The Impacts of Climate Change on Surface and Ground Water Withdrawal: A New Global Data Base of Costs and Returns of Irrigation

Part I: Background, Method, and Data

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Abstract

This study introduces an improved global economic framework for investigating the impacts of climate change while focusing on local water constraints and international trade of agricultural products. This study measures the likely impacts of a counterfactual change in "irrigation yield gap" on irrigation expansion, groundwater withdrawal, surface water withdrawal, and international trade of agricultural commodities. We construct proposed economic framework based on GTAP (Global Trade Analysis Project) model, a widely used global model, to investigate various economic impacts. We extend GTAP Water Data Base (Haqiqi et al., 2016) by adding new global database on irrigation efficiency; introducing irrigation services as sectors; new global database of costs and returns of irrigation; introducing energy, capital, and labor inputs for water extraction and on-farm water distribution; distinguishing surface water from groundwater; and considering different irrigation technologies. We also introduce demand and supply of irrigation services by river basin AEZs (agro-ecological zones). Then, we calculate the likely impact of a counterfactual scenario of climate change (change in relative yields of irrigated and non-irrigated crops).

JEL: C68, Q24, Q25, F18.

Keywords: Water Resources; Irrigation Efficiency; Climate change; Input-Output; Production Technology.

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1- Introduction

How do regional and global economies respond to likely changes in the global ecosystem? Specifically, how regional agriculture may adapt to predicted climate change? How important is the role of irrigation and water resources for this adaptation? The hypothesis of this research is that irrigation role is quite significant compared to other adaptation channels. We will investigate this hypothesis by constructing a global general equilibrium model with a detailed irrigation technology structure. This structure considers the connection between regions through commodity markets and international trade.

The answer to these questions is important for farmers, agricultural investors, and policymakers. Our findings will notify farmers not only about the direct impacts of climate change on their farm but also about the indirect impacts through markets and prices. The investors will learn where irrigation will be more profitable. In addition, policymakers will learn how important irrigation is for the resilience of the agriculture system.

Agriculture is responsible for around 70 percent of global water withdrawal. Although only around 20 percent of global cropland is irrigated, they are contributing to 40 percent of total production of crops (World Bank, 2017). Despite the potentials for irrigation, there are concerns about the pressure on water resources. Population and income growth implies growing demand for water in food production, as well as competing demands from other sectors. Moreover, a warming climate may increase water requirement by crops. Water supply, on the other hand, is anticipated to reach a deficit of more than 50 percent in some areas by 2030 (Adams et al., 2009). In coming decades, climate change is predicted to increase the chance of drought in certain regions of the world. Figure 1 illustrates that the likelihood of severe droughts will increase in almost all regions of the world during 2020-2039 compared to the baseline period 1986-2005; while this likelihood is even higher during the 2040-2059. This will raise the question of how rainfed agriculture and water resources will be affected by these changes.

