Low Water - High Growth in South Asian Economies

Summary Report

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March 2017

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1. Introduction

Background

South Asia faces serious challenges in water availability. Those challenges are expected to increase in the coming years as populations and demand for food grow, the competition for water from non-agricultural sectors increases, and climate change aggravates the water stress in some river basins. Even without taking account of climate change the amount of water available for irrigation is estimated to drop by between 20-40 percent in several important riven basins in the region. The additional impact of climate change is variable and could be positive in some basins but add to the scarcity in others.

Such changes are bound to have important economic consequences. This report analyzes these consequences in an economy-wide context. It separates the implications of the growing scarcity of water in South Asia for economic and demographic reasons from those related to climate change. Furthermore, it evaluates specific measures that could be taken to addresses the economic and physical constraints against sustainable water management in the region. The aim is to develop a comprehensive analytical basis to support South Asia's decision-makers in promoting policies that achieve higher levels of water efficiency, facilitate economic growth in the presence of water scarcity, and promote climate resilience to help farmers to maintain their income in the face of severe climate conditions.

The objective of the study was to develop an analytical tool (similar to those used in low carbon studies) that would be robust, user friendly and transferrable to the client countries. Simulations on which the report is based validate and illustrate the use of such a tool. They do not aim to cover all aspects of water scarcity but rather to focus on key ones and demonstrate the kinds of results that can be obtained.

Methods of Analysis

A new computable general equilibrium model has been developed to analyze the impacts of economic and climatic changes on the agricultural and other sectors of the economy, taking special account of the role of water scarcity. Water is modelled as an input in production and its supply is specified at the river basin level by ago-ecological zone.

It is self-evident that water is a key input for any economy: without it nothing could be produced nor could anyone survive. The study of the role of water in an economy-wide context, however, has so far been limited and simplistic. Water is usually treated as something exogenous, available in a given quantity in different forms – as rainfall, as ground water and as surface water. Resources are allocated to collect it, purify it where necessary, and then allocate it to different uses according to existing rules for allocation within the economy. But the demand for water as an input across sectors other than agriculture is not modeled explicitly. Nor is the pricing of water, which can play a role (albeit limited) in allocating water, taken into account.

The economic importance of water, especially in economies heavily dependent on agriculture, and the effects of climate change on the availability of water across river basins, is the justification for the present work. It offers some new developments in the way water is included in economy-wide models of the economies of South Asia, and analyses the impacts of changes in water supply at the river basin level under alternative rules for the allocation of water. The results show where pressures are likely to be felt because of climate change, across the whole economy, in sectoral and macroeconomic terms; and what impacts different policies could have in alleviating those pressures.

Section 2 of the report describes the model and its innovative features. Section 3 gives details on the economic structure of the economies of South Asia and the role of water in them. Section 4 reports simulations that use the model to estimate the impacts of policies designed to improve efficiency in water use under different cost assumptions. Section 5 provides conclusions on the findings and next steps.

This report is a summary of a longer report that provides more details on the modelling and the analysis (Low Water High Growth Phase I, 2016). References to data in this report include the Main Report as well as sources where sections of that Main Report have been published (with disclaimer).

2. Modelling the role of water in South Asian economies

As noted, a key purpose of the modelling is to account explicitly for water as an input in the production process for all sectors, agricultural and non-agricultural. The important innovations in the present work can be summarized as follows:

i. It is the first multi-national level economy model that explicitly traces water use by country both at the river basin level, and further by the Agro-Ecological Zones (AEZs) within each riven basin. A large river basin could serve several AEZs.

ii. It incorporates water into the production function of all economic activities, including crops, livestock, industries, and water utility services. All sectors of the economy therefore compete for water and its marginal value in different uses can be calculated.

iii. Unlike existing Computable General Equilibrium (CGE) models, this model distinguishes between rain-fed and irrigated crops to better capture the links between demands for irrigation and food production.

iv. The model takes into account the fact that price of water could be different across uses and vary by river basin and AEZ even within a country.

v. The database used in this research is the best currently available at the global scale. The biophysical information includes crop production, harvested area, land cover items, and water used, which match with the national and international databases of the World Bank and the Food and Agriculture Organization of the United Nations (FAO).

The following is a brief non-technical description of how the model works. At any point in time the national income of each country is allocated to three groups: private consumption of various goods, public consumption (the government collects a portion of the household's income and spends it on public goods), and savings.

On the production side, each industry is represented by a single firm that uses primary factors (labor, capital, land, and resources, including water) and intermediate inputs to produce a final good. Firms sell their outputs to other firms (as intermediate inputs), to the private household, to government, and for investment. They can also export some of their output if it is a tradable commodity, and import some of their intermediate inputs. These goods are differentiated by country and so the model can track bilateral trade flows.

The features described above are standard for most economy-wide models (also referred to as CGE Models). Many of them use the Global Trade Analysis Project (GTAP) database as described in the next section. Within this family of models the special features of the present model are the following:

i. Competition for labor, capital, and resources takes place at the national level. While labor and capital are mobile inputs, which can move freely across uses, this is not true for resources, such as land and water, which have no, or only limited, mobility. Competition for water takes place at the River Basin (RB) level. In each river basin a portion of water goes for irrigation and the rest goes for other uses. As each river basin may serve several AEZs, these AEZs compete for irrigation water.

ii. In each RB-AEZ the area of available managed land is divided between forest, pasture and cropland. Within cropland irrigated and rain fed crops compete for land. This means that competition for water for irrigation also takes place at the spatial resolution of RB-AEZ. In this model water can be moved from one AEZ to another within a river basin but at a cost and subject to constraints.

iii. Given that water often cannot move freely across uses and AEZs within a RB owing to water rights, quotas, and other constraints, such constraints are accounted for in the model through three parameters. The first governs the allocation of available water in a river basin between three main uses: irrigated crops, livestock, and industrial and domestic uses. The second manages the allocation of water for irrigation across AEZs of a river basin. The third allocates water across irrigated crops within a river basin. The magnitudes of these parameters determine the degree of water mobility. For instance, when water shares across uses is fixed the first parameter is set at zero, when water cannot be moved across AEZs, then the second parameter should be set at zero and allocation of irrigated water across crops cannot be changed the third parameter is set at zero. The larger the magnitude of the parameter the easier it is to move water across AEZs. Since the true values of these parameters are not known, we could test for sensitivity of the results to different values.

iv. Three groups of users purchase managed water directly: producers of crops, livestock producers, and the water utility. The database gives the initial distribution of water across the RB-AEZ according to actual observations and determines the initial distributions of water demanded by these sectors. For the case of the water utility sector, it determines the sales to industries, households, and government. Again, the database sets the initial distribution of water sold by water utility sector.

v. Households have a demand for water from the water utility supplier, which is a function of water price and income.

The model, in common with other CGE models, determines the inputs and outputs of all sectors of the economy, as well as all those prices that are determined so as to equate the desired demand and supply for inputs and outputs. More details of the modelling can be found in Burniaux and Truong, 2002; Hertel et al., 2010, Taheripour, Hertel and Tyner, 2011, Taheripour, Hertel and Liu, 2013a, 2013b.

The parameters of the model are partly set from empirical data and partly determined so as to reproduce the actual structure of production of goods and services, use of resources and international trade in a given year. This calibration forms the basis from which further investigations can be carried out by changing the exogenous variables and by varying the parameters of the model.

3. Baseline data for South Asia

South Asia is a major crop producer, accounting for a third of world rice production, a fifth of sugar crops and around one-sixth of wheat production. Except for rice, not much is traded internationally. Yields for several crops are below international levels. Of total water demand in the region agriculture accounts for over 80%, everywhere except in Sri Lanka where it makes up about half. The mix of ground water and surface water varies widely by river basin and country.

The data for this study is taken from the widely-used GTAP database Release 9, which represents the world economy in 2011. It covers the economies of 140 countries/regions and divides economic activities into 57 sectors and is the only available database providing systematic and consistent information for so wide a range of countries, including trade flows between these countries.

For the purposes of this study GTAP was modified by: (a) dividing crops into irrigated and rain fed, (b) explicitly modelling of water for agriculture, (c) modelling electricity as two sectors (hydro and non-hydro) as opposed to a single sector, (d) modelling biofuel production and consumption as additional activities.

Figure 1 shows the land use map (2000) within the major basins in South Asia (Stibig et al., 2003). Cropland is the major land use in the region with 3,019,000 km^2, a little more than 50 percent of the total area of SAR.

Key features of South Asian economies where water has a key role are the following:

i. The region is a major crop producer in world terms (it accounts for a third of world rice production, a fifth of sugar crops and around one-sixth of wheat production) but it does not trade much of it internationally, with the exception of rice.

ii. South Asia has relatively low yields for a number of crops (though not all). For example, in 2011, yields in South Asia relative to the USA were as follows: rice (46%); wheat (96%); coarse grains (20%); oilseeds (54%); sugar crops (95%); and other crops (31%). Where yields are low several factors are responsible, such as small land parcels, lack of new agricultural knowledge, poor soil quality, low water efficiency, undeveloped commodity markets, and lack of access to credit.

iii. A big portion of the managed land of South Asia (75%) is cropland, followed by pasture (16%) and forests (9%). About 23% of India's cropland is distributed among dry AEZs with a short growing period. The rest (77%) is distributed among the rich moist AEZs with a longer growing period.

iv. The share of agriculture in total water withdrawal was more than 80% everywhere in South Asia in 2011, except for Sri Lanka where it was 51%. The Ganges, Indus and Brahmaputra are the main river basins covering Bangladesh, India, Pakistan and Nepal. Altogether 42% of all cropland is irrigated in the region, with about 56% of the irrigation coming from groundwater[1].

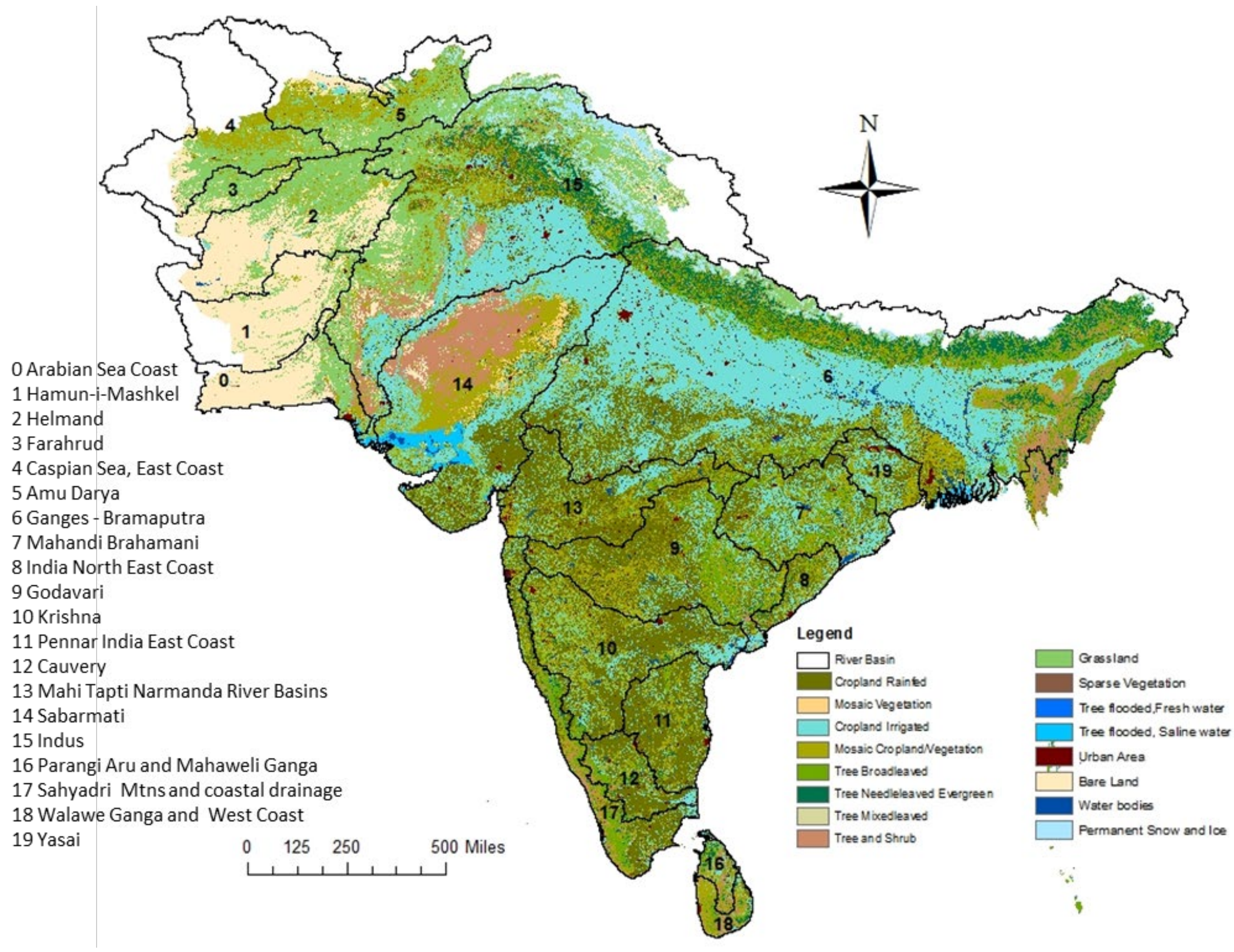
v. Water withdrawal can be divided into the surface and groundwater categories. The share of underground water in some river basins in India is relatively large, examples are: 47% in Brahmani; 46% in Mahi Tapi; 40% in Sahyadri Ghats; 36% in Godavari; and Ganges 34%. The shares of underground water withdrawal in Pakistan and Bangladesh were 34% and 79% in 2011, respectively. This is important because there is evidence that groundwater extraction rates are not sustainable in many AEZs.

vi. Non-hydroelectricity (mainly produced by thermal power plants) was a large share of total power production in South Asia in 2011. It was about 97% in Bangladesh, 95% in Sri Lanka, 90% in India and 85%, in Pakistan. Nepal is an exception, with electricity being basically produced by hydro generators. The demand for cooling water in thermal power plants is growing and a potential source of conflict with other demands, in particular in India.

vii. In South Asia only India was producing biofuels in 2011: about 348 million liters of ethanol and 116 million liters of biodiesel. In global terms this is very small – less than 0.05% -- although there are plans for significant expansion.

[1] http://www.fao.org/docrep/017/i1688e/i1688e.pdf.

Fig. 1. Land use map within the basins of SAR



4. Impacts of scarcity and climate change: key results

Water Scarcity by 2050

By 2050 Irrigation water supply will be reduced in a number of river basins but the impacts are variable. In Bangladesh declines of between 18% and 21% are expected in the Brahmaputra and Ganges basins. In India the declines will range from a low of 1% (Mahi Tapi) to a high of 90% (Luni). In Nepal the Ganges river basin will have a decline of 1%. In Pakistan the Indus is projected to decline by 43%. These decline increase the value of water. The other consequences are a decline

in food production; an increase in food imports; an increase in food prices; a shift from irrigated to rain fed crops; and a decline in GDP. In all cases the biggest impacts are found to be in Pakistan.

The initial analysis used the GTAP model to look at the consequences of water scarcity arising from an increase in demand for water while water supply is limited. It focused on the year 2050 and ran the model with any water deficit in each country being met by reducing the amount available for agriculture.

The first observation is that there is a scarcity problem in some river basins, independently of any climate change effects[2]. In the absence of any further investment, supply of water for irrigation will drop by the percentages shown in Table 1.

Table 1. Expected changes in water supply for irrigation in South Asia by country and river basin (% change in 2011-2050)

Country	River Basin	Reduction in irrigation water (%)	Country	River Basin	Reduction in irrigation water (%)
Bangladesh	Brahmaputra	-17.9	India	Indus	-7.1
Bangladesh	Ganges	-21.3	India	Krishna	-42.6
India	Cauvery	-49.6	India	Luni	-89.5
India	Chotanagpur	-23.8	India	Mahi Tapti	-1.2
India	Eastern Ghats	-34.5	India	Sahyada	-5.7
India	Ganges	-15.7	Nepal	Ganges	-0.8
India	Godavari	-19.7	Pakistan	Indus	-42.7
India	East Coast	-42.1	R. of S. Asia	Indus	-43.8

Note: River basins with no or small change in water scarcity are not included in this table

Source: Liu et al. 2013.

The simulations show the key consequences of decline of irrigation water supply in the region as follows (more details are given in Taheripour et al., 2016a):

i. There is an increase in the 'shadow price' or opportunity cost of water (i.e. the value of a unit of water in terms of what it produces) of between 10% and 60% across most of South Asia, with the exception of Pakistan, where the increase is a massive 230% to 350%. These sharp increases reflect the fact that crop production in Pakistan is heavily reliant on irrigation and major water shortages are expected.

ii. Food production declines almost everywhere in South Asia. In Bangladesh and India, the falls are between 3% and 7% depending on the crop. In Nepal and Sri Lanka the declines are much smaller – the greatest decline is around 1% and there is even an increase in output for some crops, such as oilseeds. In Pakistan, however, the story is different. Wheat output declines by 29%, rice by 12%, coarse grains by 17% and the category of 'other crops' by 40%.

iii. The reduction in supply of water increases net imports of food products by significant amounts. In Bangladesh, net imports go up by $621 million, in Nepal by $ 7 million, in Pakistan by $4.8 billion, in Sri Lanka by $82 million and in India by $5.5 billion. To put these figures in perspective, India's imports of food and related items in 2014 were around $13 billion. Thus the increase due to water scarcity would represent an increase of 42%. Importing more food

[2] Details of the demand for water by sector on which these figures are based are available in Taheripour et al., 2016a.

products puts significant pressure on the trade balances of the economies of these countries but it also helps these nations to reduce the adverse impacts of water scarcity on their food security.

iv. While importing more food products reduces the adverse impacts of water scarcity on the domestic supply, it cannot fill the entire gap in markets for products and that increases food prices. Prices of major food items – including crops, meat and livestock products – and processed foods increase by 8.5%, 9%, 4%, 21%, 2% and 8% in Bangladesh, India, Nepal, Pakistan, Sri Lanka and the rest of South Asia respectively. Consequently, water scarcity has the potential to increase food prices that could harm the food security of South Asia's poor families.

v. Water scarcity alters the mix of rain-fed and irrigated agriculture with the share of rain-fed agriculture going up due to the reduction in water for irrigation. It is this decline in irrigated areas that is responsible for the decline in output. In India the share of crops grown on rain-fed land go up by 12 million hectares while those on irrigated land go down by 10.6 million hectares, making a net increase in agricultural land of 1.5 million hectares (equal to 1.8% of area under crops). In Bangladesh the net increase is 87,000 hectares, in Nepal 7,000, in Pakistan 209,000, in Sri Lanka 1,000 and in the Rest of South Asia 17,000. These increases in area for farming is met through conversions in forest and pasture land, with the relative shares varying from country to country. This shift to rain-fed agriculture translates into dependency in rainfall for crop production, thus it increases vulnerability of food production to weather shocks substantially.

vi. The above changes will have economy-wide impacts. Reduction in the water supply for irrigation causes a fall in the GDP in 2050 of 2.7%, 1.4%, 0.2%, 5.2%, 0.3% and 0.4% in Bangladesh, India, Nepal, Pakistan, Sri Lanka and the rest of South Asia respectively. The falls are as percentages of 2011 GDP.

Water scarcity and climate change

Climate changes are expected to reduce yields of most major crops by 2050 in the countries in South Asia. Rice, wheat and maize yields decline everywhere but irrigated and rain fed areas are affected differently. The analysis of these impacts is separated into two cases (a) assuming the demand for water under the new climate regime will be met and the scarcity of water due to other factors will not be present and (b) the climate change impacts are imposed on top of those arising from the scarcity that is expected to occur for other reasons.

A number of studies have looked at various pathways by which climate change is linked to economic activity. These include changes in precipitation as well as temperature, both of which have an effect on crop yields. Existing studies show these effects to be substantial in some river basins but with lots of variations across basins. Moreover, there is a great deal of uncertainty about the magnitude of the effects, which increases the further out in the future one looks.

The analysis examined the consequences of climate change, taking into account of trade as an important mitigating factor. Several studies have shown that with trade across regions within a country and between countries, the effects of declines in yields can be reduced significantly and the present study confirms those findings. The innovative features of the present research are the greater spatial detail for agriculture, the breakdown of crops between irrigated and rain fed and the consideration of climate change **apart from and in addition to** the water scarcity arising from other factors considered above.

The direct impact of climate change is to change yields of crops, in general reducing them. Table 2 summarizes the estimates for the change between 2011 and 2050 in the case of on the Representative

Concentration Pathway (RCP) 4.5, which represents an average climate change scenario[3]. It draws on state-of-the-art estimation of crop responses to climate change for South Asia, based on several General Circulation Models (GCMs) and crop models at the global scale with a 0.5 by 0.5 degree resolution. The impacts are substantial in some cases, but with major differences between countries in the region and also between irrigated and rain-fed crops. A few crops are expected to benefit (rain fed soybeans and sugarcane in India and rain fed sugarcane in Nepal and Pakistan) but with these exceptions all the rest show declines in yields.

Given these changes in relative and absolute crop yields, farmers will respond by altering the crop mix, and changing their demand for inputs, especially water. In the analysis that follows the consequences of these changes have been analyzed under two assumptions: (a) that the demand for water under the new climate regime will be met and the scarcity of water estimated above will not be present and (b) the climate change impacts are imposed on top of those arising from the scarcity that is expected to occur for other reasons.

Table 2. Projected percentage changes in crop yields in South Asia for 2011-2050 (%)

Country	Crop Type	Rice	Wheat	Corn	Soybeans	Sugarcane
Bangladesh	Irrigated	-10.7	-10.5	-6.0	-9.0	-8.1
	Rain-fed	-9.2	-18.8	-5.0	-24.7	-9.9
	Total	-10.0	-14.8	-5.0	-21.5	-8.2
India	Irrigated	-8.3	-8.0	-5.7	-10.7	-4.6
	Rain-fed	-13.1	-12.3	-4.4	10.7	10.7
	Total	-10.5	-8.6	-4.6	6.1	-3.1
Nepal	Irrigated	-7.5	-6.2	-2.4	-4.8	20.6
	Rain-fed	-9.4	-5.5	-5.9	-6.9	22.4
	Total	-8.7	-6.2	-5.7	-6.7	21.3
Pakistan	Irrigated	-6.7	-7.4	-7.5	-9.0	-6.4
	Rain-fed	-13.4	-17.7	-1.4	-3.3	37.0
	Total	-6.7	-8.1	-4.0	-5.9	1.5
Sri Lanka	Irrigated	-6.9	-	-	-	-5.6
	Rain-fed	-12.3	-	-7.2	-	-
	Total	-8.1	-	-	-	-
Rest of South Asia	Irrigated	7.7	-7.2	-0.1	0.0	-
	Rain-fed	-17.3	-0.4	11.5	-1.3	-
	Total	5.2	-3.2	2.3	-0.5	-

Impacts of climatic changes in the absence of water scarcity for other reasons

The effects of climate change alone are to increase the demand for water by varying amounts in different river basins. If this demand can be met, the mix of crops grown changes, to reflect the relative changes in their yields. Rice, wheat and grains decline in all the countries and oilseeds show big declines in Bangladesh, Nepal, Pakistan and Sri Lanka. There is also a move to more irrigated area, which increases by 5.2 million hectares, while the rain fed area declines by 4.8

[3] This RCP represents an intermediate mitigation scenario which assumes temperature will not exceed 2 degrees Celsius by 2100 relative to 1900. Crop model (LPJML) was developed under the assumptions from GCM (HADGEM2-ES).

million. The difference is made up from deforestation. The economy wide analysis also projects a decline in GDP, which is between 0.1 and 0.3% of 2011 GDP.

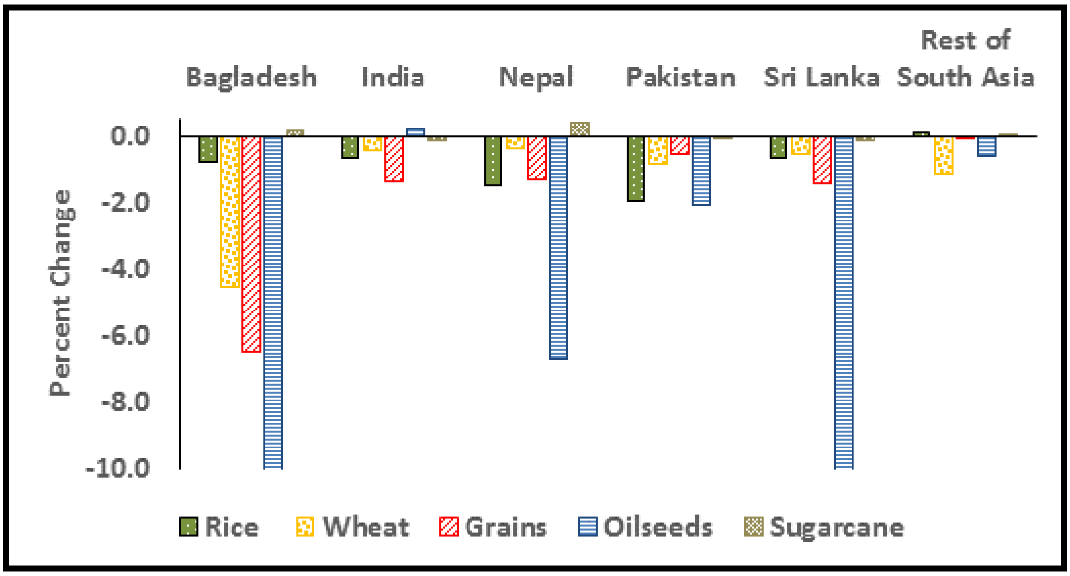
Looking at the impacts of climate change separately from that of other scarcity on the amount of water available we find that the demand for water goes up in several river basins. The major increases are:

- Bangladesh: Brahmaputra (9.3%) and Ganges (15.4%).
- India: Brahmaputra (45.1%), Brahmari (5.3%), Eastern Ghats (18.8%), East Coast (16.1%), Indus (17.6%), Sahyada (7.9%), and Thai Myan Malay (61.4%).
- Nepal: Ganges (3.7%) and Indus (3.0%).
- Pakistan: Western Asia (36.2%)
- Rest of South Asia: Brahmaputra in (23.1%)

Only in India, does the demand for water drop slightly in a few basins. In overall terms, climatic factors will increase the demand for water in India in 2030 by about 0.4% on account of changes in the relative productivities of rain-fed and irrigated crops.

Assuming these increases in water demand can be met, changes in the rain-fed and irrigated yields due to climate change alter the mix of irrigated and rain-fed crops. The modeling indicates a decline in production of the crops more negatively affected by climate change (rain-fed rice, rain-fed wheat and rain-fed oilseeds); and an increase in the production of the less negatively affected ones, or those where is a positive impact of climate change (irrigated oilseeds, irrigated grains and sugarcane). The net effect of the changes, however, even when water is available as required, is a reduction in crop output, as shown in Figure 2.

Figure 2. Percent change in crop outputs due to climate-induced yield changes, if water supply is not constrained

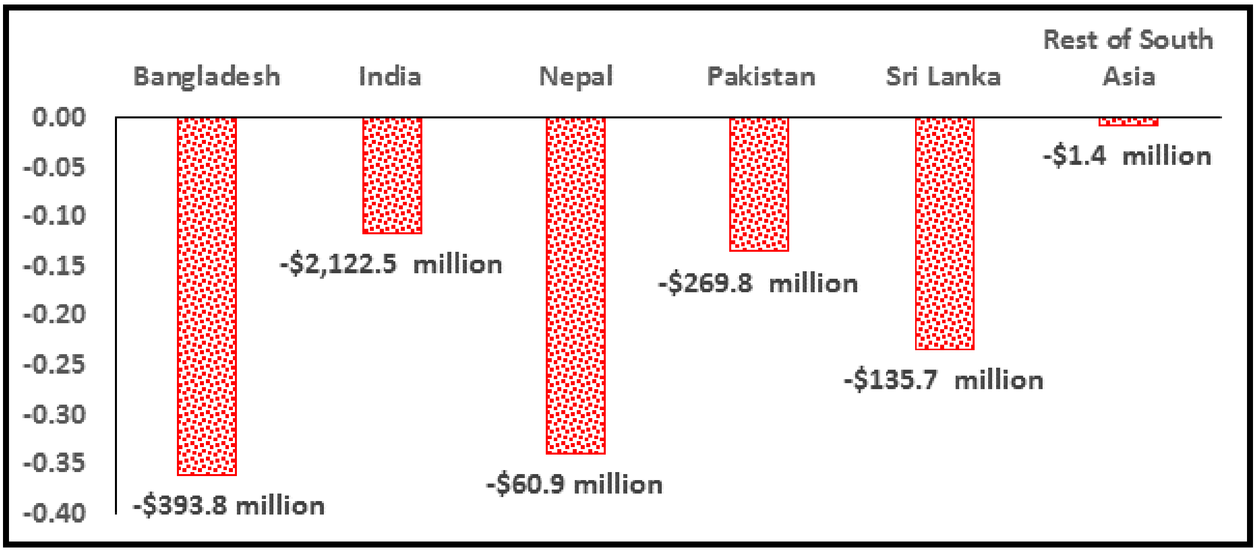


The results indicate that even if water supply is not limited, climate change harms outputs of the main staple crops in South Asia during 2011-2050. While moving towards irrigation could partially mitigate some adverse impacts of climate change on agricultural outputs, it could not eliminate all the negative impacts. These changes in relative yields of rain-fed and irrigated crops also have an impact on the amount of land that is farmed as rain fed and the amount farmed as irrigated. Given the availability of water, demand for irrigated cropland will increase almost across all river basins in South Asia to mitigate adverse impacts of climate-induced crop yield changes.

The reverse is expected to happen for the case of rain-fed cropland. Relatively large conversion from rain fed land to irrigated land could occur in several river basins such as: Brahmaputra and Ganges in Bangladesh; Brahmaputra, Brahmari, Eastern Ghats, Godavari, East Coast, Indus, and Sahyada in India; Ganges in Nepal; and Indus in Pakistan. In short, if water supply is unlimited, total irrigated area could increase by 5.2 million hectares in South Asia to mitigate some adverse impacts of climate-induced crop yield changes. The corresponding reduction in rain-fed area is about 4.8 million hectares. Therefore, these changes could increase demand for cropland by about 0.4 million hectares, which of course generates deforestation.

Finally, we have the overall economy-wide effects of the agricultural impacts initiated by climate change. The shifts to irrigated agriculture described above would generate new job opportunities and improve economic activities at the national level. However, the overall negative impacts of climate change on agricultural outputs are strong enough to harm economies of South Asia which depend heavily on agricultural activities. As shown in Figure 3, even when there is no restriction on water supply, economies of South Asia will lose a portion of their GDP due to climate-induced crop yield changes. The magnitudes of GDP losses are not large in terms of percentage changes in GDP (between 0.1% for India and Pakistan and 0.3% for Bangladesh and Nepal); however, their monetary values are considerable. The monetary values of losses at 2011 constant prices in 2050 are expected to be about $394 million for Bangladesh, $2,122 million for India, $60 million for Nepal, $270 million for Pakistan, and $135 million for Sri Lanka. The rest of South Asia does not lose significantly, if water supply for irrigation is available.

Figure 3. Percent change in GDP in 2050 due to climate-induced crop yield changes if water supply is unlimited (figures on the bars represent monetary values of changes at 2011 prices)



Impacts of climatic changes when water scarcity for other reasons is accounted for

The combined effects of scarcity and climate change are more significant than the simple sum of the two.

- **When climate change is added to the water scarcity the shadow price of water doubles in Bangladesh and rises by over 70% in some key basins in India. In Pakistan it increases by a factor of 3-4.**
- **The climate effects cause crop outputs to decline a further 1-2% for all countries on top of the effects due to scarcity alone, except in Bangladesh where the additional decline is 9-14%. The value of crops declines by an additional 1% everywhere except in Bangladesh where the decline is around 3%.**

- **Net imports of food items increase quite significantly in all countries.**
- **Price rises for food items are much higher when the combined effect of scarcity and climate change is considered.**
- **Total irrigated area decreases by 9 million hectares and the rain-fed area goes up by about 11.5 million hectares. The gap of 2.5 million hectares generates more deforestation compared with the results of the scarcity alone case.**
- **GDP losses are much greater than in the case where water is not scarce. Losses of GDP by 2050 are now (with figures in parenthesis giving the losses without water scarcity): Bangladesh, 5.2% (0.35%); India, 1.8% (0.12%); Nepal, 0.8% (0.32%); Pakistan, 5.6% (0.13%); Sri Lanka, 0.6% (0.24%); Rest of South Asia, 0.5% (0.02%).**

In the presence of water scarcity, the available water for irrigation will fall in many river basins as projected in Table 1. Consequently, the increased demand for irrigation water under climate change will not be met. An important indicator of that gap is the increase in the shadow price (or opportunity cost) of water across South Asia. The increase in this shadow price on account of water scarcity has already been noted; with climate change the increase is even greater. The increase in the shadow price of water was projected to go up by between 10% and 60% by 2050 on account of the increasing scarcity of water. Adding the climate change factor raises this figure: in Bangladesh is rises to around 100% across basins and in it goes up to more than 70% in the Eastern Ghats, Ganges, and Indus. In Nepal it rises to between 50% and 70%. The opportunity cost of water for irrigation in Pakistan now increases by 300 to 400 percent instead of 232 to 352%. It is important to note that in South Asia, the actual price of water for irrigation is extremely low everywhere in the base year (2011) and if it stays as it is the difference between the opportunity cost of water and its price will reflect an increase in the inefficiency with which water is allocated.

The reduction in available water for irrigation in combination with climate-induced crop yield changes severely harms crop production and also affects livestock and processed foods. Table 3 compares the impacts for different crops by looking at the change between 2011 and 2050 under projected water scarcity as well as under that scarcity when climate change is added to the picture. The following effects are observed:

i. Crop outputs decline further due to climate change by between 1 and 2 percent in most cases. The exception in Bangladesh, where wheat and coarse grain output decline by 9-14 percent.

ii. The value of crops and processed foods declines by an additional 1% in all countries except Bangladesh where the decline is around 3%. The biggest effect in terms of value is on crops; livestock and processed foods exhibit relatively small falls.

iii. There is a further decline in net exports of food items due to climate change (i.e. more imports are required). The size of the effect is biggest in percentage terms in Bangladesh, Nepal and Sri Lanka. In India, net exports decline by a further 28% due to climate change, while in Pakistan they decline by only 6%. While these reductions in net exports (or increases in net imports) of food products help economies of South Asia to mitigate a portion of the negative impacts of water scarcity and climate-induced crop yield changes on the food security, they put a major pressure on the trade balances of these economies over time.

The reductions in crop outputs due to water scarcity and climate-induced crop yield changes lead to higher crop prices across South Asia. Recall that the increases in crop prices due to water scarcity were around 9% in Bangladesh and India. Now with climate change effects included the increases are much larger – around 15-35% in these countries. In Nepal where the increase was about 4%, it now comes out in the range of 12-24%. In Pakistan where the average increase was 21% due to water scarcity alone, it now becomes 80-120% for rice and wheat. In Sri Lanka there was only a small increase due to scarcity of 2% -- that now becomes around 5% for rice and wheat and over 20% for oil seeds. The countries where large increases in food are predicted for 2050 would need to take action to prevent vulnerable groups falling into poverty.

The mix of irrigated and rain-fed land in the presence of water scarcity and climate change moves in the opposite direction from the case where water is not scarce: in the latter irrigated areas increase but in the former the water scarcity eliminates irrigated areas in some river basins and extends rain-fed areas. In this case irrigated cropland in India goes down in several basins by the following amounts: Chotanagpui (215 thousand hectares), Eastern Ghats (250 thousand hectares), Ganges (2,559 thousand hectares), Godavari (-519 thousand hectares), East Coast (-473 thousand hectares), Indus (541 thousand hectares), Krishna (-1,924 thousand hectares), and Luni (-1,346 thousand hectares). The area of irrigated cropland drops also a lot in Pakistan, in the Indus basin by 1.9 million hectares. In short, in the presence of water shortage and climate change, total irrigated area decreases by 9 million hectares in South Asia. The corresponding increases in rain-fed area is about 11.5 million hectares. Therefore, demand for cropland goes up by 2.5 million hectares, which of course generates more deforestation compared with the results of the scarcity alone case.

Finally, there are the economy-wide effects. These are now greater than in the case where water was not scarce. Losses of GDP by 2050 are now (with figures in parenthesis giving the losses without water scarcity): Bangladesh, 5.2% (0.35%); India, 1.8% (0.12%); Nepal, 0.8% (0.32%); Pakistan, 5.6% (0.13%); Sri Lanka, 0.6% (0.24%); Rest of South Asia, 0.5% (0.02%). The addition effect of water scarcity on GDP loss is huge – more than an order of magnitude. The corresponding monetary values of the losses at 2011 prices are Bangladesh ($5,668 million), India ($32,794 million), Nepal ($138 million), Pakistan ($11,220 million), Sri Lanka ($340 million), and Rest of South Asia ($117 million).

The results indicate that in the presence of water scarcity and climate change governments will have to push for reforms that increase the efficiency with which water is used. As noted, the opportunity cost rises considerably with these changes and if water prices remain as they are the inefficiencies are exacerbated. In the next two sections we consider alternative measures to increase the efficiency of water use: one related to the use of water for thermal power plants and the other the use of water in irrigation through investment in more efficient systems.

Sensitivity of results to assumed impacts of water stress and climate change

Given the significant uncertainties about the size of the impact that water stress and climate change will cause, it is important to consider the sensitivity of the results to variations in these effects. This has been done by looking at the effects on GDP when the shock from water stress is 50 percent higher than the base case and 50 percent lower. The base case changes are as given above for the six countries/regions. To analyze the impacts of 50 percent lower and higher levels of water stress a 95 percent confidence interval has been calculated. This is based on the assumption that there is a uniform distribution of impacts between the lower bound (a 50% lower impact than the base case) and the upper bound (a 50% higher impact than the base case). The results are shown in Table 4. The effects on GDP lie within a range of no more than +/- 26 percent of the Base Case. This maximum range occurs for Pakistan. In Nepal there is no discernible effect on GDP within this range and in the other countries the range is +/-6-7%. So, as far as GDP implications of uncertainty about the water stress are concerned the results appear to be quite robust, with Pakistan being something of an outlier.

Table 3: Changes in Food Production and Net Exports under "Water Scarcity" and under "Water Scarcity and Climate Change" (2011-2050)

		Bangladesh		India		Nepal		Pakistan		Sri Lanka		Rest of S. Asia	
	Due to:	Water Scarcity	Scarcity +CC	Water Scarcity	Scarcity +CC	Water Scarcity	Scarcity +CC	Water Scarcity	Scarcity +CC	Water Scarcity	Scarcity +CC	Water Scarcity	Scarcity +CC
% Change in Crop Output	Rice	-2.9	-6.6	-3.9	-5.4	0	-2.8	-11.8	-14	-0.4	-1.4	-2.1	-2.7
	Wheat	-4.5	-18.6	-3.2	-4.6	-0.4	-1.7	-29.1	-30	-1.5	-2.2	-1.2	-3
	Coarse Grains	-3.8	-13	-2.7	-4.6	-0.3	-1.8	-17.1	-17.8	0	-1.5	-0.8	-1.2
	Oil Seeds	-4.6	-21.6	-7.2	-7.7	0.7	-7.6	-14.4	-16.1	2.6	-16.8	-3.8	-5.9
	Sugar Crops	-3.1	-5.4	-2.6	-3.2	-0.3	-0.8	-8.3	-8.8	-0.2	-0.4	-2.3	-2.4
% Change in Value	Crops	-4.2	-9.1	-4	-5.1	0.1	-3.5	-25.6	-26.8	0.0	-0.5	-0.3	-0.5
	Livestock	-2.3	-4.6	-1.5	-1.9	-0.3	-1.0	-1.2	-1.3	-0.5	-0.7	-2.3	-2.6
	Processed Food	-2	-4.2	-3.3	-4.2	-0.5	-2.7	-7.5	-8.2	-0.6	-1.0	-2.9	-3.5
	Total	-2.9	-6.2	-3.2	-4.1	-0.1	-1.5	-9.7	-10.4	-0.3	-0.9	-1.4	-1.7
Change in Net Exports $ Mn.	Crops	-500	-1,078	-2,533	-3,254	5	-58.0	-5,330	-5,635	49	22.0	-25	-28.0
	Livestock	5	12	-202	-263	-2	-12.0	312	343	-3	-1.0	-31	-36.0
	Processed Food	-126	-284	-2,742	-3,505	-10	-41.0	241	212	-29	-38.0	-98	-118.0
	Total	-621	-1,350	-5,477	-7,022	-7	-111.0	-4,776	-5,080	18	-17.0	-153	-182.0

Table 4: Sensitivity of Impacts on GDP to Variations in the Size of the Water Stress (% Decline)

Country/Region	Base Case	95% Confidence Interval	
Bangladesh	5.24	4.93	5.55
India	1.80	1.67	1.93
Nepal	0.77	0.77	0.77
Pakistan	5.59	4.11	7.06
Sri Lanka	0.58	0.54	0.62
Rest of South Asia	0.54	0.50	0.58

Source: Own calculations

5. Policies and measures to address water scarcity in South Asia

Measures will have to be taken to address the water scarcity problem in South Asia identified in this report. Two options are considered: improvements in water use efficiency in irrigation and changes in technology that reduce water demand in thermal plants.

