation development based on proportional water allocation strategy within the whole basin (SS3 and SS4) results in lower adverse effect on water use in Egypt. However, the negative impacts remain substantial in most agricultural sectors especially under the IPCC's A2 scenario. Since the Nile waters are already heavily used for irrigation in Egypt and to a lesser extent in Sudan, vast irrigation expansion in the basin increases water use upstream at the expense of Egypt. The combination of climate change and unilateral irrigation development (SS5 and SS6) is particularly critical for Egypt as it results in a 4 to 42 percent decrease in water use across the 7 agricultural sectors.

Climate change and irrigation development tend to increase agricultural water use in Ethiopia, Sudan and the EQL region (Table 5). Climate change alone would have a mixed effect on water use in Ethiopia and Sudan in the sense that water use increases in some sectors and somewhat decreases in others. In the EQL region, water use deceases modestly in all sectors for the IPCC's A2 scenario but increases substantially across all sectors for the IPCC's B1 scenario, which predicts wetter climate for the region. Additional irrigation development would result as expected in a tremendous rise in agricultural water use in all the Nile basin countries except Egypt. Climate change combined with irrigation development increases water use by 567 to 2083 percent in Ethiopia, 1 to 81 percent in Sudan, and 87 to 224 percent in the EQL region. The relative changes in agricultural water use in Ethiopia and the EQL region are enormous since irrigated agriculture and hence irrigation water use in these regions is limited in the baseline scenario. The percentage change in water use across agricultural sectors in Sudan is relatively lower due to the already higher irrigation water use here in the baseline scenario. The combination of climate change and a unilateral irrigation development strategy (SS5 and SS6) would result in the highest increase in water use in all sectors since this means that these countries would divert as much of the available water as possible to realize their irrigation development goals.

Table 5: Percentage change in irrigation water allocation across agricultural sectors in 2050 as a result of climate change and irrigation development compared to the baseline scenario

	Rice	Wheat	Other Cereals	Other crops	Vegetables & Fruits	Oil seeds	Sugar cane & sugar beet
SS1							
Egypt	-2.4	-32.7	-16.6	-1.7	-6.0	-14.6	-0.4
Ethiopia	-8.4	-1.5	6.5	-1.5	4.0	-20.2	-2.6
Sudan (pre-2011)	-3.1	-12.6	2.1	-8.7	22.3	-13.7	11.7
EQL Region	-11.0	-1.6	-3.6	-3.2	-1.0	-4.6	-3.9
SS2							
Egypt	-2.7	-24.4	-14.3	-8.5	-5.2	-13.8	-2.0
Ethiopia	-11.5	-2.2	6.0	5.6	5.8	-21.3	-3.7
Sudan (pre-2011)	-1.1	-9.9	0.5	-3.7	20.3	-9.3	11.3
EQL Region	30.3	12.8	14.0	10.2	35.8	17.1	10.0
SS3							
Egypt	3.0	-26.9	-8.9	11.3	1.9	-7.8	8.2
Ethiopia	862.5	640.8	787.4	1981.3	629.3	1111.4	571.1
Sudan (pre-2011)	18.0	-1.3	11.7	0.5	36.4	4.2	20.9
EQL Region	180.3	172.1	97.4	161.3	138.0	104.8	88.6
SS4							
Egypt	2.4	-18.1	-6.3	3.1	2.3	-6.8	6.2
Ethiopia	845.6	634.0	777.6	1999.4	639.2	1094.9	567.2
Sudan (pre-2011)	16.4	0.7	9.3	4.5	32.7	9.5	20.1
EQL Region	212.0	196.3	112.9	185.3	161.7	117.9	101.3
SS5							
Egypt	-10.3	-42.0	-22.5	-12.5	-11.0	-21.9	-4.0
Ethiopia	907.8	671.3	824.2	2063.9	659.4	1163.6	599.5
Sudan (pre-2011)	80.4	16.7	26.5	30.3	56.0	45.5	35.5
EQL Region	191.8	184.4	104.3	173.5	146.3	111.5	95.2
SS6							
Egypt	-10.6	-33.6	-20.0	-18.8	-10.2	-20.6	-5.8
Ethiopia	888.3	663.5	812.8	2083.1	669.0	1145.5	594.0
Sudan (pre-2011)	80.5	17.7	23.2	34.0	49.0	50.9	34.5
EQL Region	223.5	208.4	119.9	197.4	170.3	124.5	107.9

Municipal and industrial water use in the basin is also expected to change due to climate change and irrigation expansion. To examine these changes, we took the output of the water services sector as a proxy for raw water use by the municipal and industry sectors (Table 6). Egypt, which has the highest use rater in the basin (66.2%), shows substantial increase in municipal and industry water use. municipal and industrial water use tends to decline or remain more or less stable in Ethiopia and Sudan while it shows considerable simulated increases in the EQL region when climate change is combined with irrigation development. Overall, the effect of climate change only on municipal and industrial water use in the basin is limited (1.02 – 1.59 km^3). Similar results are observed for climate change plus irrigation development (0.88 – 2.14 km^3) pertaining to municipal and industrial water use in the basin. An increase in water use due to climate change only is more pronounced for the IPCC's B1 scenario than the IPCC's B1 scenario.