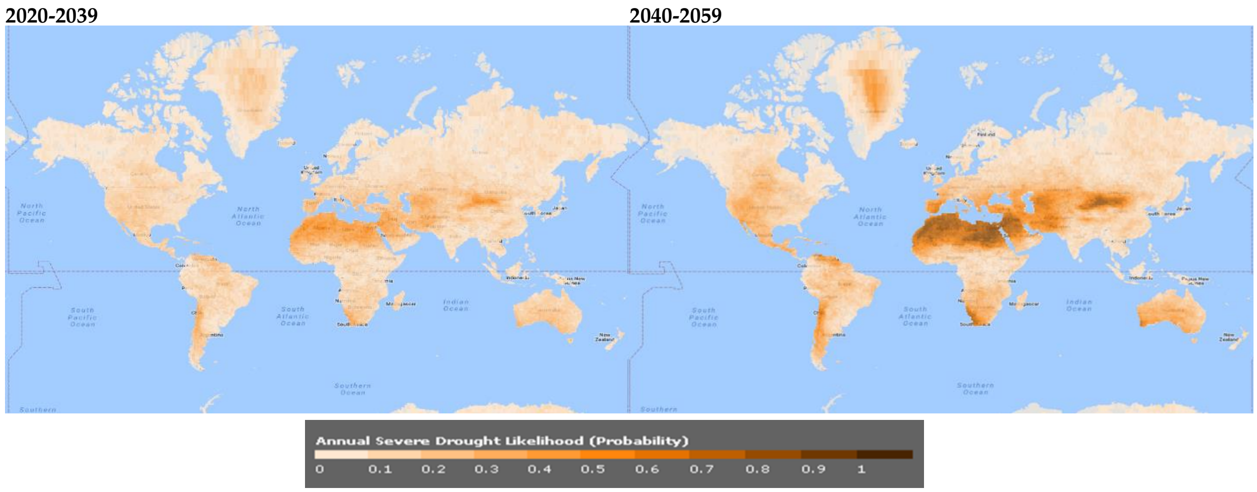

Figure 1: Change in Annual Severe Drought Likelihood (compared to 1986-2005 baseline)
Source: The World Bank Climate Change Knowledge Portal, CMIP5, RCP8.5, CCSM4.

Several studies claim that climate change will reduce crop yields severely in some specific agricultural hotspots (Burke et al., 2015; Schauberger et al, 2017; Blanc et al., 2017). On the other hand, some studies show that climate change will increase irrigation water demand (Kreins et al., 2015). Other studies predict that increase in irrigation demand due to climate change will put further stress on limited groundwater resources (Falloon and Betts, 2010). Likewise, some studies state that climate change will cause a shift from surface water into groundwater for agriculture (Hanson et al., 2012). However, the impact on yield is not homogeneous around the world. The change in irrigated and non-irrigated yield will be heterogeneous across regions, due to differences in natural conditions, such as climatic conditions or soils quality, or differences in land management policies (Kastner et al., 2014). On the other hand, the human system interaction can offset part of the damages or benefits from new climate conditions. In addition, international trade can reduce the damages and intensify food security in different regions (Liu et al., 2014).

While many studies focus only on the physical side of the yield change, the final impact on a country depends on human system's ability to adapt. Ignoring adaptation channels may lead to overestimating/underestimating the impacts. The adaptation can happen through changes in irrigation efficiency, rainfed substitution, change in crop mix, relocation, and international trade (Haqiqi and Hertel, 2016). The foundation of each likely channel is well developed in economics and theories of international trade. Heckscher–Ohlin theory of international trade suggests that relatively water-abundant countries will export more water-intensive goods. In general, this theory states that when countries are trading, a country will export those commodities which use the abundant factors in their production and will import those commodities that require factors of production that are scarce in that country. This theory considers the difference in factor intensities in commodities, and differences in factor endowment of countries in trade flows. Moreover, a Ricardian specific-factor model of trade suggests substitution towards rainfed crop production creates another source of adaptation strategy to water scarcity. Finally, a Melitz-type model of trade suggests that water scarcity may shift industry output from low irrigation productivity to high irrigation efficiency high productivity farms (Haqiqi and Hertel, 2016). This paper tries to construct a computable framework based on these theoretical foundations.

However, the proposed computable framework requires more information than what is already available. We introduce a new global database on costs of irrigation activities. We consider GTAP database as our global cost structure of agricultural activities. However, we take a different approach compared to GTAP Water Data Base. We split the GTAP database into irrigated and rain-fed crops by considering both irrigation benefits (yield differences) and irrigation costs (land, labor, energy, and capital).

2- Method

There are several global studies trying to link the economic system to climate change. Among them, the ENVISAGE-W (Haqiqi et al., 2016), GTAP-BIO-W (Liu et al., 2014), SIMPLE-G (Liu et al., 2017), GCAM (Kim et al., 2006), and IGSM-WRS (Strzepek et al. 2012) are the most relevant. While GTAP-BIO-W model can capture the changes in crop mix and relocation, it ignores changes in irrigation efficiency. While SIMPLE-G considers the relocation by having a gridded approach to crop production, it ignores the crop-mix changes and irrigation efficiency improvements. Although ENVISAGE-W captures the international trade channel, it ignores the heterogeneity within a region. The MIT model of IGSM-WRS also ignores changes in irrigation efficiency.

This study suggests an economic framework for analyzing irrigation withdrawal, which considers several adaptation channels. We have four main economic decision makers in crop production. 1) We assume that landowners in each location will optimize the allocation of land to rainfed and irrigated systems. 2) Farmers are optimizing production by choosing the mix of inputs. 3) Water-distributing agents minimize the irrigation costs (water distribution) by choosing between irrigation technologies. 4) In addition, water-extracting agents optimize water extraction by choosing between groundwater and surface water. All the functional forms follow either CES (constant elasticity of substitution) or CET (constant elasticity of transformation). For the rest of the economy, we follow standard GTAP assumptions on production, consumption, and international trade.