Improvements in water use efficiency (WUE)

Improvements in WUE can play a major role in closing the gap created by the growing demand for water and the decline in supply due to climate change. The impacts of improvements of between 10% and 40% have been examined allowing for the costs of such improvements financed by reducing electricity subsidies to consumers. The model concludes that:

- **Food production goes up by around 1% with a 10% gain in WUE and by 4% with a 40% improvement. Bangladesh, Pakistan, and rest of South Asia experience larger percentage gains in their crop outputs compared to India, Nepal and Sri Lanka.**
- **Net exports of food products increase in all South Asian countries except for Sri Lanka.**
- **Improvements in WUE reduce the prices of food products. For example a 40% improvement in WUE would reduce the price index of crops by 18.9% in Bangladesh, 12.4% in India, 11.1% in Nepal, 16.6% in Pakistan, 4.5% in Sri Lanka, and 17.3 % in rest of South Asia. The reduction in the price of livestock products is smaller than that of crops in each region.**
- **WUE improvements increase irrigated areas and reduce rain fed ones. A 10% increase in WUE increases the areas of irrigated cropland by about 3%. A 40% results in an impact that is approximately 4 times greater. At the same time WUE improvements reduce rain fed areas in most countries so total cropland declines by a small amount. Pakistan is an exception to this.**
- **Impacts on the power sector are to reduce output slightly (1-3%) and to increase the prices more significantly (5-25%).**
- **Improvements in WUE up to 40% can be economically justified in Bangladesh, India, and Sri Lanka. In Nepal, after a 20% improvement, the economic gains are smaller than costs. In Pakistan and rest of South Asia, an improvement in WUE over 30% may not be economically profitable.**

The study has evaluated the economy-wide impacts of improvements in water use efficiency in irrigation. According to the FAO, average world irrigation efficiency was around 50% in 2005/2007. In other words, about one-half of the water withdrawal was "lost" between the source and the destination. In South Asia water use efficiency is around 25-30% in Bangladesh (Mondal, 2010), 45% in India (CWC, 2011) and 30% in Pakistan (Bhutta and Smedem, 2007). This compares with figures of 49% for China (Cui and Huang, 2012) and 50-60% for Japan and Taiwan (Postel and Vickers, 2004)[4]. There is considerable scope of increasing the levels in South Asia. In the case of India, for example, The Ministry of Water Resources has estimated that irrigation efficiency from surface water could be raised from 30% currently to 60% by 2050 and that from ground water from 55% to 75%[5]. The macroeconomic implications of such improvements, however, have not been estimated. They will depend of

[4] The figures quoted are averages for both surface water and groundwater. There are two different but related concepts that refer to efficiency of water used in irrigation. The first refers to the ratio between water that actually transpires by crops and water withdrawal for irrigation. This usually refers to water use efficiency (WUE) and is the one used here. The second concept refers to crop yields per volume of water withdrawal for irrigation. This usually measures Water Productivity (WP) and is also referred to by some as water use efficiency. Note also that the concept of WUE is subject to debate (Frenken and Gillet, (2012)). A portion of water lost in irrigation systems could flow back to the river, recharge the aquifers, or be captured and reused. So the ratio of WUE may underestimate the efficiency of irrigation systems.

[5] http://wrmin.nic.in/writereaddata/Guidelines_for_improving_water_use_efficiency.pdf.

course on the measures undertaken to make the improvements and the costs involved. In this section some possible measures and their impacts are considered.
The GTAP model has estimated changes in GDP and other key indicators if the countries in the region improve WUE by levels by 10% to 40% from current levels[6] in steps of 10%.

Improvements in WUE can be made by a number of actions, including reduction in over irrigation, no till farming, optimizing fertilizer application rates, using systems of rice intensification, improvements in the existing water infrastructure (collection and conveying systems), mulching in rice production, using micro irrigation technologies (sprinkler and drip irrigation), and many more. Some of these methods (e.g. reduction in over irrigation, no till farming, optimizing fertilizer application rates) improve WUE at no or low costs. The extent to which these low cost methods contribute to WUE, however, is limited. To save more water in irrigation involves using costly technologies such as micro irrigation, advanced rice cultivation and irrigation methods, or improvement in water infrastructure.

Many papers have examined the costs, returns, and rate of improvement in WUE for a range of water-saving technologies at farm level (e.g. Hasanain et al., 2012; Singh et al., 2010; Radha et al., 2009; Palanisami et al. 2011; Wallace, 2000). Limited information is available, however, at the macro level in this area. The analysis here draws on new research carried out at the Massachusetts Institute of Technology by Winchester et al. (2016) who developed a set of stepwise irrigated land supply functions for major river basins across the world. These functions were introduced into a CGE model (EPPA[7]) to examine the impact of water scarcity on food, bioenergy and deforestation at global scale. These supply functions show the costs of expansion in irrigated cropland due to water saving activities.

Using the results of this research a set of stepwise investment schedules were developed for South Asia, which show required investment for four levels of 10%, 20%, 30%, and 40% improvement in WUE by county for South Asian economies. They are summarized in Table 5. The table shows that on average WUE in irrigation can be improved by 10% in India with $27 investment per hectare of irrigated cropland. For 20%, 30%, and 40% improvement in WUE the investment costs grow to $63, $142, and $289 per hectare of irrigated land indicating a rising marginal cost of improvements, which is what one would expect. As the table shows, investment costs vary across regions: India and Pakistan represent the lowest and heights cost schedules, respectively.

Table 5. Costs of improvement in water use efficiencies in South Asia by country (USD/hectare)

Level of improvement in water use efficiency	Bangladesh	India	Nepal	Pakistan	Sri Lanka	Rest of South Asia
10%	31	27	33	35	41	35
20%	74	63	78	83	96	83
30%	167	142	176	186	216	186
40%	340	289	358	380	440	380

These cost schedules were used to evaluate the capital requirements for improvement in WUE in our simulations. In addition a mechanism was defined to finance these investment costs. In this mechanism the public sector pays the investment costs by reducing the existing electricity subsidy rates. In South Asia consumption of electricity is highly subsidized, especially to farmers who pay the lowest tariff rates and receiving the highest subsidy. It is frequently

[6] A 40% improvement in WUE would mean going, in the case of India, from 30% currently for surface water irrigation to 42% and for ground water from 55% currently to 77%. So the upper bound of the range considered is less than the identified potential for improvement for surface water and about the same as the potential for ground water according to the Ministry of Water in India.
[7] https://globalchange.mit.edu/research/research-tools/eppa

argued that these subsidies encourage over consumption of electricity and water. In the simulations reported here it is assumed that the overall investment costs of improvement in WUE will be financed by a public loan (with 5% annual interest rate) and the loan will be paid off in 15 years by reduction in electricity subsidies.

The results of the investment program are as follows:

i. *Food production* goes up significantly in South Asia. With a 10% improvement in WUE, it is projected to increase annually by the following amounts (in 2011 prices and as percentages of GDP) in each of the countries: Bangladesh, $739 million (1.4%), India, $7,887 million (1.2%), Nepal, $46 million (0.6%), Pakistan $1,847 million (1.3%), Sri Lanka, $81 million (0.3%), Rest of South Asia, $214 million (2.2%). With a 40% improvement in WUE, the corresponding the figures grow to: Bangladesh, $2,717 million (5%), India, $26,426 million (4%), Nepal, $111 million (1.4%), Pakistan, $6,102 million (4.4%), Sri Lanka, $212 million (0.9%), and Rest of South Asia, $611 million (6.3%).

ii. *Changes in crop production* vary by country and crop as can be seen in Figure 4. Bangladesh, Pakistan, and rest of South Asia experience larger percentage gains in their crop outputs compared to India, Nepal and Sri Lanka. Outputs of all crops and in particular coarse grains, oilseeds, and other crops go up in Bangladesh. In India rice and oilseeds go up by more than others. In Nepal, changes in crops outputs, even at 40%, remain small, in particular for coarse grains and other crops. Production of wheat and other crops grow more than rice and coarse grains, oilseeds and sugar crops in Pakistan. In Sri Lanka only outputs of rice and wheat grow due to improvement in WUE[8].

iii. *Improvement in WUE increases the net exports of food products* of South Asian countries, except for Sri Lanka (the net exports of food products of this country drops slightly at all levels of improvement in WUE). With a 10% improvement in WUE, the net exports of food products of Bangladesh, India, Nepal, Pakistan, and the rest of South Asia will increase by $290 million, $2,189 million, $25 million, $797 million, and $136 million at 2011 constant prices, respectively. The corresponding figures with a 40 percent improvement in WUE will be about $1,017 million, $7242 million, $59 million, $2,784 million, and $368 million, respectively. These figures show that India, Pakistan, and Bangladesh could gain significantly in trade of food products, if they use their water resources more efficiently. Of course expansion in food production and exports could positively affect rural income and living condition in these regions.

iv. *Improvements in WUE reduce the prices of food products in South Asia*, by varying amounts by region and food product. For example a 40% improvement in WUE would reduce the price index of crops by 18.9% in Bangladesh, 12.4% in India, 11.1% in Nepal, 16.6% in Pakistan, 4.5% in Sri Lanka, and 17.3 % in rest of South Asia. These falls would contribute significantly to poverty reduction and reduced hunger. The reduction in the price of livestock products is smaller than that of crops in each region. With a 40% improvement in WUE the price index of livestock products drops by 11.4%, 5%, 7.7%, 1% and 8% in Bangladesh, India, Nepal, Sri Lanka, and Rest of South Asia, respectively. In Pakistan, however, the price index of livestock goes up slightly, by 2.3%. Improvement in WUE in irrigation encourages farmers to convert some pastureland to crop production in Pakistan and that negatively affect output of livestock industries. Finally, with 40% improvement in WUE the price index of processed food decreases by 5.2%, 6.1%, 10.4%, 2.9%, and 12% in Bangladesh, India, Nepal, Sri Lanka, and Rest of South Asia, respectively. The price index of processed food goes up slightly by 1.6% in Pakistan.

[8] The gap between the irrigated and rain fed crops yields explains in part the observed variations in the regional impacts of WUE on crop outputs. Improvement in WUE saves water on existing irrigated land and that provides an opportunity to use a portion of saved water to convert rain fed cropland to irrigated cropland. In these circumstances, the gain in crop production depends on the difference between the irrigated and rain fed crop yields. If the difference is not large, the expansion in crop production will be limited. However, if the difference is large, then crop production grows significantly. For example, in general, in India the difference between the rain fed and irrigated yields are not large on average. Hence, an improvement in WUE in this country generates moderate gains in crops outputs. However, in Bangladesh, Pakistan, and rest of South Asia where irrigation contributes more to crop yields, an improvement in WUE, generates larger changes in crops outputs.

Figure 4: Crop Output Changes with Changes in WUE

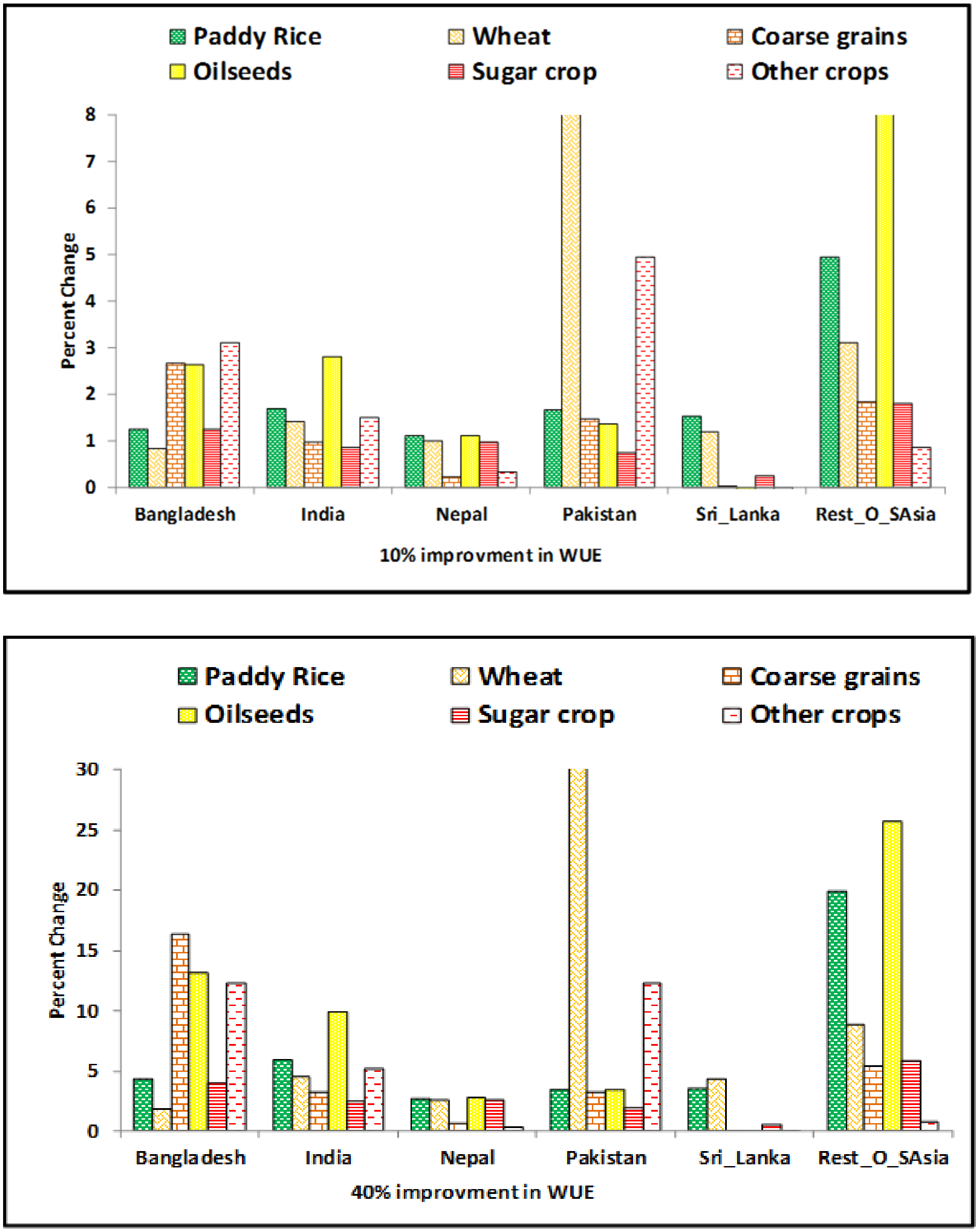
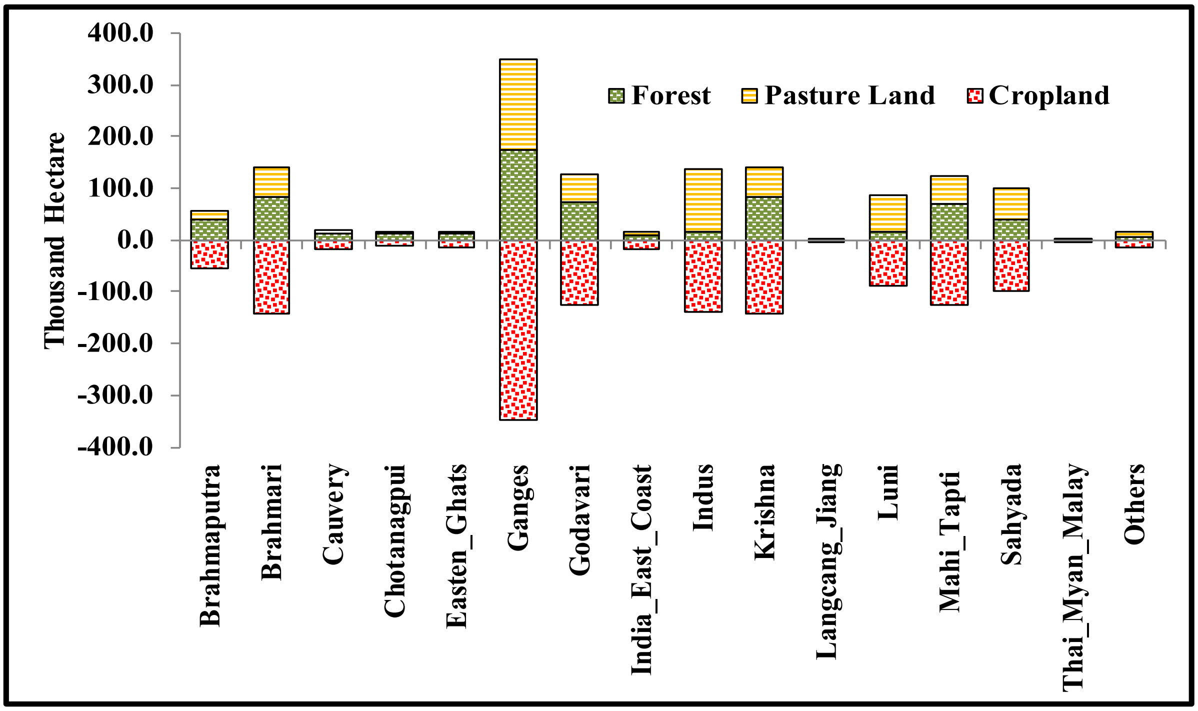


Figure 5. Land use changes in India by river basin (top panel) and by AEZ (bottom panel) due to 20% improvement in water use efficiency



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Brahmari
Cauvery
Chotanagpui
Easten_Ghats
Ganges
Godavari
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Indus
Krishna
Langcang_Jiang
Luni
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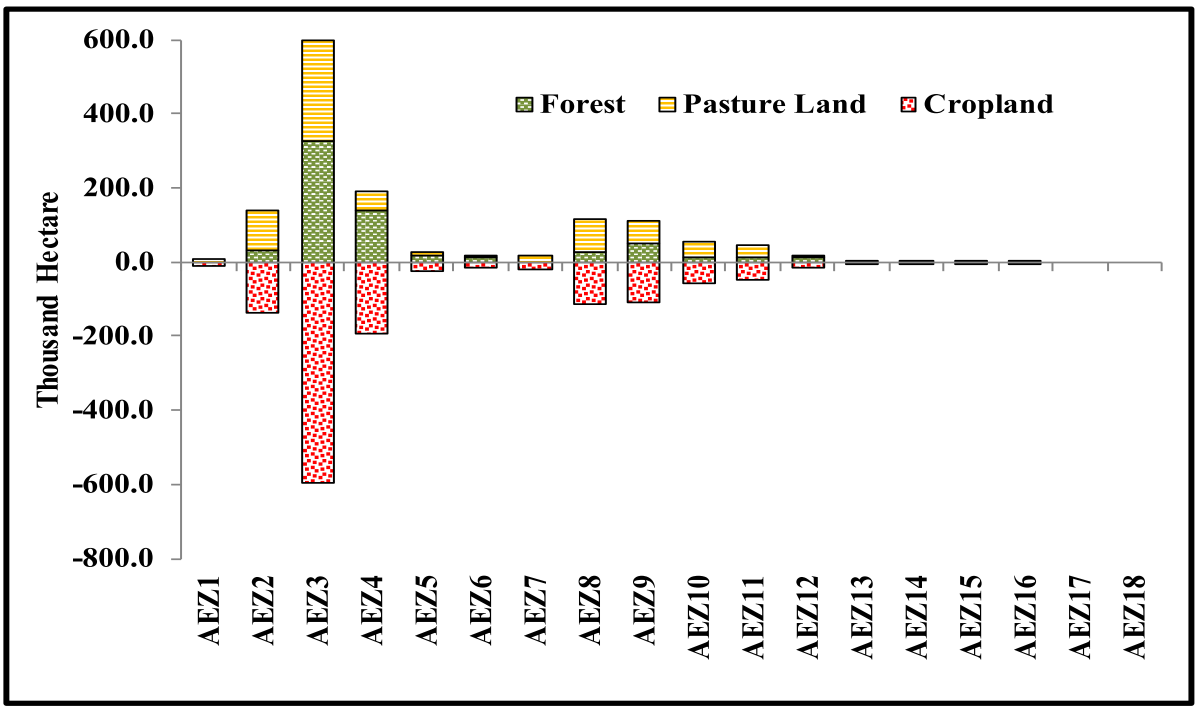
Others



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iv. *WUE improvements have major impacts on land use*. First and foremost, they reduce rain-fed areas and increase irrigated areas: For example, a 10% in WUE increases the areas of irrigated cropland by 268 thousand hectares, 5,503 thousand hectares, 87 thousand hectares, 544 thousand hectares, 20 thousand hectares, and 126 thousand hectares in Bangladesh, India, Nepal, Pakistan, Sri Lanka, and rest of South Asia. The corresponding figures for 40% improvement in WUE are 1,086 thousand hectares, 21,444 thousand hectares, 210 thousand hectares, 2,085 thousand hectares, 46 thousand hectares, and 435 thousand hectares. These large expansions in irrigated areas could improve the food security of South Asia a great deal in the face of climate change. Details of land use changes by river basin and AEZ for India are shown in Figure 5.

v. *WUE improvements also reduce the demand for cropland in total and that generates some incentives for reforestation*. For example, a 40% increase in WUE reduces demand for cropland by 244 thousand hectares, 2,545 thousand hectares, 11 thousand hectares, 1.3 thousand hectares, and 27 thousand hectares in Bangladesh, India, Nepal, Sri Lanka, and rest of South Asia. In Pakistan at this level of improvement in WUE harvested area of irrigated land extends more that the reduction in rain fed areas and therefore total harvested area increases by 95 thousand hectares, thereby causing some land conversion form forest and pasture to cropland. In the case of India the picture can be more complex, as improvements in WUE generate different land use pattern changes across the country. On average, however, there is a decline in total cropland with an increase in WUE across all major river basins; for example a 20% improvement in WUE results in major reductions in the Ganges (by 349,000 hectares), Krishna (142,000 hectares), Brahmari (141, 300 hectares) and Mahi-Tahi (125,000 hectares). In return, the areas of forest and pastureland grow across all river basins.

vi. *Prices of electricity and produced goods are affected, since electricity subsidies are reduced to finance the improvements in WUE*. The changes in production when investment costs are passed on to the producers are -2.6%, 1.5%, -0.5%, 0.5%, 0.1%, and -1.5% for Bangladesh, India, Nepal, Pakistan, Sri Lanka and Rest of South Asia respectively. Thus the production of electricity drops when electricity subsidies are reduced to finance the investment costs of improvement in WUE. The reduction in electricity subsidy increases the consumer price of electricity as well. The changes are 11.8%, 5.3%, 6.7% 11.7%, 3.5%, and 25% in Bangladesh, India, Nepal, Pakistan, Sri Lanka, and rest of South Asia, respectively.

vii. The economy-wide gains of improvement in WUE are shown in Table 6, which gives the changes in GDP when investments in WUE are costless and when they have a cost as given in Table 4[9]. The costs reduce the gains in GDP but the latter are still significant. The gains decline as addition investments are made to go from 10% to 40% WUE improvements but they are still positive for all countries up to a 20% improvement. Only in the case of going from 20% to 30% in Nepal and in going from 30% to 40% in Pakistan and the Rest of South Asia is the change in GDP negative.

Table 6. Marginal impact of each level of improvement in water use efficiency on GDP at 2011 constant prices with and without investment costs (million $)

[9] It is important to note that the impacts of improvements in WUE on GDP are not the same as the impacts on welfare, or real income of households at constant prices. For instance, a 40% improvement in WUE increases the real GDP of Bangladesh, India, Nepal, Pakistan, Sri Lanka, and Rest of South Asia by $3,610 million, $22,539 million, $17 million, $1,392 million, $295 million, and $148 million at 2011 constant prices, respectively. The corresponding welfare impacts for this simulation are $4,381 million, $19,065 million, -$83 million, $3,130 million, $402 million, and $45 million. Hence, from the consumers' points of view the monetary value of improvements in WUE is higher than the gains in GDP in Bangladesh, Pakistan, and Sri Lanka and the reverse is true in India, Nepal, and Rest of South Asia.

Cost assumption	If improvement in water use efficiency is costless				Improvement in water use efficiency needs additional investment costs			
Rate of Improvement in WUE	10%	20%	30%	40%	10%	20%	30%	40%
Bangladesh	1,216	1,098	986	878	1,146	1,013	835	615
India	8,696	7,335	6,275	5409	8,175	6,646	4,873	2,845
Nepal	34	24	17	11	29	17	-2	-27
Pakistan	1,160	910	725	562	986	665	187	-447
Sri Lanka	146	101	75	58	138	91	51	14
Rest of South Asia	100	74	53	34	90	60	22	-24

viii. In conclusion, Table 6 shows that improvement in WUE up to 40% can be economically justified in Bangladesh, India, and Sri Lanka. In Nepal, after 20% improvement in WUE, the economic gains are smaller than costs. In Pakistan and rest of South Asia, an improvement in WUE over 30% may not be economically profitable[10].

Changes in technology for cooling thermal plants in India

Continued use of wet cooling for thermal power plants will increase demand for water significantly as the power sector expands. The consequences will be a decline in the value of food production and an increase in net imports. Total loss of welfare is estimated at $3 billion in 2050. A shift to closed-loop dry-cooling thermal power plants could almost eliminate water demand for thermal plants. As long as the costs of such a shift are less than 7.5% above the costs of wet-cooling there will be a gain in welfare.

If India continues to use wet cooling thermal plants, demand for water for electricity generation will increase sharply as the economy grows in future. By 2050 the increases relative to 2011 range from 16-fold in the Eastern Ghats and the Brahmani Basin to 5-fold in the Krishna and 4-fold in the Ganges. A number of other river basins face but significant increases. If these demands for water are met the available water for irrigation will decline. The impacts of these changes have been analyzed under two assumptions: (a) the wet-cooling technology continues to be used and (b) there is a shift to a more efficient dry cooling technology, which costs more and therefore has implications for capital costs in the power sector.

Under the assumption of continued use of the present technology the additional fall in the supply of water for irrigation would reduce the value of food production in 2050 by $3.4 billion. The overall loss due to water scarcity for India in 2050 is estimated at around $20.8 billion, making the losses due to cooling demand equal to about 16% of that figure. The implied increase in net food imports due to the demand for cooling is $999 million in 2050, amounting to about 18% of the net imports due to water scarcity. Hence one can see that this demand for water constitutes a significant part of the impact of water scarcity. In terms of land use the impacts of this scarcity are to increase total cropland by 1.5 million hectares. Of that about 16% is induced by the demand for cooling water for the thermal plants. The economy-wide impacts the overall welfare cost of the wet cooling demand is a reduction of $3.3 billion in 2050, which is about 13% of the overall loss of GDP in that year attributed to water scarcity.

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[10] This comparison of costs and benefits is a preliminary guide to the benefits and costs of improvements in WUE. A more comprehensive exercise would have to take account of the timing of the investments and the time profile of the benefits. In general one can expect upfront costs, with benefits to come later, which would reduce the estimated net benefit figure. On the other hand the increase in GDP is not a one off occurrence – we can expect it to continue into the future. That should enhance the value of the investments in WUE, the extent of which will depend on the discount rate. Such an analysis should be undertaken as a follow up to this paper.

If a shift is made to dry cooling almost all the water used by the thermal plants is saved and the entire welfare loss of $3.3 billion is avoided, if the change can be made at no cost. This, however is not the case. The costs of making the switch are not known in detail, so a range is considered – from 2% more investment compared to wet cooling technologies up to 10%. It turns out that as long as the cost of the investment in dry cooling is less than 7.5% above the costs of wet cooling the switch will raise welfare.

5. Conclusions and next steps

The report shows how the prospects for development in South Asia are likely to be affected by the way in which water is used, especially for agriculture. The growth in demand for food will increase the demand for water, making it scarcer. If present levels of efficiency in water use and present policies for allocating water, are not changed this scarcity will be cause a decline in food production, an increased dependence on imports, higher food prices and a decline in GDP by 2050. These impacts will occur irrespective of any climate change. When the effects of climate are included to those of scarcity, the effects vary across river basins but the overall national impact on GDP and food prices is notably greater.

The results are tested for sensitivity by varying the level of water stress by +/- 50 percent. The effects in terms of declines in GDP are generally small (ranging from practically zero to 6-7%), with the exception of Pakistan, where the range is +/-26%.

The case for some policy change to improve water use efficiency and take other measures to reduce water demand is therefore very strong and the potential for doing so is also clear. Measures to improve use of water in irrigation have been shown to be justified even allowing for the costs of such implementing such measures. Furthermore the finance for the programs can come from reductions in electricity subsidies to agriculture with an overall impact that is positive to the economy. Another area where water scarcity can be reduced with significant macroeconomic and cross sectoral benefits is by reducing the demand for water for thermal cooling plants.

Further work is needed to evaluate these policy measures in greater detail. One aspect is in terms of the timing of any investments and the time profile of the benefits. The second is the distributional implications of the options and how they may be addressed. The third is a more spatially detailed assessment of where action will be most urgently needed to address water scarcity issues in the face of climate change.

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Low-Water High Growth in South Asia-Phase II: A General Equilibrium Modeling Approach

Introduction

Background

South Asia faces serious challenges in water availability, which are expected to increase in the coming years as populations and demand for food grow, the competition for water from non-agricultural sectors increases, and climate change aggravates the water stress in some river basins. Even without taking account of climate change the amount of water available for irrigation is estimated to drop by between 20-40% in several important river basins in the region. The additional impact of climate change is variable and could be positive in some basins but add to the scarcity in others.

Such changes are bound to have important economic consequences. This report analyzes these consequences in an economy-wide context. It separates the implications of the growing scarcity of water in South Asia for economic and demographic reasons from those related to climate change. Furthermore, it evaluates specific measures that could be taken to addresses the economic and physical constraints against sustainable water management in the region. The aim is to develop a comprehensive analytical basis to support South Asia's decision-makers in promoting policies that achieve higher levels of water efficiency, facilitate economic growth in the presence of water scarcity, and promote climate resilience to help farmers to maintain their income in the face of severe climate conditions.

Methods of Analysis

It is self-evident that water is a key input for any economy: without it nothing could be produced nor could anyone survive. The study of the role of water in an economy-wide context, however, has so far been limited and simplistic. Water is usually treated as something exogenous, available in a given quantity in different forms – as rainfall, as ground water and as surface water. Resources are allocated to collect it, purify it where necessary, and then allocate it to different uses according to existing rules for allocation within the economy. But the demand for water as an input across sectors other than agriculture is not modeled explicitly. Nor is the pricing of water, which can play a role (albeit limited) in allocating water, taken into account.

The economic importance of water, especially in economies heavily dependent on agriculture, and the effects of climate change on the availability of water across river basins, is the justification for the present work. It offers some new developments in the way water is included in economy-wide models of the economies of South Asia, and analyses the impacts of changes in water supply at the river basin level under alternative rules for the allocation of water. The results show where pressures are likely to be felt because of climate change, across the whole economy, in sectoral and macroeconomic terms; and what impacts different policies could have in alleviating those pressures.

Chapter 1 describes how the database has been constructed. Chapter 2 elaborates on the modelling framework developed. Chapter 3 analyzes the impacts of improvements in water use efficiency in irrigation on the agricultural sector and on the economy more widely. Chapter 4 reports the economy-wide impacts of climate change. Chapter 5 examines the energy-water-climate linkages, specifically from water for electricity. Chapter 6 offers some conclusions.

Chapter 1: Database Construction

1.1. **Introduction**

The database developed for this research is a modified version of the GTAP (Global Trade Analysis Project) database release 9 which represents the world economy in 2011 (Narayanan et al., [1]). The original database represents economies of 140 countries/regions and divides economic activities into 57 categories. The GTAP Database is a publicly available and fully documented economic dataset, which is constructed by balancing various data components from different sources across the world including but not limited to: 1) a bilateral trade dataset obtained from the United Nations Commodity Trade dataset; 2) a tariff dataset obtained from the MacMAP database developed by the International Trade Centre; 3) a macro-economic dataset obtained from the World Bank; 4) a dataset on agricultural production and domestic support for several countries obtained from the Organization for Economic Co-operation and Development; 5) and finally a dataset including national Input-Output (I-O) tables collected by several researchers across the world, usually constructed by their national statistical agencies. The GTAP database is the only available database which provides input-output tables for a wide range of countries and is utilized by thousands of researchers worldwide. It is a key input into many contemporary applied general equilibrium analyses of global economic issues.

Several modifications are made to this GTAP standard database to make it suitable for this research. The first major modification divides crop sectors into irrigated and rainfed categories. The standard GTAP database does not distinguish between irrigated and rainfed crops. One objective of this research is to examine consequences of water scarcity for crop production. Given that water scarcity could affect irrigated and rainfed crop activities in different ways, we divided each crop sector of the standard GTAP database into two independent sectors: irrigated and rainfed.

The second important modification enhances the standard GTAP database to better represent consumption of water in its alternative uses and supply of water by river basin. The standard GTAP database includes a water utility sector (Water-Util) which represents the distribution of water across its alternative uses and the costs of its collection, purification, and distribution. This sector does not represent the main uses of water in agricultural activities. We modify the standard database to include water withdrawal for agricultural activities.

The third major modification divides the electricity sector of the standard GTAP database into hydro and non-hydro subsectors to better understand the nexus between economic growth and demand for electricity on one hand, and expansion in electricity production on the other, as well as water scarcity, which is a big concern in South Asia. The standard GTAP database represents the electricity industry under one aggregated sector. Dividing this into hydro and non-hydro subsectors enables us to model the demand for water in producing non-hydro-electricity.

The last important modification brings biofuels into the database. The standard GTAP database does not represent production and consumption of biofuels although many countries currently produce significant amounts of biofuels. We introduced production and consumption of biofuels into our databases to make it more consistent with real world observations. This modification will allow us to examine the consequences of biofuels production for the economies of South Asia, as an option in future research.

Data modifications along with some other important changes and improvements are first explained in this chapter. Then we review some important aspects of the new databases which we developed for our dynamic and static models.

1.2. Land use database: Dividing crop industries into irrigated and rainfed

To divide crop industries of GTAP database version 9 into the irrigated and rainfed categories we followed Taheripour et al. [2]. These authors divided the standard crop industries of the GTAP version 6 (which represent crops produced in 2001) into the irrigated and rainfed categories using the gridded database developed by Portman et al. [3]. We replicated their work for the GTAP database version 9 with a minor twist. Unlike the original work which assumes that the energy intensities of irrigated and rainfed crops are identical, we assumed that the energy intensities of irrigated crop industries are twice that of their rainfed counter parts.[11]

To accomplish this line of modification, we developed a land use database representing irrigated and rainfed harvested area and crop produced by country, river basin (RB), agroecological zone[12] (AEZ), and six aggregated crop categories (paddy rice, wheat, coarse grains, oilseeds, sugar crops, and other crops) for 2011. The land use dataset also provides data on land cover (including accessible forest, cropland and pasture) by country and RB-AEZ for 2011. The land use dataset is built on global land cover and land use databases documented in Monfreda et al. [4] and Ramankutty and Foley [5] as well as on global forestry data developed by Sohngen and Tennity [6]. In addition, we used the dataset developed by Portman et al. [3] to distinguish between irrigated and rainfed crops. Here we represent some major aspects of our land use and crop database for 2011.

Table 1.1 shows the share of South Asia in global crop production. It shows that South Asia produces 31.3% of rice, 19.4% of sugar crops, and 16.9% of wheat produced across the world in 2011. The shares of South Asia in all crop categories were less than 10% in this year.

Table 1.1. Share of South Asian in the global crop production in 2011 (%)

Description	South Asia	Rest of the World	World
Rice	31.3	68.7	100.0
Wheat	16.9	83.1	100.0
Coarse Grains	4.5	95.5	100.0
Oilseeds	6.2	93.8	100.0

[11] The energy intensity of irrigation systems varies across irrigation systems and regions. The crop budgets developed for irrigated and rainfed crops by University of Nebraska indicates that the energy intensity of irrigated crops could be up to three higher than the rainfed crops. The more advanced irrigation systems consume more energy. Here we assume twice as an average.

[12] The concept of agro-ecological zone (AEZ) has been used since 1978. An AEZ is comprised of all parts of grid cells on a georeferenced map that have uniform soil and climate characteristics. For details see: http://www.fao.org/nr/land/databasesinformation-systems/aez-agro-ecological-zoning-system/en/

Sugar Crops	19.4	80.6	100.0
Other Crops	8.7	91.3	100.0

India is the largest crop producer in South Asia and is relatively an important crop producer at the global scale. India accounts for 69.6% of rice, 73.5% of wheat, 82.6% of coarse grains, 91.6% of oilseeds, 84.3% of sugar crops, and 87.9% of other crops produced in South Asia in 2011. In general, the shares of other countries in crops produced in South Asia are not large, as shown in Figure 1.1. Bangladesh has only a large share in rice (22.3%) and Pakistan has considerable shares in wheat (21.3%), coarse grains (9.2%), and oilseeds (13.6%), as shown in Figure 1.1.

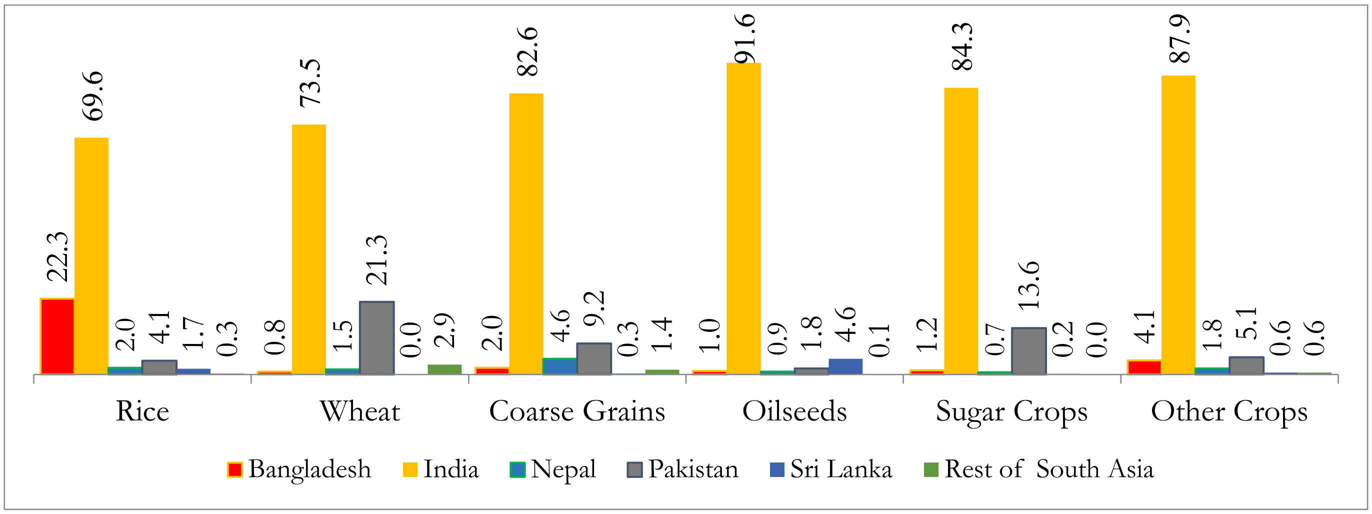


Figure 1.1. Proportion of crop production in South Asia Region (%)

While South Asia is a relatively large crop producer at the global scale (as shown in Table 1.1), it does not trade crops with the rest of the world. Crops produced in the region are mainly used locally, with the exception of rice (Figure 1.2). In other words, South Asia has a weak trade relationship with the rest of the world in commodity markets – and even within the region, cross border linkages are relatively weak. This weak relationship could harm food security in South Asia in the case of extreme climate events, as we will discuss in this research.

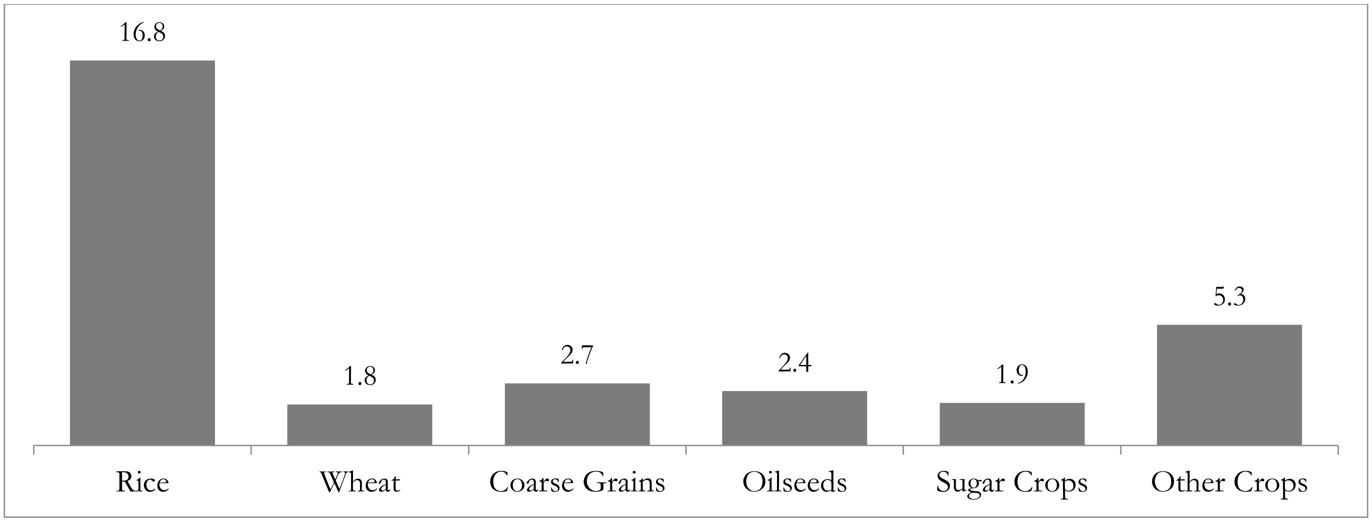


Figure 1.2. South Asia Region share of global exports of crops in 2011 (%)

While South Asia accounts for a relatively large share of global crop production, crops are produced with low yields in the region. In 2011, yields were about: 3.7 tonnes per hectare (t/ha) for rice; 2.9 (t/ha) for wheat; 1.7 (t/ha) for coarse grains; 1.5 (t/ha) for oilseeds, 66.1 (t/ha) for sugar crops; and 5.3 (t/ha) for other crops. As shown in Figure 1.3, these yields were significantly lower than their corresponding figures in the rest of the world (except for wheat and sugar crops). Rice yield in South Asia for instance is about 76% of rice yield in the rest of the world.