Table 6: Change in municipal and industrial water use as a result of climate change and irrigation development compared to the baseline scenario

	Municipal and industrial water use in benchmark equilibrium (km^3)	Change in output of water services (%)	Change in municipal and industrial water use (km^3)
SS1			
Egypt	9.3	17.3	1.61
Ethiopia	1.03	0.3	0.00
Sudan (pre-2011)	0.86	-1.9	-0.02
EQL Region	2.85	-0.2	-0.01
Total	**14.04**		**1.59**
SS2			
Egypt	9.3	11.0	1.02
Ethiopia	1.03	0.2	0.00
Sudan (pre-2011)	0.86	-1.4	-0.01
EQL Region	2.85	0.3	0.01
Total	**14.04**		**1.02**
SS3			
Egypt	9.3	14.6	1.35
Ethiopia	1.03	-6.7	-0.07
Sudan (pre-2011)	0.86	-0.8	-0.01
EQL Region	2.85	6.7	0.19
Total	**14.04**		**1.47**
SS4			
Egypt	9.3	8.1	0.75
Ethiopia	1.03	-6.9	-0.07
Sudan (pre-2011)	0.86	-0.5	0.00
EQL Region	2.85	7.3	0.21
Total	**14.04**		**0.88**
SS5			
Egypt	9.3	21.6	2.01
Ethiopia	1.03	-6.8	-0.07
Sudan (pre-2011)	0.86	0.2	0.00
EQL Region	2.85	7.0	0.20
Total	**14.04**		**2.14**
SS6			
Egypt	9.3	14.1	1.31
Ethiopia	1.03	-6.9	-0.07
Sudan (pre-2011)	0.86	0.4	0.00
EQL Region	2.85	7.5	0.21
Total	**14.04**		**1.46**

Table 7 shows the subsequent effects of the change in water use under the different scenarios on agricultural production in the Nile basin countries. Climate change (SS1 and SS2) adversely affects agricultural production in the downstream countries Egypt and Sudan, which rely heavily on irrigated agriculture. Agricultural production falls up to 31 and 26 percent in Egypt and Sudan, respectively, due to climate change. In upstream countries, where agriculture is predominantly rainfed, the effect of climate change on production is mainly limited to certain sectors in Ethiopia and in most cases negligible in the EQL region. The impact of climate change in combination with irrigation development on agricultural output in Egypt depends on the applied water rights allocation rules. If irrigation development in the basin follows a proportional water rights allocation strategy (SS3 and SS4), Egypt faces lower adverse impacts of climate change to a certain extent. Egypt experiences substantial negative effect on its agriculture if the Nile basin countries all adhere to a unilateral irrigation development approach. In that case, agricultural production in Egypt falls between 4 and 45 percent across the agricultural sectors except for vegetables and fruits where output remains stable.

Climate change coupled with irrigation development affects agricultural production positively in Ethiopia and the EQL region. In Ethiopia, agricultural production shifts to rice, other grains and crops and oil seeds where output increases 16 to 194 percent at the expense of the remaining sectors where output falls by 13 to 31 percent. Climate change combined with irrigation development enhances output in all agricultural sectors in the EQL region. However, increases in output are most prominent in the region's rice, wheat and other grains and crops sectors where output rises by 54, 97 and 70 percent, respectively. In Sudan, agricultural output decreases in all sectors (1.5 to 23%) due to climate change and irrigation expansion based on a proportional water allocation strategy (SS3 and SS4). Despite a considerable increase in irrigation water use, agricultural production declines in Sudan mainly due to substantial decline in irrigated and rainfed yield induced by climate change. Unilateral irrigation development (SS5 and SS6) tends to enhance output in many of the country's agricultural sectors (1 to 40%). Unilateralism allows Sudan to increase its irrigation demand and hence irrigated land substantially and tends to compensate for the adverse effects of climate change induced decline in crop yield in many agricultural sectors of the country. Irrigation development generally favors rice and oil seeds production in Sudan.

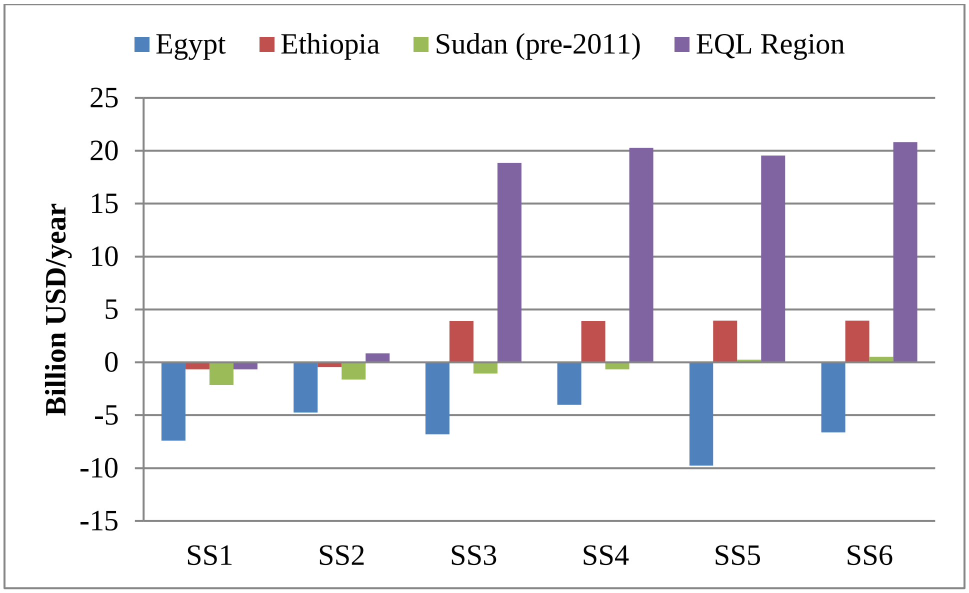
Table 7: Percentage change in agricultural production in 2050 as a result of climate change and irrigation development compared to the baseline scenario