The model assumes that improvement in irrigation efficiency requires capital and it may change the labor and energy inputs for irrigation. It also assumes that improvement in irrigation efficiency is region-specific due to regional differences in the price of energy, labor, and capital. Figure 3 shows the suggested structure of irrigated production. The model considers the wasted water as an input to enable us considering impacts of water pricing or taxes. It also assumes that subsidies and taxes on capital, energy, and labor inputs for irrigation sectors will follow the rates of crop production sectors. This is important especially for regions with high subsidies on irrigation inputs. The model also introduces substitution among water extraction activities (surface and groundwater) and substitution across distribution activities (drip, sprinkler, gravity).

2-1- GTAP-IRRG assumptions

The basic production structure in the GTAP model is shown in Figure 2. An Approach to incorporating irrigation withdrawal into the GTAP model could be through introducing a different production activity for each output/region combination. In this model, we split crop production activity into irrigated and non-irrigated production. Figure 3 depicts the production structure of the irrigated system. Note that the production structure remains the same for all locations. However, input shares vary by region and by location within each region.

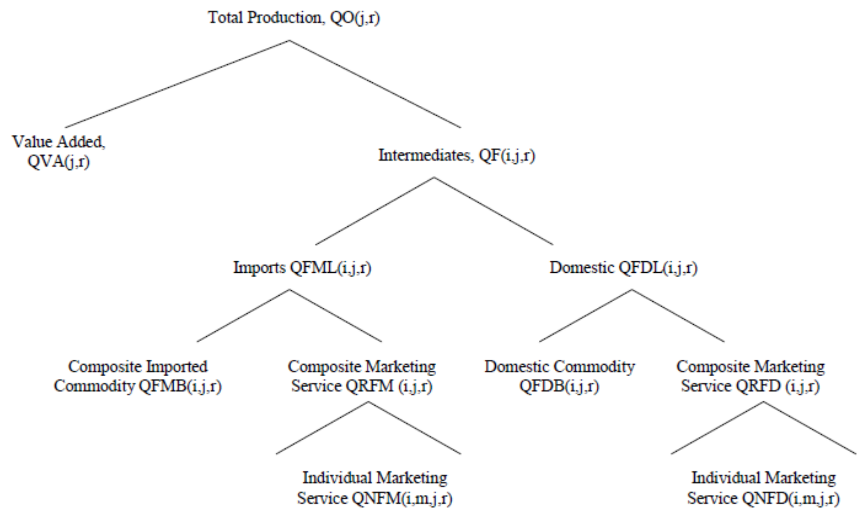

Figure 2: Production structure in GTAP model

We assume irrigation enters the production system as an intermediate input. There is substitution elasticity among irrigation technologies. Each irrigation technology has a different share of energy and capital and labor. In addition, water extraction activities also require a different amount of capital and energy.