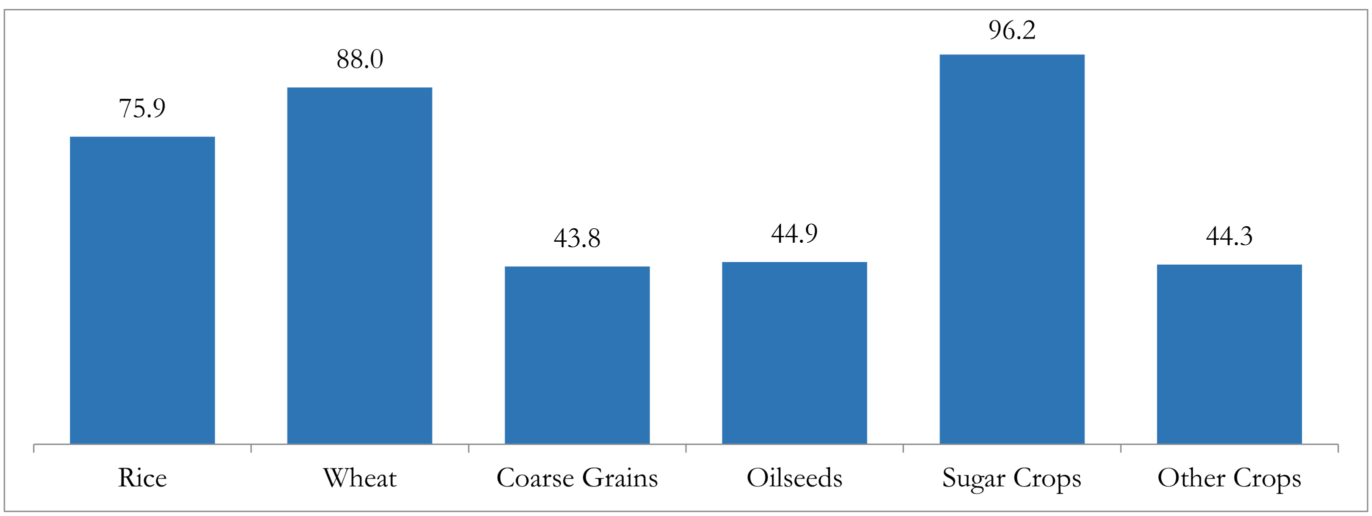


Figure 1.3. South Asia yields compared with the rest of the world yields:

(South Asia yield / Rest of the world yield)*100

While yields are generally lower in South Asia compared with the rest of the world, some of them are extremely far below the yields of advanced economies. For example, in 2011, yields in USA over South Asia were about: 8 over 3.7 (t/ha) for rice; 8.7 over 1.7 (t/ha) for coarse grains; 2.8 (t/ha) over 1.5 for oilseeds; and 17 over 5.3 (t/ha) for other crops.

India produces about 18.5% of irrigated crops produced across the world while it owns about 24% of the global irrigated land in 2011. India also uses about 26% of global water used for irrigation. Pakistan is another country which massively uses irrigation in South Asia. India produces 14.4% of irrigated crops produced in South Asia and owns 16.8% of irrigated area in the region. Pakistan uses about 8.7% of global water used for irrigation.

Consider now available land resources including cropland, accessible managed forest, and pastureland in South Asia.[13] The total area of managed land in South Asia is about 292.6 million hectares. The shares of Bangladesh, India, Nepal, Pakistan, Sri Lanka, and Rest of South Asia in total managed land of the entire region are 4.7, 68.4, 2, 10.4, 1.8 and 12.9% respectively. The largest portion of the managed land of South Asia is cropland (74.9%) followed by 16.4% pasture land and 8.7% forest. This means that South Asia has limited land to support livestock and forest activities, but has a relatively large base for crop production.

Cropland in South Asia is scattered across different agro-ecological zones (AEZs) as shown in Table 1.2. In Bangladesh, croplands are exclusively located in AEZ4 and AEZ5, with abundant moisture and long growing periods. About 23% of India's cropland are distributed among dry AEZs with short growing periods (i.e. AEZs: 1, 2, 7, 8, 13, and 14). The rest of India's cropland (77%) is distributed among the rich moist AEZs with long growing periods.

Table 1.2. Distribution of land by AEZ in South Asia

	Bangladesh	India	Nepal	Pakistan	Sri Lanka	Rest of South Asia	South Asia
AEZ1	0.0	1.6	0.0	14.5	0.0	0.0	2.8
AEZ2	0.0	7.8	0.0	0.0	0.0	0.0	6.1
AEZ3	0.0	44.0	4.2	0.0	2.0	0.0	34.5
AEZ4	22.8	18.2	35.9	0.0	17.5	0.0	15.9
AEZ5	77.2	3.8	4.2	0.0	14.2	0.0	6.5
AEZ6	0.0	1.1	0.0	0.0	66.3	0.0	1.5
AEZ7	0.0	3.7	0.0	56.4	0.0	14.2	9.6
AEZ8	0.0	10.1	0.0	7.8	0.0	66.7	11.6
AEZ9	0.0	7.8	0.0	5.4	0.0	1.5	6.8
AEZ10	0.0	0.8	16.7	9.7	0.0	1.1	1.9
AEZ11	0.0	0.7	25.4	3.0	0.0	1.8	1.3
AEZ12	0.0	0.4	11.0	2.8	0.0	0.4	0.8
AEZ13	0.0	0.0	0.2	0.1	0.0	9.8	0.4
AEZ14	0.0	0.0	0.6	0.3	0.0	4.3	0.2
AEZ15	0.0	0.0	1.4	0.0	0.0	0.0	0.1
AEZ16	0.0	0.0	0.4	0.0	0.0	0.2	0.0
AEZ17	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AEZ18	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[13] Other types of land including unmanaged forest, savanna, grass land, shrub land, and built up land are not included in this analysis.

In Nepal, land is scattered across several non-dry AEZs. Land in Sri Lanka is basically divided in AEZ4, AEZ5, and AEZ6 which are again non-dry AEZ. Unlike Bangladesh, India, Nepal, and Sri Lanka, available cropland in Pakistan and Rest of South Asia is basically distributed across dry AEZs (i.e. AEZs: 1, 2, 7, 8, 13, and 14) as shown in Figure 1.4. In Pakistan, 79% of the cropland land is located in dry AEZs. The corresponding share in Rest of South Asia is about 95%. Hence, food production in Pakistan and the Rest South Asia will be faced with major challenges if water is not available for irrigation.

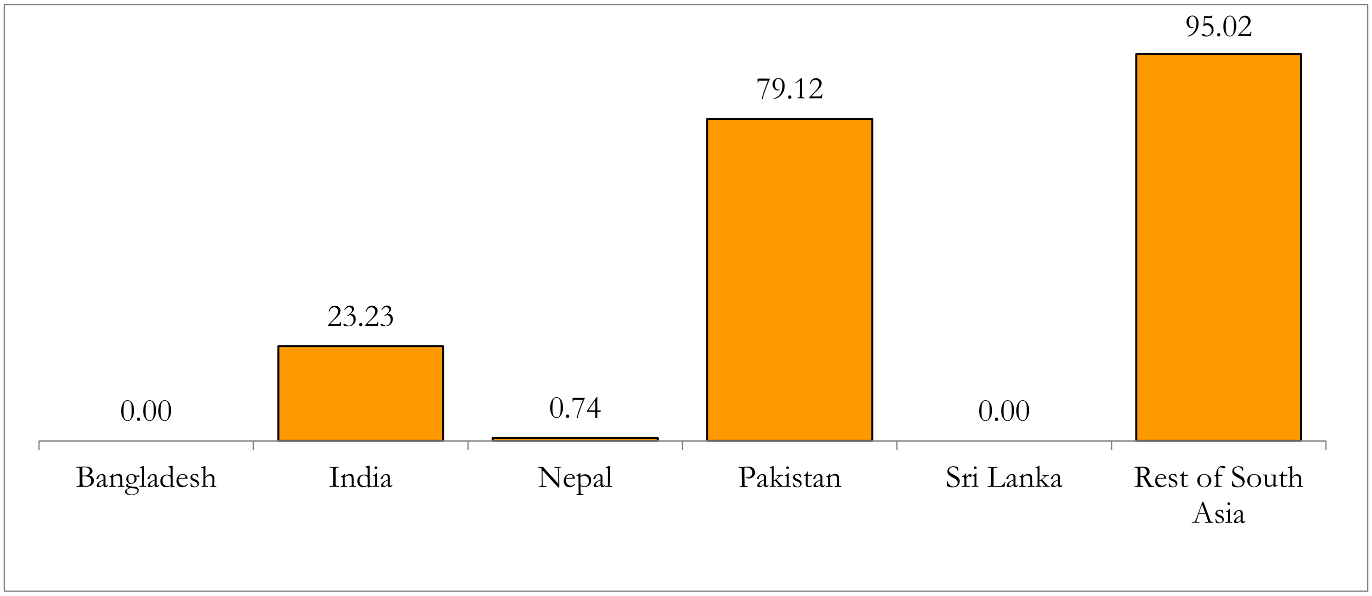


Figure 1.4. Share of dry AEZs (i.e. sum of AEZ1, AEZ2, AEZ7, AEZ8, AEZ13, and AEZ14) in available cropland in South Asia in 2011

In addition to the distribution of land resources by AEZ, our database represents the distribution of these resources by river basin. Four river basins including Brahmaputra, Ganges, Thai-Myan-Malay, and Others serve entire Bangladesh in our database. The shares of the two first basins in total harvested area of Bangladesh were about 45.3% and 47.6% in 2011. Two river basins, the Ganges and Indus, serve Nepal. About 99% of the area harvested in Nepal belongs to the Ganges. Pakistan is divided between three river basins: Indus, Western Asia, and Other. The Indus serves 98% of total harvested area of Pakistan. Sri Lanka is served basically by its main river basin. Several river basins, including Amudarja, Brahmaputra, Indus and Western Asia, serve the Rest of South Asia. The only country which is supported by several river basins is India. Figure 1.5 represents these river basins and their shares in total harvested area of India in 2011. As shown in this graph Ganges, Krishna, and Indus have the largest shares (34, 11.4 and 11.2%, respectively) in total harvested area of India.

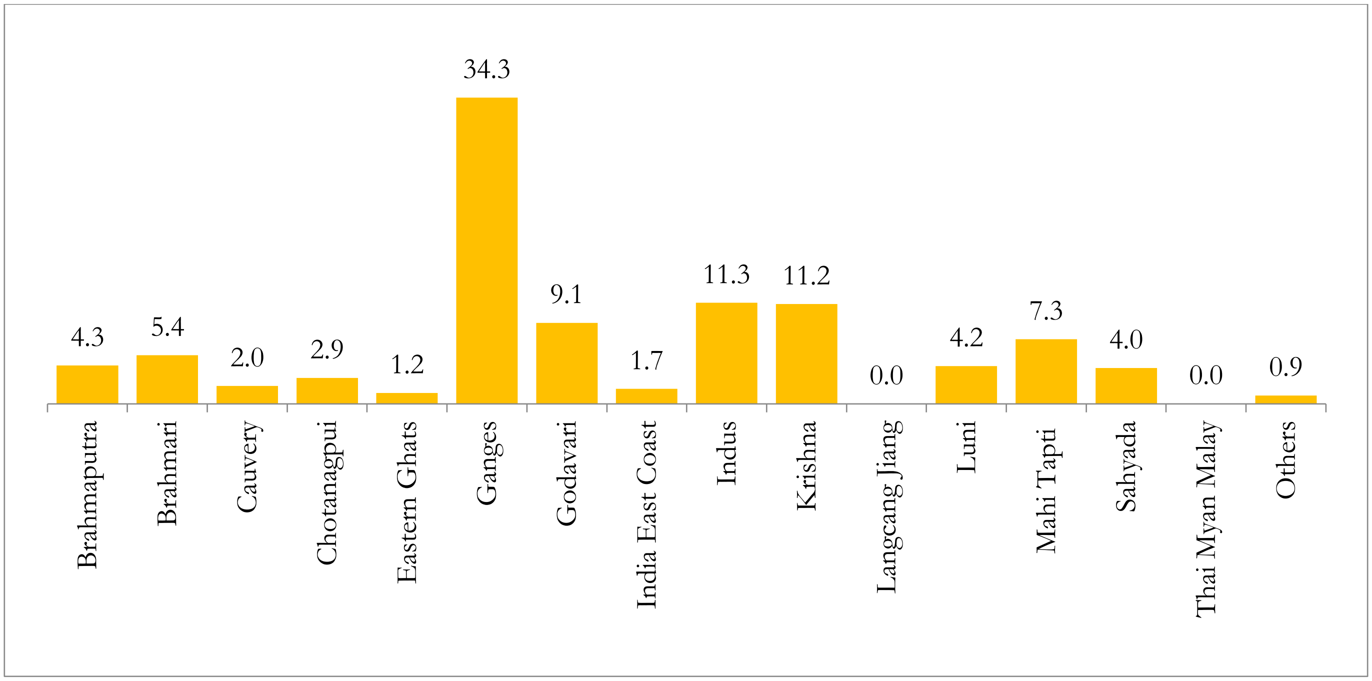


Figure 1.5. Distribution of India's harvested area by river basin (%)

The land use and crop production database developed for this research provides detailed information on: 1) land resources including managed forest, cropland, and pastureland; 2) irrigated and rainfed crops produced (including rice, wheat, coarse grains, oilseeds, sugar crops, other crops); and 3) harvested areas by country, AEZ, and River basin. In particular, one can find the following data items for 2011.

- Accessible forest by river basin-AEZ,
- Cropland area by river basin-AEZ,
- Pasture land by river basin-AEZ,
- Irrigated harvested area by river basin-AEZ and by crop type,
- Rainfed harvested area by river basin-AEZ and by crop type,
- Irrigated crop production by river basin-AEZ and by crop type,
- Rainfed crop production by river basin-AEZ and by crop type.

For example, we devolved three maps (see Map1.1, Map 1.2 and Map 1.3) which represent India's forest, pasture, and cropland distributions by river basin.

1.3. **Introducing water into the GTAP base**

Taheripour et al. [7] introduced irrigated water as an endowment into the cost structure of irrigated crop industries of the GTAP database version 6. We followed and extended their work to introduce water as an input into the cost structures of crop and non-crop industries of GTAP database version 9. The following basic assumptions and principles are used in this regard.

a) Managed blue water[14] is introduced into the cost structures of irrigated crops, livestock industries, and water utility sector (Water-Util) as an endowment,
b) Value added of water for each irrigated crop is determined according to the difference between the irrigated and rainfed crop yields[15] in each river basin-AEZ,
c) Blue water used in irrigated crops is determined at the river basin-AEZ level using the database developed by Siebert and Döll [8],
d) Given the information provided in (b) and (c) an implicit price (a shadow price) for water used in irrigated crops is calculated at river basin level,
e) It is assumed that the price of managed water used in livestock industries is identical to the shadow value of managed water used in irrigated crops,
f) It is assumed that the shadow price of water used in the water utility sector is twice of the shadow price of water used in agriculture (i.e. irrigated crops and livestock),
g) Other industries, households, and government buy managed water from the water utility sector,
h) Industrial and municipal water uses plus water used by livestock industries in 2011 are estimated at river basin based on the information obtained from the data developed by IFPRI.
i) Given the provided information in (e) to (g) value added of water used by the water utility sector and livestock industries are determined.
j) The GTAP input-output tables are modified to represent sales of water by the water utility sector to non-agricultural industries, households, and government.

We now present some key results from these modifications. First consider Figure 1.6 which represents water withdrawal in South Asia. In 2011 water withdrawal from surface and underground sources in Bangladesh, India, Nepal, Pakistan, Sri Lanka, and Rest of South Asia was about 38.4 billion cubic meters (BCM), 830 BCM, 8.3 BCM. 190.2 BCM, 7.8 BCM, and 17.4 BCM, respectively. Hence, India and Pakistan were the main users of water in South Asia.

[14] This refers to surface and ground water withdrawal for irrigation.
[15] The difference between the irrigated and rainfed yields for each crop in particular country-RB-AEZ represent the contribution of irrigation, for details see Taheripour et al. [7].

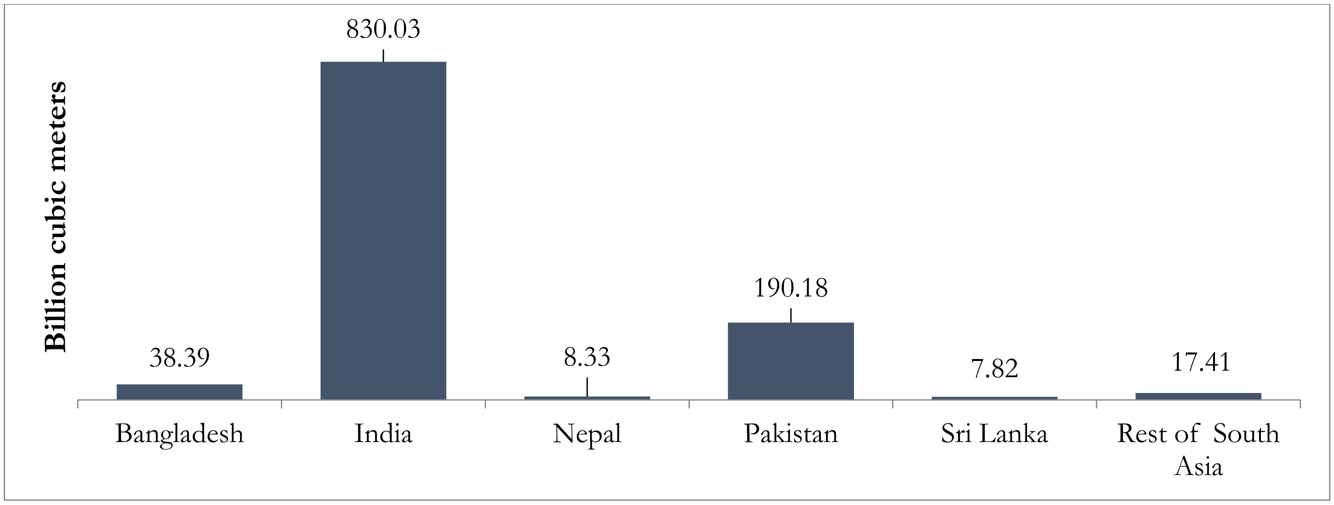


Figure 1.6. Water withdrawal in South Asia in 2011

Agriculture accounted for more than 80% of the total water withdrawn throughout South Asia in 2011 with the exception of Sri Lanka, where 51.3% was used for irrigation (Figure 1.7).

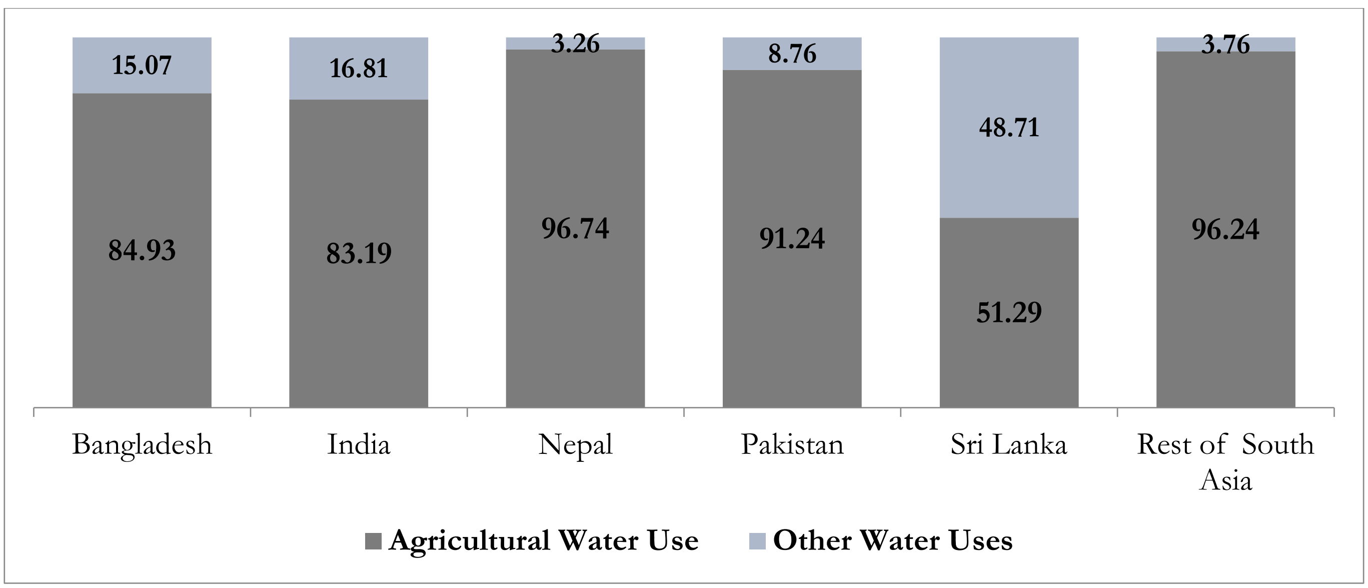


Figure 1.7. Shares of agricultural and non-agricultural uses in water withdrawal in South Asia in 2011

Now consider distribution of water used for irrigation across different crops by region in Figure 1.8. As shown in this figure in Bangladesh and Sri Lanka water is basically used for rice. Elsewhere in the region, water is used to produce both rice and wheat.

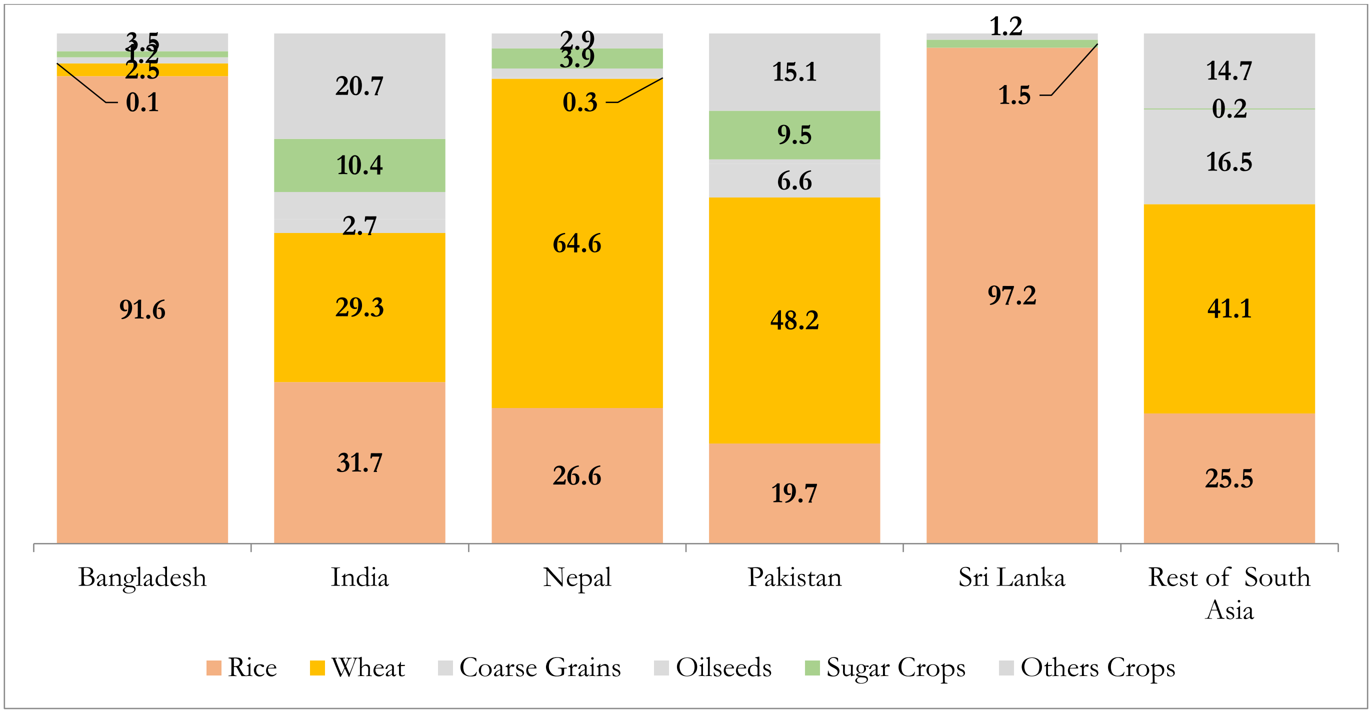


Figure 1.8. Distribution of water for irrigation across crops in South Asia in 2011 (%)

Our database shows distribution of water withdrawal by river basin as well. Figure 1.9 shows shares of major river basins in total water withdrawal of Bangladesh, Nepal, Pakistan, Sri Lanka, and Rest of South Asia in 2011. Figure 1.10 shows the same information for India. In India, the shares of Ganges, Indus, Krishna, and Godavari in water withdrawal were about 40.4%, 17.7%, 8.6% and 8% in this year.

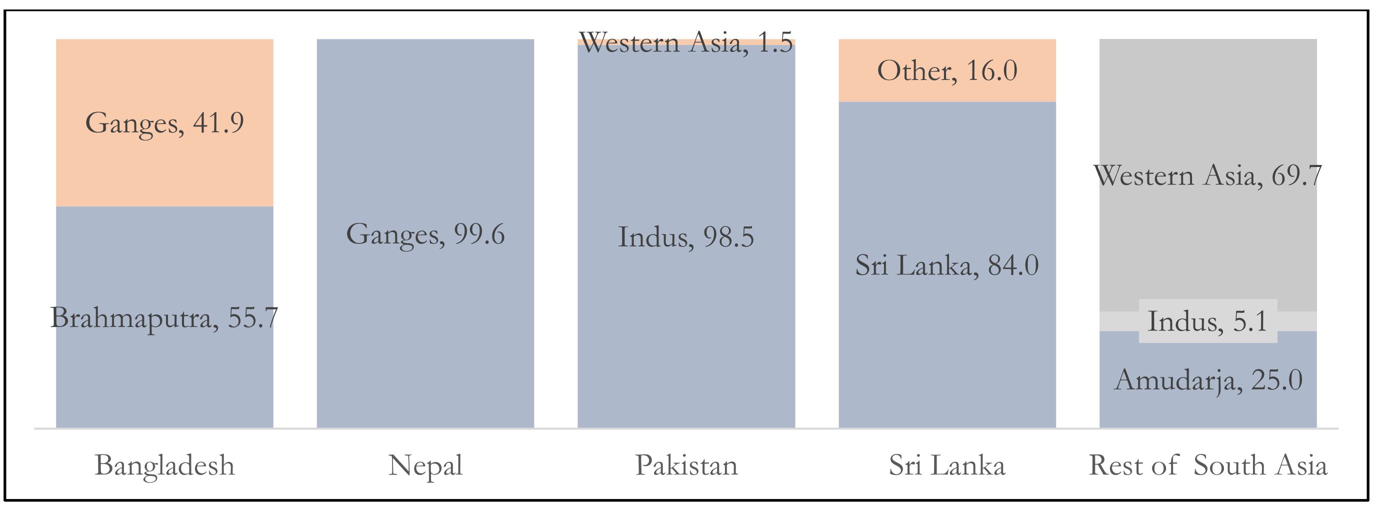


Figure 1.9. Distribution of water withdrawal by river basin in South Asia (except India) in 2011

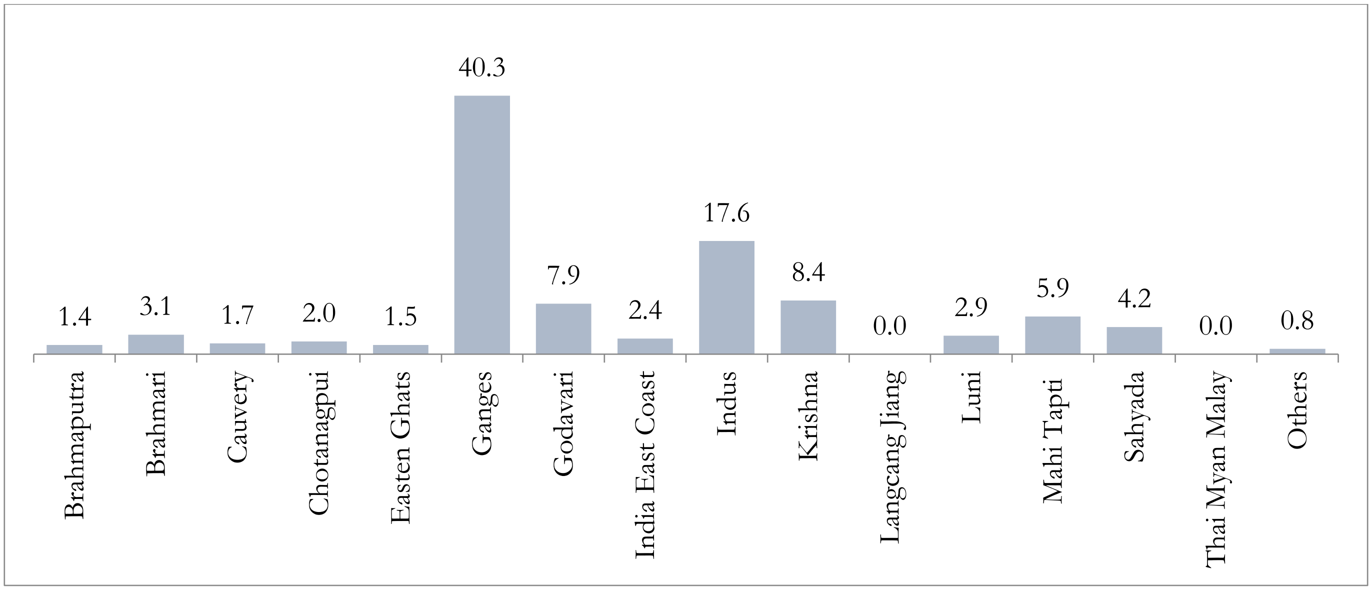


Figure 1.10. Distribution of water withdrawal by river basin in India in 2011

Water withdrawal is divided into the surface and underground sources. Figure 1.11 represents the share of these two categories in total water withdrawal by river basin in South Asia in 2011. As shown in this figure the share of underground water in some river basins in India is relatively large, examples are: 47% in Brahmani; 46% in Mahi Tapi; 40% in Sahyadri Ghats; 36% in Godavari; and Ganges 34%. The share of underground water withdrawal in Pakistan and Bangladesh were 15 and 11% respectively. This share was limited in other countries in South Asia.

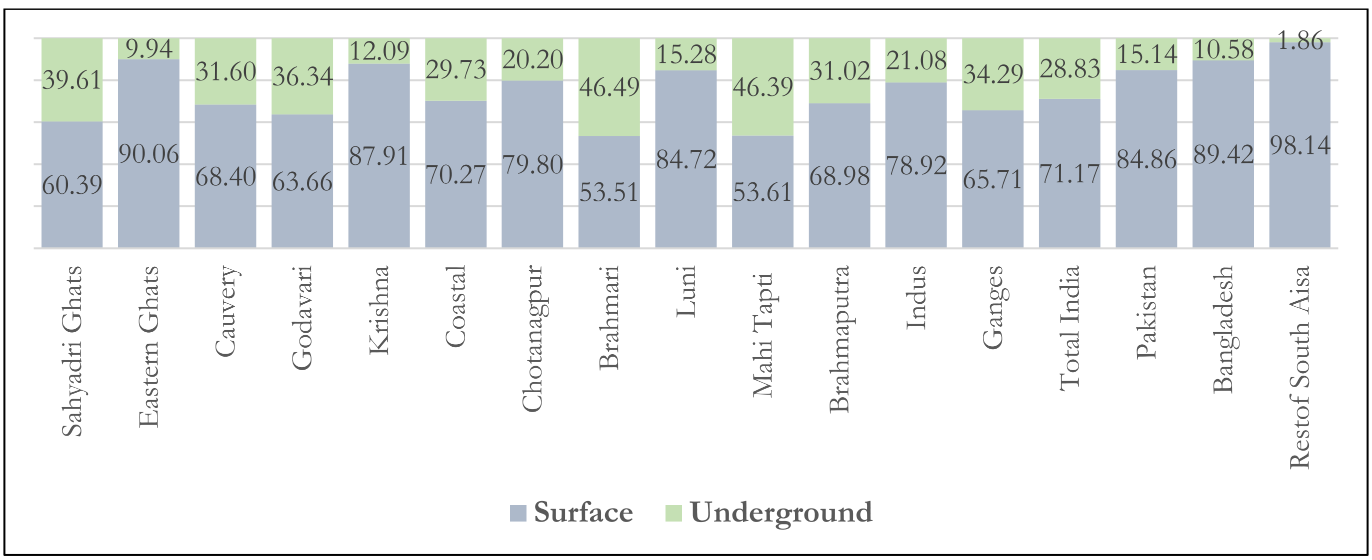


Figure 1.11. Shares of surface and underground water in total water withdrawal in South Asia in 2011

Finally, consider India's distribution of water withdrawal for non-agricultural uses by river basin. As shown in Figure 1.12 the Ganges river basin provides about 38.6% of water for non-agricultural uses. The shares of other basins in water for non-agricultural uses of water vary from negligible values to as much as 9%.

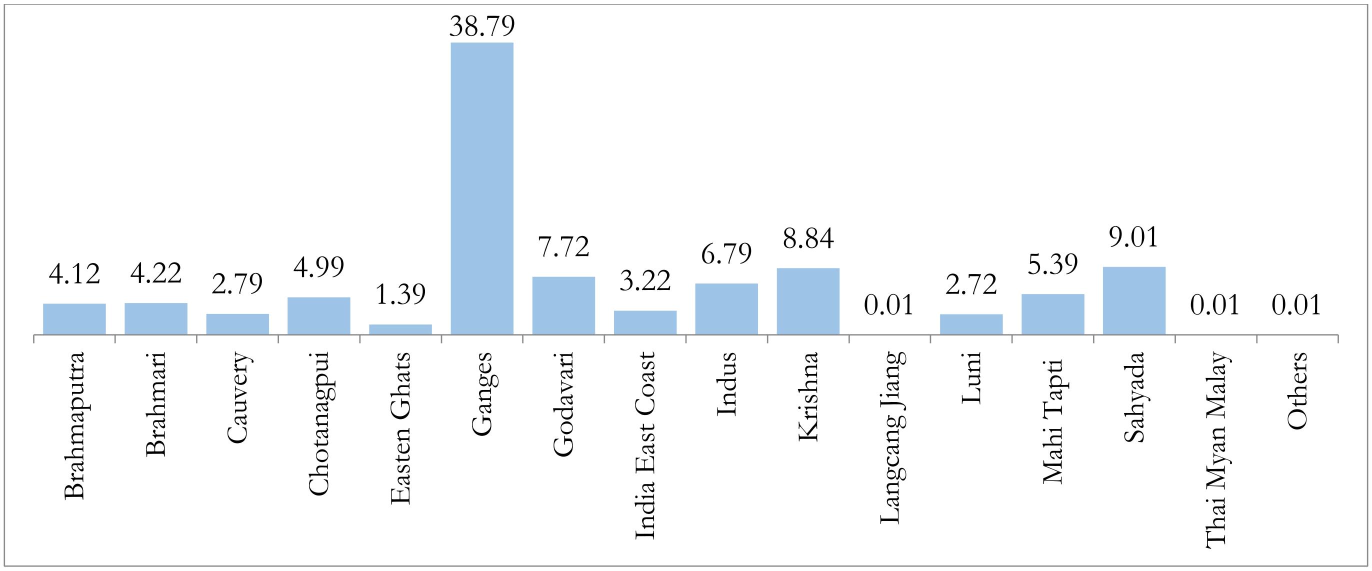


Figure 1.12. Distribution of India's water withdrawal for non-agricultural uses by river basin in 2011

In general form our database one can take the following data items

- Water withdrawal by river basin-AEZ for irrigation by crop,
- Water withdrawal by river basin-AEZ for livestock,
- Water withdrawal by river basin-AEZ for non-agricultural uses.

Introducing hydro and non-hydroelectricity sectors

The standard GTAP database represents production and distribution of electricity under one sector named "ely." Because hydro and non-hydro electricity producers may be affected by water scarcity in different ways we split the "ely" sector into two distinct electricity sectors of Ele-Hydro and Ele-Non-Hydro. To accomplish this task, we used the SplitCom program (Horridge [9]) which is designed to split a GTAP standard sector into two (or more) new sectors. The program needs some criteria to run the process. We used the production shares of hydro and non-hydro producers in total production of electricity of each region to run the split program. Production shares are obtained from the International Energy Agency database for 2011. Figure 1.13 represents the shares of new sectors in total electricity output of each region. As shown in this graph, in general non-hydroelectricity (which is mainly produced by thermal power plants) has a large share in South Asia in 2011. The only exception Nepal where electricity is basically produced from hydro generators. It is important to note that South Asia produces a limited amount of electricity and has a very small share in the global electricity production. In 2011 only about 5.5% of the global electricity out was produced in South Asia and that was mainly produced in India (80%).

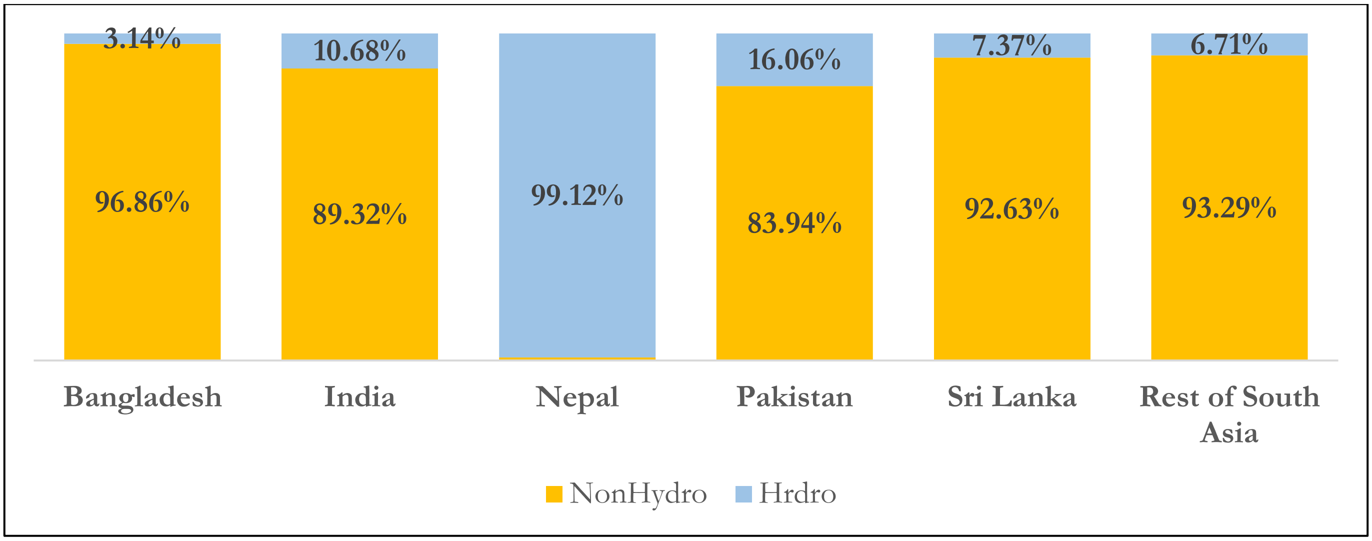


Figure 1.13. Shares of hydro and non-hydro in market for electricity in 2011

1.4. **Biofuels**

In recent years, several attempts have been made to introduce biofuels in the GTAP database and model. We followed the work in this area and introduced ethanol and biodiesel in the GTAP database version 9. To accomplish this task, we collected data on biofuels produced in 2011 by country and followed Taheripour et al. [10] and Taheripour and Tyner [11] to define proper cost structures for these industries for 2011 and introduce them into the database.

In 2011, the global outputs of ethanol and biodiesel were about 86.7 billion liters and 23.4 billion litters, respectively. The main biofuel producers in this year were United States of America, Brazil and some members of European Union. India was producing about 348 million liters of ethanol and 116 million liters of biodiesel in 2011. South Asia is not a major global biofuel producer.

1.5. **Other modifications and corrections**

In addition to the above modifications we made the following modifications and corrections in the GTAP database version 9 as well.

- The standard GTAP database aggregates feed and food industries under one category (ofd). We divided this sector into two distinct sectors of food and feed.
- The standard GTAP database aggregates all activities associated with producing of vegetable oils under on sector (vol). We divided this sector into two separate industries of C-vol (crude vegetable oil industry) and R-vol (refined vegetable oil. The C-vol industry crushes oilseeds and produces crude vegetable oil and oil meals and the R-vol uses refined vegetable oils.
- The standard GTAP database does not represent biofuel by-products. We introduced these by-products to better reflect consequences of biofuel production.
- The original GTAP database version 9 misrepresents production and consumption for the water utility sector, in particular in South Asia. We fixed this issue using the GTAP-Adjust program,

documented in Horridge [12]. This involves re-balancing the data matrices to meet the targets in terms of totals and cost/sales shares.

1.6. Aggregation schemes

To concentrate on the South Asian economies, we aggregated the global economy into 7 regions including: Bangladesh, India, Nepal, Pakistan, Sri Lanka, Rest of South Asia, and Rest of World. The implemented commodity and industry aggregation schemes are shown Table 1.3. As shown in this table, the model divides all economic activities into 46 industries and 40 commodities. Unlike the standard GTAP databases which represent a one to one mapping between industries and commodities the static database developed for this research represents three types of mapping between commodities and industries.

- Two industries produce one commodity;
- One industry produces two commodities;
- One industry produces one commodity.

In our model and its database each crop is produced by two producers. For example, as shown in Table 1.3, wheat can be produced with irrigation (represented by IWheat) and/or with no irrigation (represented RWheat). Production of electricity follows this type of mapping as well. This means that hydro and non-hydro electricity producers provide electricity.

On the other hand, in this database the grain ethanol industry (EthnaolC) produces two commodities: Ethanol (Ethnaol1) and Dried Distiller's Grains with Solubles (DDGS). The crude vegetable oil industry (C-vol) also produces two products: Crude vegetable oil (C-vol) and oil meals (VOBP). All other industries follow the traditional one to one mapping.

We divided primary inputs into 804 categories to represent land and water by river basin and AEZ with the following details.

- Four rows for skilled labor, unskilled labor, capital, and resources;
- 400 rows for water by RB-AEZs (20 RBs times 18 AEZs for water used by irrigated crop irrigated plus 20 rows for water used in livestock industries and 20 rows for water used in the water utility sector);

400 rows for land by RB-AEZs (20 RBs times 18 AEZs for land plus 40 dummy rows to match with the arrangement for water.