	Rice	Wheat	Other cereals	Other crops	Vegetables & Fruits	Oil seeds	Sugar cane & sugar beet
SS1							
Egypt	-10.9	-36.1	-17.6	-10.5	-0.4	-12.4	-4.3
Ethiopia	-9.1	3.0	-0.1	-15.0	-1.0	-17.0	1.6
Sudan (pre-2011)	-19.1	-18.3	-8.7	-25.7	-8.6	-23.4	-4.3
EQL Region	-11.1	-0.9	-0.4	0.3	-4.1	-1.3	-0.1
SS2							
Egypt	-7.7	-24.4	-12.0	-7.4	-0.2	-8.3	-2.9
Ethiopia	-12.7	1.9	-0.9	-9.1	-0.8	-18.4	-0.3
Sudan (pre-2011)	-15.9	-15.2	-7.4	-19.8	-8.6	-17.1	-3.3
EQL Region	11.5	0.4	0.3	0.7	2.9	2.4	0.1
SS3							
Egypt	-12.8	-35.3	-16.2	-14.0	-0.1	-12.2	-3.6
Ethiopia	17.5	-13.2	-19.1	194.0	-26.9	44.0	-31.0
Sudan (pre-2011)	-5.8	-14.0	-4.5	-22.9	-8.0	-10.7	-2.2
EQL Region	50.8	83.9	1.5	61.9	3.5	3.7	1.6
SS4							
Egypt	-9.5	-23.2	-9.8	-11.0	0.2	-7.5	-2.1
Ethiopia	16.2	-13.3	-19.0	193.7	-26.6	43.5	-30.8
Sudan (pre-2011)	-5.7	-11.6	-3.5	-17.9	-8.1	-3.0	-1.5
EQL Region	53.2	93.2	1.6	67.9	3.6	3.3	1.7
SS5							
Egypt	-16.9	-44.5	-22.1	-18.2	-0.3	-18.4	-5.4
Ethiopia	18.4	-13.2	-19.0	194.0	-26.8	44.3	-30.9
Sudan (pre-2011)	36.9	-8.7	0.5	-6.8	-8.4	19.5	-0.1
EQL Region	52.0	87.9	1.6	64.7	3.5	3.4	1.7
SS6							
Egypt	-13.5	-32.7	-15.9	-15.1	0.0	-13.5	-3.7
Ethiopia	17.0	-13.3	-18.9	193.7	-26.6	43.8	-30.7
Sudan (pre-2011)	39.2	-7.3	1.1	-1.8	-8.6	28.1	0.4
EQL Region	53.9	96.7	1.6	70.4	3.5	2.9	1.8

Changes in output induced by climate change and irrigation development in the Nile basin influence market prices. The average price of agricultural products increases sharply in Egypt in all sectors except vegetables and fruits where prices decrease across all scenarios (see the Table in Appendix E). Climate change in the Nile basin (SS1 and SS2) causes a substantial increase in agricultural prices due to increasing water shortage. However, combined with irrigation development and following a proportional water allocation rule (SS3 and SS4), a relatively lower increase in prices results due to slightly improved agricultural production. Following the pattern of change in production, the price increase is higher (12 to 51%) in the case of a unilateral irrigation development (SS5 and SS6) compared to the 9 to 39 percent price rise in the case of climate change only (SS1 and SS2). Market prices of agricultural products rise in Ethiopia, Sudan and the EQL region as well (Appendix E). However, the rise in the average market prices of crops in these countries is relatively small compared to the same rise expected in Egypt. The surge in crop prices in Egypt depends upon the plunge in crop production induced by climate change and irrigation development upstream. Prices increase in the other Nile countries as well due to climate change induced changes in agricultural production (SS1 and SS2). The rise in market prices in these countries under climate change coupled with irrigation development scenarios is mainly attributable to the rise in export demand despite the improved conditions for agricultural production. The simulation results reveal an increase in the export of agricultural products from Ethiopia, Sudan and the EQL region to Egypt and other regions, adding to the price increase. Total agricultural exports from these countries increase by 72.1 to 76.6 billion USD per year under the climate change and irrigation development based on a proportional water allocation rule (SS3 and SS4). These numbers increase to 74.7 to 79 billion USD per year under climate change with a unilateral water development strategy (SS5 and SS6).

Figure 2 shows the effects of the climate change and irrigation development scenarios on real GDP of the Nile basin countries. Climate change alone (SS1 and SS2) inflicts a substantial loss in real GDP of USD 6 to 10.9 billion on the Nile basin economy in 2050. Relative to the projected GDP's for 2050, modeled GDP losses are 0.93-1.46 percent for Egypt, 0.53-0.76 percent for Ethiopia, and 1.66-2.21 percent for Sudan. The EQL region experiences a change in real GDP of +0.19/-0.16 percent for the IPCC's B1/A2 scenarios. In absolute terms, Egypt incurs most of this loss in real GDP (a share of 68 to 79%) in the basin due to climate change. If climate change is combined with irrigation development based on a proportional water allocation rule (SS3 and SS4), the basin-wide gain in real GDP is in the order of USD 14.9 to 19.5 billion per year, of which Ethiopia and the EQL region gain USD 3.9, and USD 18.9 to 20.3 billion respectively, while Egypt and Sudan lose USD 4 to 6.8 and USD 0.66 to 1.06 billion, respectively. Climate change coupled with a unilateral irrigation development strategy (SS5 and SS6) causes a substantial loss in real GDP of USD 6.6 to 9.8 billion in Egypt's economy, while it results in a small gain of USD 0.2 to 0.5 billion in Sudan. The increase in real GDP for Ethiopia and the EQL region under the SS5 and SS6 scenarios remain the same as under the SS3 and SS4 scenarios. The changes in real GDP in the Nile basin economies due to climate change only (SS1 and SS2) translate, on average, into economic growth rates of -1.2, -0.6, -1.9 and 0.02 percent for Egypt, Ethiopia, Sudan and the EQL region, respectively. Changes in real GDP due to climate change and irrigation development induce, on average, an economic growth of -1.3, 4.6, -0.2 and 4.6 percent in the economies of Egypt, Ethiopia, Sudan and the EQL region, respectively.