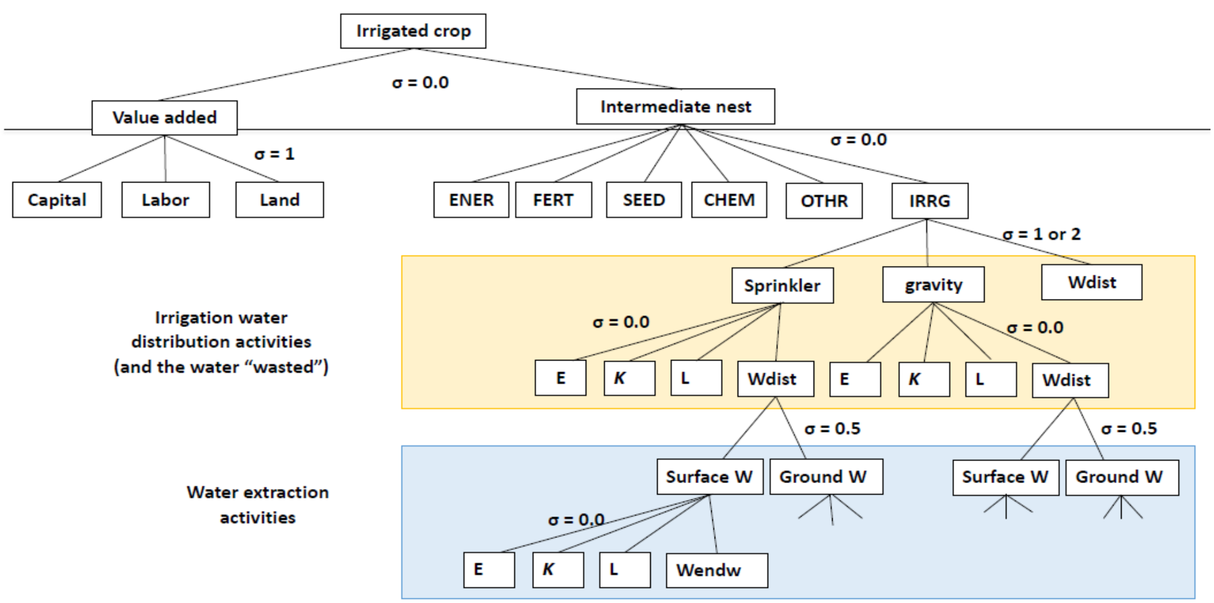

Figure 3: Structure of irrigated production

2-2- Selected equations in a linearized format

The solution to the optimization problem of our four agents is included in the GTAP model. The linearized version of behavioral equations for irrigated crop producers is provided as the following. In the first nest, value added and intermediate goods are combined to produce the irrigated crops:

$$qva_{j,r} + ava_{j,r} = qo_{j,r} - ao_{j,r} - \sigma_o\left[pva_{j,r} - ava_{j,r} - ps_{j,r} - ao_{j,r}\right] \quad (1)$$

Following GTAP notation, in this relationship, the letter "*p*" at the beginning of the variables represents the percentage change in the price of production and the letter "*q*" at the beginning of the variables represents the percentage change in the quantity of production. Therefore, *qo* represents the percentage change in the quantity of irrigated crops and *qva* represents the percentage change in the quantity of composite value added which is a CES combination of primary factors including capital, labor, and land. In addition, *ao* represents the technical change in irrigated crops production and *ava* represents the technical change in primary factors. Indices *i, j, k,* and *r*, represent goods, industries, primary factors, and regions, respectively. Finally, σ_o indicates the elasticity of substitution between value added composite and intermediate commodity composite.

$$pva_{j,r} = \sum_{k\in ENDW} SVA_{k,j,r} + \left[pfe_{k,j,r} - afe_{k,j,r}\right] \quad (2)$$

$$qfe_{i,j,r} + afe_{i,j,r} = qva_{j,r} - \sigma_{va}\left[pfe_{i,j,r} - afe_{i,j,r} - pva_{j,r}\right] \quad (3)$$

Where σ_{va} is the elasticity of substitution between primary factors. In the intermediate composite nest, different commodities are combined in a CES function. In equation (4), *qf* represents the quantity of intermediate good *i* in industry *j* and region *r*, and index *w* represents water distribution activities including sprinkler, drip and, gravity. Note that for non-irrigated good, the quantity of *w* is zero.

$$qf_{i,j,w,r} = \sum_{i\in TRAD} qo_{j,r} - \sigma_o\left[pf_{i,j,w,r} - po_{j,r}\right] \quad (4)$$

Moreover, *qw* represents the quantity of composite irrigated commodity which is a CES combination of three water distribution activities.

$$qw_{j,r} = \sum_{i \in TRAD} qf_{i,j,w,r} - \sigma_W \left[pw_{j,r} - pf_{i,j,w,r}\right] \quad (5)$$

Where σ_w is the elasticity of substitution between goods produced using different water distribution activities. Goods produced using sprinkler and gravity extraction activities are a CES combination of primary factors including energy, capital, and land and water extraction activities including surface water and ground water.

$$qfe_{i,j,r} = qw_{j,r} - \sigma_{ds}\left[pfe_{i,j,r} - pw_{j,r}\right] \quad (6)$$

Where σ_{ds} is the elasticity of substitution between goods produced using surface water and ground water. Similarly, goods produced form different water extraction activities are a CES combination of goods produced using surface water and ground water. In the following equations *qwg* represents goods produced using ground water and *qws* represent goods produced using surface water.

$$qwg_{j,r} = qw_{j,r} - \sigma_{ex}\left[pwg_{j,r} - pw_{j,r}\right] \quad (7)$$

$$qws_{j,r} = qws_{j,r} - \sigma_{ex}\left[pws_{j,r} - pwe_{j,r}\right] \quad (8)$$

Where σ_{ds} the elasticity of substitution between primary factors and goods produced using water extraction activities. Finally, goods produced using surface water are a CES combination of primary factors including energy, capital, land, and waste water. As mentioned before, we entered waste water in irrigated crop production structure in order to be able to consider the impacts of water pricing or taxes.

$$qfe_{i,j,r} = qws_{j,r} - \sigma_s\left[pfe_{i,j,r} - pws_{j,r}\right] \quad (9)$$

Where σ_s is the elasticity of substitution between primary factors and waste water.