Table 1.3. Industry and commodity aggregation scheme

Industries	Commodities	Original GTAP sectors	Industries	Commodities	Original GTAP sectors
IPaddy_Rice	Paddy_Rice	PDR	Proc_Rice	Proc_Rice	PCR
RPaddy_Rice			Proc_Food	Proc_Food	A portion of OFD
IWheat	Wheat	WHT	Proc_Feed	Proc_Feed	A portion of OFD
RWheat			Biodiesel	Biodiesel	New sector
ICrGrains	CrGrains	GRO	EthanolC	Ethanol1	New sector

RCrGrains				DDGS	
IOilseeds	Oilseeds	OSD	Ethanol2	Ethanol2	New sector
ROilseeds			Coal	Coal	COA
ISugar_Crop	Sugar_Crop	C_B	Oil	Oil	OIL
RSugar_Crop			Gas	Gas	GAS, GDT
IOthAgri	OthAgri	V_F, PFB, OCR	Oil_Pcts	Oil_Pcts	P_C
ROthAgri			Primary_Ind	Primary_Ind	OMN
Forestry	Forestry	FRS	Ele_Hydro	Electricity	ELY
Dairy_Farms	Dairy_Farms	RMK	Ele_NHydro		
Ruminant	Ruminant	CTL, WOL	Textile	Textile	TXT
NonRuminant	NonRuminant	OAP	Chem	Chem	CRP
Proc_Dairy	Proc_Dairy	MIL	En_Int_Ind	En_Int_Ind	I_S, NFM, FMP
Proc_Rum	Proc_Rum	CMT	Oth_Ind	Oth_Ind	WAP, LEA, LUM, PPP, MVH, OTN, ELE, OME, OMF
Proc_NonRum	Proc_NonRum	OMT	Water_Util	Water_Util	WTR
Cveg_Oil	Cveg_Oil1	A portion of VOL	Transport	Transport	OTP, WTP, ATP
	VOBP	A portion of VOL	Services_P	Services_P	CNS, TRD, CMN, OFI, ISR, OBS, ROS
Rveg_Oil	Rveg_Oil	A portion of VOL	Services_G	Services_G	OSG
Fishery	Fishery	FSH	Services_D	Services_D	DWE
Bev_Sug	Bev_Sug	SGR			

1.7. Database review

Table 1.4 shows that India is the largest economy of South Asia, with $1,882 billion GDP in 2011. The second largest economy in the region is Pakistan with $214 billion GDP, followed by Bangladesh with $112 billion GDP.

Table 1.4 Major macro figures in 2011: GTAP database versus World Bank database

Description	Bangladesh	India	Nepal	Pakistan	Sri Lanka	Rest of South Asia	Rest of World
GDP (current US billion $)	**112**	**1,882**	**19**	**214**	**59**	**22**	**69,171**
Agriculture (% of GDP)	15.9	18.7	32.6	12.0	21.4	31.7	3.9
Industry (% of GDP)	34.9	29.3	16.5	33.2	32.1	15.1	33.3
Services (% of GDP)	49.2	52.0	50.9	54.8	46.5	53.2	62.8
Total of sectors	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Household exp. (% of GDP)	75.8	62.4	87.2	88.0	73.5	101.5	58.7
Investment (% of GDP)	24.4	33.7	24.4	13.6	28.4	23.4	23.2
Government exp. (% of GDP)	5.6	12.1	10.9	10.6	15.5	15.0	17.8
Export (% of GDP)	25.2	19.9	7.6	14.5	20.9	17.1	28.5
Imports (% of GDP)	-31.0	-28.1	-30.1	-26.6	-38.3	-57.1	-28.2
Total of users	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Table 1.4 shows that Sri Lanka, Nepal, and Rest of South Asia are very small economies with limited national incomes. The gross national products of these countries were about $59 billion, $19 billion, and $22 billion in 2011. Table 1.4 also shows distribution of GDP across major sectors (including agriculture, industry, and services), and distribution of GPD among different expenditure groups (including private consumption, government expenditure, investment, and exports) across the world. This table and Figure 1.14 indicate that the economies of South Asia have relatively similar production structures - shown by the distribution of GDP between agriculture, industry, and service sectors. In these economies, agriculture accounted for a relatively big share of GDP in 2011, from 12% in Pakistan to 31.7% in Rest of South Asia. The share of agriculture in the rest of the world was about 3.9% in this year. South Asian economies still rely heavily on agricultural activities. The share of industrial activities in GDP is around 30 to 34% in economies of South Asia and the rest of the world. The only exceptions are Nepal and Rest of South Asia, with 16.5% and 15.1% for the share of industrial activities in total GDP. The share of services in GDP is around 50% in South Asia. This share is about 63% in the rest of the world.

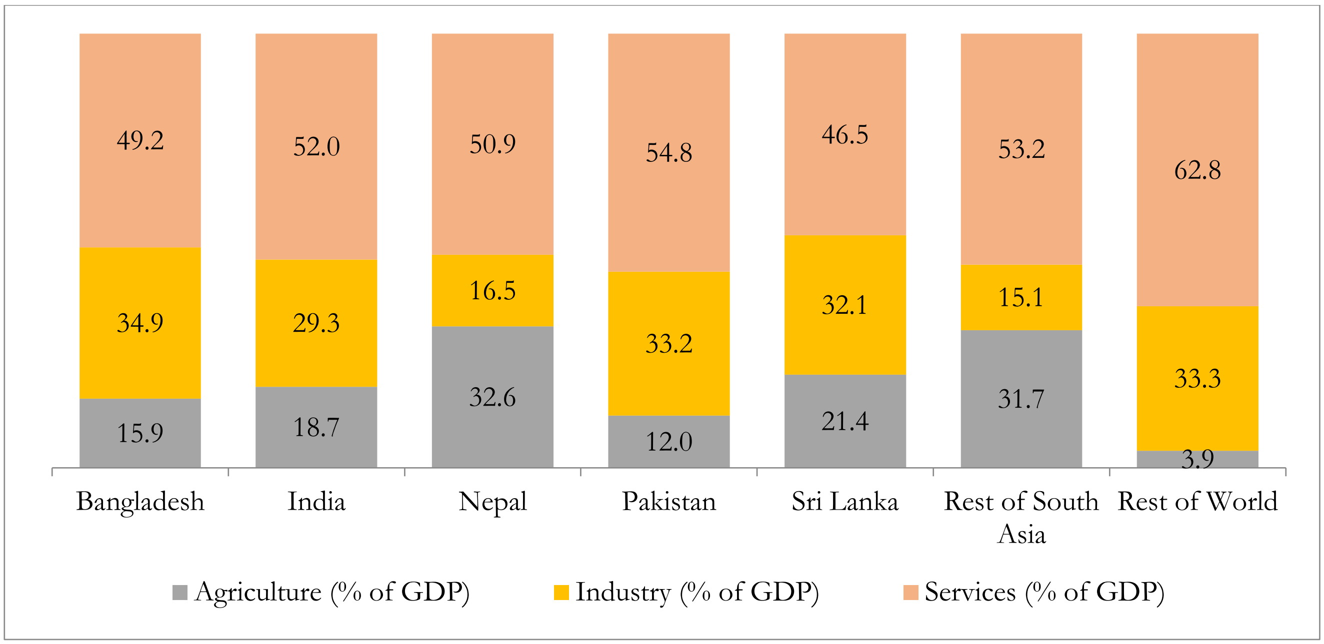


Figure 1.14. Distribution of GDP between major economic activities in 2011

Figure 1.15 represents distribution of GDP across private consumption, government expenditures, investment, and exports by region in 2011. This figure indicates that Bangladesh and Nepal had the largest and smallest export shares (25.2 and 7.6% respectively) in South Asia in 2011. Nepal is not an exporting country.

As shown in Figure 1.15, India and Pakistan had the largest and smallest investment shares (33.4 and 13.6%) in South Asia in 2011. This indicates that India is preparing for faster growth. Figure 1.15 shows the share of household expenditures in GDP is high among all economies of South Asia compared to the rest of the world. For example, about 88% of GDP of Pakistan consumed by households in 2011, while the corresponding rate for the rest of world was 58.7%

Finally, Figure 1.15 shows that the share government expenditures in GDP in economies of South Asia were around 6 to 16% in 2011, lower than the corresponding figure for Rest of World (about 18%).

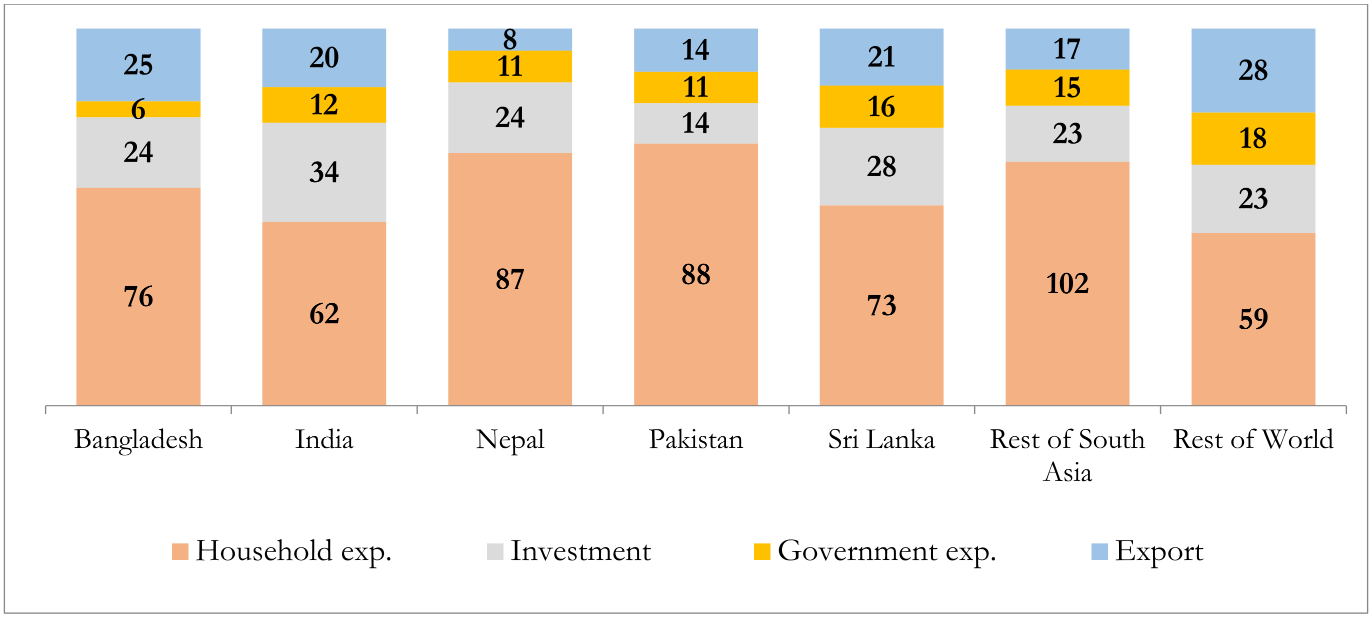
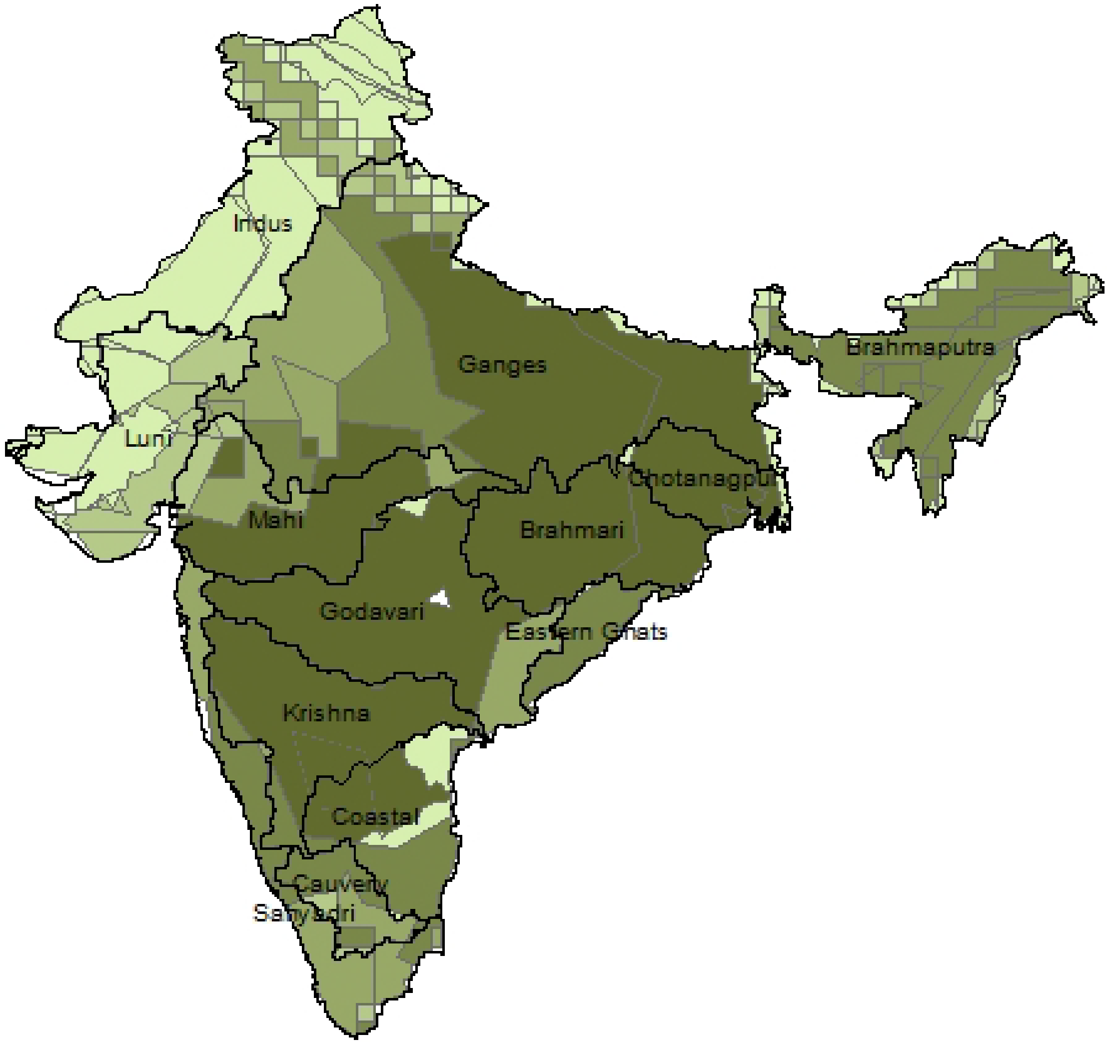
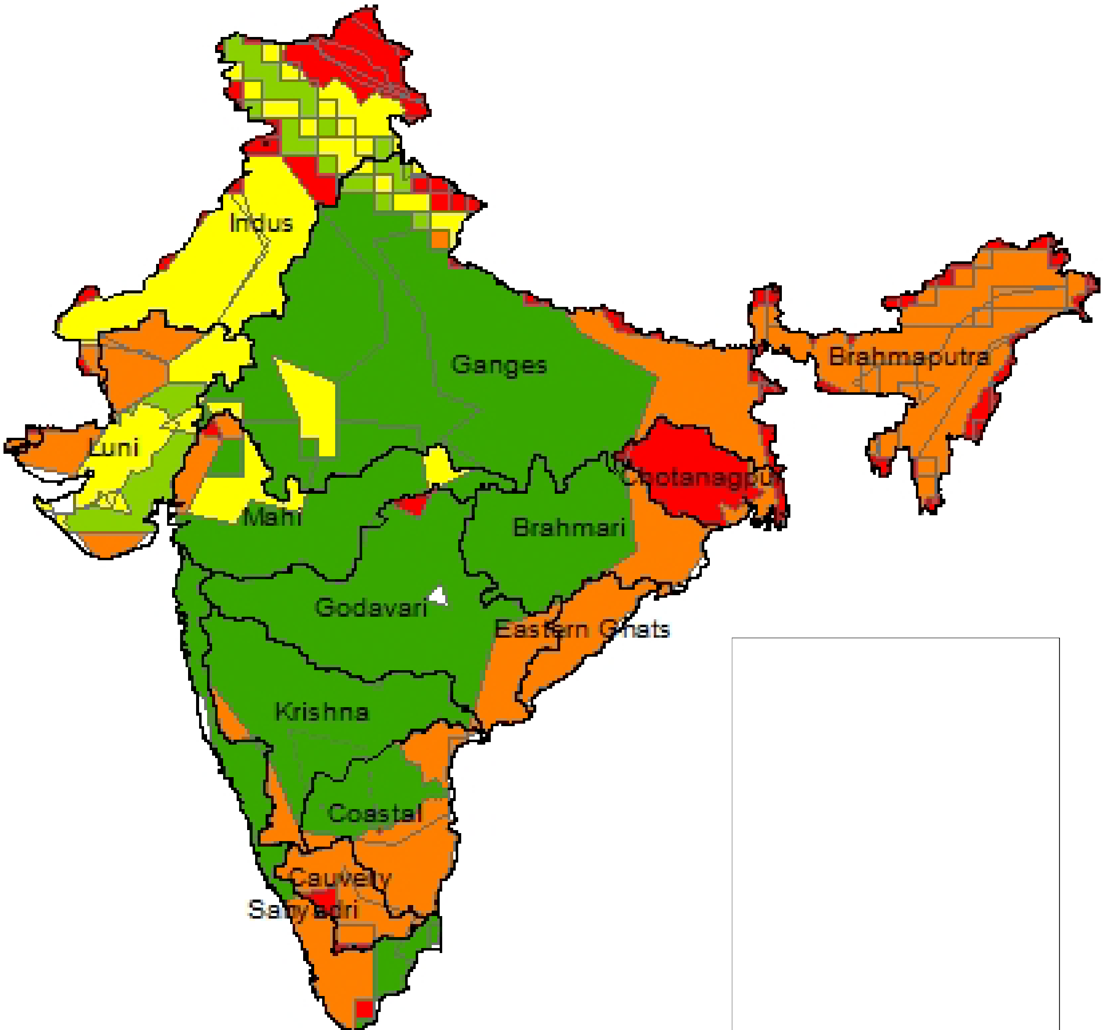
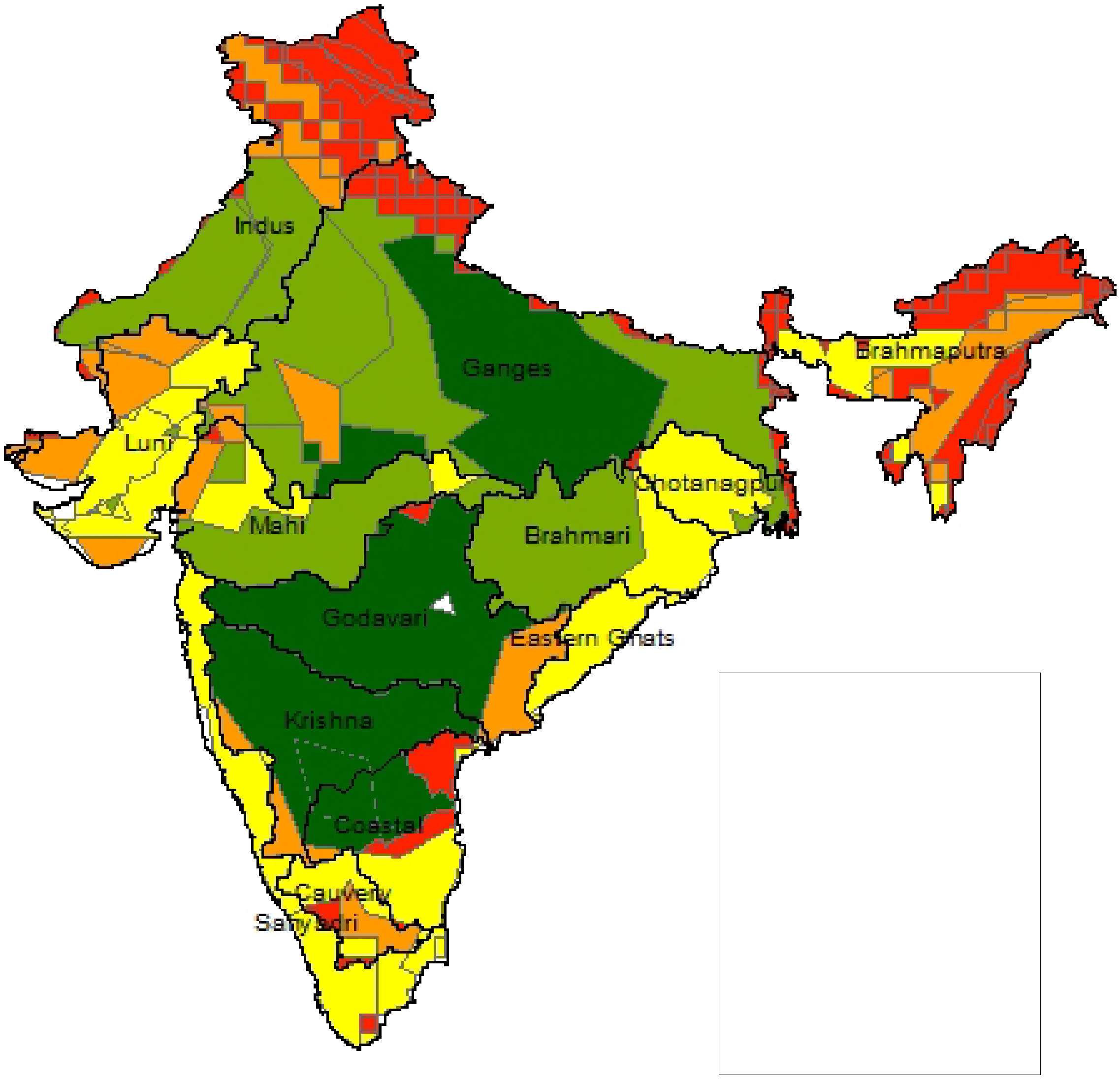


Figure 1.15 Spending category by percentage of GDP (2011)



Map 1.1. Accessible managed forest in India (figure are in 1000 hectares)


Indus
Ganges
Brahmaputra
Luni
Chotanagpur
Mahi
Brahmari
Godavari
Eastern Ghats
Krishna
Coastal
Cauvery
Sahyadri



Map 1.3. Cropland in India

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Chapter 2: Modeling Framework

2.1. Introduction

Many studies have tried to provide economy-wide analyses of water management and policy and water scarcity (shortage) using Computable General Equilibrium models (CGE). An early work in this area developed by Berck et al. [1] introduced water explicitly into a small single region CGE model to examine the economic impacts of water shortage in the San Joaquin Valley in California. Following this initial work, several authors included water in a number of CGE models to perform economic analysis of water management and policy. Fadali et al. [2] have listed many of these models. These models which have been used in various applications carry the following common core characters.

1. Water is an input in the production functions of crop sectors. Only a few small single models take into account water used in non-agricultural sectors.[16]
2. Most of the existing models were developed to examine water issues in a small region or a river basin. Only a few CGE models examined water issues at a global scale[17].
3. Supply of water is usually an exogenous variable in the CGE models. Some CGE models were linked with hydrology models to better capture the link been economic and biophysical variables.[18] Even in these hybrid models water supply remains exogenous in the CGE part.
4. In many models water is a sluggish endowment with limited mobility. Usually a regional market clearing condition allocates water among its alternative uses. A few models used other techniques or ad-hoc restrictions (or quotas) to allocate water among its alternative uses.[19]
5. Global CGE models do not distinguish between the surface and ground water. Some single region or single river basin models distinguished between these two types of water resources.[20]

The CGE modeling framework developed and used in this research (GTA-BIO-W) extends the above common characters in several directions. The GTAP-BIO-W was originally developed at the Center for Global Trade Analysis Project (GTAP). It is a static CGE model which combines economic and biophysical information on land and water. It is designed to examine the nexus between agricultural activities, industrial and energy sectors, and trade in the presence of climate change and water scarcity by region at a global scale. The GTAP-BIO-W used in this research carries the following major advantages comparted to the other existing Water-CGE models.

[16] As an example, Luckmann et al. [3] developed a single region CGE models which takes into account water in non-agricultural uses.

[17] For example, for the first time, Berrittella et al. [4] introduced water into a global CGE model (GTAP-W) as an input in the production function of crops and the water utility sector at the national level. Calzadilla [5] extend this model by dividing value added of cropland into irrigated and rainfed.

[18] For example, Robinson and Gueneau [6] combined a CGE model with a hydrology model. However, these authors run the CGE and the hydrology models separately in a sequence.

[19] For example, Berck et al. [1] used linear programing to allocate water across crops.

[20] As an example, Diao et al. [7] provided some economic analyses on using surface and ground water in Morocco.

1. It is the first global CGE model which explicitly traces water by country at the river basin level by Agro-Ecological Zones (AEZs). A large river basin could serves several AEZs.
2. It incorporates water into the production function of all economic activities including crops, livestock, industries, and water utility services. Therefore, all economic activates compete for water.
3. Unlike all other existing CGE models, this model distinguishes between the rainfed and irrigated crops to better capture the links between demands for irrigation and food.
4. The nested Constant Elasticity of Substitution (CES) production functions are used in this model[21]. Hence, it allows the user to examine alternative assumptions on substitution between water and other input in particular for capital and land.
5. This model takes into account heterogeneity in the price of water and traces demand for and supply of water by country at the river basin level by AEZ.[22] This means that the marginal value of water could be different at different places and across uses.
6. Unlike all other CGE models, it use a nested Constant Elasticity of Transformation (CET) functional form to model the supply side of water[23]. This is consistent with the real world observations. As explained in this chapter, the data and modelling structure take into account the real world rigidities. While some adjustment of water use across sectors is possible, it is by no means freely mobile like other mobile inputs such as labor or capital. This is a standard method to model a sluggish input like water which cannot move freely across uses and across regions.
7. The database used in this research is the best currently available at the global scale. The biophysical information includes crop production, harvested area, land cover items, and water used which match with the national and international databases including the World Bank and the Food and Agriculture Organization of the United Nation (FAO).

In recent years, the model has been frequently used to analyze multidisciplinary research topics on food, energy (including biofuels), land and water resources, climate change, water scarcity and other related topics. The GTAP-BIO-W model was built on the standard GTAP model developed by Hertel [8] and follows the same modeling structure. In this chapter we first briefly introduce the main aspects of the GTAP modeling structure. Then we introduce the GTAP-BIO-W model and explain a set of new modifications which we implemented to make this model suable for our research.

2.2. Overview of GTAP modeling framework

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[21] A nested CES production function divides production inputs into several sub groups and assign different elasticity of substitution parameters between the inputs of each nest and among the nests. For example see Figure 2.5 which represent the nesting structure of our CGE model.

[22] In a competitive market all users of a commodity pay the same price for that commodity. When there are rigidities in the market for an endowment (or a commodity), the users pay different prices for that endowment (or commodity). This represents heterogeneity in price paid by users. For example, when water cannot freely move from agricultural uses to non-agricultural uses due to the existing restrictions (e.g. quotas, water rights, or any other social restrictions), agricultural and non-agricultural users of water pay different prices for water. In this case water is not a homogenous commodity across its alternative uses.

[23] For details see section 2.31.

GTAP is a multi-commodity, multi-regional, computable general equilibrium model which traces production, consumption, and trade of a wide range of goods and services at a global scale. As represented in Figure 2.1.

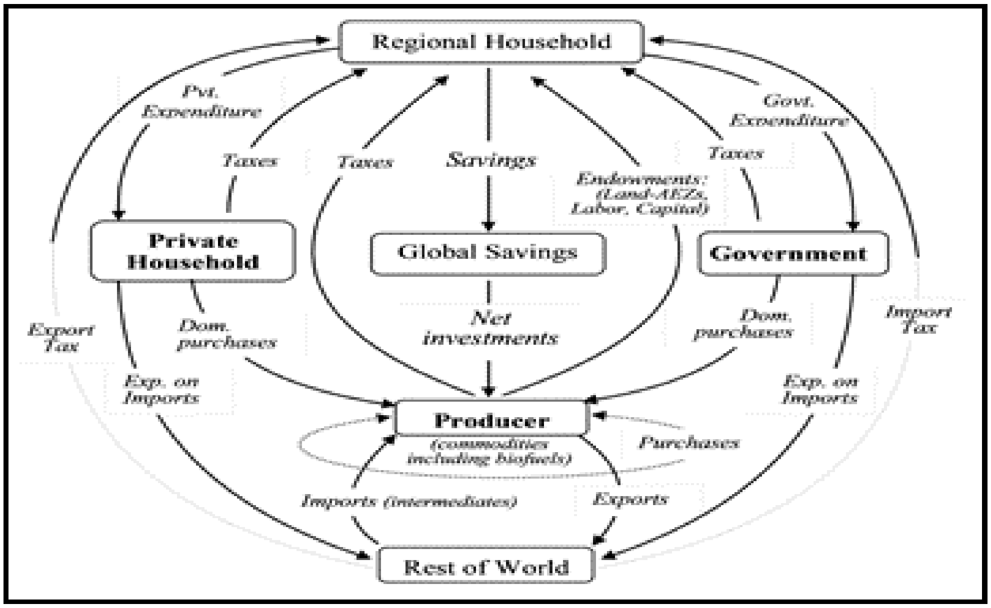

Figure 2.1. An overview of standard GTAP model

In this model in each country a hypothetical *regional household* receives all the income in its region and allocate it over three categories: private household (consumer), government expenditures, and savings, as governed by a utility function.[24] On the production side, each industry is represented by a single firm that maximizes profits subject to a production function that combines primary factors (including labor capital, land, and resources) and intermediate inputs to produce a final good. Firms pay wages/rental rates to the regional household in return for the employment of land, labor, capital, and natural resources. Firms sell their outputs to other firms (as intermediate inputs), to the private household, government, and investment. Since this is a global model, firms also export the tradable commodities and import the intermediate inputs from other countries. These goods are assumed to be differentiated by country and so the model can track bilateral trade flows. Taxes (and subsidies) go as net tax revenues (subsidy expenditures) to the regional household from private household, government, and the firms. The rest of the world gets revenues by exporting to private households, firms and government. These revenues are spent on export taxes and import tariffs, which eventually go to the regional household. This rest of world composite is actually made up of many other regions – with the same utility and production functions as for the regional household at the top of this figure. The standard GTAP model is fully presented in Hertel [8]. This book has been cited in publications and is available online.

2.3. GTAP-BIO-W Model

[24] GTAP is a global model. It divides the world-economy into a number of distinct countries (or regions). In each country (or region) a hypothetical regional household aggregates the demand side of the economy. The regional households represent the demand side of their economies in the world market. For details see Hertel [8]. The single country CGE models do not usually use this set up.

This model is built on an extension of the original GTAP model (i.e. the GTAP-E [9, 10]) which is a static model and allows substitution among energy inputs. It assumes energy and capital are substitutable inputs in economic activities, except for primary energy sectors such as gas, coal, and oil. In a series of modifications [e.g. 11-13] land by AEZ, biofuels, and biofuels by-products were introduced in this model to make it suitable to study the economic and environmental impacts of biofuel production and policies. The new model has been identified as GTAP-BIO and widely used to examine the consequences of biofuel production at the global scale (examples are: [14-17]). Then in an intensive set of modifications the GTAP-BIO model is modified to trace supplies of and demands for land and water resources within a country at a spatial resolution of river basin (RB) by AEZ[25] level at the global scale and to take into account competition for water across its alternative uses [18-20]. The model developed due to this set of modifications is named GTAP-BIO-W. The model used in this research is the only advanced global water CGE model which traces demand for and supply of water by country at RB-AEZ level and takes into account competition for water across agricultural and non-agricultural uses.[26] In what follows we explain the major aspects of this model along with the changes we made for this research.

2.3.1. Water and land resources in GTAP-BIO-W

Figure 2.2 represents the GTAP-BIO-W approach in allocating primary inputs including labor, capital, resources, land, and water. In this model, competition for labor, capital, and resources takes place at the national level. This means that firms compete for these primary inputs only at that level. In figure 2.2 the competition for these endowments occurs within the green box which represents a national economy including serval river basins. Sectors take labor, capital, and resources from the national pool. Labor and capital are as usual mobile inputs. This means that these resources move freely across uses. Following the standard GTAP model, resources are modeled as "sluggish" endowments that cannot be moved easily from one sector to another.

Competition for water, however, takes place at the RB level. As shown Figure 2, an economy may have several river basins. In each river basin water has two main uses. A portion of water goes for irrigation and the rest goes for other uses. As shown in Figure 2.2 each river basin may serve several AEZs. So AEZs of each RB compete for irrigation, see the blue box. The GTAP-BIO-W model also represents available managed land at the RB-AEZ level. In each RB-AEZ the area of available managed land is divided between forest, pasture and cropland, as shown in Figure 2.2. Then irrigated and rainfed crops compete for cropland. Land cannot move across RB-AEZs. The irrigated crop industries compete for managed water in each RB at the AEZ level. This means that competition for water for irrigation also takes place at the spatial resolution of RB-AEZ. Finally, irrigated crops compete for irrigated cropland and rained crops compete for rainfed cropland. In this model, water can move from one AEZ to another one in a river basin. A water transformation elasticity governs the movement of water across the AEZs of a river basin, as explained in the following.

[25] Henceforth, we refer to this spatial resolution as RB-AEZ

[26] Our database resents countries by river basins at the global scale. However, in this research an aggregated version of this database is used to focus on the economies of South Asia.

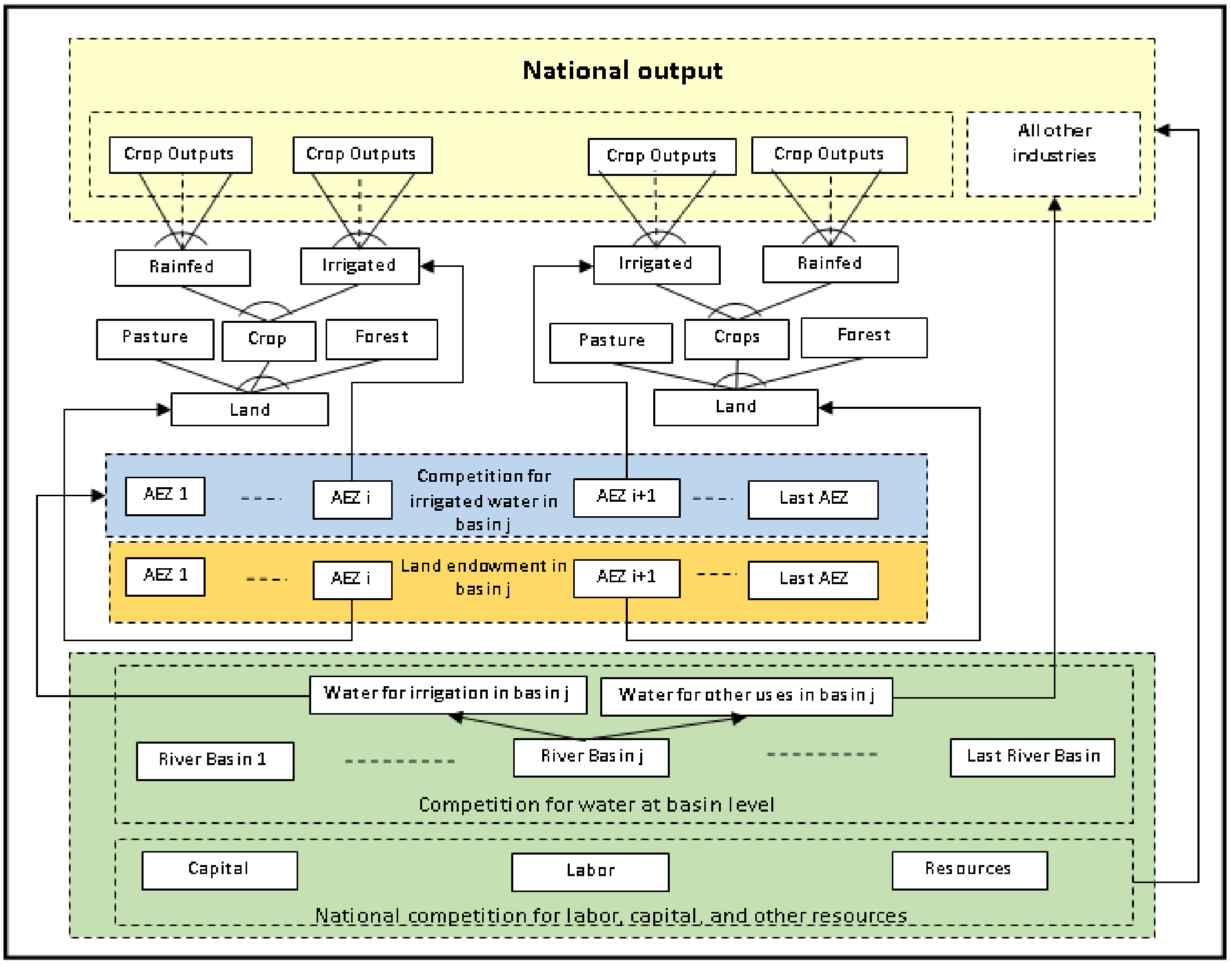

Figure 2.2. Structure of the GTAP-BIO-W static model

In the earlier version of this model water was permitted to move freely with no restriction across AEZs of a RB. According to the fact that water often cannot move freely within RBs due to water rights, quotas, and other constraints, we altered the model to restrict movement of water across AEZs of a RB. Figure 2.3 represents the nesting structure of supply of water in the new GTAP-BIO-W used in this research. In this nesting structure three parameters of σ_r, σ_z, and σ_c control the supply side of water in a RB. The first parameter (i.e. σ_r which represents water transformation elasticity across main uses) governs allocation of available water of a river basin across three main uses: 1) water to irrigated crops; 2) water for livestock, and 3) water for industrial and domestic uses. When $\sigma_r = 0$, this means that water cannot move across the major uses in a river basin. However, if $\sigma_r < 0$, then water can move across uses. The larger the magnitude of $|\sigma_r|$, the easier to move water across the main uses. The second parameter (i.e. σ_z which represents water transformation elasticity across AEZs) manages allocation of water for irrigation across AEZs of a river basin. If water cannot move across AEZs of a river basin, then $\sigma_z = 0$. The larger the magnitude of $|\sigma_z|$, the easier to move water across AEZs of a river basin. For example, if moving water from one AEZ to another AEZ is very costly then the size of σ_z should be very close to zero. Finally, the third parameter (i.e. σ_c which represents water transformation elasticity across crops) allocates water across irrigated crops. If water cannot move across crops of a river basin, then $\sigma_c = 0$. The larger the magnitude of $|\sigma_c|$, the easier to move water across crops.

It is important to note that these water transformation elasticities can be used to impose any restriction on the movement of water across uses, AEZs, and crops. This set up provides a unique environment to examine all kinds of rigidities in the supply side of the market for water. Since the true values of these elasticities are unknown, one can test the sensitivity of the model results with respect to changes in these parameters.

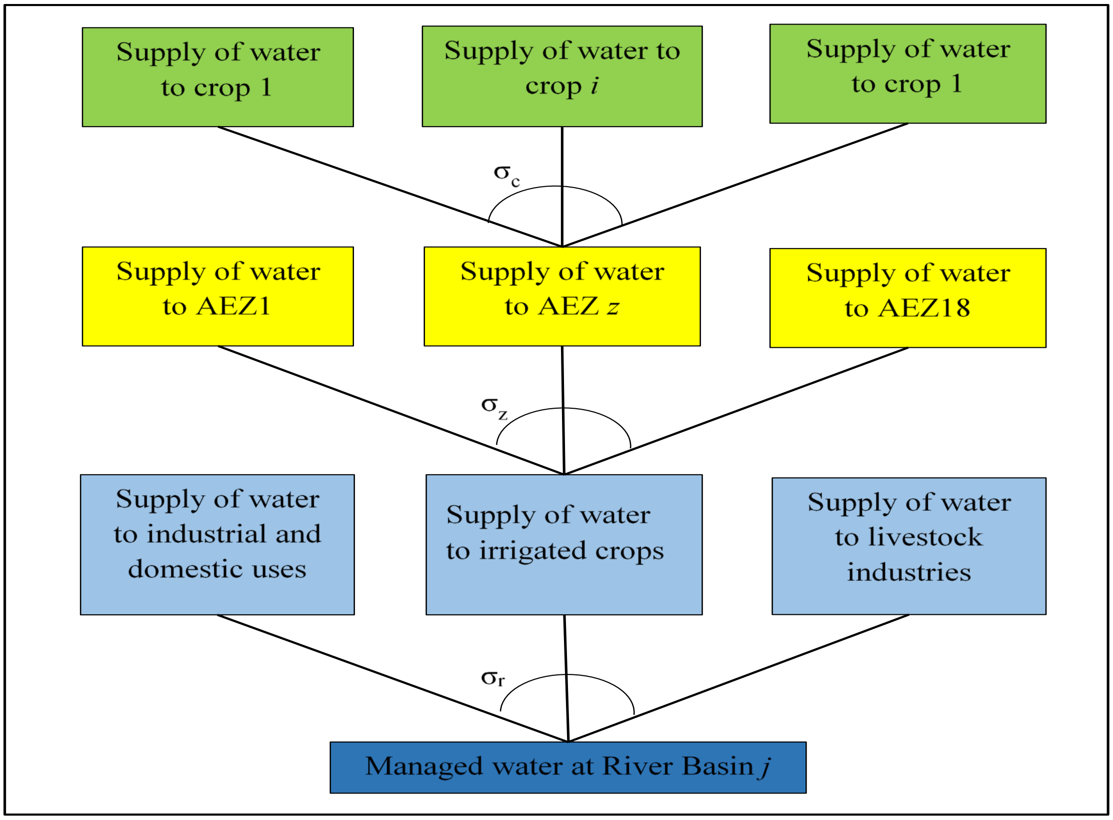

Figure 2.3: Water supply in the new GTAP-BIO-W model

Following the existing water CGE models, as explained in the next section of this chapter, water is introduced into the production function of firms to determine the intermediate demand for water. Three groups of users purchase managed water directly: irrigated crop sectors, livestock producers, and water utility (Water-Util). The crop producers usually use a big portion of water withdrawal for irrigation in each river basin. The GTAP-BIO-W database represents the distribution of water across the main uses in the base year according to FAO data and explained in the first chapter of this report. Each irrigated crop sector (say irrigated wheat) can get water from any river RB-AEZ. The database determines the initial distribution of water across the RB-AEZ according to actual observations. The livestock sectors can purchase water from available river basins. Finally, the Water-Util sector also can purchase water from available river basins. The database determines the initial distributions of water demanded by the livestock and Water-Util sectors. The Water-Util sector sales processed water to all other industries, households, and government. Again, the database determines the initial distribution of water sold by the Water-Util sector. Finally, it is import to note that the GTAP-BIO-W model, like any other CGE model, determines optimal allocation of all primary factors of production (including water) among their alternative uses given the existing data and model parameters.