Figure 2: Change in real GDP due to climate change and irrigation development relative to the predicted baseline scenario



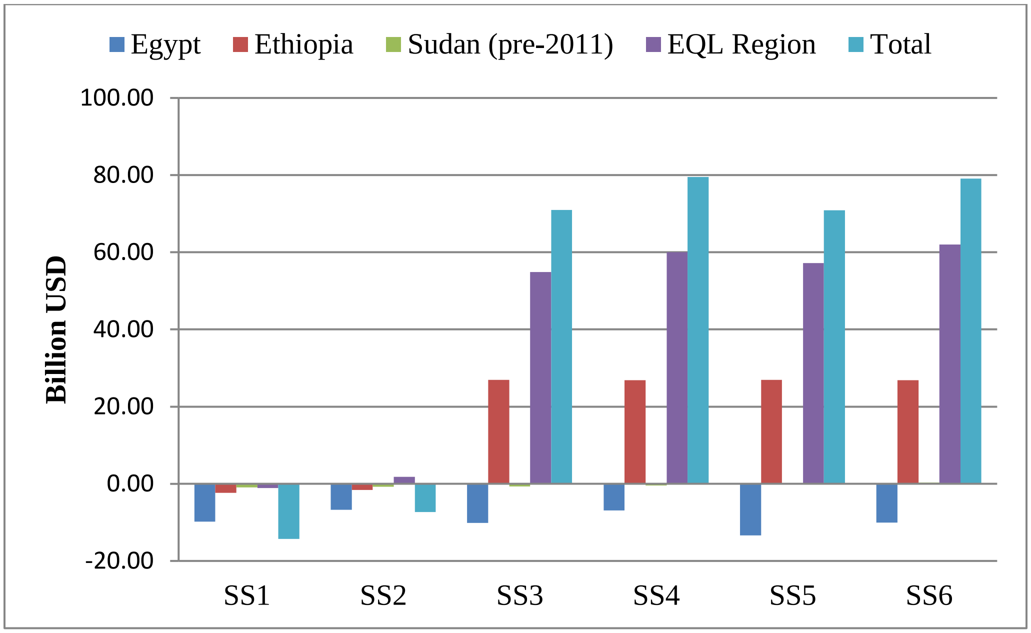
Overall, the economic growth effects due to climate change and irrigation development and the consequent reallocation of water are generally not favorable for Egypt. Climate change only (SS1 and SS2) causes economic contraction in the other Nile countries as well, albeit to a lesser extent compared to that expected in Egypt. Irrigation expansion compensates for the adverse impacts of climate change and induces modest economic growth in Ethiopia and the EQL region. Sudan gains slight increase in real GDP if climate change is combined with irrigation development based on a unilateral irrigation development strategy (SS5 and SS6).

Climate change and irrigation development in the Nile basin are expected to influence the marginal value of water in irrigated agriculture and municipal and industrial use. The market price of irrigation water is used to assess the marginal value of water used for irrigation, while the marginal value of water in municipal and industrial use is measured using the price of the output of the water services sector as a proxy. The results reveal that the price of irrigation water increases by 80 to 85 percent in Ethiopia and decreases by 78 to 90 percent in Sudan due to climate change. In Egypt, the price of water in agriculture decreases for the IPCC's A2 scenario (-18%) and increases for the IPCC's B1 scenario (+60%). The price of water in irrigated agriculture in the EQL region increases by 95 percent and decreases by 80 percent for the IPCC's A2 and B1 scenarios, respectively. The combination of climate change and irrigation development results in a 12 to 100 percent decline in the price of irrigation water in all the Nile basin countries. The price of irrigation water in Ethiopia, Sudan and the EQL region decreases substantially as more water is diverted for irrigation development upstream at the expense of Egypt. In Egypt, the decline in water price is attributable to a substantial decline in the productivity of irrigated agriculture. While water scarcity due to increased upstream abstraction increases the average irrigation water price in Egypt by 42 to 229 percent, the decline in the productivity of irrigated agriculture induced by climate change depresses the average irrigation water price by 114 to 209 percent, resulting in a net decline in the price and hence marginal value of water in the country's irrigated agriculture.