3- Data

To measure the impacts of change in irrigated and rainfed yield on international trade, we need to know the importance of water and irrigation in crop production. Specifically, how important are the water extraction activities in crop production in each region? What is the cost structure of water distribution? And how important are labor, capital, and energy in irrigation?

We construct a database to address these questions. The most relevant available global data on irrigation and rainfed structure is GTAP-WATER database (Haqiqi et al., 2016). This Data Base disaggregates land to river basin and AEZs and provides a measure for the value of water in irrigation using yield gaps. We improve this Data Base by introducing more detailed information on the cost structure of irrigated and non-irrigated production. The observed cost structure of irrigated and rainfed production differs not only by land input but also by other inputs. For example, Table 1 shows the cost share of corn production in the US in irrigated vs non-irrigated regions according to USDA. It shows that share of land, energy and capital recovery for mostly non-irrigated regions are 30%, 3%, and 14%, respectively; while they are 20%, 6% and 20% for mostly irrigated regions for 2015.

Table 1. Corn production costs according to USDA Costs and Returns database.

	Non-irrigated*		Irrigated**	
Item	2015	2016	2015	2016
Opportunity cost of land	30%	30%	20%	20%
Fertilizer	20%	18%	17%	15%
Seed	15%	16%	13%	13%
Capital recovery of machinery and equipment	14%	15%	20%	21%
Chemicals	4%	4%	5%	5%
Repairs	3%	4%	6%	6%
Opportunity cost of unpaid labor	3%	4%	5%	5%
General farm overhead	3%	3%	3%	3%
Fuel, lube, and electricity	3%	2%	6%	5%
Custom operations 3/	2%	3%	4%	4%
Taxes and insurance	1%	1%	2%	2%

* Prairie Gateway region which has mainly irrigated corn. ** Heartland region which has mainly non-irrigated corn.

We split the GTAP database into irrigated and non-irrigated crops by considering both irrigation benefits (yield differences) and irrigation costs (land, labor, energy, and capital). For yield differences, we employ the same gridded input as GTAP Water Data Base, mainly from Siebert and Döll (2010). Figure 4 shows the value of production in each grid for wheat and rice.

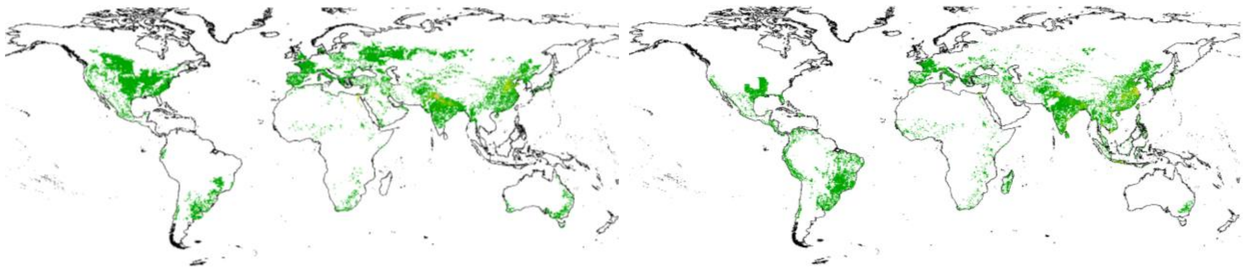

Figure 4. (a) Value of irrigated wheat by 5 min grid cells (b) Value of irrigated rice by 5 min grid cells

Source: authors' calculation based on Siebert and Döll (2010), and GTAPv9 for the year 2011

The information about the share of irrigation technologies is obtained from FAO AQUASTAT and FAO GMIA 5.0. Jägermeyr et al. (2015) provide the information about global irrigation efficiency. Global groundwater data is provided by Befus et al. (2017). And global groundwater table depth is from Fan et al. (2013). Figure 5 shows the water withdrawal for producing wheat and rice considering blue water requirement and irrigation efficiency.