2.3.2. Production functions and derived demands for inputs

The GTAP-BIO-W is based on the GTAP-BIO model which uses a multi-level nested Constant Elasticity of Substitution production function. As shown in Figure 2.4 in this production function inputs are divided into broad categories of: intermediate inputs and value added and energy. In general, there is no substitution among intermediate inputs. However, the GTAP-BIO model allows some substitution among feed items used in the livestock industry (for details see [16]). The composite of value added and energy is a CES combination of primary inputs including skilled and unskilled labor, land, natural resources, and capital-energy composite. A non-zero elasticity of substitution is among these inputs. As shown in figure 2.4, the GTAP-BIO model assumes capital and energy are substitutable inputs. This means that firms can move away from energy and use more capital in response to higher energy prices and vice versa. In this model firms also can select a mix of energy items (including coal, oil, gas, electricity, petroleum products, and biofuels) to maximize their profit and according to their energy need and energy prices. For example, when price of natural gas goes down electricity producers could shift away from coal and use more gas to produce electricity.

We modified this nesting structure to handle firms' demand for water. A major objective of this research is to examine consequences of changes in water scarcity for economies of South Asia. Several factors such as expansion in demand for water, lack of water infrastructure, and changes in climate conditions could increase water scarcity and intensify competition for water among water users. When water scarcity rises the opportunity costs of water (price of water) will increase compared to the prices of other factors of production such as labor, capital, and energy and that will induce incentives to save water and substitute this input with other production factors. We made changes in the supply side of the GTAP-BIO-W model to make substitution between water and other inputs possible. To accomplish this task, we examined several input demand nesting structures and finally implemented the nesting structure presented in Figure 2.5.

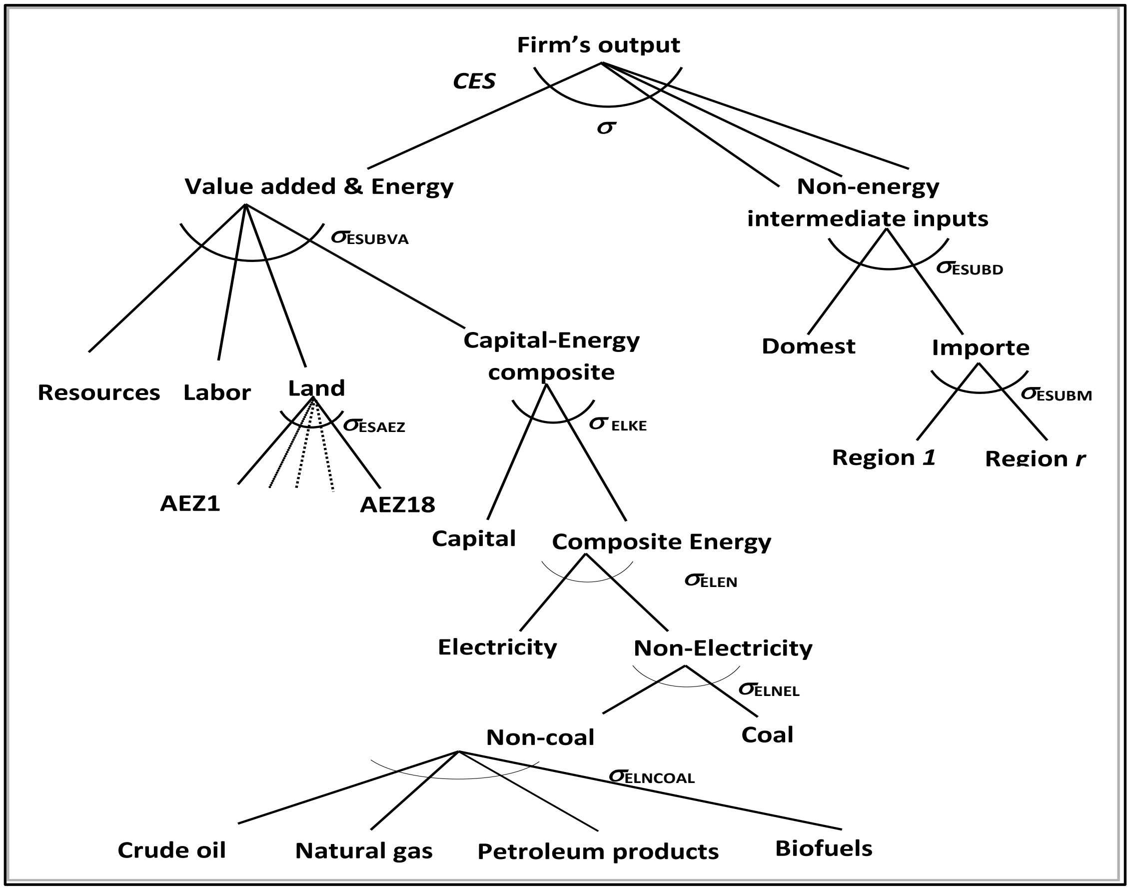

Figure 2.4: Production function and input demand structure in GTAP-BIO model

The new nesting structure is very similar to the original nesting structure. The main difference is a new nest (see the blue boxes in Figure 2.5) which we included to handle demand for water. At the bottom of the new nest we mix managed water (unprocessed water withdrawal which is a primary input) and water utility (an intermediate input provided by water utility). Then we mix water and land as two compliment inputs. Finally, we defined a nest where the mix of water-land can be combined with the mix of labor-capital-resources-energy. Notice that Figure 2.5 represent a general format. However, some sectors may not use of the inputs presented in this general format. For example, some sectors do not use land or only crop sectors use water for irrigation.

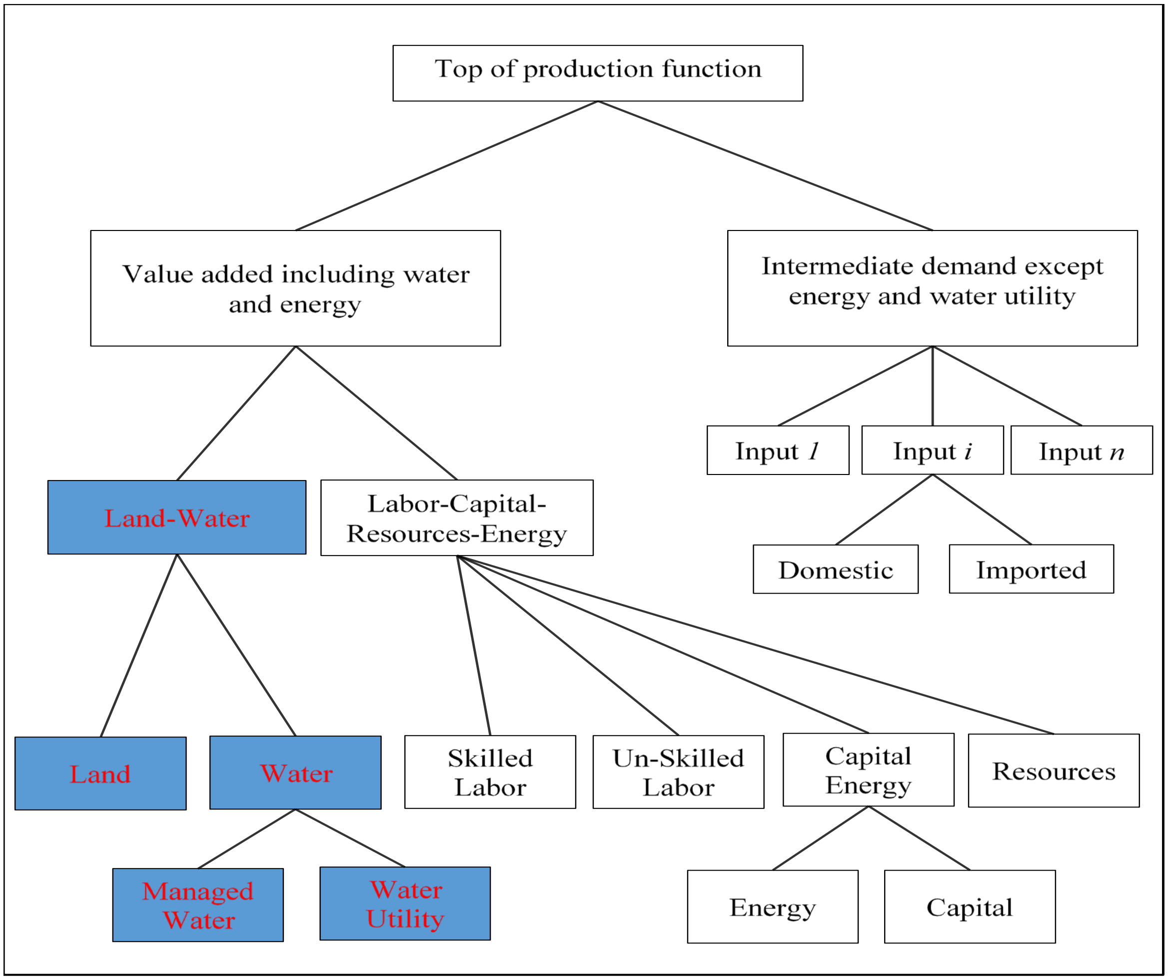

Figure 2.5: Production function and input demand structure in new GTAP-BIO-W model

2.3.3. Household demand for final goods and services

The structure of household demand in the GTAP-BIO-W model is presented in Figure 2.5. The demand structure presented in this figure is identical to the demand structure of the GTAP-BIO model. In this demand structure the private household uses a mix of substitutable energy products. Hence, in response to changes in the relative prices of energy products it can move away from expensive energy sources to cheaper items. Of course, in the new model water (processed water by the water utility sector) is an implicit commodity in the household demand stricture.

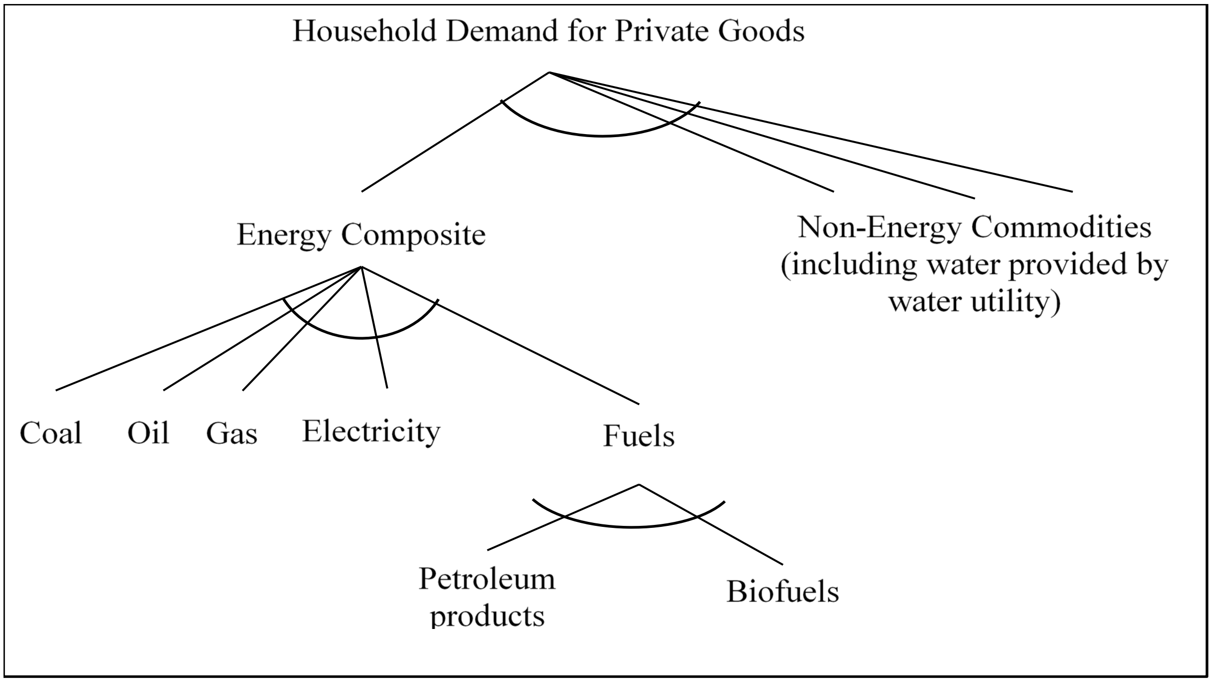

Figure 2.5: Household demand for goods and services in new GTAP-BIO-W model

2.3.4. Brief summary of GTAP-BIO-W model

This model is an advanced version of the static standard GTAP model which traces demands for and supplies of a wide range of commodities including biofuels, primary sources of energy and electricity at the global scale by region. It also takes into account resource constraints and models allocation of limited resources including labor, capital natural resources, water, and land among its alternative uses. It divides crop producers into rainfed and irrigated and traces water and land resources and their demands at the spatial resolution of RB-AEZ n each country/region. In this model, water can move across its alternative uses within a river basin with limited movement across AEZs and accounts for global trade for goods and services.

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Chapter 3: Improvement in Water Use Efficiency in Agriculture

3.1. Introduction

It is widely acknowledged that economies of South Asia will face major water challenges over the coming decades (e.g. UNESCO, 2012; Rosegrant et al., 2013; and Rodriguez et al., 2013). Population growth coupled with economic growth will significantly extend demand for water in these economies, in particular for irrigation where water use efficiency (WUE) is significantly low.[27] Of course, with no improvement in water use efficiency, these economies will need considerable investment to expand their water supply to meet the growing demand for water. However, several studies have argued that it is possible to satisfy the growing demand for water (and land as well) by improving water use efficiency (WUE) in irrigation and other uses of water (e.g. Molden, 1997; McKinsey, 2009; and World Bank, 2014; Sharma et al., 2015, and may more). While several papers have addressed the potential for improved WUE in South Asia (Hasanain et al., 2012; Singh et al., 2010; Radha et al., 2009; Palanisami et al. 2011; Wallace, 2000; and many more), to the best of our knowledge, no one has examined the extent to which WUE could affect macro-economic outcomes, production, and trade in these economies.

While WUE in irrigation is significantly low in South Asia, the share of agriculture in the GDP of these countries is relatively large (e.g. 16% in Bangladesh, 19% in India, 32% in Nepal, 12% in Pakistan, and 21% in Sri Lanka in 2011). In addition, crop production in these countries heavily relies on irrigation. The share of irrigated cropland in total cropland was 40% in South Asia in 2011. The corresponding figure for the rest of the world was 17% in this year. India alone produces 18.5% of irrigated crops produced across the world, while it owns 24% of the global irrigated land in 2011. Therefore, any improvement in WUE or crop yield could generate significant gains in the national income of these countries.

The existing literature shows that the gap between actual and potential crop yields is quite large in South Asia. For example, a recent study conducted by the World Bank (2014) indicates that the attainable wheat and paddy rice yields are twice their actual yields in many of India's states. Of course, any yield improvement could help to use water and land resources more efficiently by increasing the "crop per drop" of water. WUE can be improved in agricultural and non-agricultural activities as well. However, since irrigation is massively used in South Asia, WUE improvement in irrigation appears to have greater potential in this region than in the rest of the World. There are two ways to increase WUE in irrigation: (a) improvements in the delivery of irrigation water to the crop, and (b) improvements in the utilization of water by the plant, once it has been delivered. Both are quantitatively important. In a comprehensive study, McKinsey & Company found that WUE could be improved significantly in Asia (McKinsey 2009). For example, this research shows that the demand for water will be about 1,498 BCM in 2030 in India and that about 756 billion cubic meters of this demand can be met

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[27] There are two different but related concepts that refer to efficiency of water used in irrigation. The first one refers to the ratio between water that actually transpires by crops and water withdrawal for irrigation. This usually refers to water use efficiency (WUE). The second concept refers to crop yields per volume of water withdrawal for irrigation. This usually refers to Water Productivity (WP). These two concepts represent two sides of the same coin. Several studies have shown that WUE is low in South Asia, regardless of the method and year of estimation. For example, Seckler et al. (1998), Rohwer et al. (2007), and Frenken (2011) have shown that the overall WUE in irrigation in South Asia is generally low, below 40% in many countries. Several papers also have shown that WP in South Asia compared to other regions is also low (for example, consider Cai and Rosegrant (2003)). Note that the concept of WUE is subject to debate (Frenken and Gillet, (2012)). A portion of water lost in irrigation systems could flow back to the river, recharge the aquifers, or be captured and reused. So the ratio of WUE may underestimate the efficiency of irrigation systems.

by saving in irrigation water at reasonable costs. In addition, in a recent policy guideline published by the Ministry of Water Recourses of India (2014), the Government of India has committed to the implementation of conservation policies to improve WUE across all uses 20% by 2017.

While several papers have addressed the potential for improved WUE in South Asia, to the best of our knowledge, no one has examined the extent to which WUE could affect macro-economic outcomes, production, and trade in these economies. This paper contributes to the existing literature by assessing the economy-wide implications of WUE in South Asia.

This paper modifies and uses an advanced computable general equilibrium (CGE) model coupled with biophysical data on land and water resources by Agro-ecological zone (AEZ) at a river basin level to examine: 1) the economy-wide consequences of improved WUE in South Asia; 2) the extent to which enhanced WUE can increase food production and improve food security in South Asia; and 3) how WUE alters demand for irrigated land and affects land use across South Asia.

We develop several alternative scenarios to cover a wide range of WUE rates in irrigation under alternative assumptions on the required capital costs to improve WUE in irrigation. We first assume that no investment is needed to improve WUE. Then we alter this assumption by including costs of improvements in WUE in irrigation.

3.2. Model

The modeling framework used in this paper is an extension of the GTAP-E model (Burniaux and Truong (2002) and Mcdougall and Golub (2007)) which is a static model and allows substitution among energy inputs. It assumes energy and capital are substitutable inputs in economic activities, except for primary energy sectors such as gas, coal, and oil. In a series of modifications (including but not limited to Keeney and Hertel (2008); Birur et al. (2008); and Taheripour et al. (2010)) land by AEZ, biofuels, and biofuels by-products were introduced in this model to make it suitable to study the economic and environmental impacts of biofuel production and policies. The new model has been identified as GTAP-BIO and widely used to examine the consequences of biofuel production at the global scale (examples are: Hertel et al. (2010); Tyner et al. (2011); Taheripour et al. (2011); and Beckman et al. (2012)). Then in an intensive set of modifications the GTAP-BIO model is modified to trace supplies of and demands for land and water resources within a country at a spatial resolution of river basin (RB) by AEZ[28] level at the global scale and to take into account competition for water across its alternative uses (Taheripour et al. (2013a); Taheripour et al. (2013b); and Liu et al. (2.14)). The model developed due to this set of modifications is named GTAP-BIO-W. It traces demand for and supply of water by country at RB-AEZ level[29] and takes into account competition for water across agricultural and non-agricultural uses. In what follows we explain the major aspects of this model.

Figure 1 represents the GTAP-BIO-W approach in allocating primary inputs including labor, capital, resources, land and water. In this model competition for labor, capital, and resources takes place at the national level. This means that firms compete for these primary inputs only at that level. In Figure 1 the competition for these endowments occurs within the green box which represents a national economy including serval river basins.

[28] Henceforth, we refer to this spatial resolution as RB-AEZ

[29] Our database resents countries by river basins at the global scale. However, in this research an aggregated version of this database is used to focus on the economies of South Asia.

Sectors take labor, capital, and resources from the national pool. Labor and capital are as usual mobile inputs. This means that these resources move freely across uses. Following the standard GTAP model, resources are modeled as sluggish endowments. This means that they cannot move easily across sectors.

Competition for water, however, takes place at the RB level. As shown Figure 1, an economy may have several river basins. In each river basin water has two main uses. A portion of water goes for irrigation and the rest goes for other uses. As shown in Figure 1 each river basin may serve several AEZs. So AEZs of each RB compete for irrigation, see the blue box. The GTAP-BIO-W model also represents available managed land at the RB-AEZ level. In each RB-AEZ the area of available managed land is divided between forest, pasture and cropland, as shown in Figure 1. Then irrigated and rainfed crops compete for cropland. Land cannot move across RB-AEZs. The irrigated crop industries compete for managed water in each RB at the AEZ level. This means that competition for water for irrigation also takes place at the spatial resolution of RB-AEZ. Finally, irrigated crops compete for irrigated cropland and rained crops compete for rainfed cropland. In this model, water can move from one AEZ to another one in a river basin. A water transformation elasticity governs the movement of water across the AEZs of a river basin, as explained in the following.

3.3. Examined experiments

Using the GTAP-BIO-W model we developed several experiments to examine the extent to which WUE in irrigation affect economies of South Asia. Given that the extent to which the economies of South Asia can improve WUE in irrigation is uncertain, we test four different levels of efficiency gains: 10, 20, 30, and 40%. We examined improvement in WUE under two alternative cost assumptions. We first assume that improvement in WUE is costless. This give us an upper limit of the gains. Then, we developed four experiments which take into account the fact that improvement in WUE needs additional investment. There are several alternatives methods including reduction in over irrigation, no till farming, optimizing fertilizer application rates, using systems of rice intensification, improvements in the existing water infrastructure (collection and conveying systems), mulching in rice production, using micro irrigation technologies (sprinkler and drip irrigation), and many more to improve WUE. Some of these methods (e.g. reduction in over irrigation, no till farming, optimizing fertilizer application rates) improve WUE at no or low costs. However, the extent to which these low-cost methods contribute to WUE is limited. To save more water in irrigation using costly technologies such as micro irrigation, advanced rice cultivation and irrigation methods, or improvement in water infrastructure are required.

Many papers examined the costs, returns, and rate of improvement in WUE for many water saving technologies at farm level (e.g. Hasanain et al., 2012; Singh et al., 2010; Radha et al., 2009; Palanisami et al. 2011; Wallace, 2000; and many more). However, limited information at macro level is available in this area. McKinsey (2009) has developed a stepwise water availability supply curve for India. This supply curve covers a wide range of alternative methods which can be implemented to save consumption of water or extend its supply. It shows that water supply (including saving in consumption of water) can be expanded in India by 756 billion cubic meters with a tiny investment of $5.9 billion, less than 0.8 cents per cubic meter. Given that the extent to which low costs methods could reduce water consumption is limited and that the advanced irrigation and cultivation methods are expensive, this figure seems too small. According to Palanisami et al. (2011) the average costs of saving in water consumption with sprinkler and drip irrigation systems were about 14 cents and 16 cents, respectively, for those farmers who installed these systems in 7 states of India prior to 2010. The corresponding cost in McKinsey curve is less than 3 cents.

In a new research developed at the Massachusetts Institute of Technology, Winchester et al. (2016) developed a set of stepwise irrigated land supply functions for major reviver basins across the world. These functions were introduced into a CGE model (EPPA) to examine the impact of water scarcity on food, bioenergy and deforestation at global scale. These supply functions show the costs of expansion in irrigated cropland due to water saving activities. Using the results of this research we developed a set of stepwise investment schedules which show required investment for four levels of 10, 20, 30, and 40% improvement in WUE by county for South Asian economies (top panel of Table 1). For example, this table shows that on average WUE in irrigation can be improved by 10% in India with $27 investment per hectare of irrigated cropland. For 20, 30, and 40% improvement in WUE the investment costs grow to $63, $142, and $289 per hectare of irrigated land. These figures show that the investment costs grow with an increasing margin as the level of improvement in WUE expands. The higher the level of improvement in WUE the higher the investment costs per hectare. As shown in the top panel of Table 1, the investment costs per hectare vary across regions. India and Pakistan represent the lowest and heights cost schedules, respectively. We used these cost schedules and irrigated areas of each country to evaluate the capital requirements for each level of improvement in WUE at 2011 prices, (bottom panel of Table 1). This table indicates that the capital requirement for an improvement in WUE by 10% in Bangladesh, India, Nepal, Pakistan, Sri Lanka, and rest of South Asia are about $212 million, $2,000 million, $49 million, $608 million, $36 million, $62 million. The size of capital requirement grows as the level improvement in WUE grows in each country. The largest levels of capital requirement belong to India and Sri Lanka at each level of WUE, since these two countries hold the largest and smallest irrigated area in South Asia.

Then a mechanism is defined to finance these investment costs. In this mechanism, the public sector pays the investment costs by reducing the existing electricity subsidy rates. In South Asia consumption of electricity is highly subsidized everywhere across all courtiers. The electricity subsidies paid in Bangladesh, India, Pakistan, and Sri-Lanka were about 2.63%, 0.32%, 1.31%, and 0.47% of their GDP in 2011 (Clements et al., 2013). Among all electricity users, agricultural usually pays the lowest tariff rates and receives the highest subsidy rates in South Asia. The agricultural electricity tariff rate in Bangladesh, India, Nepal, Pakistan, and Sri Lanka were about 2.6 cents, 3.5 cents, 5 cents, 6.2, and 13.6 cents in 2011. The corresponding industrial tariff rates were about 5.4 cents, 11.3 cents, 9.5 cents, 10.3 cents, and 9.1 cents in 2011 (Jamil, 2014). The agricultural electricity subsidy rates in Bangladesh, India, Pakistan, and Sri-Lanka were about 55%, 41%, 29%, and 23%, and 11% in 2011. It is frequently argued that these subsidies encourage over consumption of electricity and water in agriculture. In our simulations, it is assumed that the overall investment costs of improvement in WUE will be financed by a public loan (with 5% annual interest rate) and the loan will be paid off in 15 years by reduction in electricity subsidies paid to all electricity users.

The experiments introduced in this section are examined in a comparative static framework. In each experiment, we impose the desired rate of improvement in WUE as an exogenous shock to the current economy. Then we compare the simulation results with the status quo conditions. Hence, as usual, our comparative static analysis, ignores the time period where the economy moves from its current state to the new equilibrium.

3.4. Results

Simulation results if improvement in WUE is costless

Impacts on food production and imports. Food production goes up significantly in South Asia even with a 10% improvement in WUE, and it grows as efficiency improves (Table 2). With a 10% improvement in WUE, food production would increase annually by $739 million (1.4%), $7,887 million (1.2%), $46 million (0.6%), $1,847 million (1.3%), $81 million (0.3%), and $214 million (2.2%) at 2011 constant prices in Bangladesh, India, Nepal, Pakistan, Sri Lanka, and rest of South Asia, respectively (Table 2). With a 40% improvement in WUE, the corresponding figures would grow to $2,717 million (5%), $26,426 million (4%), $111 million (1.4%), $6,102 million (4.4%), $212 million (0.9%), and $611 million (6.3%), respectively (Table 2).

Now consider the impacts of improvement in WUE on the production of individual crops (Figure 2). Bangladesh, Pakistan, and rest of South Asia experience larger percentage changes in their crop outputs compared to India, Nepal and Sri Lanka. Outputs of all crops and in particular coarse grains, oilseeds, and other crops grow in Bangladesh. In India rice and oilseeds grow more than others. In Nepal, changes in crops outputs even at 40% remain small, particularly for coarse grains and other crops. Production of wheat and other crops grow fast and more than rice, coarse grains, oilseeds, and sugar crops in Pakistan. In Sri Lanka, only outputs of rice and wheat grow due to improvement in WUE. Finally, outputs of rice, wheat and oilseeds grow in rest of South Asia as shown by Figure 2.

The gap between the irrigated and rainfed crops yields could explain the observed variations in the regional impacts of WUE on crop outputs. An improvement in WUE saves water on existing irrigated land and that provides an opportunity to use a portion of saved water to convert rainfed cropland to irrigated cropland due to expansion in irrigation.[30] In these circumstances, the gain in crop production depends on the difference between the irrigated and rainfed crop yields. If the difference is not large, the expansion in crop production will be limited. However, if the difference is large, then crop production grow significantly. For example, in general, in India the difference between the rainfed and irrigated yields are not large on average. Hence, an improvement in WUE in this country generates moderate gains in crops outputs. However, in Bangladesh, Pakistan, and rest of South Asia where irrigation contributes more to crop yields, an improvement in WUE, generates larger changes in crops outputs.

Obviously, expansion in crop supply due to improvement in WUE directly enhances the food security of South Asian countries. However, improvement in WUE indirectly advances the food security of South Asia as well. As mentioned above improvement in WUE provides an opportunity to converted rainfed cropland to irrigated cropland. Given that irrigated crops are less vulnerable to the extreme weather conditions, expansion in irrigated crops enhances food security as well. The extent to which improvement in WUE enhances production of irrigated crop is shown in Figure 3, which represents changes in the market share of rainfed in total production

[30] A portion of saved water due to improvement in WUE could be transferred to non-agricultural uses as well.

of each crop due to improvement in WUE at 10 and 40% levels. For example, a 40% improvement in WUE decreases the market share of rainfed wheat in total production of wheat by 7.8%, 2.7%, 1.5%, 1.7%, 4%, and 19.2% in Bangladesh, India, Nepal, Pakistan, Sri Lanka, and rest of South Asia, respectively. The corresponding reductions for oilseeds are 8.2%, 14.6%, 6.2%, 23%, .01%, and 14.7%. Similar patterns are apparent for other crops as well. This line of enhancement in food security will be discussed in the next section when we analyze induced land use changes of improvement in WUE.

The expansion in food production due to improvement in WUE increases the net exports of food products (crops, livestock products, and processed food) from South Asia (Table 3). Improvement in WUE extends the net exports of food products of South Asian countries except for Sri Lanka. The net exports of food products of this country drop slightly at all levels of improvement in WUE.[31] With a 10% improvement in WUE, the net exports of food products of Bangladesh, India, Nepal, Pakistan, and the rest of South Asia will increase by $290 million, $2,189 million, $25 million, $797 million, and $136 million at 2011 constant prices, respectively. The corresponding figures with a 40% improvement in WUE will be about $1,017 million, $7,242 million, $59 million, $2,784 million, and $368 million, respectively. These figures show that India, Pakistan, and Bangladesh could gain significantly in trade of food products, if they use their water resources more efficiently. Expansion in food production and exports could positively affect rural income and living condition in these regions.

Price impacts. Improvement in WUE reduces the prices of food products in South Asia. However, the price impact varies by region and food product. For example, other factors being the same, a 40% improvement in WUE could reduce the price index of crops by 18.9% in Bangladesh, 12.4% in India, 11.1% in Nepal, 16.6% in Pakistan, 4.5% in Sri Lanka, and 17.3% in rest of South Asia. The rate of reduction in the price index of livestock products is smaller than the rate reduction in the crop price index in each region. With 40% improvement in WUE the price index of livestock products drops by 11.4%, 5%, 7.7%, 1% and 8% in Bangladesh, India, Nepal, Sri Lanka, and Rest of South Asia, respectively. Unlike these countries, in Pakistan the price index of livestock goes up slightly by 2.3%. Improvement in WUE in irrigation encourages farmers to convert some pastureland to crop production in Pakistan and that negatively affect output of livestock industries, which leads to an increase in the price of livestock products. Finally, with 40% improvement in WUE the price index of processed food decreases by 5.2%, 6.1%, 10.4%, 2.9%, and 12% in Bangladesh, India, Nepal, Sri Lanka, and Rest of South Asia, respectively. The price index of processed food goes up slightly by 1.6% in Pakistan.

In conclusion, the positive impacts of improvement in WUE on food production plus its negative impacts on food prices jointly improve food security of South Asia and that helps households to pay lower prices for food products in this low income region.

Land use impacts. Improvement in WUE in irrigation reduces the rainfed harvested areas and increases irrigated areas. For example, a 10% improvement in WUE increases the areas of irrigated cropland by 3.9% (or 268 thousand hectares), 7.3% (or 5503 thousand hectares), 5.9% (or 87 thousand hectares), 3.1% (or 544 thousand hectares), 2.3% (or 20 thousand hectares), and 7% (or 126 thousand hectares) in Bangladesh, India, Nepal, Pakistan, Sri Lanka, and rest of South Asia (Table 4). The corresponding figures for 40% improvement in WUE are 16% (or 1086 thousand hectares), 28.5% (or 21,444 thousand hectares), 14.2% (or 210 thousand hectares),

[31] Expansion in income due to improvement in WUE increases demand for vegetable and fruit faster than their outputs in Sri Lanka and that leads to a reduction in net exports of food products of this country.

12% (or 2,085 thousand hectares), 5.1% (or 46 thousand hectares), and 24% (or 435 thousand hectares). These large expansions in irrigated areas could meaningfully improve the food security of South Asia against climate change.

Since harvested areas are usually more productive than their rainfed counterpart, an improvement in WUE reduces demand for cropland and that generates some incentives for reforestation (expansions in forest and natural pasture land) across South Asia except for Pakistan (Table 5). For example, a 40% increase in WUE reduces demand for cropland by 2.5% (or 244 thousand hectares), 1.5% (or 2,545 thousand hectares), 0.4% (or 11 thousand hectares), 0.1% (or 1.3 thousand hectares), and 0.3% (or 27 thousand hectares) in Bangladesh, India, Nepal, Sri Lanka, and rest of South Asia. In Pakistan at this level of improvement in WUE harvested area of irrigated land extends more than the reduction in rainfed areas and therefore total harvested area increases by 0.4% (or 95 thousand hectares) and therefore we observe some land conversion form forest and pasture to cropland. So, in general, improvement in WUE generates plausible impacts on reforestation in South Asia as well.

Land and water endowments in India, unlike other countries in South Asia, are scattered across many river basins and different agro-ecological zones which representing different climate condition and length of growing periods. Since an improvement in WUE could generate different land use pattern across India, here we study the land use impacts of improvement in WUE in India by river basin and AEZ, limiting analyses to the cases of 20% improvement in WUE. The top panel of Figure 5 shows changes in cropland, forest, and pastureland areas by river basin. This figure indicates that with 20% improvement in WUE, the area of cropland shrinks across all river basins, with major reductions in Ganges (by 349,000 hectares), Krishna (142,000 hectares), Brahmari (141,300 hectares), Indus (137,000 hectares), and Mahi-Tahi (125,000 hectares). In return, the areas of forest and pastureland grow across all river basins.

The bottom panel of Figure 5 shows changes in cropland, forest, and pastureland areas by AEZ. This figure shows that with 20% improvement in WUE, areas of cropland in India shrink across several AEZs, with major reductions in AEZ3 (by 598,000 hectares), AEZ4 (192,000 hectares), AEZ2 (138,800 hectares), AEZ8 (115,000 hectares), and AEZ9 (111,000 hectares). Again, in return the areas of forest and pastureland grow across these AEZs.

The top panel of Figure 6 represents changes in the mix of irrigated and rainfed croplands by river basin with a 20% improvement in WUE. Irrigated area grows largely in several river basins including Ganges (by 4.2 million hectares), Indus (2 million hectares), Krishna (1.2 million hectares), and Godavari (1 million hectares). Finally, the bottom panel of Figure 6 shows changes in the mix of irrigated and rain-fed croplands by AEZ with a 20% improvement in WUE. As shown in this figure, irrigated area grows largely in AEZ3 (5.1 million hectares), AEZ4 (1.9 million hectares), AEZ8 (1.8 million hectares), and AEZ9 (1.4 million hectares).

Economy-wide impacts. WUE improvement also positively affects the GDP of South Asian countries and the impact grows with the rate of improvement (Figure 7). For example, a 10% improvement in WUE increases the GDP of Bangladesh, India, Nepal, Pakistan, Sri Lanka, and rest of South Asia by 1.1%, 0.5%, 0.2%, 0.6%, 0.2%, and 0.5%, respectively. The corresponding annual monetary gains of these increases at 2011 constant prices are $1,216 million for Bangladesh, $8,696 million India, $34 million for Nepal, $1,160 million for Pakistan, $146 million for Sri Lanka, and $100 million for rest of South Asia (Figure 7). With a 40% improvement in WUE, GDP grows by 3.8%, 1.5%, 0.5%, 1.7%, 0.7%, and 1.2% in Bangladesh, India, Nepal, Pakistan, Sri Lanka, and the rest of South Asia, respectively. The corresponding annual monetary gains of these increases at 2011 constant prices are $4,178 million for Bangladesh, $27,715 million India, $87 million for Nepal, $3,357 million for Pakistan, $380 million for Sri Lanka, and $260 million for rest of South Asia.

Improvement in WUE in irrigation enhances GDP through several channels. First it extends crop production which boosts agricultural output (including livestock and forestry). Since the share of agriculture in GDP is relatively high in South Asia, this significantly increases GDP through the backward linkages among the agricultural and non-agricultural activates. Improvement in WUE releases some water and that that helps non-agricultural sectors to grow as well. This extends employment in South Asia, where the rate of unemployment is usually high.

It is important to note that our static simulations show that GDP grows with a decreasing margin as the level of improvement in WUE increases (figure 8). The decreasing rate of marginal contribution of improvement in WUE matches with the economic principle of decreasing marginal product of an increasing input in a static framework. In long run when economies of South Asia grow over time any additional drop of saved water could generate growing marginal outputs when water scarcity hit these economies.

Simulation results when improvement in WUE needs additional investment

Impacts on outputs, net exports, and price of food products and land use implications. These impacts remain the same as the costless cases with minor difference, regardless of the level improvement in WUE. This is because the public sector pays the costs of improvement in WUE with a uniform reduction in electricity subsidies across all users. So the corresponding results presented in previous section remain valid for the new cases.

Impacts on production and price of electricity. Because electricity subsidies are reduced to finance the improvements in WUE, this policy affect the production and price of electricity across South Asia. To examine these impacts, the changes in the production and price of electricity are compared for a 40% improvement in WUE under the two cases of with and without investment costs. With no investment costs for improvement in WUE, production of electricity changes by -1%, 2.6%, 0.5%, 2.6%, 1%, and 1.5% in Bangladesh, India, Nepal, Pakistan, Sri Lanka, and rest of South Asia, respectively. The corresponding changes for the case of with investment costs are -2.6%, 1.5%, -0.5%, 0.5%, 0.1%, and -1.5%. These figures show that production of electricity drops in the second case, when electricity subsidies are reduced to finance the investment costs of improvement in WUE. The reduction in electricity subsidy increases the consumer price of electricity as well. With no investment costs for improvement in WUE, consumer price of electricity changes by 5.9%, 0.7%, -1.2% 4.4%, 0.4%, and -0.9% in Bangladesh, India, Nepal, Pakistan, Sri Lanka, and rest of South Asia, respectively. The corresponding changes for the case of with investment costs are 11.8%, 5.3%, 6.7% 11.7%, 3.5%, and 25%. These figures are significantly higher than their corresponding figure for the costless case.

Economy-wide impacts. The economy-wide gains of improvement in WUE (measured in terms of changes in GDP) decreases when we take into account costs of improvement in WUE. For example, as mentioned before a 10% improvement in WUE increases GDP of Bangladesh, India, Nepal, Pakistan, Sri Lanka, and rest of South Asia respectively by $1,216 million, $8,696 million, $34 million, $1,160 million, $146 million, and $100 million at 2011 constant prices when we assumed improvement in WUE is costless. The corresponding figure drop to $1,146 million, $8,175 million, $29 million, $986 million, $138 million, and $90 million when we account for costs of improvement in WUE (Figure 9).

As we observed in the costless cases, GDP grows with a decreasing margin as we move towards the higher levels of improvement in WUE. When we account for the investment costs, in some countries the marginal contribution become negative at higher levels of improvement in WUE. For example, consider the case of Pakistan where the first 10% improvement in WUE increases GDP by $1,160 million and the last 10% (from 30% to 40%) increases GDP by $562 million when we assumed improvement in WUE is costless. The corresponding figures are about $986 million and -$447 million when we take into account the investment costs (Table 6). This indicates that the gains of improving WUE from 30% to 40% do not cover the costs of this improvement. Three factors contribute to this observation. First as mentioned before, the marginal productivity of water is decreasing in a static framework. Second, the marginal costs of improvement in WUE grow as we move towards the higher levels of WUE. Third, the excess burden of reduction in electricity subsidy grow as we cut these subsides more. Table 6 indicates that the marginal impact of improvement in WUE on GDP becomes negative at higher levels of improvement in WUE in Nepal, and rest of South Asia as well.

In conclusion, Table 6 shows that improvement in WUE up to 40% can be economically justified in Bangladesh, India, and Sri Lanka. In Nepal, after 20% improvement in WUE, the economic gains are smaller than costs. In Pakistan and rest of South Asia, an improvement in WUE over 30% may not be economically profitable.

3.5. Conclusion

Using an advanced computable general equilibrium model (GTAP-BIO-W) this chapter shows that improvement in water use efficiency in irrigation increases production of food items in South Asia, significantly. Improvement in water use efficiency has positive impacts on production of non- agricultural sectors as well. In addition, improvement in water use efficiency in irrigation has significant and positive impacts on the net food exports of South Asian economies, with an overall improvement in the trade balances of these countries. Improvement in water use efficiency leads to lower food prices and provides the opportunity to extend irrigated areas across South Asia and that leads to reforestation and more security in food production. Improvement in water use efficiency in irrigation generates major GDP gains across south Asia. Improvement in WUE up to 40% can be economically justified in Bangladesh, India, and Sri Lanka. In Nepal, after 20% improvement in WUE, the economic gains are smaller than costs. In Pakistan and rest of South Asia, an improvement in WUE over 30% may not be economically profitable.