The effect of climate change and irrigation expansion on the price of water used for municipal and industrial purposes is found to be relatively small. Climate change alone results in a 1 to 6 percent decline in the price of municipal and industrial water in all the Nile basin countries except the EQL region where the average price remains stable. The price rises by 13 and 3 percent in Ethiopia and the EQL region, respectively, and falls by 2 to 4 percent in Egypt when climate change is combined with irrigation development throughout the basin. In Sudan, the average price of municipal and industrial water decreases by 2 to 3 percent under climate change and irrigation development based on a proportional water allocation strategy (SS3 and SS4) and increases by 1 to 2 percent if the Nile basin countries adopt a unilateral irrigation development strategy (SS5 and SS6). Overall, climate change tends to give water used in the basin's irrigated agriculture a relatively higher marginal value. However, the marginal value of irrigation water plunges sharply as irrigation development substantially increases irrigation water use in all the Nile countries except Egypt. Hence, climate change combined with irrigation expansion results in a relatively higher value for municipal and industrial water use, indicating the potential economic gain of reallocating water from irrigated agriculture to domestic and industrial use in the basin.

Changes in the value of agricultural production in the basin resulting from climate change and irrigation development are considered in evaluating the economic value of water across the Nile basin countries (Figure 3). Climate change coupled with the existing water allocation in the basin causes a loss of USD 14.3 and 7.3 billion in the total value of agricultural production in the basin for the IPCC's A2 and B1 scenarios, respectively. Egypt incurs the highest proportion of the loss, amounting to 69 and 92 percent of the total, respectively. Climate change affects Egypt mainly through its adverse effect on the productivity of irrigated land and irrigation water. According to the simulation results, both effects account for 73 to 85 percent of the loss in the value of agricultural production in the country due to climate change. The climate change induced decline in land and water productivity results in a substantial decrease of the productivity of irrigated agriculture and hence the value of irrigation water in Egypt. Relative to the effect of climate change only, irrigation development and the consequent reallocation of water from Egypt to the other Nile basin countries exacerbates the loss in the value of agricultural production in Egypt by 2.3 to 3.6 percent if irrigation expansion is based on a proportional water allocation strategy. If the Nile basin countries pursue a unilateral irrigation development policy, the value of agricultural production in Egypt falls by 36 to 50 percent compared to the loss the country incurs in the climate change only situation. Irrigation development has a limited effect on the value of agricultural production in Sudan. Nevertheless, substantial upstream water abstraction for irrigation development in Ethiopia and the EQL region induces an increase in the value of agricultural production in these countries resulting in a net basin-wide gain of USD 70.9 to 79.6 billion. An increase in irrigation water use and the associated increase in irrigated land, combined with the limited impact of climate change on land and water productivity, increase the value of irrigated production and hence the economic value of irrigation water in these countries. Overall, the results demonstrate the negative impact of climate change on the economic value of water in Egypt's irrigated agriculture. However, a reallocation of water to upstream countries results in an enormous increase in the value of agricultural production in the basin as a whole. The results concur to those on real GDP reported in Figure 2.

Figure 3: Change in the total value of agricultural production due to climate change and irrigation development relative to the predicted baseline scenario



With a view to assess the impact on model results of the assumption made on the effect of elevated CO_2 on crop yield in the basin, a second set of simulation is conducted assuming only half of the CO_2 fertilization effects in crop yields shown in lab-based experiments will be realized in the Nile basin agriculture. The results demonstrate more pronounced adverse effects of climate change on agricultural production and hence real GDP and economic growth in the basin (see Appendices F and G). Compared to those based on lab-based CO_2 fertilization effects on crop yield, these results show substantially higher decline in agricultural production due to climate change which results in 15 to 18 percent lower basin wide real GDP in the case of climate change only (SS1 and SS2). The decline in the basin's real GDP decreases to 5 to 12 percent when climate change is combined with irrigation development. This results in relatively lower rate of economic growth in all the Nile basin countries.

A CGE modeling framework was used here to account for the fact that the river basin is shared by several countries that all depend on the water resources, hence requiring a multi-country CGE model that represents all the Nile riparian economies. In addition, a global CGE model is used to accommodate the open economy character of the countries that share the basin. However, the model results show that the Nile basin countries have a very small effect on the global economy and world market price levels.

5. Sensitivity analysis

In order to test the robustness of the estimated effects of climate change and irrigation development in the Nile basin economies, a sensitivity analysis of the model results was carried out, varying the imposed shocks based on the policy scenarios on the one hand, and changing the production structure's substitution elasticities on the other hand. The sensitivity of the results is tested in the former case by assuming a plus and minus 25 percent change in irrigated land and water supply due to climate change and irrigation expansion plans in the Nile basin. In the latter case the applied elasticities of substitution between irrigated land and irrigation water are assumed to be 25 percent lower and higher. The 95 percent confidence intervals around the estimated model results are derived following the procedure outlined in Burfisher (2011). The results are presented in Table 7 and show no change in sign for the rate of economic growth for the Nile countries under the climate change (for IPCC's A2 scenario) combined with irrigation development based on a proportional water allocation rule (SS3) at the 95 percent confidence level. The modeled scenario outcomes presented before fall within the 95 percent confidence intervals, indicating that these results are robust. The same applies to the changes in the parameter values of the substitution elasticity.

Table 8: 95% confidence intervals around the percentage change in real GDP due to climate change and irrigation development for a ±25% change in the applied elasticity of substitution between irrigated land and irrigation water and for a ±25% change in the shocks applied to irrigation water and irrigated land.