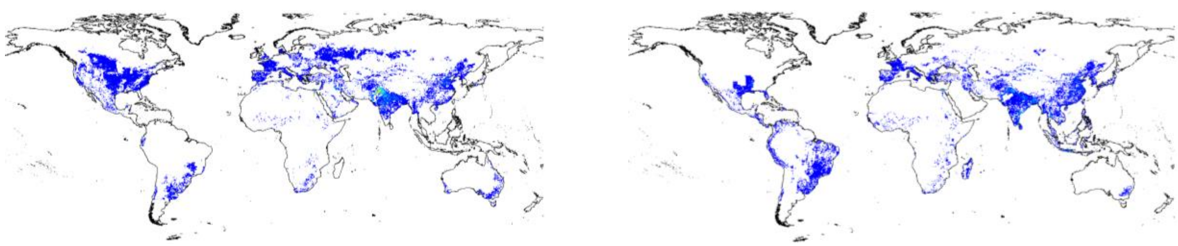

Figure 5. (a) Water withdrawal by irrigated wheat (b) Water withdrawal by irrigated rice

Source: authors' calculation based on Siebert and Döll (2010), Jägermeyr et al. (2015), FAO AQUASTAT

The main contribution of this study is calibration of the physical amount and value of energy, labor, and capital for irrigation. We assume that unit cost of groundwater withdrawal is changing by river basin (well depth) but not by AEZ. We also assume that the unit cost of water distribution is not changing within a region and across crops. We construct relative input requirement matrix for extraction and distribution of one cubic meter of water by region and by river basin. The reference matrix is obtained from cost structures provided by USDA Natural Resources Conservation Service, Michigan, as well as Farm and Ranch Irrigation Surveys. The reference matrix is updated for each region assuming a low capital-intensive country assigns less capital to the same technology compared to a high capital-intensive country. Energy requirement is calculated using outputs from Brozović et al. (2010) and Plappally and Lienhard (2012) from Center for Clean Water and Clean Energy, MIT. The physical energy data is converted to values using regional energy prices and implicit subsidies as in Chepeliev (forthcoming).

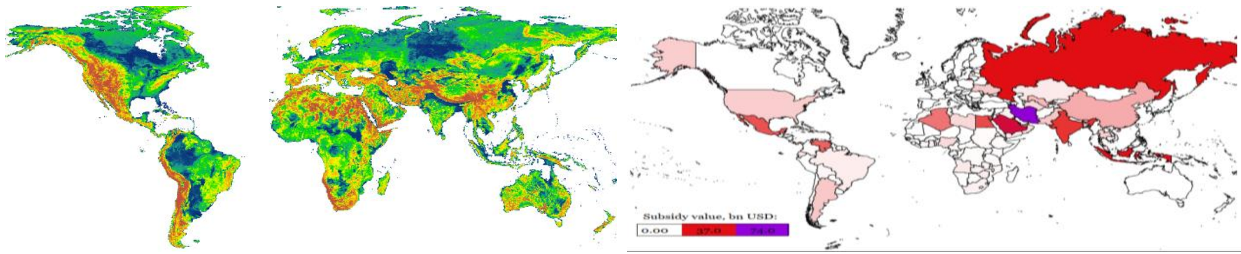

Figure 6. (a) Energy required to extract groundwater (b) total energy subsidy by each region

Source: (a) Authors' calculation based on Fan et al. (2013) and USDA-FRIS. (b) Chepeliev (forthcoming)

3-1- Discussion on the constructed Data Base

The Data Base and the Model will be available online after careful review. We try to keep the consistency with national data of the GTAP Data Base. We are also trying to keep the consistency of sub-regional "patterns" to our spatial information. Finally, we try to match our cost structure to the observed statistics of inputs and costs of irrigation.

Initial calculations of the database suggest that irrigated cost share of p_c (petroleum and coal products), cns (construction), ely (electricity), and wtr (water) will be higher compared to non-irrigated crops. Although the share of capital and labor is higher in irrigated production, the share of land is lower compared to non-irrigated. However, the share of isr (insurance) will be lower for irrigated crops and higher for rainfed crops.

4- Impacts of climate change on water resources

[TO BE COMPLETED]

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