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Table 1. Costs of improvement in water use efficiencies in South Asia by country at 2011 prices

Description	Level of improvement in WUE	Bangladesh	India	Nepal	Pakistan	Sri Lanka	Rest of South Asia
Average costs for each level of improvement in WUE ($/ha)	10%	31	27	33	35	41	35
	20%	74	63	78	83	96	83
	30%	167	142	176	186	216	186
	40%	340	289	358	380	440	380
Capital requirement for each level of improvement in WUE (million $)	10%	212	2000	49	608	36	63
	20%	503	4735	116	1441	86	149
	30%	1132	10667	260	3245	193	336
	40%	2307	21736	531	6612	393	685

Table 2. Impacts of improvement in WUE on food production at constant 2011 prices (million $)

Rate of Improvement in WUE	Food Item	Bangladesh	India	Nepal	Pakistan	Sri Lanka	Rest of South Asia
10%	Crops	453	4495	24	1512	20	111
	Livestock Products	57	827	7	11	4	20
	Processed food	229	2565	15	324	58	83
	Total	739	7887	46	1847	81	214
	% change over 2011	1.4	1.2	0.6	1.3	0.3	2.2
20%	Crops	891	8534	40	2919	30	205
	Livestock Products	111	1554	12	8	7	33
	Processed food	435	4731	27	539	101	147
	Total	1438	14819	79	3466	138	385
	% change over 2011	2.7	2.2	1.0	2.5	0.6	4.0
30%	Crops	1314	12180	48	4208	36	285
	Livestock Products	164	2199	15	-4	9	41
	Processed food	620	6583	36	689	134	194
	Total	2097	20961	100	4893	180	520
	% change over 2011	3.9	3.2	1.3	3.6	0.8	5.3
40%	Crops	1720	15479	52	5334	40	341
	Livestock Products	214	2774	18	-23	11	47
	Processed food	783	8174	41	791	161	223
	Total	2717	26426	111	6102	212	611
	% change over 2011	5.0	4.0	1.4	4.4	0.9	6.3

Table 3. Impacts of improvement in WUE on net exports of food products at constant 2011 prices (million $)

Rate of Improvement in WUE	Food Item	Bangladesh	India	Nepal	Pakistan	Sri Lanka	Rest of South Asia
10%	Crops	239	1144	9	1040	-24	47
	Livestock Products	-2	59	3	-37	-1	15
	Processed food	53	987	13	-206	12	74
	Total	290	2189	25	797	-13	136
20%	Crops	459	2179	14	1992	-41	85
	Livestock Products	-4	107	6	-67	-1	26
	Processed food	101	1808	23	-388	21	128
	Total	556	4094	43	1538	-21	239
30%	Crops	662	3118	16	2843	-54	118
	Livestock Products	-6	147	7	-91	-1	34
	Processed food	142	2500	29	-544	29	166
	Total	798	5765	53	2208	-26	317
40%	Crops	848	3974	17	3567	-64	140
	Livestock Products	-8	181	8	-110	-1	39
	Processed food	176	3087	34	-672	36	189
	Total	1017	7242	59	2784	-30	368

Table 4. Changes in irrigated and rainfed harvested areas due to improvement in WUE (1000 hectares)

Rate of Improvement in WUE	Food Item	Bangladesh	India	Nepal	Pakistan	Sri Lanka	Rest of South Asia
10%	Irrigated area	267.6	5502.7	87.2	544.0	20.3	125.7
	Rainfed area	-326.2	-6193.1	-92.0	-556.0	-20.7	-138.0
	Total	-58.7	-690.4	-4.8	-11.9	-0.4	-12.3
20%	Irrigated area	533.2	11030.8	163.8	1083.3	32.8	250.1
	Rainfed area	-651.9	-12374.3	-171.5	-1084.3	-33.6	-270.9
	Total	-118.7	-1343.5	-7.7	-1.1	-0.8	-20.8
30%	Irrigated area	800.7	16363.4	203.9	1608.6	40.7	364.0
	Rainfed area	-981.1	-18325.0	-213.5	-1576.4	-41.8	-389.2
	Total	-180.4	-1961.6	-9.6	32.1	-1.1	-25.2
40%	Irrigated area	1085.8	21443.5	210.2	2084.7	45.9	434.7
	Rainfed area	-1330.0	-23988.8	-221.6	-1990.1	-47.2	-461.5
	Total	-244.2	-2545.3	-11.4	94.6	-1.3	-26.8

Table 5. Changes in land cover due to improvement in WUE (1000 hectares)

Rate of Improvement in WUE	Food Item	Bangladesh	India	Nepal	Pakistan	Sri Lanka	Rest of South Asia
10%	Forest	43.0	332.3	2.1	-0.2	-0.2	0.0
	Cropland	-58.7	-690.4	-4.8	-11.9	-0.4	-12.3
	Pasture	15.6	358.1	2.7	12.1	0.7	12.3
20%	Forest	87.0	647.9	3.6	-0.3	-0.4	0.0
	Cropland	-118.7	-1343.5	-7.7	-1.1	-0.8	-20.8
	Pasture	31.7	695.7	4.2	1.4	1.2	20.8
30%	Forest	132.2	947.3	4.6	-0.1	-0.6	0.0
	Cropland	-180.4	-1961.6	-9.6	32.2	-1.1	-25.2
	Pasture	48.2	1014.3	5.0	-32.0	1.6	25.2
40%	Forest	267.6	5502.7	87.2	544.0	20.3	125.7
	Cropland	-326.2	-6193.1	-92.0	-556.0	-20.7	-138.0
	Pasture	-58.7	-690.4	-4.8	-11.9	-0.4	-12.3

Table 6. Marginal impact of each level of improvement in water use efficiency on GDP at 2011 constant prices with and without investment costs (million $)

Cost assumption	If improvement in water use efficiency is costless				Improvement in water use efficiency needs additional investment costs			
Rate of Improvement in WUE	10%	20%	30%	40%	10%	20%	30%	40%
Bangladesh	1216	1098	986	878	1146	1013	835	615
India	8696	7335	6275	5409	8175	6646	4873	2845
Nepal	34	24	17	11	29	17	-2	-27
Pakistan	1160	910	725	562	986	665	187	-447
Sri Lanka	146	101	75	58	138	91	51	14
Rest of South Asia	100	74	53	34	90	60	22	-24

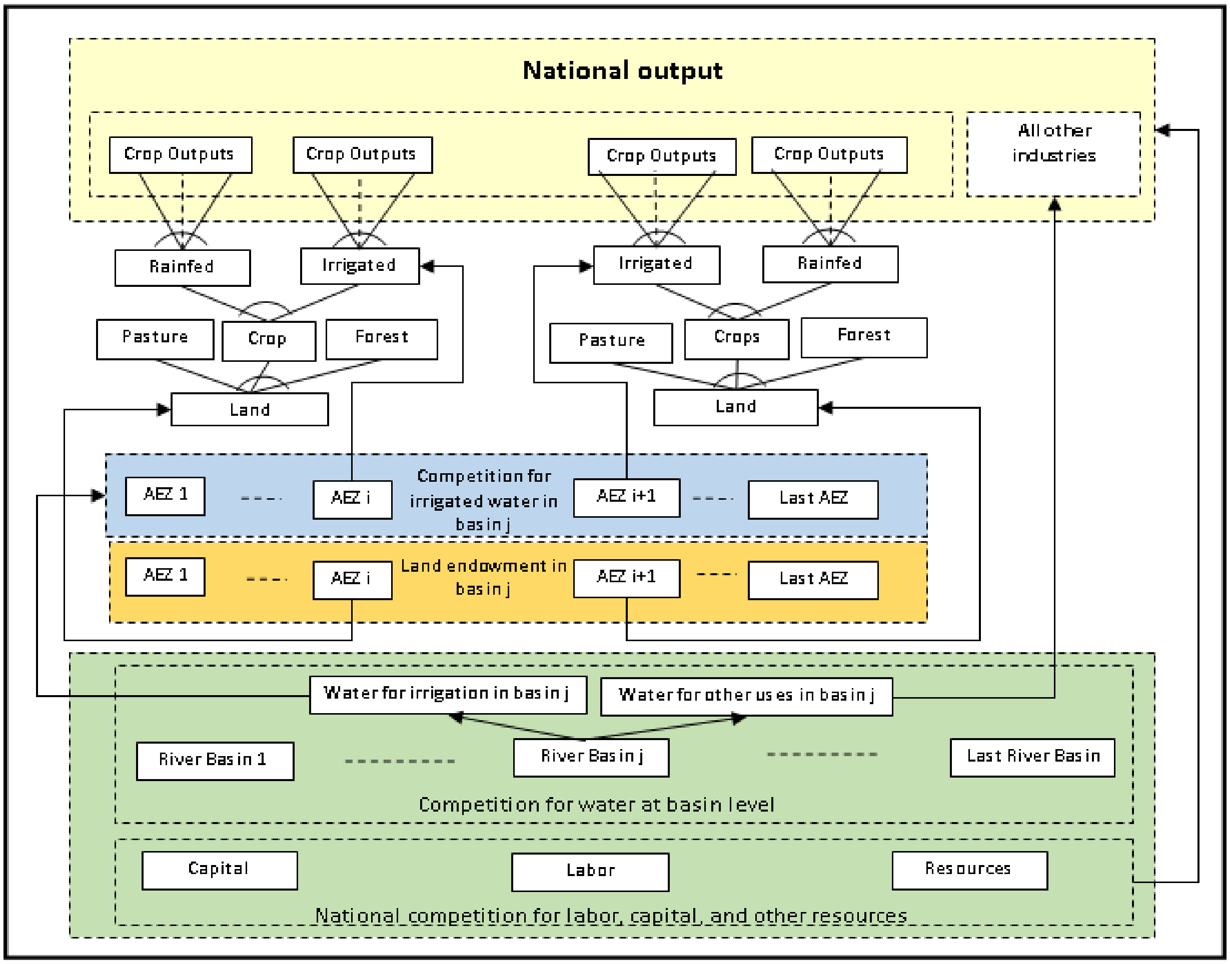


Figure 1. Structure of the GTAP-BIO-W static model

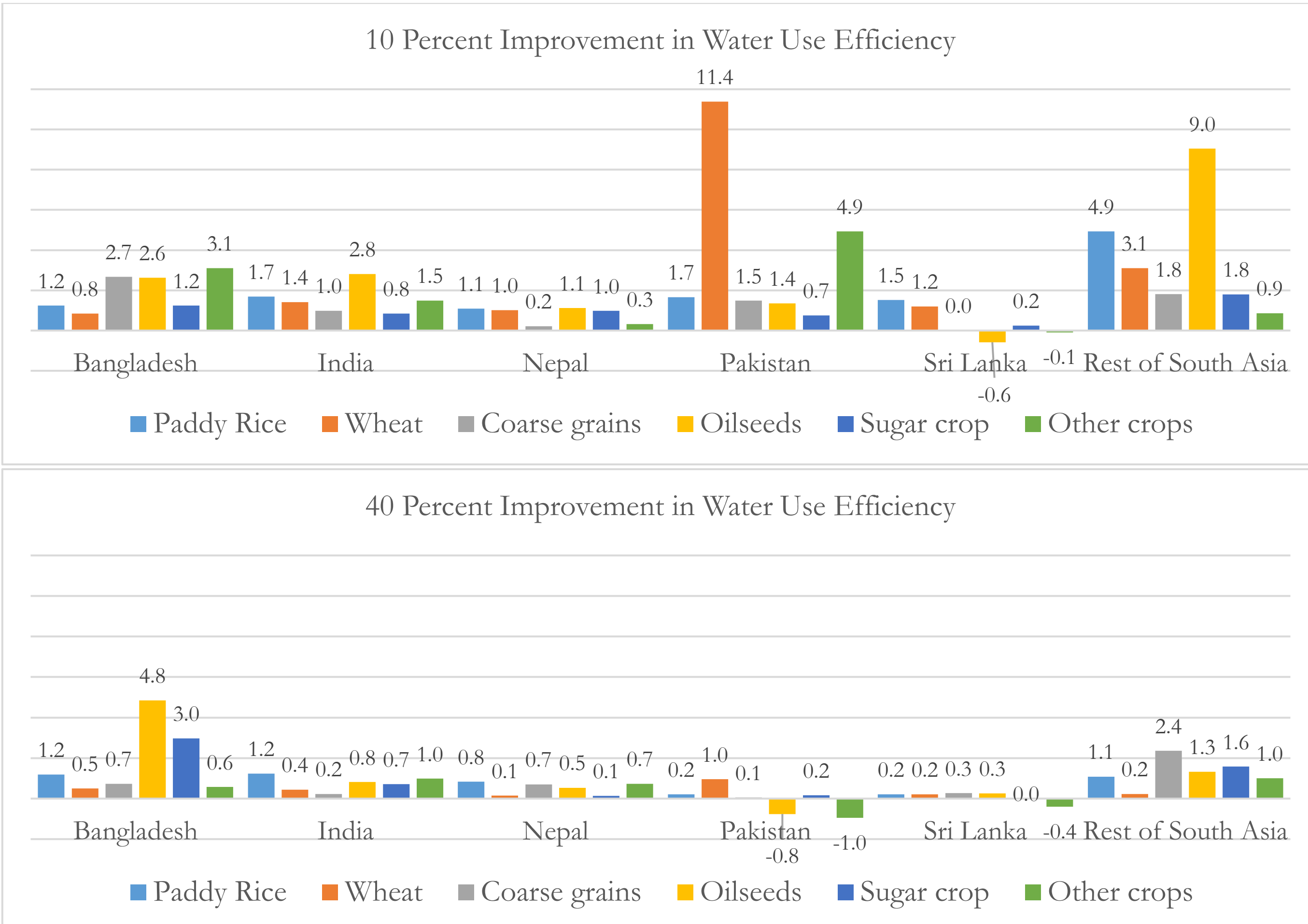


Figure 2. **Impacts of improvement in water use efficiency on crop outputs in South Asia**

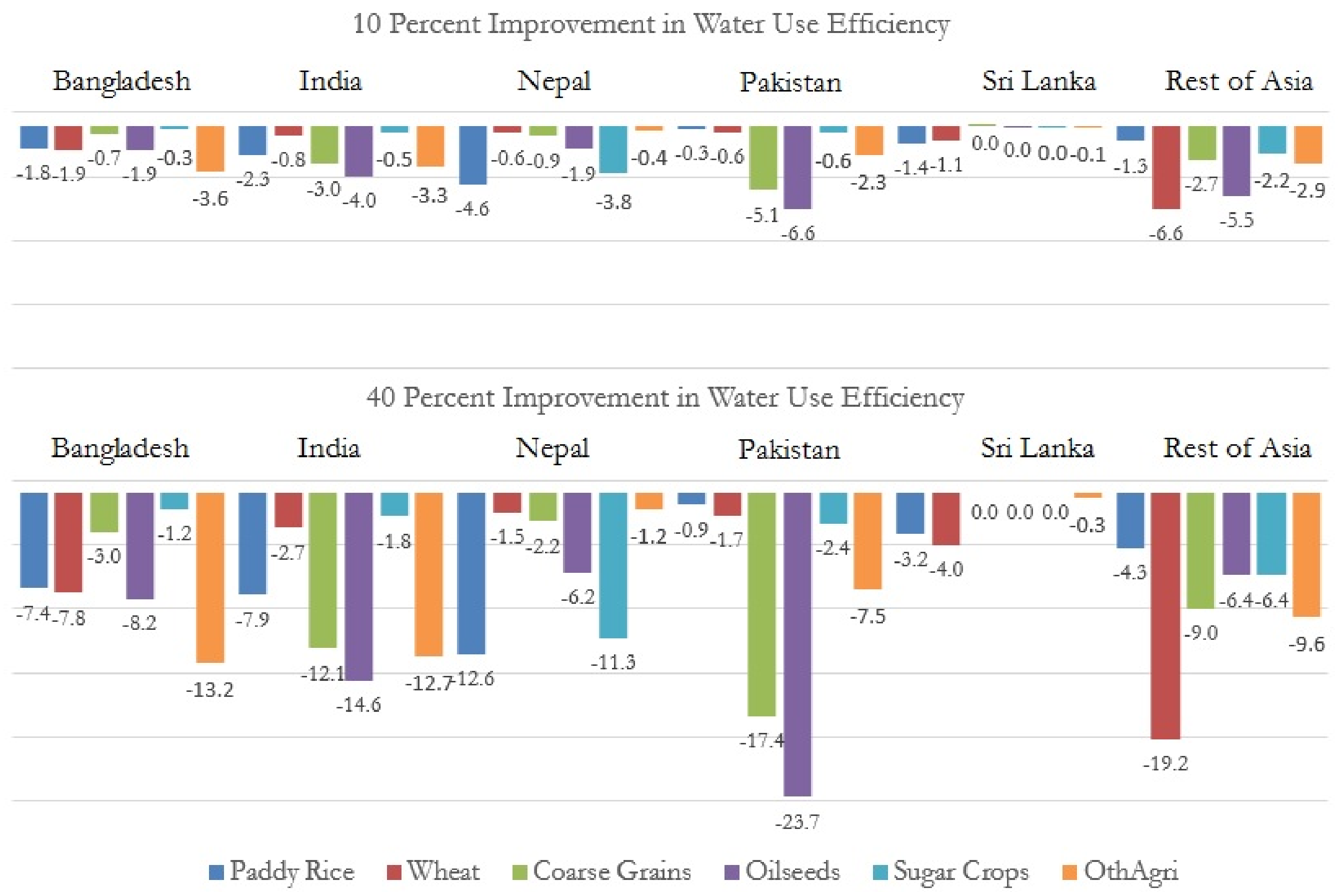


Figure 3. Reduction in the market shares of rainfed crops due to improvement in water efficiency

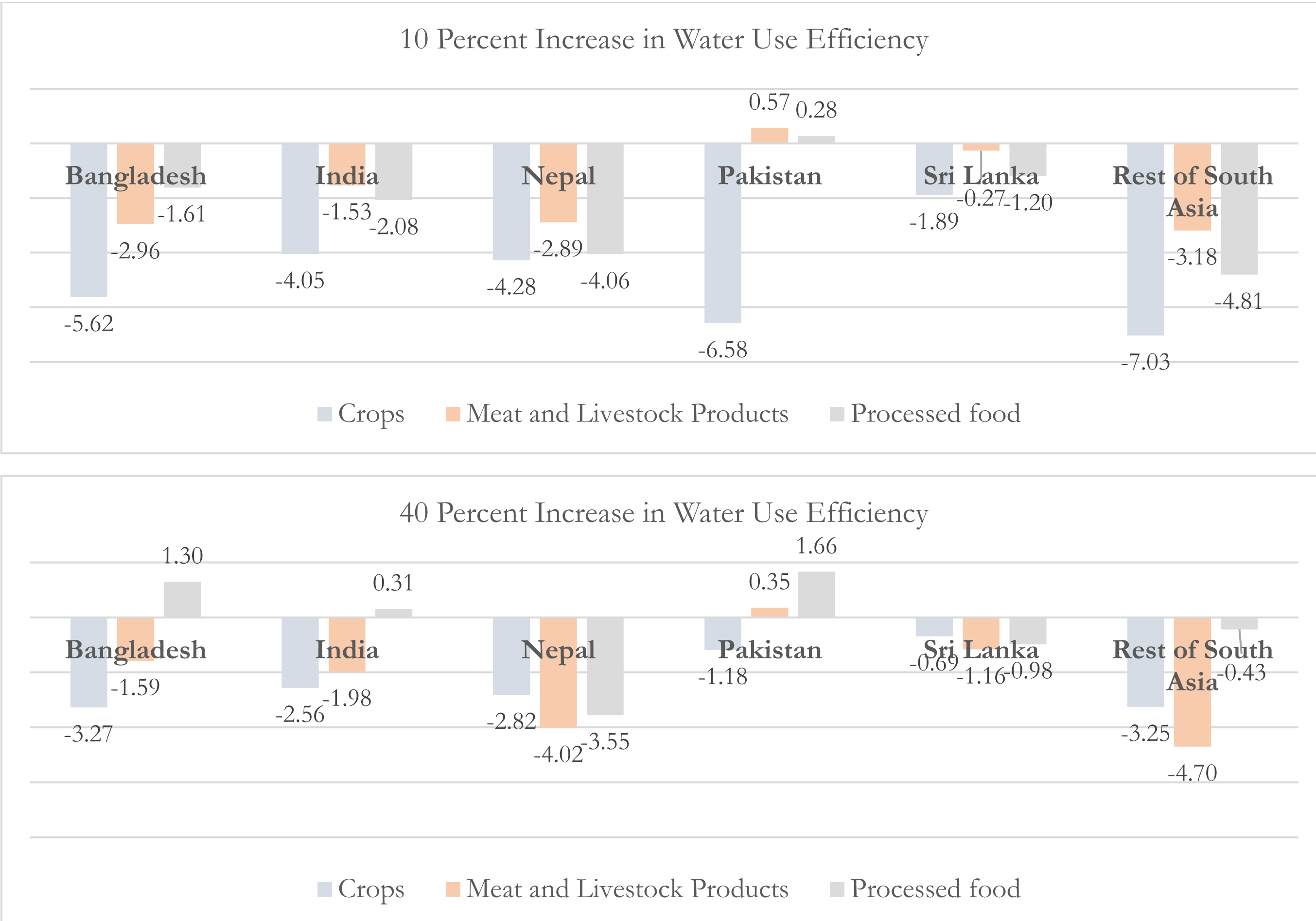
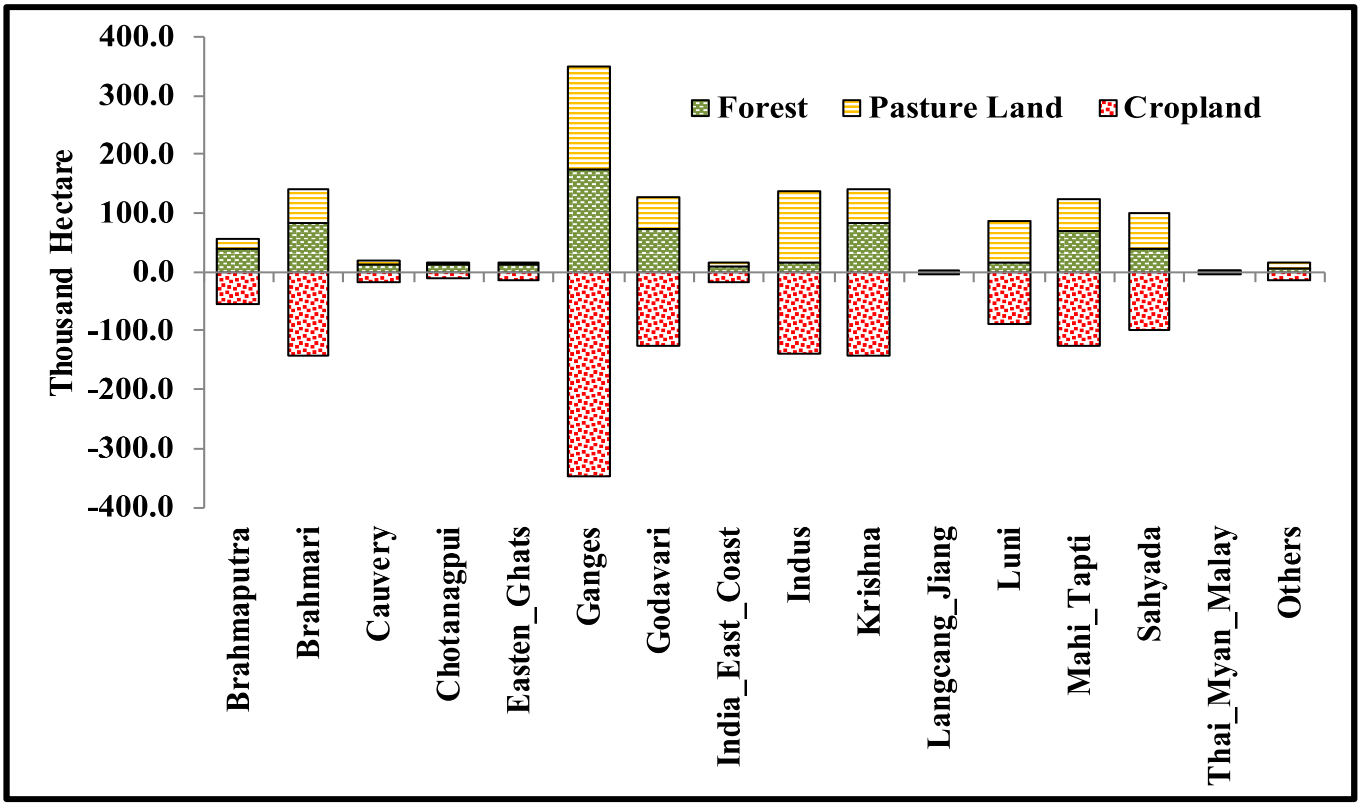


Figure 4. Impacts of improvement in water use efficiency on prices of food items in South Asia



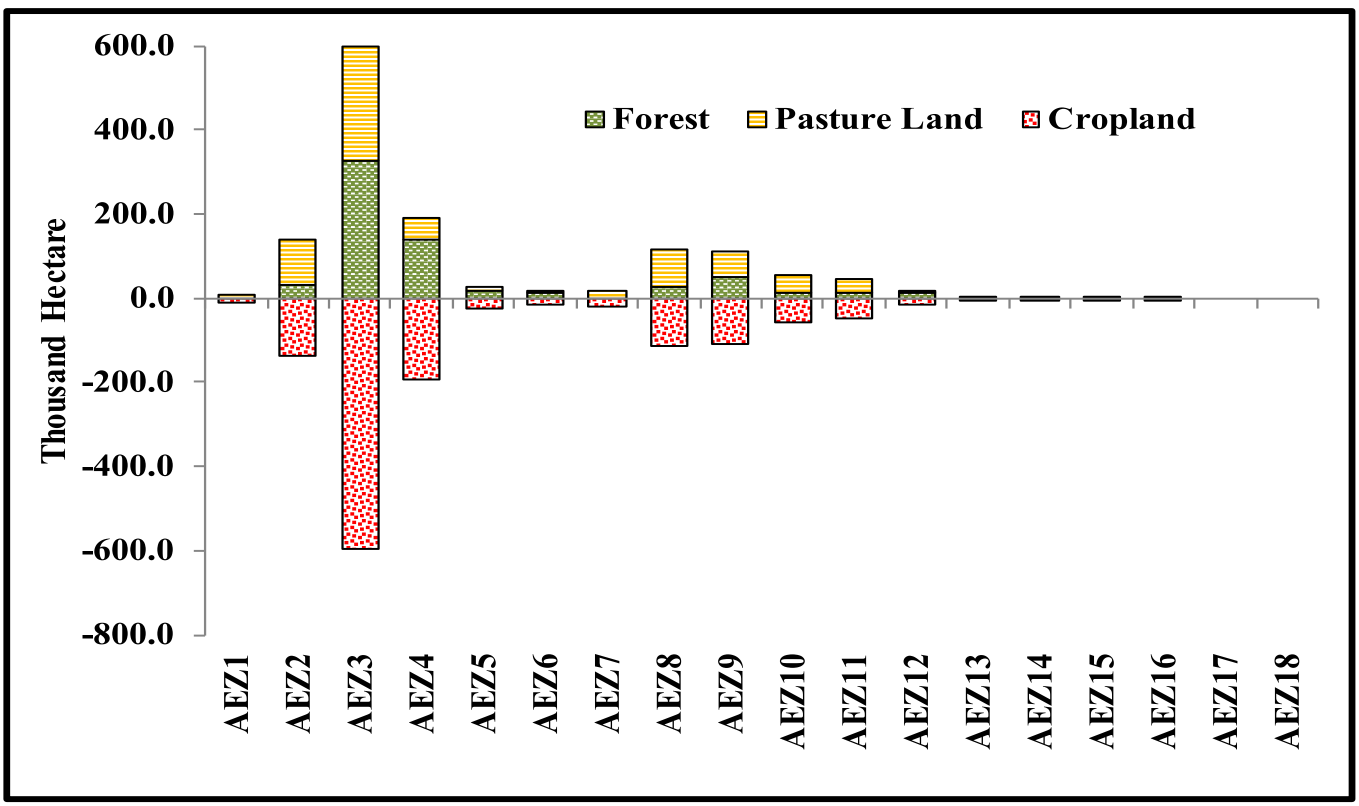
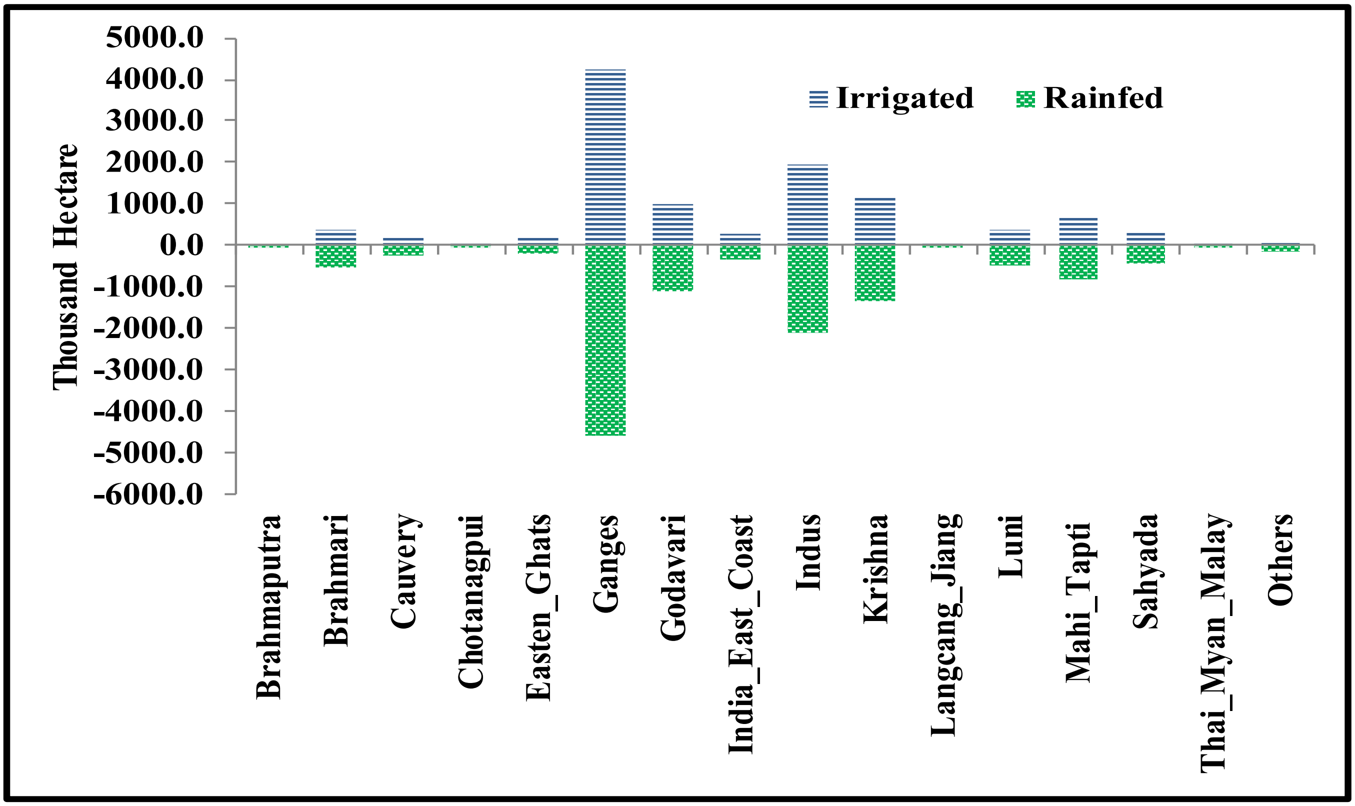


Figure 5. Land use changes in India by river basin (top panel) and by AEZ (bottom panel) due to 20% improvement in water use efficiency



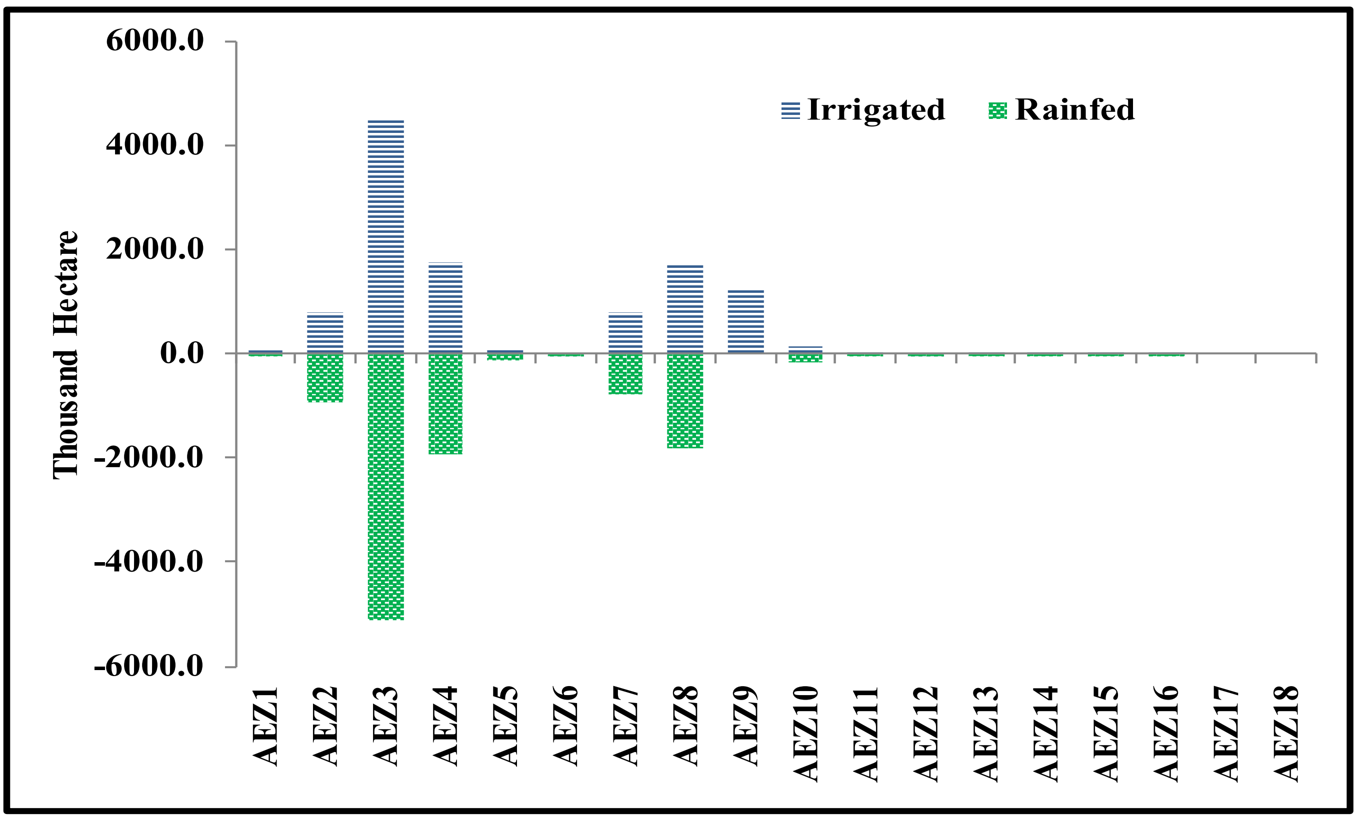


Figure 6. Changes in rainfed and irrigated cropland in India by river basin (top panel) and by AEZ (bottom panel) due to 20% improvement in water use efficiency

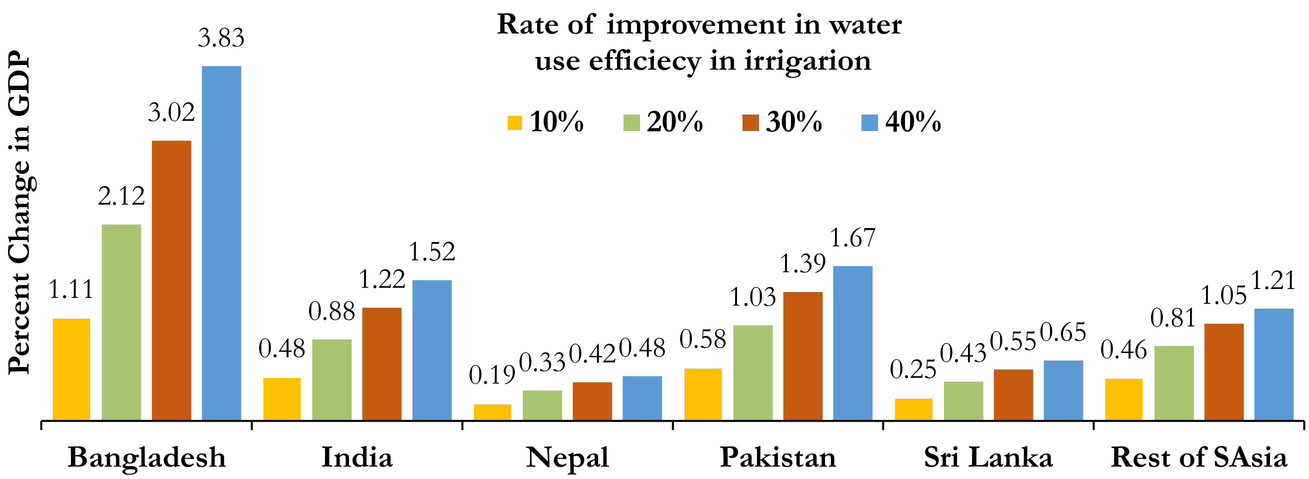


Figure 7. Percent changes in GDP (top panel) and their monetary values at 2011 constant prices (bottom panel) due to improvement in water use efficiency in irrigation in South Asia: Improvement in water use efficiency is costless

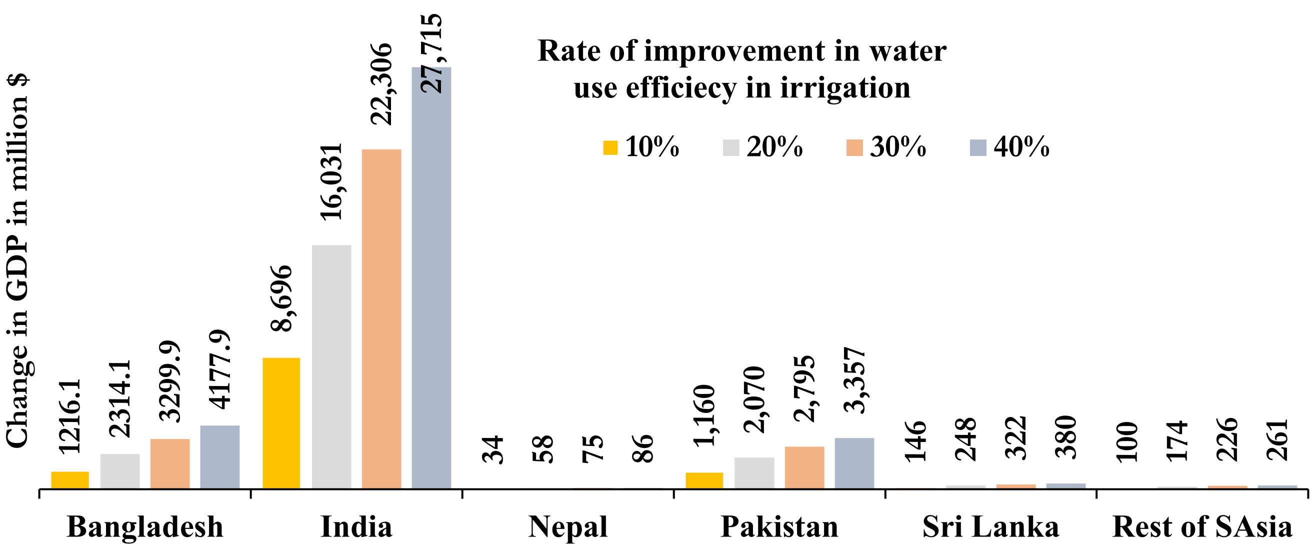


Figure 8. Marginal impacts of different levels of improvement in water use efficiency on GDP of South Asian economies: Improvement in water use efficiency is costless.

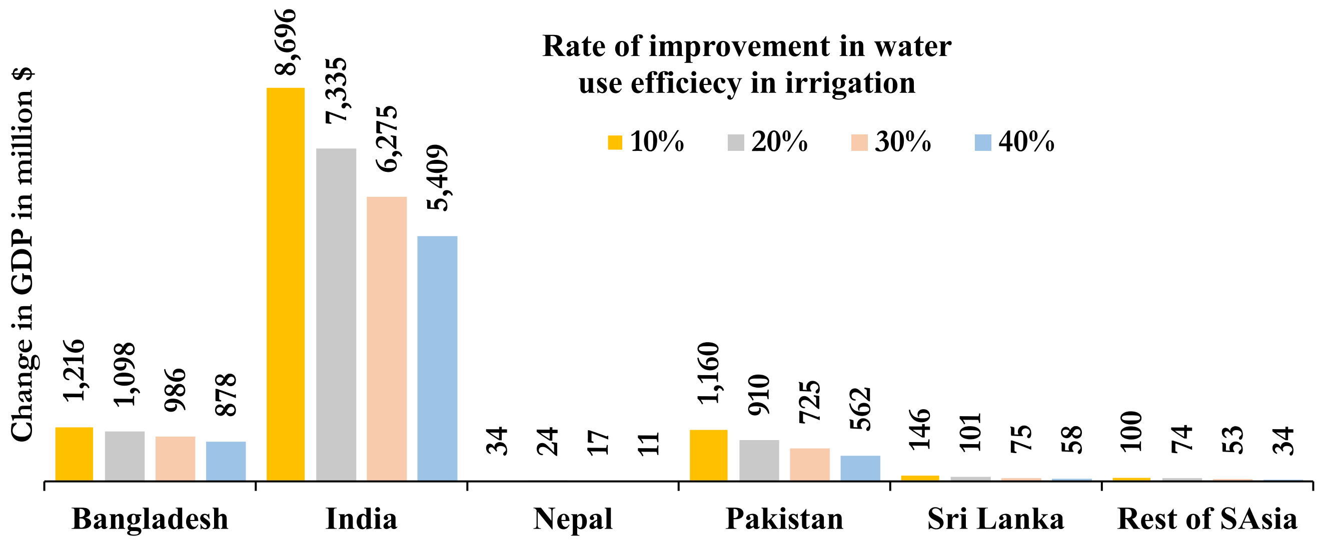


Figure 9. Percent changes in GDP (top panel) and their monetary values at 2011 constant prices (bottom panel) due to improvement in water use efficiency in irrigation in South Asia: Improvement in water use efficiency needs additional investment costs.

Chapter 4: Agricultural Production, Irrigation, Climate Change, and Water Scarcity

4.1. Introduction

The economies of South Asia have been growing relatively quickly in recent years. The major economies of this region including Bangladesh, India, Nepal, Pakistan, and Sri-Lanka were growing with average growth rates of 6%, 7.2%, 4.5%, 4.2%, and 5.6% in 2000-2015, respectively. In this period, population has also continued to increase in these counties by 1.3%, 1.4%, 1.2%, 2.1%, and 0.8% on average per year, correspondingly. Population growth coupled with economic growth will translate into strong growth in food demand and hence crop production in South Asia. Given that about 60% of crops produced in this region are irrigated, this will likely require a major expansion in demand for water for irrigation, assuming no major improvement in water use efficiency in irrigation. Growing demand for irrigation, when coupled with industrial, residential, and commercial demands for water, is projected to result in intense competition for water in South Asia, particularly in India and Pakistan (UNESCO [1], Rosegrant et al. [2], and Rodriguez et al. [3]). However, the intensity of this competition will not be uniform across different River Basins (RB) and Agro Ecological Zones (AEZs) of South Asia. In particular, in warmer and dryer AEZs, climate change may increase demand for irrigation as an adoption strategy to higher temperature and volatile weather condition. On the other hand, in some AEZs, climate change may positively affect rainfed crop yields and hence reduce demand for irrigation and weaken intensity of water scarcity. Therefore, while irrigation adoption is commonly suggested as an important alternative response to climate change, changes in water scarcity (either due to expansion in demand for water in non-agricultural uses, increase in population, higher demand for food, lack of water infrastructure, or induced by climate change itself) can differentially affect both the supply of water and the demand for additional irrigation in agriculture across AEZs.