		±25% change in elasticity of substitution between irrigated land and irrigation water		±25% change in irrigated land and water supply	
	Modeled value	Mean % change in real GDP	St.dev.	Mean % change in real GDP	St.dev.
Egypt	-1.34	-1.34	0	-1.34	0.04
Ethiopia	4.58	4.58	0	4.58	0.04
Sudan (pre-2011)	-1.08	-1.08	0.01	-1.08	0.04
EQL Region	4.36	4.36	0	4.35	0.23

6. Discussion and conclusions

The study presented here employs a multi-region, multi-sector computable general equilibrium (CGE) modeling framework to assess the economy-wide impacts of climate change and irrigation development in the Nile basin. The effects of six different scenarios of exogenous (climate change) and endogenous (irrigation development) change are evaluated in terms of irrigation water use across the 7 most important agricultural sectors, agricultural production, market prices and economic growth measured as the change in real GDP. Moreover, the economic value of water in agriculture and non agricultural sector (municipal and industry use) as well as water use across the Nile basin countries is examined. The findings of the study reveal that climate change adversely affects mainly Egypt, located downstream in the Nile river basin, and to a lesser extent Sudan. In the upstream countries Ethiopia and the EQL region, where irrigated agriculture is still limited, the impact of climate change is relatively limited. In all cases, the adverse impacts are more pronounced under the IPCC's A2 scenario than the B1 scenario.

When climate change is accompanied by future irrigation development, this results in modifications of the distribution of water endowments across the riparian countries. Irrespective of future property rights to water (proportional sharing or unilateral development), further development of the irrigation potential in the basin entails a significant reallocation of water from the most downstream country Egypt to the other Nile basin countries. This reduces water supply and hampers agricultural production and would hence have severe economic implications for Egypt, especially if the basin countries adhere to a unilateral strategy in developing their irrigation potential. Egypt is very vulnerable to economic losses, even under current water allocation conditions, as its water and irrigated land endowments are expected to diminish over time due to future climate change.

The combination of climate change and irrigation development is expected to yield positive effects in Ethiopia and the EQL region. This is mainly due to the existing vast irrigation expansion plans in these countries. Irrigation development improves water endowments and enhances agricultural production in these countries. Agricultural production tends to increase in Sudan in the case of unilateral irrigation development. In all other cases, the country's agricultural production decreases mainly due to climate change induced decline in yield. The potential gains in terms of agricultural production and exports of agricultural produce from a reallocation of water to upstream countries are substantial and in the order of magnitude of 70.9 to 79.6 billion USD in term of value of agricultural production and 14 to 20 billion USD in terms of real GDP. The marginal value of water in irrigated agriculture tends to be higher than that in municipal and industrial use. When climate change is accompanied by irrigation development water tends to have a relatively higher marginal value in municipal and industrial use.

The results on the impact of climate change are more or less consistent to previous findings on a global scale (Calzadilla et al., 2011a). The findings show that climate change is expected to reduce agricultural production and welfare and raise prices of agricultural crops. However, the total economic impact of climate change on agricultural production in countries where irrigated agriculture is not yet very developed, such as Ethiopia and the EQL region, is found to be significantly lower. As a result, real GDP remains fairly stable under climate change in these countries. Like Calzadilla et al. (2013 and 2014), we show that an expansion of the irrigation potential in these countries offsets and reverses the impacts of climate change. The irrigation development plans compensate for the climate change induced decline in agricultural production and improve agricultural production locally in a number of agricultural sectors in the upstream countries Ethiopia, Sudan and the EQL region. Irrigated agriculture makes a difference in the upstream countries where agriculture is currently still heavily dependent on the vagaries of weather uncertainty and erratic rainfall.

Finally, the static nature of the GTAP-W model constitutes a major limitation of the study presented here. A dynamic GTAP-W model based on the dynamic GTAP model is theoretically expected to be able to better absorb shocks due to climate change and irrigation development in the Nile basin countries through adjustments in the national capital stocks, such as the investments in durable irrigation infrastructure. However, despite the static nature of our model, the results of the current analysis demonstrate the potential risk of combined climate change and vast irrigation development ambitions in the basin. In order to prevent intensified competition for scarce water resources in the basin, a cooperative water sharing approach seems crucial to maximize the basin-wide economic value of the Nile waters. This could include the development of joint basin-wide infrastructure policies to reduce the immense system-wide evaporation losses so as to augment the volume of water supply. Improvements in irrigation efficiency would also help to significantly improve water use per unit of output, thereby improving the effective supply of water in the basin. Moreover, in the long term, a shift away from growing water-intensive crops such as rice and promoting more intensive economic cooperation, taking advantage of the Nile countries' competitive advantages (e.g. diversifying economic activities in favor of for example manufacturing in Egypt, the economically most advanced country in the basin), seems imperative to ease the looming water scarcity conditions and prevent the potential of water related conflicts in the basin.

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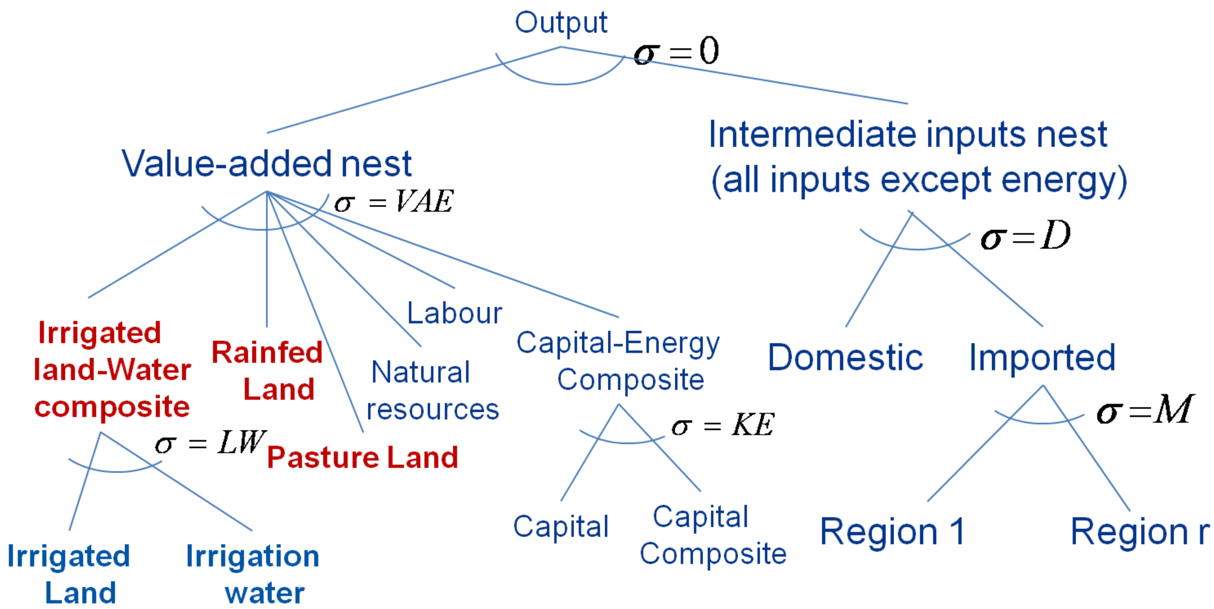
Appendix A: Revised GTAP-W: Nested Tree Structure for Production Process



Appendix B: Regional Aggregation

Region	Description
Ethiopia	Ethiopia
Sudan (pre-2011)	Sudan, including South Sudan
Egypt	Egypt
Equatorial Lakes Region	Democratic Republic of Congo (DRC), Uganda, Kenya, United Republic of Tanzania
Rest of North Africa (Rnf)	Morocco, Tunisia, Rest of North Africa
Rest of Sub-Sahara Africa	Cote d'Ivoire, Senegal, Rest of WAEMU, Ghana, Nigeria, Rest of ECOWAS, Cameroon, Rest of CAEMC, Rest of SADC, Rest of COMESA, Botswana, South Africa, Rest of South African CU, Madagascar, Malawi, Mauritius, Mozambique, Zambia, Zimbabwe, Rest of Sub-Saharan Africa
Rest of the World	Oceania, East Asia, Southeast Asia, South Asia, North America, Latin America, European Union 25, Rest of Europe, Middle East,

WAEMU: West African Economic and Monetary Union
ECOWAS: Economic Community of West African States
CAEMC: Central African Economic and Monetary Community
SADC: South African Development Community
COMESA: Common Market for Eastern and Southern Africa
CU: Customs Union

Appendix C: Sectoral Aggregation

Sector	Detail Description
I. Agricultural Sectors	
Paddy	paddy
Wheat	wheat
Other cereals	Cereal grains not elsewhere classified (nec),
Other crops	Plant-based fibers; crops nec; processed rice,
Vegetables and fruits	Vegetables, fruit, nuts
Oilseeds	Oil seeds
Sugar	Sugar cane, sugar beet
Livestock and meat products	Cattle, sheep, goats, horses; animal products nec; raw milk; wool, silk-worm, cocoons; meat: cattle, sheep, goats, horses; meat products nec;
II. Non-agricultural sectors	
Coal	Coal
Crude	Oil
Gas	Gas; gas manufacturing, distribution
Petroleum	Petroleum, coal products
Electricity	Electricity
Processed food	Vegetable oils and fats; dairy products; sugar; food products nec; beverages and tobacco products
Extraction and manufacturing	Forestry; fishing; minerals nec; textiles; wearing apparel; leather products; wood products; paper products, publishing; chemical, rubber, plastic prods; mineral products nec; ferrous metals; metals nec; metal products; motor vehicles and parts; transport equipment nec; electronic equipment; machinery and equipment nec; manufactures nec;
Water	Water
Services	Construction; trade; transport nec; sea transport; air transport; communication; financial services nec; insurance; business services nec; recreation and other services; public administration, defense, health, education; dwellings

Appendix D. Elasticity of substitution between irrigable land and irrigation

Regions	Substitution elasticity
Egypt	0.08
Ethiopia	0.05
Sudan (pre-2011)	0.05
EQL Region	0.05
Rest of North Africa	0.08
Rest of Sub-Sahara Africa	0.05
Rest of the World	0.07

Source: Adapted from Calzdilla et al. (2011a)

Appendix E: Percentage change in the market price of agricultural products under different climate change and irrigation development scenarios relative to the baseline scenario