This chapter uses an advanced computable general equilibrium (CGE) model in combination with biophysical data on land cover, harvested area, crop production, water used in irrigation, crop yield responses to climate change, and water scarcity measures to examine: 1) the consequences of climate change for South Asia's agricultural and food products; 2) the extent to which water scarcity can affect the irrigation adoption and demand for water across South Asia; and 3) how water scarcity, climate change, and trade jointly alter land use changes in this part of the world.

Many papers have studied the impacts of climate change on crop yields and food security (e.g. Lobell et al. [4] and Nelson et al. [5]). These studies demonstrate how changes in climate variables affect food security across the world. However, they do not provide a clear picture on the interactions between climate change, crop yield, and water scarcity. More recent papers (e.g. Willis et al. [6] and Marshal et al. [7]) have taken into account these interactions and show that while climate change can induce incentives for irrigation, water scarcity may limit the extent that irrigation adoption can be implemented. While these papers and the earlier work in this area provide valuable economic and biophysical analyses of the impacts of climate change for crop production and food security, they ignore the interplay between climate change and international trade. Some papers have examined the interaction between trade and climate change. For example, Reilly et al. [8] have shown that trade can improve food security in regions which their crop production will be negatively affected by climate change factors. This paper and its successors (e.g. Baldos and Hertel [9]) usually ignore water scarcity induced by climate change and or economic factors. In a recent paper Liu et al. [10]) have shown that trade can mitigate the consequences of future irrigation short falls in regions where water scarcity threaten their food security as well. However, this paper ignores the impacts of climate change on crop yield in the presence of water scarcity.

This chapter aims to enhance the existing literature by developing an analytical framework which allows us to examine the interactions between climate change, crop yield, water scarcity, and trade and their implications for South Asian economies. In what follows we first introduce our modeling framework and its database. Then, examined scenarios are presented. The next section describes the numerical results followed by the conclusion.

4.2. Modeling framework and its background

Many studies have developed and used CGE models to study the economic and environmental consequences of climate change, water scarcity, and water management. An early work in this area developed by Berck et al. [11] introduced explicitly water in a small single region CGE model to examine the economic impacts of water shortage in the San Joaquin Valley in California. Following this initial work, several authors included water into a number of CGE models to perform economic analysis of water management and policy. Fadali et al. [12] have listed many of these models. These models which have been used in various applications carry several common features including but not limited to the following. i) Water is an input in the production functions of crop sectors.[32] ii) Most of the existing models were developed to examine water issues in a small region or a river basin.[33] iii) Supply of water is usually an exogenous variable in the CGE models.[34] iv) In many models water is a sluggish endowment with limited mobility.[35] v) Global CGE models do not distinguish between the surface and ground water.[36]

The CGE modeling framework developed and used in this research (GTA-BIO-W) extends the above common characters in several ways. The GTAP-BIO-W is an advanced version of the standard GTAP model originally developed by Hertel [18]. Several publications documented the main features of the GTAP-BIO-W model and its background (Taheripour et al. [19]; Taheripour et al. [20], Liu et al. [10], Liu et al. [21], and Taheripour et al. [22]). It is a static CGE model which combines economic and biophysical information on land and water. It is designed to examine the nexus between agricultural activities, industrial and energy sectors, and trade in the presence of climate change and water scarcity by region at a global scale. The main structure of the GTAP-BIO-W model is presented in Figure 1. As shown in this figure, the GTAP-BIO-W model carries the following major advantages comparted to the other existing global water-CGE models.

[32] A few small single region models take into account water used in non-agricultural sectors. As an example, Luckmann et al. [13] developed a single region CGE models which takes into account water in non-agricultural uses.

[33] A few CGE models examined water issues at a global scale. For example, for the first time, Berrittella et al. [14] introduced water into a global CGE model (GTAP-W) as an input in the production function of crops and the water utility sector at the national level. Calzadilla [15] extend this model by dividing value added of cropland into irrigated and rainfed.

[34] Some CGE models were linked with hydrology models to better capture the link been economic and biophysical variables. Even in these hybrid models water supply remains exogenous in the CGE part. For example, Robinson and Gueneau [16] combined a CGE model with a hydrology model. However, these authors run the CGE and the hydrology models separately in a sequence.

[35] Usually a regional market clearing condition allocates water among its alternative uses. A few models used other techniques or ad-hoc restrictions (or quotas) to allocate water among its alternative uses. For example, Berck et al. [11] used linear programing to allocate water across crops.

[36] .Some single region or single river basin models distinguished between these two types of water resources. As an example, Diao et al. [17] provided some economic analyses on using surface and ground water in Morocco.

- It is the first global CGE model which explicitly traces water by country at the river basin level by Agro-Ecological Zones (AEZs). A large river basin may serve several AEZs.
- It incorporates water into the production function of all economic activities including crops, livestock, industries, and water utility services. Therefore, all economic activates compete for water.
- Unlike all other existing CGE models, this model distinguishes between the rainfed and irrigated crops to better capture the links between demands for irrigation and food.
- The nested Constant Elasticity of Substitution (CES) production functions are used in this model[37]. Hence, it allows the user to examine alternative assumptions on substitution between water and other input in particular for capital and land.
- This model takes into account heterogeneity in the price of water and traces demand for and supply of water by country at the river basin level by AEZ.[38] This means that the marginal value of water could be different at different places and across uses.
- Unlike all other CGE models, it uses a nested Constant Elasticity of Transformation (CET) functional form to model the supply side of water. This is consistent with real world observations. As explained in this chapter, the data and modelling structure take into account real world rigidities. While some adjustment of water use across sectors is possible, it is by no means freely mobile like other mobile inputs such as labor or capital. This is a standard method to model a sluggish input like water which cannot move freely across uses and across regions.

4.3. Database

The database developed for this research is a modified version of the GTAP (Global Trade Analysis Project) database release 9 which represents the world economy in 2011 (Narayanan et al. [23]). Tis database is a publicly available and fully documented economic dataset, which is constructed by balancing various data components from different sources across the world including but not limited to: 1) a bilateral trade dataset obtained from the United Nations Commodity Trade dataset; 2) a tariff dataset obtained from the MacMAP database developed by the International Trade Centre; 3) a macro-economic dataset obtained from the World Bank; 4) a dataset on agricultural production and domestic support for several countries obtained from the Organization for Economic Co-operation and Development; 5) and finally a dataset including national Input-Output (I-O) tables collected by several researchers across the world, usually constructed by their national statistical agencies. The GTAP database is the only available database which provides input-output tables for a wide range of countries and is utilized by thousands of researchers worldwide. It is a key input into many contemporary applied general equilibrium analyses of global economic issues.

Several modifications are made into this GTAP standard database to make it suitable for this research. The first major modification divides crop sectors into irrigated and rainfed categories according to the approach

[37] A nested CES production function divides production inputs into several sub groups and assign different elasticity of substitution parameters between the inputs of each nest and among the nests.

[38] In a competitive market all users of a commodity pay the same price for that commodity. When there are rigidities in the market for an endowment (or a commodity), the users pay different prices for that endowment (or commodity). This represents heterogeneity in price paid by users. For example, when water cannot freely move from agricultural uses to non-agricultural uses due to the existing restrictions (e.g. quotas, water rights, or any other social restrictions), agricultural and non-agricultural users of water pay different prices for water. In this case water is not a homogenous commodity across its alternative uses.

introduced by Taheripour et al. (19). The second important modification follows Taheripour [20], Liu [21], and Taheripour [22] to enhance the standard GTAP database in representing the consumption of water in its alternative uses and supply of water by river basin. The third major modification divides the electricity sector of the standard GTAP database into two distinct electricity sectors: hydro and non-hydro. The last important modification following Taheripour et al. [24] brings biofuels into the database. In what follows we introduce some key aspects of this database with major attention to land, water, and crop production.

Table 1 represents distribution of cropland in south Asia. This table shows that cropland in South Asia is scattered across different AEZs. In Bangladesh croplands are exclusively located only in AEZ4 and AEZ5 – with rich moisture and long length of growing period. About 23% of India's cropland are distributed among dry AEZs with short length of growing period (i.e. AEZs: 1, 2, 7, 8, 13, and 14). The rest of India's cropland (77%) is distributed among the rich moist AEZs with long length of growing period. In Nepal land is scattered across several non-dry AEZs. Land in Sri Lanka is basically divided in AEZ4, AEZ5, and AEZ6 which are again non-dry AEZ. Unlike Bangladesh, India, Nepal, and Sri Lanka, available cropland in Pakistan and Rest of South Asia is basically distributed across dry AEZs (i.e. AEZs: 1, 2, 7, 8, 13, and 14) In Pakistan 79% of the cropland land is located in dry AEZ. The corresponding share in Rest of South Asia is about 95%. Hence, Pakistan and Rest South Asia will be faced with major challenges to produce food, if water is not available for irrigation.

In addition to the distribution of land resources by AEZ, our database represents the distribution of these resources by river basin as well. Four river basins including Brahmaputra, Ganges, Thai-Myan-Malay, and Others serve entire Bangladesh in our database. The shares of the two first basins in total harvested area of Bangladesh were about 45.3% and 47.6% in 2011. Two river basins including Ganges and Indus serves Nepal. About 99% of harvested area of Nepal belongs to Ganges. Pakistan is divided between three river basins: Indus, Western Asia, and Other. But Indus serves 98% of total harvested area of Pakistan. Sri Lanka is served basically by its main river basin named Sri Lanka. Several river basins serve including Amudarja, Brahmaputra, Indus and Western Asia serve Rest of South Asia. The only country which is supported by several river basins is India. Figure 2 represents these reviver basins and their shares in total harvested area of India in 2011. As shown in this figure Ganges, Krishna, and Indus have the largest shares (34%, 11.4% and 11.2%, respectively) in total harvested area of India. Figure 3 represents distribution of available land (forest, pasture and cropland) in India by river basin.

In 2011 water withdrawal from surface and ground sources in Bangladesh, India, Nepal, Pakistan, Sri Lanka, and Rest of South Asia was about 38.4 billion cubic meters (BCM), 830 BCM, 8.3 BCM. 190.2 BCM, 7.8 BGM, and 17.4 BCU, respectively. Hence, India and Pakistan were the main users of water in South Asia. Water is mainly used in agricultural activates in South Asia, except for Sri Lanka. As shown in Figure 4, the share of agriculture in total water withdrawal was more than 80% everywhere in South Asia in 2011, except for Sri Lanka. In that country, the share of agriculture in water withdrawal was 51.3%. This is because Sri Lanka has limited irrigated cropland. In Bangladesh and Sri Lanka water is basically used for rice. In other regions water is mainly used to produce rice and wheat.

Figure 5 shows distribution of water used for irrigation by river basin in South Asia in two different panel. The first panel represents this distribution in India. In India, the shares of Ganges, Indus, Krishna, and Godavari in water withdrawal were about 40.4%, 17.7%, 8.6% and 8% in 2011. The second panel indicates distribution of water in other countries of South Asia by river basin. As shown in this panel, Bangladesh takes water mainly from Ganges and Brahmaputra and Ganges. Nepal basically relies on Ganges and Pakistan on Indus.

Water withdrawal is divided into the surface and underground categories in our database. Figure 6 represents share of these two categories in total water withdrawal by river basin in South Asia. As shown in this figure the share of underground water in some river basins in India is relatively large, examples are: 47% in Brahmani; 46% in Mahi Tapi; 40% in Sahyadri Ghats; 36% in Godavari; and Ganges 34%. The share of underground water withdrawal in Pakistan and Bangladesh are 15% and 11%, respectively. The magnitude of this share is limited in other countries of South Asia.

South Asia produces 31.2% of rice, 19.4% of sugar crops, and 16.9% of wheat produced across the world in 2011. The shares of South Asia in other crop categories were less than 10% in this year. India is the largest crop producer in South Asia and is relatively an important crop producer at the global scale. India accounts for 69.6% of rice, 73.5% of wheat, 82.6% coarse grains, 91.6% of oilseeds, 84.3% of sugar crops, and 87.9% of other crops produced in South Asia in 2011. In general, the shares of other countries in crops produced in South Asia are not large. Bangladesh has only a large share in rice (22.3%) and Pakistan has considerable shares in wheat (21.3%), coarse grains (9.2%), and oilseeds (13.6%).

While South Asia, is relatively a large crop producer at the global scale, it does not trade crops with the rest of the world. Crops produced in this region, except for rice, are mainly used locally. In other words, South Asia has a weak trade relationship with the rest of the world in commodity markets – and even within the region, cross border linkages are relatively weak**.** This week relationship could harm food security of South Asia in response to the extreme climate events, as we will discuss in this research.

Crops are produced with low yields in South Asia. In 2011, yields in this region were about: 3.7 tonnes per hectare (t/ha) for rice; 2.9 (t/ha) for wheat; 1.7 (t/ha) for coarse grains; 1.5 (t/ha) for oilseeds, 66.1 (t/ha) for sugar crops; and 5.3 (t/ha) for other crops. These yields where significantly lower than their corresponding figures (except for wheat and sugar crops) for the rest of the world in this year. For example, rice and coarse gain yields in South Asia were about 76% and 45% of their corresponding yields in the rest of the world. While yields are generally lower in South Asia compared with the rest of the world, some of them are extremely far below the yields of advanced economies. For example, in 2011, yields in USA over South Asia were about: 8 over 3.7 (t/ha) for rice; 8.7 over 1.7 (t/ha) for coarse grains; 2.8 (t/ha) over 1.5 for oilseeds; and 17 over 5.3 (t/ha) for other crops.

Finally, in this section we review some macro aspects of economies of South Asia as shown in Table 2. This table shows that India is the largest economy of South Asia, with $1,882 billion GDP in 2011. The second largest economy in this region is Pakistan with $214 billion GDP, followed by Bangladesh with $112 billion GDP. Table 2 shows that Sri Lanka, Nepal, and Rest of South Asia are very small economies with limited national incomes. The gross national products of these countries were about $59 billion, $19 billion, and $22 billion in 2011. This table also shows distribution of GDP across major sectors (including agriculture, industry, and services), and distribution of GPD among different expenditure groups (including private consumption, government expenditure, investment, and exports) across the world. Table 2 indicates that the economies of South Asia have relatively similar production structures - shown by the distribution of GDP between agriculture, industry, and service sectors. Agriculture accounted for a relatively big share of GDP in these economies in 2011. The share of agriculture in the rest of the world was about 3.9% in this year. These figures confirm that economies of South Asia are still relying heavily on agricultural activates. In general, the share of industrial activities in GDP is around 30% to 34% in economies of South Asia. The only exceptions are Nepal and Rest of South Asia with 16.5% and 15.1% for the share of industrial activities in total GDP. The share of services in GDP is around 50% in South Asia. This share is about 63% for the rest of the world.

Table 2 represents distribution of GDP across private consumption, government expenditures, investment, and exports by region in 2011 as well. This figure indicates that Bangladesh and Nepal had the largest and smallest export shares (%25.2 and %7.6, respectively) in South Asia in 2011. This indicates that Nepal is not an exporting country. India and Pakistan had the largest and smallest investment shares (33.4% and 13.6%) in South Asia in 2011. This indicates that India is preparing for faster growth. Table 2 shows the share of household expenditures in GDP is high among all economies of South Asia compared to the rest of the world. For example, about 88% of GDP of Pakistan consumed by households in 2011, while the corresponding rate for the rest of world was 58.7% Finally, Table 2 shows that the share government expenditures in GDP in economies of South Asia were around 6% to 16% in 2011, lower than the corresponding figure for Rest of World (about 18%).

4.4. Examined experiments

Two experiments were examined in this chapter. The first experiment studies the impacts of climate change on crop yields in South Asia and their implications for demand for irrigation. The second experiment investigates the extent to which water scarcity could alter the results of the first experiment and examines the joint impacts of climate change and water scarcity on food production, land use changes, demand for water and their consequences for economies of South Asia. These two experiments are introduced in the rest of this section.

a. Experiment I: Impacts of climate change on crop yields and demand for irrigation when water supply is unlimited

Changes in climate variables have direct and indirect impacts on crop yields. Many studies have projected the long run impacts of climate change on crop yields for many climate scenarios at the global scale and also for South Asia [4, 5, and 25-29]. These studies indicate that the impacts of climate variables on crop yields vary by region, AEZ, crop type, and time and are very uncertain[39]. While the literature recognizes that the climate change will affect crop yields, many papers argued that climate change could increase climate extremes and that increases demand for irrigation as an important adaptation strategy [7, 25, 26, and 29]. Irrigation could eliminate a portion of vulnerability in crop yields induced by extreme weather events, thereby mitigating some of the risk associated with climate change. Farmers switch to irrigation when the expected gains due to irrigation are higher than the costs of irrigation (including initial investment and operation costs). When climate change affects the yields in favor of the irrigated crops, farmers switch to irrigation if the yield difference is large enough to cover the costs of irrigation. The first experiment developed in this section examines the impacts of climate change on crop yields and their consequences for demand for irrigation for the time period of 2011-2050.

To examine the impacts of climate change on crop yields in South Asia we rely on the database developed by Rosenzweig et al. [27]. These authors have evaluated the impacts of climate change on crop yields for a wide range of climate scenarios and several GCM and crop models at the global scale at 0.5 by 0.5 degree resolution.

[39] Crop models are usually used to project the impacts of climate change on crop yields. These models project different yield trajectories for each crop for a given climate condition at fine spatial fine resolutions (e.g. 0.5 by 0.5 degree resolution).

Villoria et al. [30] have made these simulation results accessible to public on the GOSHARE website under the AgMIP tool (https://mygeohub.org/tools/agmip). In what follow we use this tool to assess the impacts of climate change on rainfed and irrigated crop yields in South Asia for a representative climate scenario. To avoid extreme scenarios, we concentrate on the RCP 4.5 which represents an average climate change scenario. Among the existing crop models, we used the LPJml model to evaluate impacts of climate change on irrigated and rainfed crop yields, separately. To focus on major crops, we concentrate on five key crops including rice, wheat, corn, and soybeans and sugarcane. The following steps are followed to evaluate the impacts of climate change on selected crop yields at AEZ level by country for the period of 2011-2050.

1. Projected yields for the desired scenario and the selected crop model are downloaded at the grid cell level for the rainfed and irrigated crops for each year. We denote the projected yields with Y_{irjt}^{w}, where *w* stands for irrigation type (rainfed or irrigated), *i* is the grid cell index, *r* indicates country, *j* represents crop type, and *t* is the time index.
2. Yields are aggregated to AEZ level by country using their corresponding harvested areas in the base year. We show the results of this stage with Y_{zrjt}^{w}, where z stands for 18 AEZs.
3. Trend lines are estimated for each individual crops in each AEZ by country to summarize the findings of the second step.
4. Projected crop yields for 2011 and 2050 are obtained for the estimated trend lines for each individual crop by irrigation type, AEZ and country. We show the results of this stage for these years with $Y_{irj2011}^{w}$and $Y_{irj2050}^{w}$, respectively.
5. The results of projected crop yields for 2050 are used to calculate percent changes in crop yields between 2011 and 2050 for each individual crop, by irrigation type, AEZ and country. These figures measure impacts of climate change on crop yields by AEZ in each country.

To summarize the results of these steps we further aggregated the percent changes in crop yields by country as shown Table 3. Several conclusions can be drawn from this table: 1) climate change negatively affect crop yields across regions with few exception; 2) in some regions climate change positively affects soybeans and sugarcane yields; 3) with few exceptions rainfed crops suffer more than irrigated ones. These observations confirm that climate change affects the yields in favor of the irrigated crops which could lead to more irrigation. However, the impacts of climate change on crop yields may vary across AEZ in a country. Figure 7 which represents percentage changes in crop yields due to climate change in India by AEZ represents this important fact.

Our first experiment examines the extent to which the climate induced changes in crop yields affect demand for irrigation in South Asia and tests their economic consequences for this region by county. The approach we follow in this experiment isolates the impacts of climate change on crop yields from other factors such as population growth, technological progress, and economic growth which may affect crop yields over time. To highlight the impacts of the expected changes in crop yields due to climate change on the demand for irrigation, we assume that there is no restriction on water supply (this assumption will very altered in the subsequent experiments). Furthermore, given the fact that the supply of unskilled labor is not a major constraint in South Asia, we assumed that the real wage for this group of labor force remains constant due to the productivity shock. Finally, we exogenously impose the obtained productivity shocks on the economies of 2011 to examine how economies of South Asian reacts to these climate change impacts when we assume no water scarcity.

b. Experiment II: Impacts of climate change on crop yields and demand for irrigation when water supply is limited

As mentioned earlier, several studies confirm that many regions in South Asia will face water scarcity induced by rapid expansion in water demand in agricultural and non-agricultural uses, lack of proper water infrastructure, and/or climate change. However, only a few studies have quantified the magnitude of future water scarcity in South Asia. Rosegrant et al. [2] have measured the Irrigation Water Supply Reliability (IWSR) index as a metric for irrigation water scarcity under several alternative scenarios at a global scale by river basin for 2000 to 2050 using the IMPACT-WATER model developed by IFPRI. This index measures the gap between demand and supply of water for irrigation. If this index equals one, then there is no irrigation water shortage. For our study, following Liu et al. [10], we use the Rosegrant et al. [2] "business as usual" scenario to measure changes in irrigation water supply by river basin for the time period of 2011-2050. This scenario assumes that the current trends in population and economic growth, water use efficiency, and investment in water infrastructure will continue in future. Figure 8 represents expected changes in irrigation water supply by river basin in South Asia in 2011-2050. As shown in this figure water supply for irrigation is expected to fall significantly in several river basins in South Asia.

In the first experiment, we examined a case where water supply is not limited and hence crop producers could switch to irrigation in response to induced climate change yield losses. However, Figure 8 indicates that water supply for irrigation in many river basins is expected to fall. Hence, on one hand climate change increases demand for irrigation in many river basins. On the other hand, if economy of South Asia grows as usual, water supply for irrigation will significantly fall in several river basins. In the second experiment, we analyzed the joint impacts of these two different forces on the economies of South Asia. To achieve this goal, we impose the projected changes in water supply by river basin (presented in Figure 8) and changes in productivities of rainfed and irrigated crops as exogenous shock on the base year economies of South Asia, while we assume water supply in non-agricultural uses will remain unchanged.

4.5. Simulation Results

c. Results of Experiment I

In what follows we analyze some key selected results obtained from the first simulation. Changes in demand for irrigation, consequence for land use, impacts on crop and food production, impacts on food imports, and some macro impacts will be provided in this section.

Impacts on demand for water. When water supply is not limited, climate-induced crop yield changes alter demand for water in many river basins, significantly. As shown in Figure 9, demand for water increases significantly in many river basins including but not limited to: Brahmaputra (%9.3), Ganges (15.4%), Thai Myan Malay (8.6%) in Bangladesh; Brahmaputra (45.1), Brahmari (%5.3), Eastern Ghats (18.8%), East Coast (16.1%), Indus (17.6%), Sahyada (7.9%), and Thai Myan Malay (61.4%) in India; Ganges (3.7%) and Indus (3.0%) in Nepal; Western Asia (36.2%) in Pakistan; and Brahmaputra in Rest of South Asia (23.1%). Only in India, demand for water drops slightly in a few basins including Chotanagpui (-8.7%), Ganges (-5.4%), Krishna (-4.2%), Luni (-11.7%), and Mahi Tapti (-11.8%).

To understand factors which affect these changes, consider two representative river basins of India: Ganges and Indus. In India climate-induced crop yield changes increase demand for water in Indus by 17.6% (or 25.8

billion cubic meter) and reduce demand for water in Ganges by 5.4% (18.1 billion cubic meters). Ganges serves several relatively dry and semi dry AEZs where the difference between irrigated and rainfed yields large. In these AEZ reductions in rainfed crop yields are significantly larger than their corresponding changes for rainfed crops. Hence in these AEZ, when water supply is not limited, rainfed crop producers switch to irrigation to hedge against climate change and mitigate a portion of its negative impacts. Hence, in this river basin, (and also other basins with similar conditions) demand for irrigation goes up. On the other hand, Indus serves basically several water-rich and humid AEZ where crops are mostly irrigated, rainfed and irrigated yields are not very different, and climate change impacts on rainfed and irrigated yields are similar. In these AEZ since both rainfed and irrigated crops suffer from climate change, crop production and hence demand for irrigation drops over time and hence we observe a reduction in demand for water in Indus in India (and other basins with similar conditions). In the next experiment, we examine the extent to which water scarcity could alter these findings.

Impacts on crop production. When there is no water scarcity and additional water is available at a constant price, changes in the rainfed and irrigated yields due to climate change alter the mix of irrigated and rainfed crops in market at the national level as shown in Figure 10. This figure indicates that, if water is available, climate change will promote outputs of irrigated crops in most cases and negatively affect their rainfed counterpart. As shown in Figure 11, the net of these changes is usually negative, except for sugarcane which seems performs better under climate change. This means that even if water supply is not limited, climate change harms outputs of main staple crops badly in South Asia during 2011-2050. In another world, moving towards irrigation could only partially mitigate some adverse impacts of climate change on agricultural outputs, it could not eliminate all the negative impacts. The next experiment shows that the impacts of climate change on crop yields get worse, when we take into account the fact that supply of water in limited.

Land use impacts. Here we only examine changes in the mix of irrigated and rainfed land as presented in Figure 10. This figure confirms that, if water supply is unlimited, demand for irrigated cropland will increase almost across all river basins in South Asia to mitigate adverse impacts of climate-induced crop yield changes. The reverse is expected to happen for the case of rainfed cropland. Figure 12 shows that relatively large conversion from rainfed land to irrigated land could occur in several river basins such as: Brahmaputra and Ganges in Bangladesh; Brahmaputra, Brahmari, Eastern Ghats, Godavari, East Coast, Indus, and Sahyada in India; Ganges in Nepal; and Indus in Pakistan. In short, if water supply is unlimited, total irrigated area could increase by 5.2 million hectares in South Asia to mitigate some adverse impacts of climate-induced crop yield changes. The corresponding reduction in rainfed area is about 4.8 million hectares. Therefore, these changes could increase demand for cropland by about 0.4 million hectares, which of course generates deforestation.

Economy-wide impacts. We explained that if supply of water is not limited, changes in irrigated and rainfed crop yields induced by climate change will increase demand for irrigation which in return boost irrigated crop outputs and that partially mitigate some adverse impacts of climate change. Moving toward irrigation could generate new job opportunities and improve economic activities at macro level. However, the overall negative impacts of climate change on agricultural outputs are strong enough to harm economies of South Asia which heavily dependent on agricultural activities. As shown in Figure 13, even when there is no restriction on water supply, economies of South Asia will lose a portion of their GDP due to climate-induced crop yield changes. The magnitudes of GDP losses are not large in terms of percentage changes in GDP as shown in Figure 13. However, their monetary values are considerable, in particular when we take into account the losses over time between 2011 and 2015. The monetary values of losses at 2011 constant prices in 2050 are expected to be about

$394 million for Bangladesh, $2,122 million for India, $60 million for Nepal, $270 million for Pakistan, and $135 million for Sri Lanka. The rest of South Asia does not lose significantly, if water supply for irrigation is available. The next section shows that these results will change meaningfully, when we take into account the fact that water supply will be limited and diminished in the future.

d. Results of Experiment II

Impacts on demand for water. In this experiment, reduction in demand for water for irrigation at the river basin level will be identical to the reduction in water supply for irrigation induced by water scarcity - as presented in Figure 8. In analyzing the first experiment we mentioned that climate-induced crop yield changes increase demand for water for irrigation, when water supply is no limited. However, in the presence of water scarcity the available water for irrigation will be dropped in many river basins as projected in Figure 8. Hence, water scarcity blocks the demand for irrigation water and that increases the opportunity costs of water across South Asia everywhere, as presented in Figure 14. Since the intensity of water scarcity varies among river basins and water cannot move freely over them, the opportunity costs of using water in irrigation will increase at different rates across river basins. Figure 14 shows that increases are quite large in several basins. For example, in Bangladesh the opportunity cost of water increases by around 100% across basins. In India, it goes up by more than 70% in Eastern Ghats, Ganges, and Indus. In Nepal, it changes around 50% to 70%. The opportunity cost of water for irrigation in Pakistan increases by three to four folds. The Changes are not large in Sri-Lanka. In the Rest of South Asia, it fluctuates around 20% to 30%. It is important to note that in South Asia, the price of water for irrigation is extremely low everywhere in the 2011 base year.

Impacts on food production and exports. Reduction in available water for irrigation in combination with climate-induced crop yield changes severely harms crop production in South Asia in particular in drier regions as presented in the top panel of Table 4, if economies of this region continue to inefficiently use water in irrigation. In Bangladesh crop outputs drop between 7% and 22%. In India which is a big crop producer, reductions are ranged between 5% and 8%. In Pakistan, another big crop producer, crop outputs drop largely between 10% and 30%. In Nepal, Sri Lanka and rest of South Asia crop outputs also go down, but at smaller rates. The top panel of Table 4 shows also these changes for irrigated and rainfed crops, separately.

The adverse joint impact of water scarcity and climate-induced crop yield changes on food production is not limited to the reduction in crop production. Reduction in crop outputs will also affect production of livestock and processed food industries. As shown in the second panel of Table 4, water scarcity and climate-induced crop yield changes jointly drop the monetary values of all food items (including crops, livestock, and processed food) produced in Bangladesh, India, Nepal, Pakistan, Sri Lanka, and rest of South Asia in 2050 compared to 2011 by $3,364 million, $26,481 million, $168 million, $14,265 million, $237 million, and $173 million, respectively.[40] These are enormous losses, particularly when we take into account their accumulated values over time between 2011 and 2050.

[40] Evaluated at 2011 constant prices.

Water scarcity and climate-induced crop yield changes also jointly reduce the net exports imports of food products from South Asia, particularly from India and Pakistan. As shown in the lowest panel of Table 4, these factors together push down the net exports of food products from Bangladesh, India, Nepal, Pakistan, Sri Lanka, and rest of South Asia in 2050 compared to 2011 by $1,350 million, $7,022 million, $111 million, $5,080 million, $17 million, and $181 million, respectively. While these reductions in net exports (or increases in net imports) of food products help economies of South Asia to mitigate a portion of the negative impacts of water scarcity and climate-induced crop yield changes on the food security, they put a major pressure on the trade balances of these economies over time.

Impacts on crop price. Reductions in crop outputs due to water scarcity and climate-induced crop yield changes lead to higher crop prices across South Asia. Crop prices increase in Bangladesh, India and Nepal between 10% and 35% as presented in Figure 15. In Pakistan, the crop price changes are large, between 45% and 120%. In Sri Lanka and rest of South Asia crop prices increases are in between 3% to 10%, with few exceptions. These higher crop prices will negatively affect everyone in South Asia, particularly poor and low income families.

Land use impacts. The mix of irrigated and rainfed land in the second experiment where we introduce water scarcity into our analysis moves towards the opposite direction of the observed mix obtained from the first experiment. Unlike the first experiment where the water of water was not limited, in the second experiment water scarcity eliminates irrigated areas in some river basins and extends rainfed areas in those basins, as shown in figure 16. In the second experiment area of irrigated cropland in India goes down in several basins and largely in Chotanagpui (by -215 thousand hectares), Eastern Ghats (by -250 thousand hectares), Ganges, -2,559 thousand hectares, Godavari (by -519 thousand hectares), East Coast (by -473 thousand hectares), Indus by (-541 thousand hectares), Krishna (by -1,924 thousand hectares), and Luni (by -1346 thousand hectares). The area of irrigated cropland drops also largely in Pakistan in the Indus basin, by -1,935 thousand hectares. In short, in the presence of water shortage, total irrigated area decreases by 9 million hectares in South Asia. The corresponding increases in rainfed area is about 11.5 million hectares. Therefore, demand for cropland goes up by 2.5 million hectares, which of course generates more deforestation compared with the results of the first experiment.

Economy-wide impacts. In analyzing the first experiment, we learned that even when supply of water is not limited and irrigation could be expanded in response to the adverse impacts of climate-induced crop yield changes, economies of South Asia suffer from these changes. These changes in combination with water scarcity extend the adverse impacts harshly. Figure 17 indicates that these factors jointly reduce GDP of Bangladesh, India, Nepal, Pakistan, Sri-Lanka, and rest of South Asia between 2011 and 2050 by 5.2%, 1.8%, 0.8%, 5.6%, 0.6%, and 0.5%, respectively. The corresponding monetary values of these losses at 2011 prices are -$5,668 million, -$32,794 million, -$138 million, -$11,220 million, -$340 million, and -$117 million, as presented in Figure 17. These losses and their accumulation over time are massive.

To calculate the accumulated values of these loses over time we provided to distinct but correlated measures for each country. The first one assumes a linear trend and calculates annual losses between 2011-2050 according to the monetary value of the reduction in GDP for each county and add them up for 2012-2050. The second measure represents the net present value of the first measure at a 3% social discount rate. We refer to these two measures as "linear trend" and "discounted trend". Figure 18 represents the results of these calculations for each individual country. The accumulated losses of the linear trends for Bangladesh, India, Nepal, Pakistan, Sri-

Lanka, and rest of South Asia between 2011 and 2050 are about -$113.4 billion, -$655.9 billion, -$2.8 billion, -$224.4 billion, -$6.8 billion, -$2.3 billion, respectively. The corresponding discounted losses are about -$54.2 billion, -$313.3 billion, -$1.3 billion, -$107.2 billion, -$3.2 billion, and -$1.1 billion. These large losses indicate that climate-induced crop yield changes plus water scarcity could harms economies of South Asia seriously, if these economies do not take precautionary and aggressive mitigation approaches and policies against these factors.

4.6. Uncertainties

Three major items determine the magnitude of the simulation results provided in this chapter. Changes in crop yields due to climate change is the first item. We calculated these changes for RCP 4.5 which represent a moderate climate scenario. Of course, under more pessimistic climate scenarios, with higher temperatures, crop yields may drop more and that could alter our results. The extent to which economic growth could induce water scarcity is the next important item. In this chapter, we rely on the literature and used the results of a major research conducted at IFPRI on water scarcity for irrigation. More recent studies, confirms that economies of South Asia will face with major water scarcity issues as well. However, there is no consensus regarding the extent to which water scarcity will increase in future in this region. If water scarcity occurs more intensively than what IFPRI was projected, then the economic implications will get worse.

We assumed that climate change and water scarcity do not affect markets for skilled labor and capital. Several papers have shown that water scarcity and climate change could negatively affect markets for skilled and unskilled labor, reduce productivity of labor, generate idled capacities, and damage infrastructure. Our analysis ignored these adverse impacts.

4.7. Conclusions

We first examined the impacts of changes in the irrigated and rainfed crops yields induced by climate change on demand for water. We showed that the impacts of climate change on crop yields vary across crops and agro ecological zones. We showed that, if water for irrigation is not limited, climate-induced crop yield changes increase demand for irrigation and that could help to partially mitigate the impacts of climate change on crop and food production. From the first experiment, we also learned that while changes in irrigated and rainfed crop yields induced by climate change surge demand for irrigation in some river basins, they reduce demand for irrigation in some other reviver basins. We also showed that, if water for irrigation is not limited, still climate-induced crop yield changes could generate negative economy-wide impacts across South Asia.

Then we examined the combined impacts of effect of climate-induced crop yield changes and water scarcity on economies of South Asia. We showed that water scarcity, induced by expansion in water demand in non-agricultural uses and lack of water infrastructure, will block the demand for irrigation and that generate sever negative economic impacts and cause major land use changes.

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Table 1. Distribution of cropland among AEZs in South Asia

	Bangladesh	India	Nepal	Pakistan	Sri Lanka	Rest of South Asia	South Asia
AEZ1	0.0	1.6	0.0	14.5	0.0	0.0	2.8
AEZ2	0.0	7.8	0.0	0.0	0.0	0.0	6.1
AEZ3	0.0	44.0	4.2	0.0	2.0	0.0	34.5
AEZ4	22.8	18.2	35.9	0.0	17.5	0.0	15.9
AEZ5	77.2	3.8	4.2	0.0	14.2	0.0	6.5
AEZ6	0.0	1.1	0.0	0.0	66.3	0.0	1.5
AEZ7	0.0	3.7	0.0	56.4	0.0	14.2	9.6
AEZ8	0.0	10.1	0.0	7.8	0.0	66.7	11.6
AEZ9	0.0	7.8	0.0	5.4	0.0	1.5	6.8
AEZ10	0.0	0.8	16.7	9.7	0.0	1.1	1.9
AEZ11	0.0	0.7	25.4	3.0	0.0	1.8	1.3
AEZ12	0.0	0.4	11.0	2.8	0.0	0.4	0.8
AEZ13	0.0	0.0	0.2	0.1	0.0	9.8	0.4
AEZ14	0.0	0.0	0.6	0.3	0.0	4.3	0.2
AEZ15	0.0	0.0	1.4	0.0	0.0	0.0	0.1
AEZ16	0.0	0.0	0.4	0.0	0.0	0.2	0.0
AEZ17	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AEZ18	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 2. Major macro figures in 2011

Description	Bangladesh	India	Nepal	Pakistan	Sri Lanka	Rest of South Asia	Rest of World
GDP (current US billion $)	**112**	**1,882**	**19**	**214**	**59**	**22**	**69,171**
Agriculture (% of GDP)	15.9	18.7	32.6	12.0	21.4	31.7	3.9
Industry (% of GDP)	34.9	29.3	16.5	33.2	32.1	15.1	33.3
Services (% of GDP)	49.2	52.0	50.9	54.8	46.5	53.2	62.8
Total of sectors	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Household exp. (% of GDP)	75.8	62.4	87.2	88.0	73.5	101.5	58.7
Investment (% of GDP)	24.4	33.7	24.4	13.6	28.4	23.4	23.2
Government exp. (% of GDP)	5.6	12.1	10.9	10.6	15.5	15.0	17.8
Export (% of GDP)	25.2	19.9	7.6	14.5	20.9	17.1	28.5
Imports (% of GDP)	-31.0	-28.1	-30.1	-26.6	-38.3	-57.1	-28.2
Total of users	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Source: GTAP database version 11.