	Rice	Wheat	Other cereals	Other crops	Vegetables & Fruits	Oil seeds	Sugar cane & sugar beet
SS1							
Egypt	38.7	30.7	31.5	14.3	-10.6	28.5	25.9
Ethiopia	2.4	-1.3	4.0	4.3	1.5	6.8	-0.4
Sudan (pre-2011)	33.5	12.2	50.3	19.8	23.1	23.7	59.6
EQL Region	4.3	0.7	1.8	0.6	7.6	1.5	0.1
SS2							
Egypt	25.2	19.2	19.2	9.2	-7.7	18.5	17.5
Ethiopia	2.0	-0.8	4.7	2.4	0.8	6.6	0.5
Sudan (pre-2011)	24.0	9.8	43.7	13.3	26.0	14.6	43.4
EQL Region	-2.6	0.1	-0.4	0.2	-4.3	-1.0	0.1
SS3							
Egypt	32.0	28.9	29.0	10.7	-10.8	24.5	22.2
Ethiopia	-6.3	6.2	17.6	-26.7	28.4	-9.8	45.8
Sudan (pre-2011)	23.3	8.4	24.8	5.8	29.8	7.8	37.3
EQL Region	-9.1	-20.1	-2.8	-17.1	-5.9	-3.2	0.0
SS4							
Egypt	17.3	17.3	16.0	5.1	-7.6	13.4	12.5
Ethiopia	-6.5	6.0	17.3	-27.1	27.9	-10.3	45.3
Sudan (pre-2011)	14.6	6.5	20.2	0.9	32.3	1.3	26.0
EQL Region	-9.5	-21.5	-2.9	-18.3	-6.1	-3.3	0.0
SS5							
Egypt	51.4	38.9	44.3	18.7	-13.7	38.0	37.1
Ethiopia	-6.4	6.2	17.5	-26.8	28.3	-9.8	45.8
Sudan (pre-2011)	18.7	5.0	-0.2	-5.2	39.1	-7.1	15.8
EQL Region	-9.1	-20.6	-2.7	-17.5	-5.8	-3.2	0.0
SS6							
Egypt	33.8	26.0	28.3	11.7	-10.8	25.3	25.5
Ethiopia	-6.5	6.0	17.3	-27.2	27.8	-10.3	45.3
Sudan (pre-2011)	12.8	3.9	-2.6	-8.2	41.6	-11.1	9.7
EQL Region	-9.5	-21.9	-2.9	-18.7	-6.0	-3.2	0.1

Appendix F: Percentage change in agricultural production in 2050 as a result of climate change and irrigation development compared to the baseline scenario assuming only 50 percent of the lab-based CO_2 fertilization effects on crop yield will be realized in the Nile basin agriculture.

	Rice	Wheat	Other cereals	Other crops	Vegetables & Fruits	Oil seeds	Sugar cane & sugar beet
SS1							
Egypt	-12.2	-40.1	-19.1	-11.9	-0.4	-14.2	-4.7
Ethiopia	-5.4	3.9	0.6	-18.5	-1.7	-13.7	1.3
Sudan (pre-2011)	-23.2	-21.3	-9.8	-28.3	-11.0	-26.4	-5.1
EQL Region	-14.8	-1.0	-0.4	0.2	-3.9	-0.9	-0.1
SS2							
Egypt	-8.6	-28.3	-13.1	-8.3	-0.2	-9.5	-3.2
Ethiopia	-9.1	2.7	-0.2	-12.5	-1.3	-15.0	-0.6
Sudan (pre-2011)	-15.2	-16.8	-7.6	-19.8	-11.0	-17.1	-3.5
EQL Region	7.3	0.3	0.2	0.6	2.8	2.5	0.1
SS3							
Egypt	-14.1	-39.2	-17.7	-15.4	-0.1	-14.0	-4.1
Ethiopia	22.5	-13.1	-18.9	193.4	-27.0	37.7	-31.2
Sudan (pre-2011)	-9.6	-16.9	-5.4	-25.4	-10.4	-14.3	-2.8
EQL Region	36.9	84.8	1.6	62.0	3.5	4.0	1.6
SS4							
Egypt	-10.4	-26.9	-11.1	-11.9	0.2	-8.8	-2.4
Ethiopia	18.7	-13.1	-18.9	193.2	-26.8	37.1	-31.0
Sudan (pre-2011)	-4.6	-13.5	-3.7	-17.9	-10.5	-3.1	-1.7
EQL Region	47.3	93.4	1.6	68.0	3.5	3.4	1.7
SS5							
Egypt	-18.2	-48.3	-23.5	-19.6	-0.4	-20.2	-5.9
Ethiopia	23.6	-13.0	-18.9	193.5	-27.0	38.1	-31.1
Sudan (pre-2011)	30.2	-11.5	-0.2	-9.5	-10.8	14.7	-0.6
EQL Region	37.8	88.8	1.6	64.9	3.4	3.7	1.7
SS6							
Egypt	-14.3	-36.4	-17.0	-15.9	0.0	-14.8	-4.0
Ethiopia	19.5	-13.1	-18.8	193.2	-26.8	37.3	-30.9
Sudan (pre-2011)	37.8	-9.5	0.9	-1.8	-11.1	27.8	0.1
EQL Region	48.0	97.0	1.6	70.4	3.5	3.1	1.8

Appendix G: Change in real GDP in 2050 as a result of climate change and irrigation development compared to the baseline scenario assuming only 50 percent of the lab-based CO_2 fertilization effects on crop yield will be realized in the Nile basin agriculture.

	SS1		SS2		SS3		SS4		SS5		SS6	
	%	Million USD	%	Million USD	%	Million USD	%	Million USD	%	Million USD	%	Million USD
Egypt	-1.7	-8397	-1.1	-5429	-1.5	-7795	-0.9	-4713	-2.1	-10877	-1.5	-7372
Ethiopia	-0.9	-746	-0.6	-537	4.5	3882	4.6	3887	4.6	3899	4.6	3903
Sudan (pre-2011)	-2.6	-2555	-1.8	-1724	-1.4	-1365	-0.8	-756	0.0	-20	0.4	416
EQL Region	-0.2	-838	0.2	671	4.3	18522	4.7	20124	4.4	19196	4.8	20687
Total		-12535		-7019		13244		18542		12197		17634