Table 3. Projected percentage changes in crop yields in South Asia for 2011-2050 (%)

Country	Crop Type	Rice	Wheat	Corn	Soybeans	Sugarcane
Bangladesh	Irrigated	-10.7	-10.5	-6.0	-9.0	-8.1
	Rainfed	-9.2	-18.8	-5.0	-24.7	-9.9
	Total	-10.0	-14.8	-5.0	-21.5	-8.2
India	Irrigated	-8.3	-8.0	-5.7	-10.7	-4.6
	Rainfed	-13.1	-12.3	-4.4	10.7	10.7
	Total	-10.5	-8.6	-4.6	6.1	-3.1
Nepal	Irrigated	-7.5	-6.2	-2.4	-4.8	20.6
	Rainfed	-9.4	-5.5	-5.9	-6.9	22.4
	Total	-8.7	-6.2	-5.7	-6.7	21.3
Pakistan	Irrigated	-6.7	-7.4	-7.5	-9.0	-6.4
	Rainfed	-13.4	-17.7	-1.4	-3.3	37.0
	Total	-6.7	-8.1	-4.0	-5.9	1.5
Sri Lanka	Irrigated	-6.9	-	-	-	-5.6
	Rainfed	-12.3	-	-7.2	-	-
	Total	-8.1	-	-	-	-
Rest of South Asia	Irrigated	7.7	-7.2	-0.1	0.0	-
	Rainfed	-17.3	-0.4	11.5	-1.3	-
	Total	5.2	-3.2	2.3	-0.5	-

Table 4. Changes in food production due to water scarcity and climate induced crop yield changes in South Asia: Projected for 2050 accumulation

	Crop	Irrigation type	Bangladesh	India	Nepal	Pakistan	Sri Lanka	Rest of South Asia
Changes in crop outputs (% change)	Rice	Irrigated	-4.8	-5.6	1.2	-14.8	1.5	-0.1
		Rainfed	-9.0	-5.0	-6.4	65.1	-17.7	-28.7
		Total	-6.6	-5.4	-2.8	-14.0	-1.4	-2.7
	Wheat	Irrigated	-13.0	-4.9	-1.5	-31.3	-56.0	-10.8
		Rainfed	-26.5	-0.9	-5.6	8.9	0.0	6.2
		Total	-18.6	-4.6	-1.7	-30.0	-2.2	-3.0
	Coarse Grains	Irrigated	-19.4	-28.4	8.9	-62.3	0.0	-3.9
		Rainfed	-12.7	1.6	-2.6	51.8	-1.5	8.2
		Total	-13.0	-4.6	-1.8	-17.8	-1.5	-1.2
	Oilseeds	Irrigated	0.2	-50.0	0.0	-56.7	0.0	-11.6
		Rainfed	-29.2	10.9	-8.7	36.6	-16.9	2.8
		Total	-21.6	-7.7	-7.6	-16.1	-16.8	-5.9
	Sugar crops	Irrigated	-5.0	-6.2	-9.7	-17.1	-0.4	-4.4
		Rainfed	-12.2	44.9	21.2	138.4	0.0	10.1
		Total	-5.4	-3.2	-0.8	-8.8	-0.4	-2.4
Changes in values of food items (million USD)	Crops		-1,978	-14,339	-105	-8,144	-96	-29
	Livestock		-259	-3,063	-24	-526	-15	-70
	Processed food		-1,127	-9,079	-38	-5,595	-125	-74
	Total		-3,364	-26,481	-168	-14,265	-237	-173
Changes in net exports of food items (million USD)	Crops		-1,078	-3,254	-58	-5,635	22	-28
	Livestock		12	-263	-12	343	-1	-36
	Processed food		-284	-3,505	-41	212	-38	-118
	Total		-1,350	-7,022	-111	-5,080	-17	-182

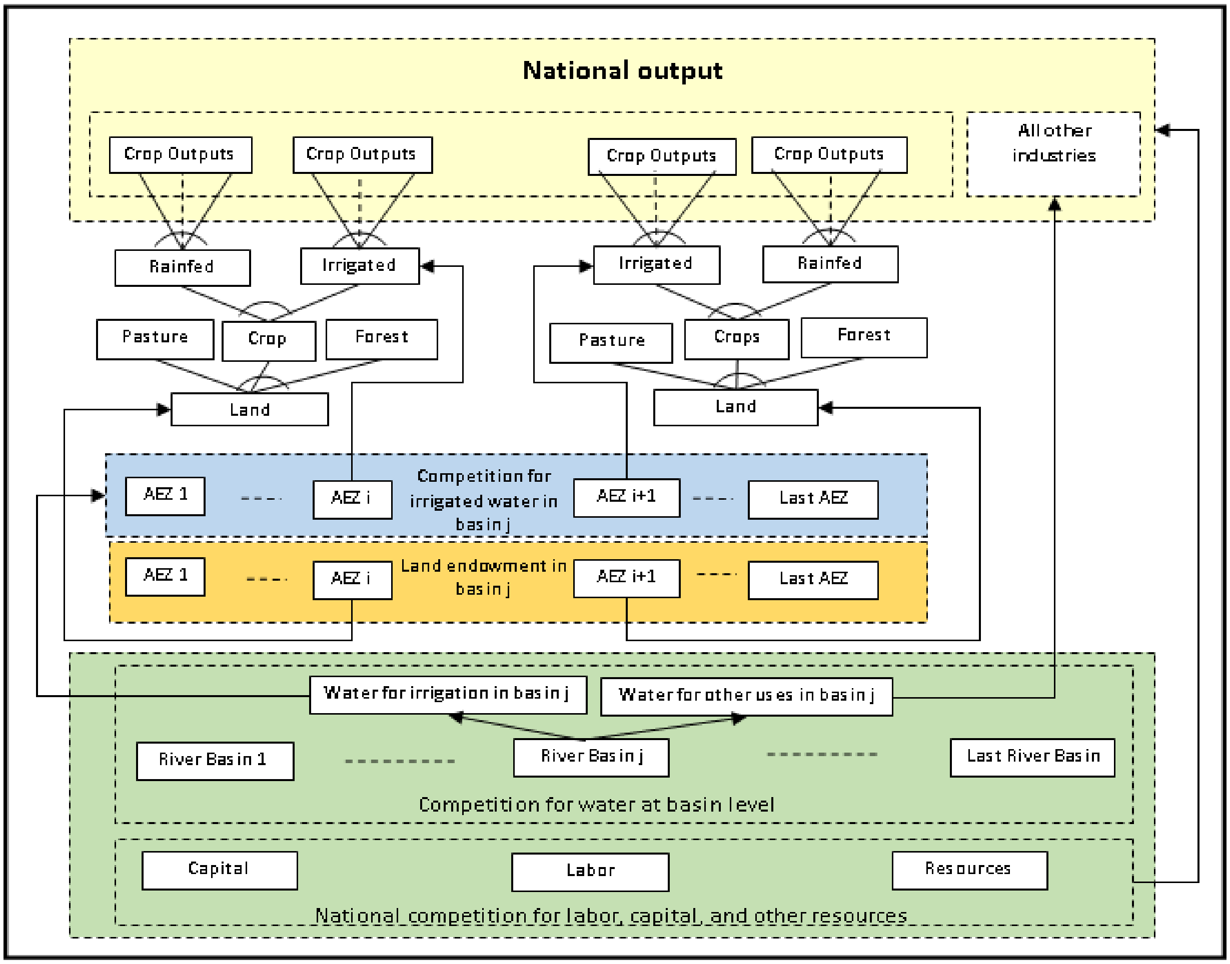


Figure 1. Structure of the GTAP-BIO-W static model (Taheripour et al. [22])

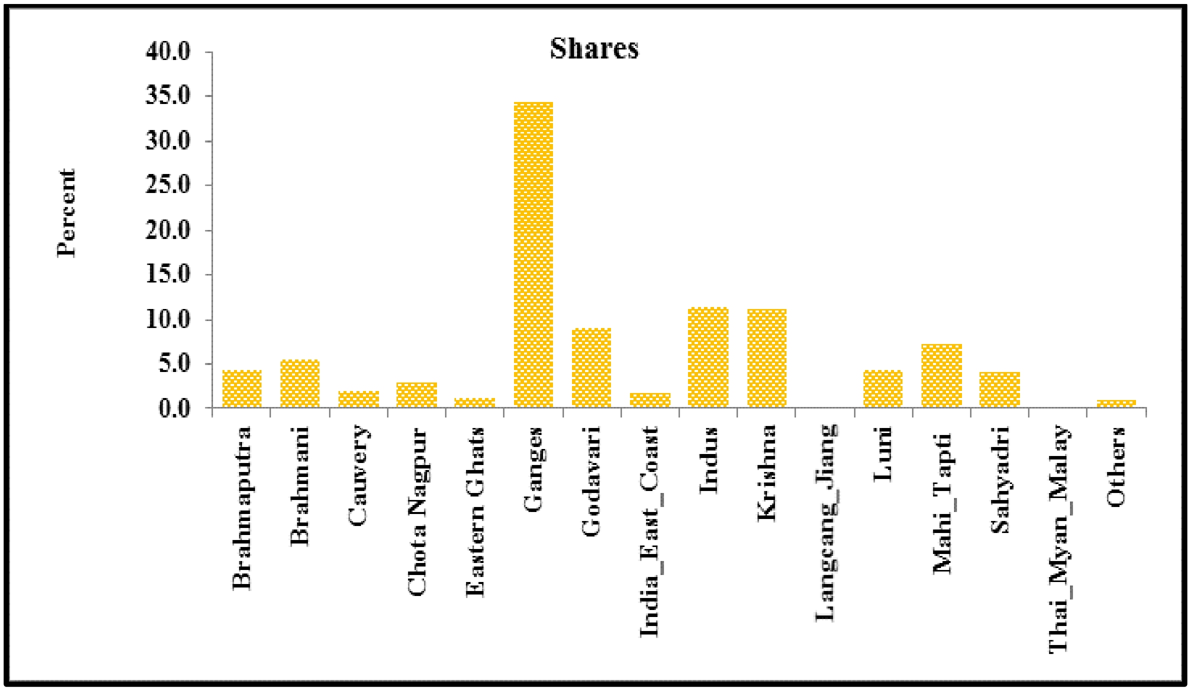


Figure 2. Distribution of India's harvested area by river basin

Figure 3. Distribution of available land in India by river basin

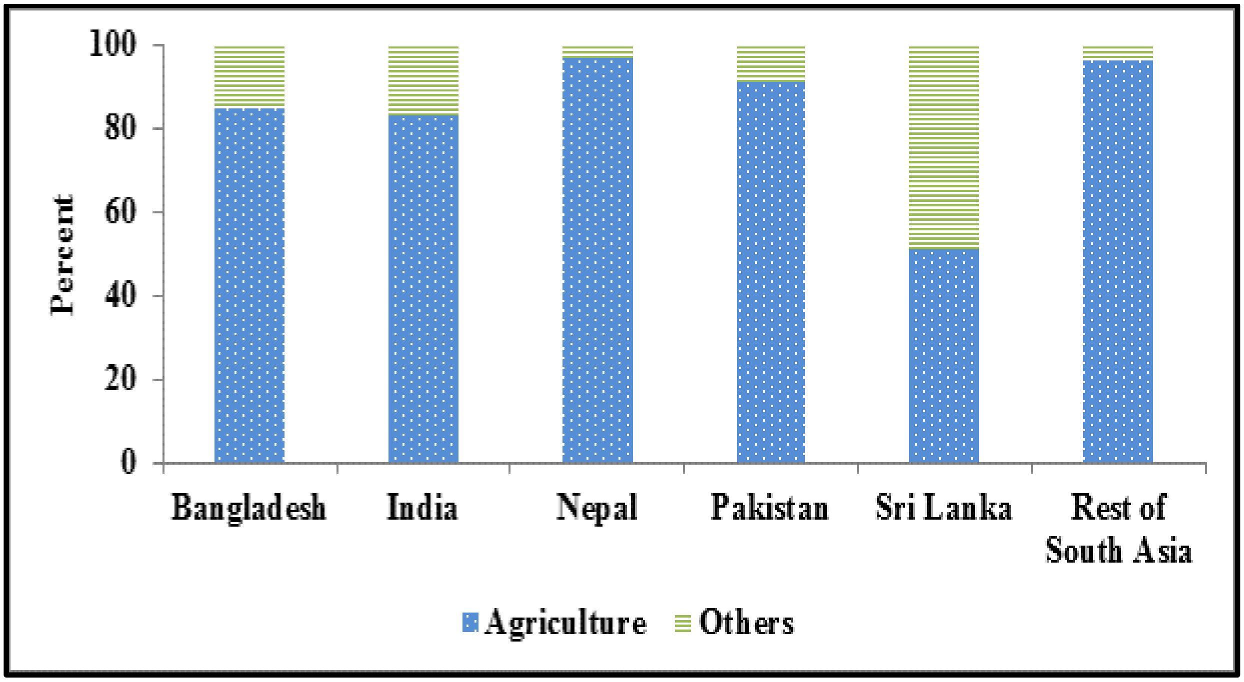


Figure 4. Shares of agricultural and non-agricultural uses in water withdrawal in South Asia in 2011

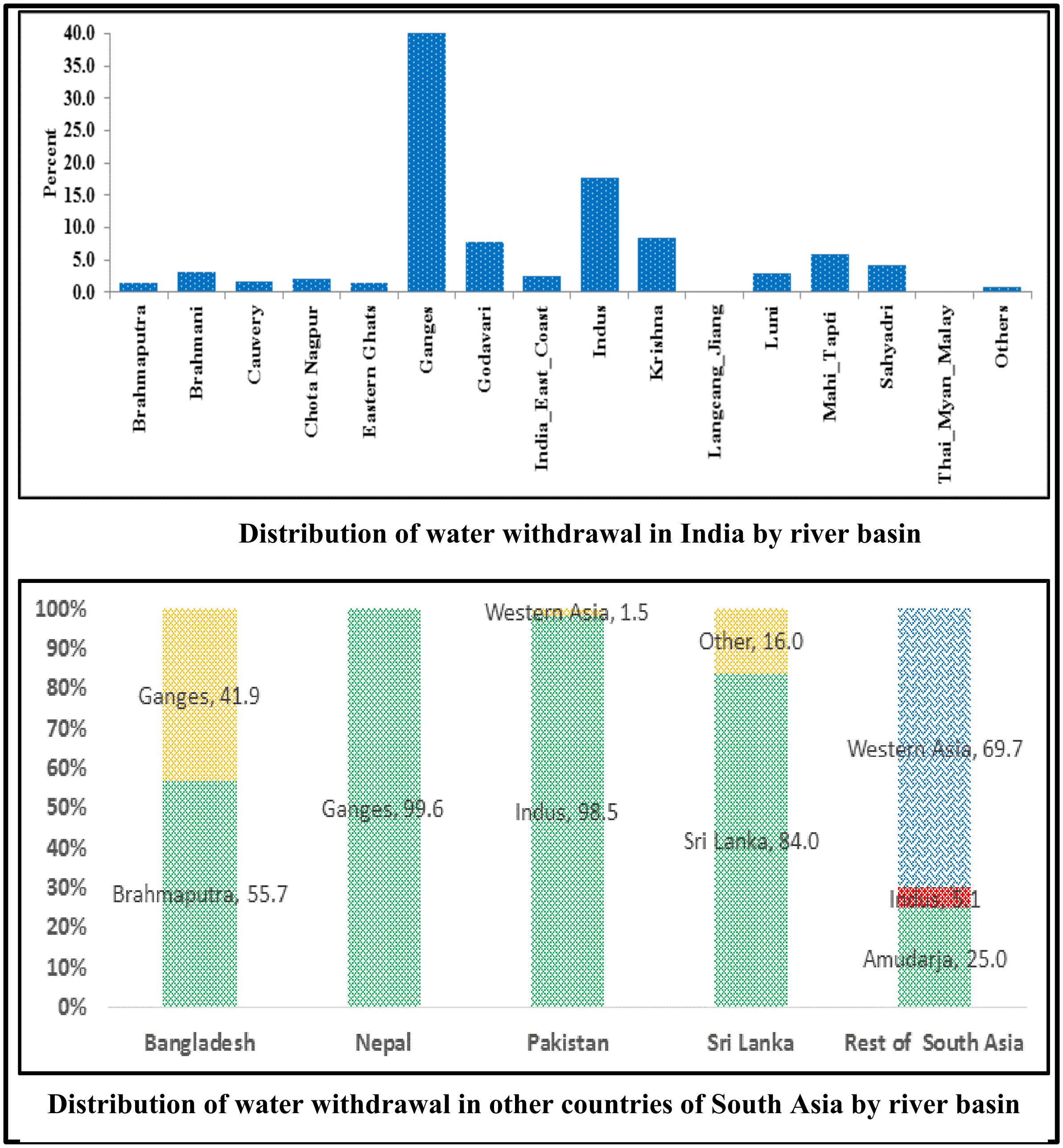


Figure 5. Distribution of water withdrawal by river basin in South Asia

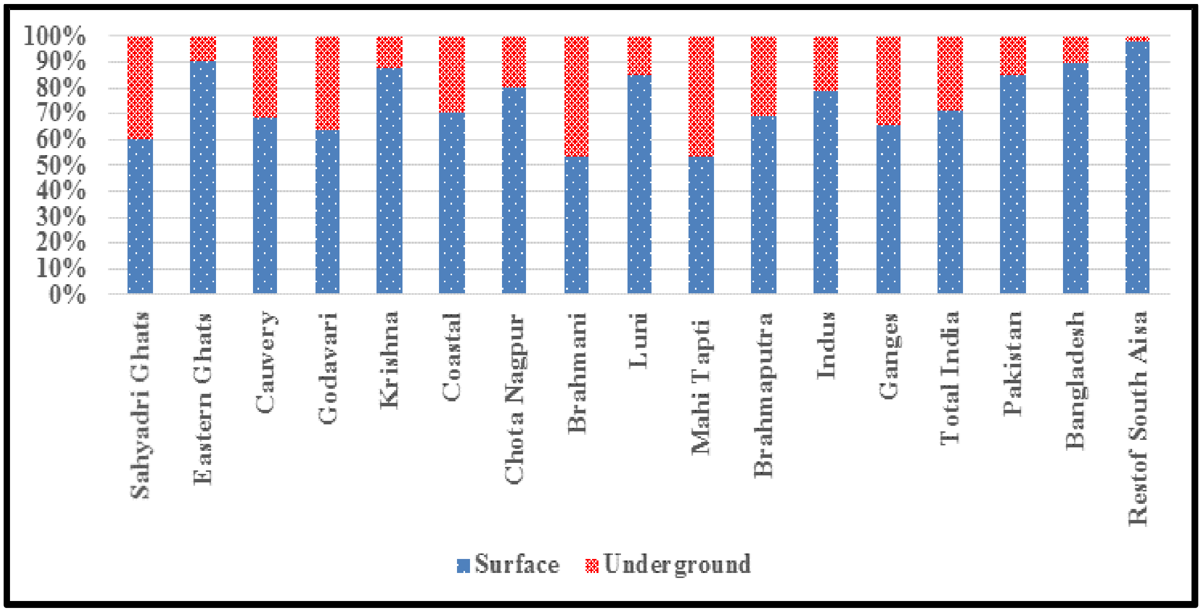


Figure 6. Shares of surface and underground water in total water withdrawal in South Asia by river basin

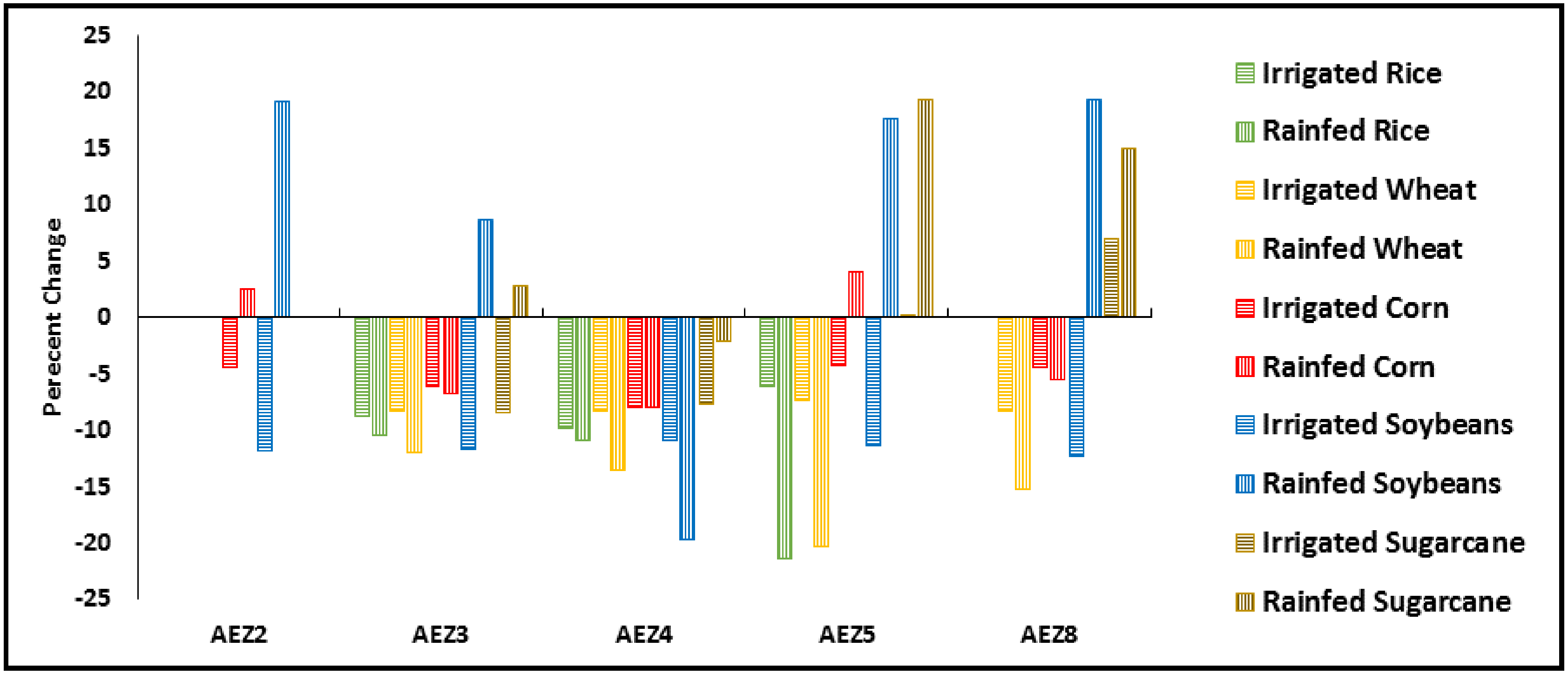


Figure 7. Projected percentage changes in crop yields in India by AEZ for 2011-2050 (AEZs with minor shares in harvested areas are intentionally ignores in this figure)

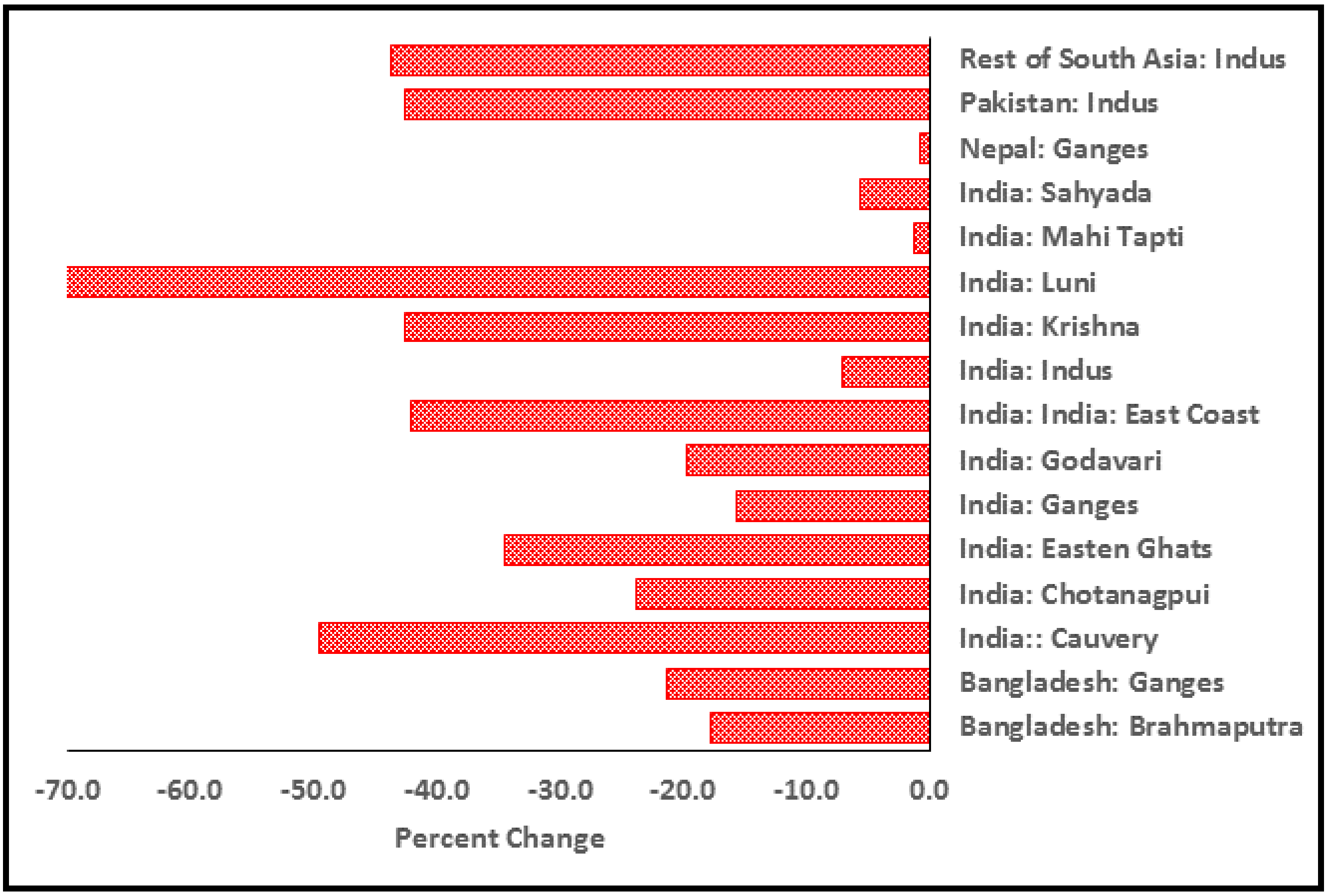


Figure 8: Projected percent changes in irrigation water supply in South Asia by river basin in 2011-50

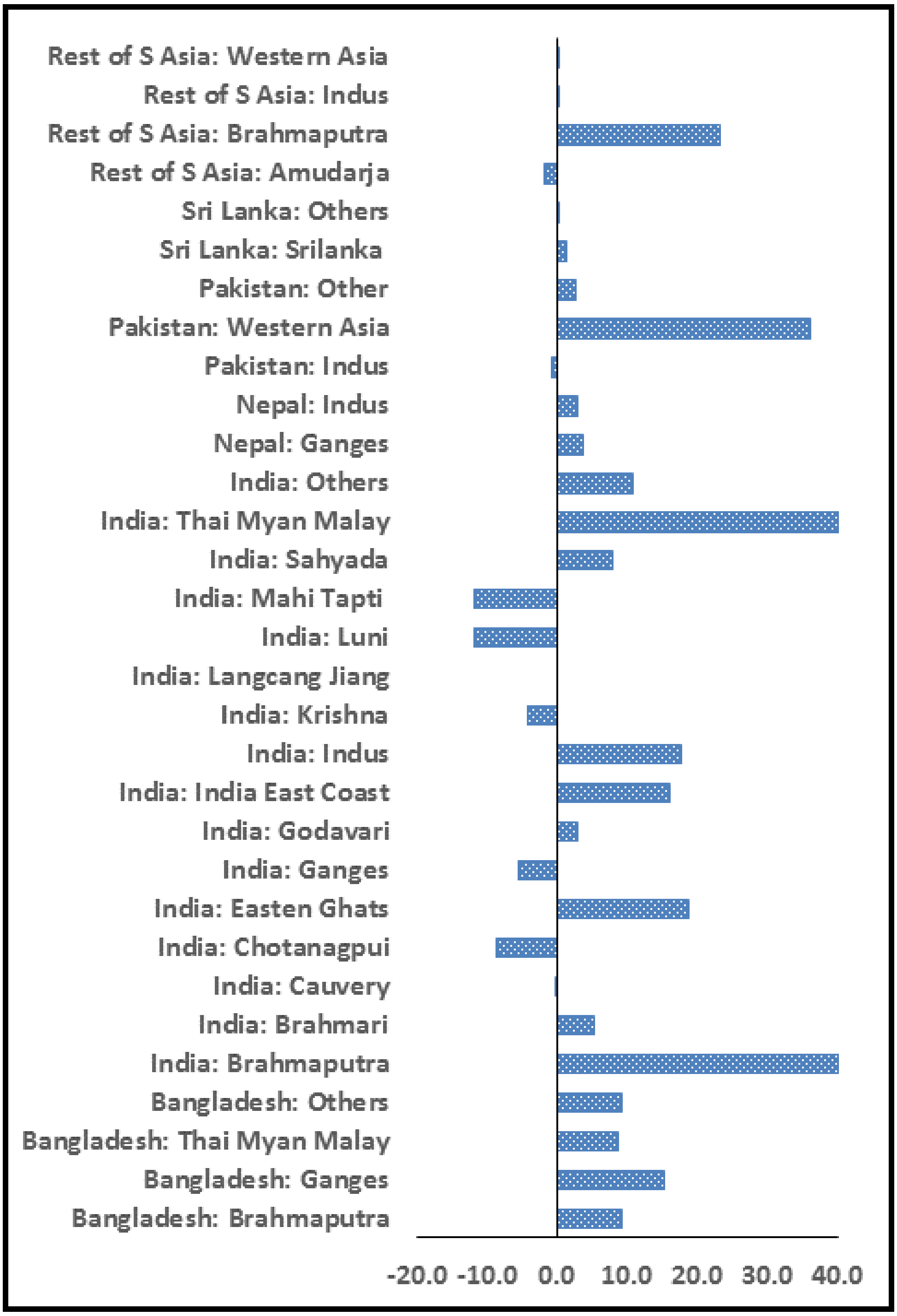


Figure 9. Percent change in demand for water for irrigation due to climate-induced crop yield changes, if water supply is unlimited

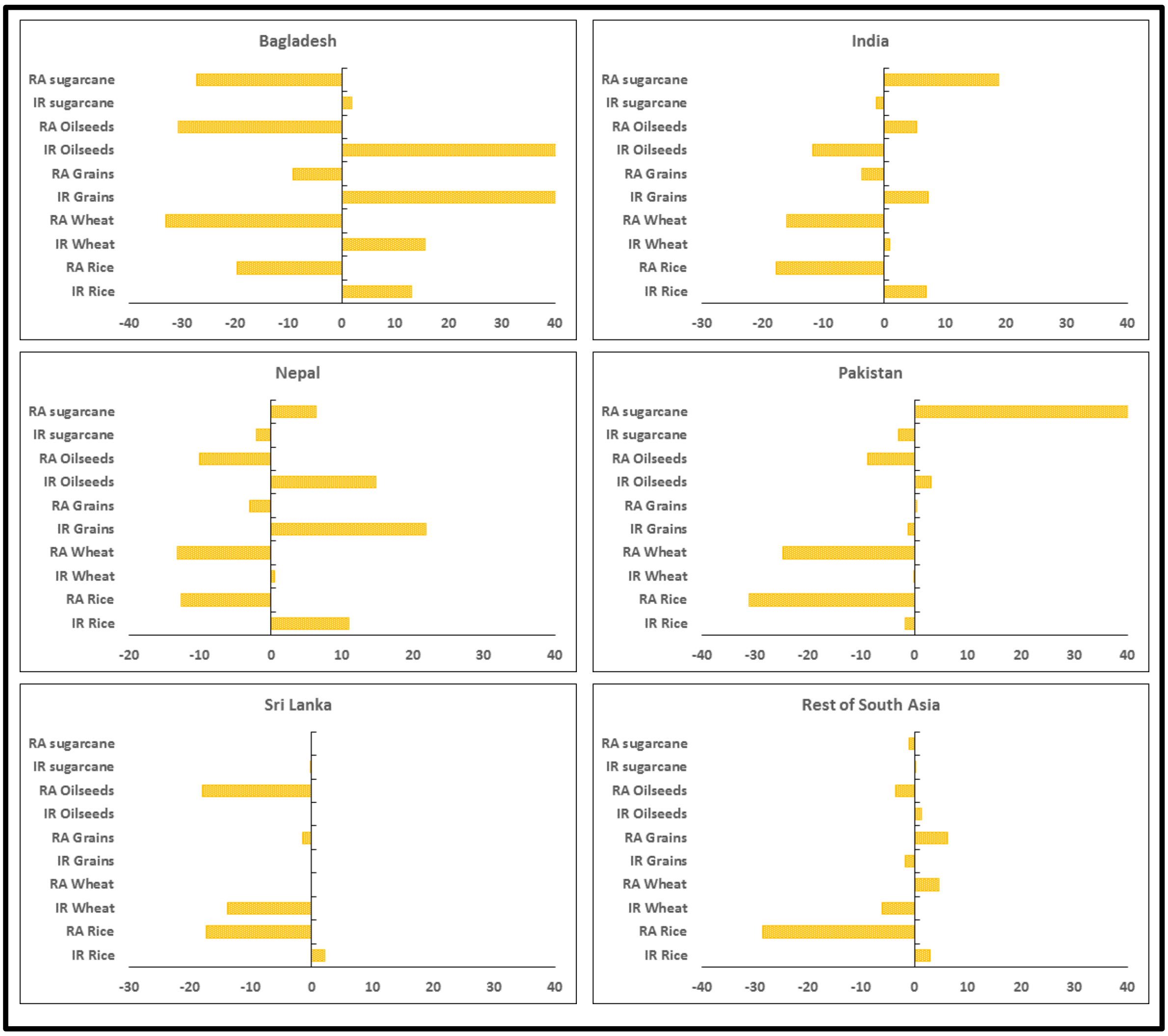


Figure 10. Percent change in irrigated and rainfed crop outputs due to climate-induced crop yield changes, if water supply is unlimited (IR and RA stand for irrigated and rainfed, respectively)

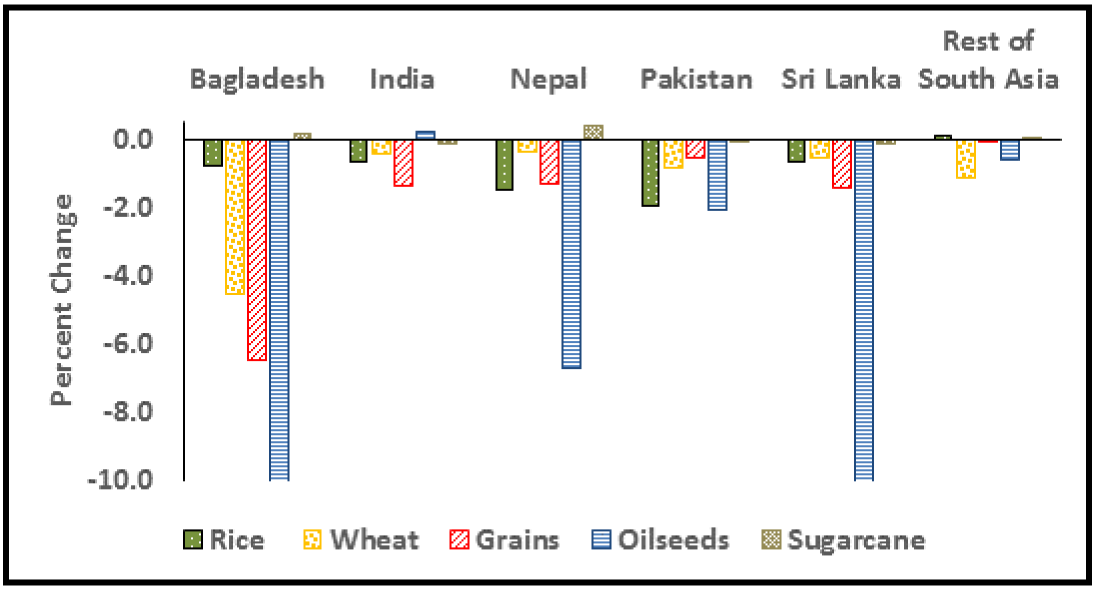


Figure 11. Percent change in crop outputs due to climate-induced crop yield changes, if water supply is unlimited

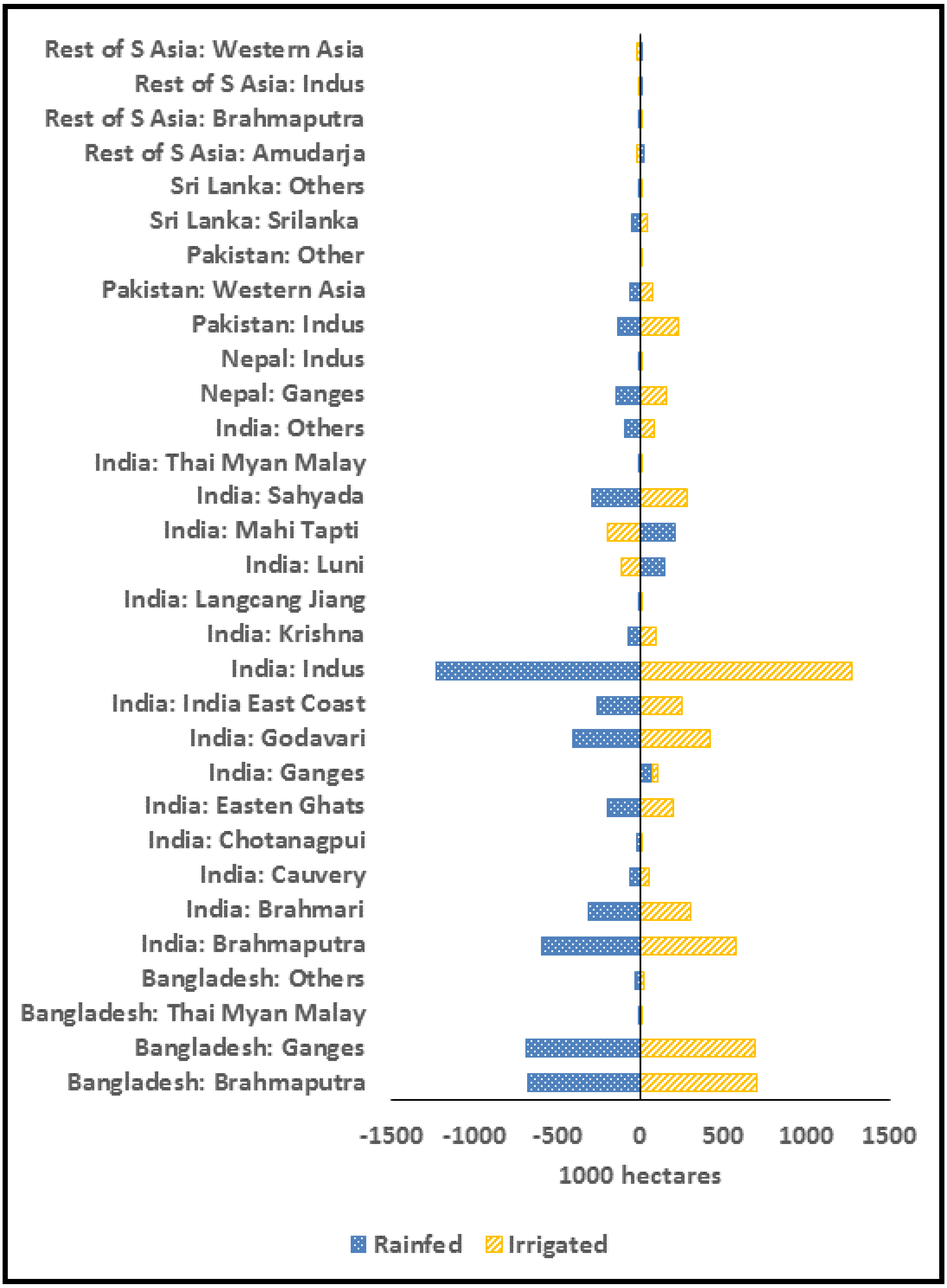


Figure 12. Percent change in the mix of irrigated and rainfed harvested areas due to climate-induced crop yield changes, if water supply is unlimited in South Asia

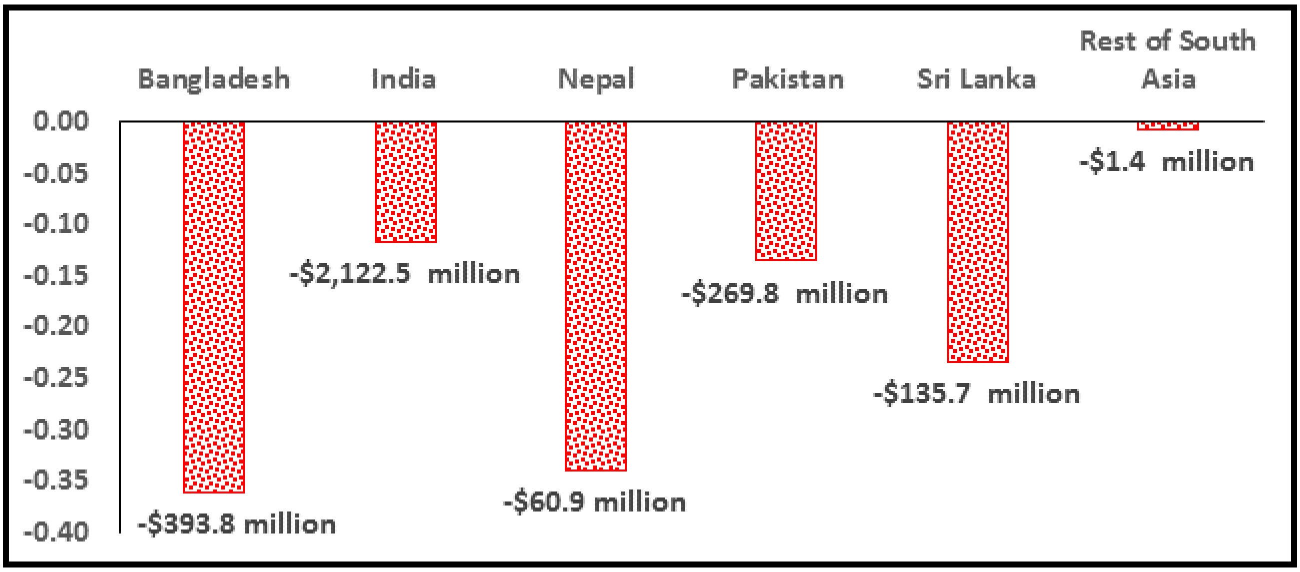


Figure 13. Percent change in GDP due to climate-induced crop yield changes, if water supply is unlimited (figures on the bars represent monetary values of changes at 2011 constant prices)

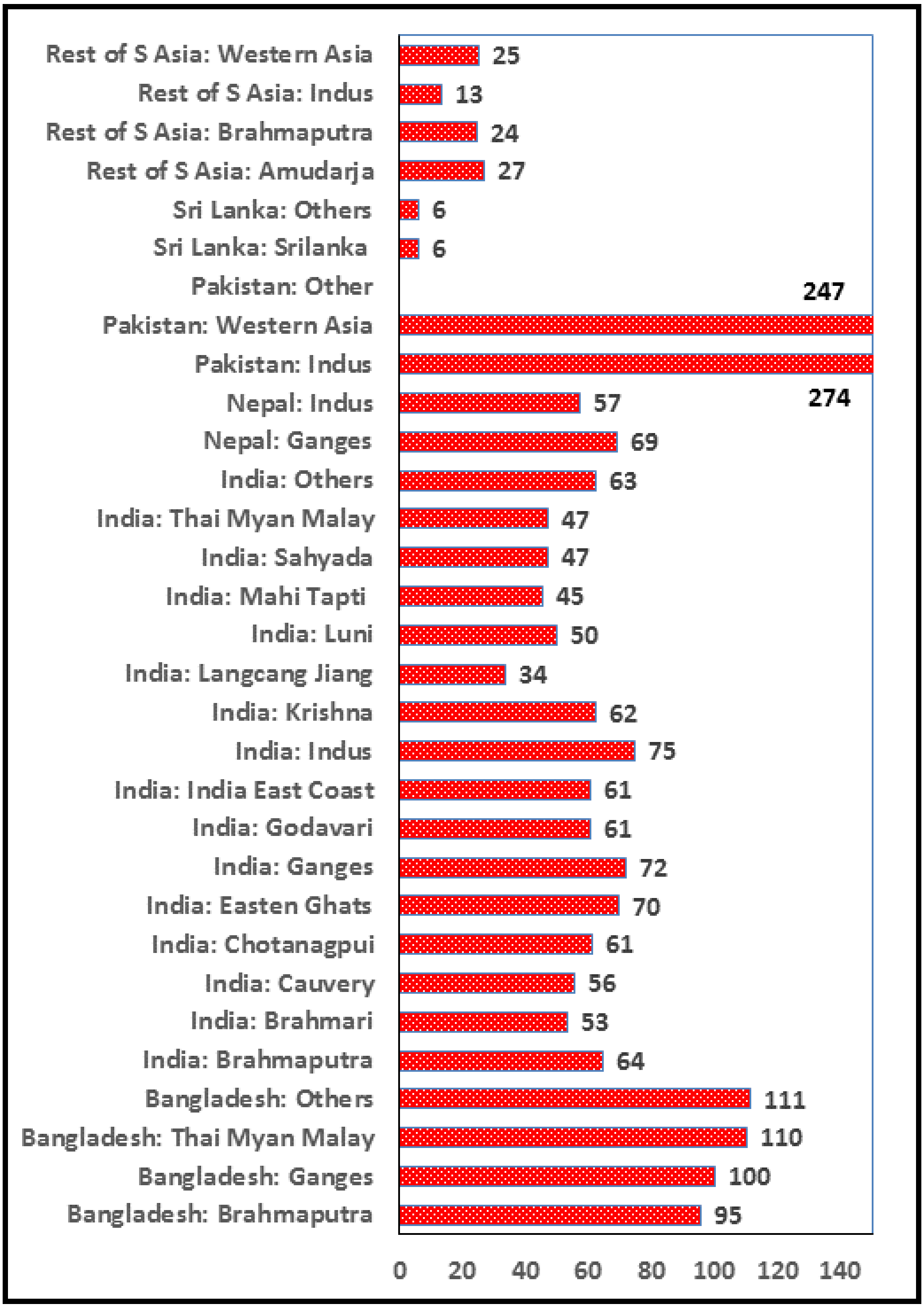


Figure 14. Percent change in price of water across South Asia by river basin due to water scarcity and climate-induced crop yield changes (figures of Western Asia and Indus basins in Pakistan are out of scale)

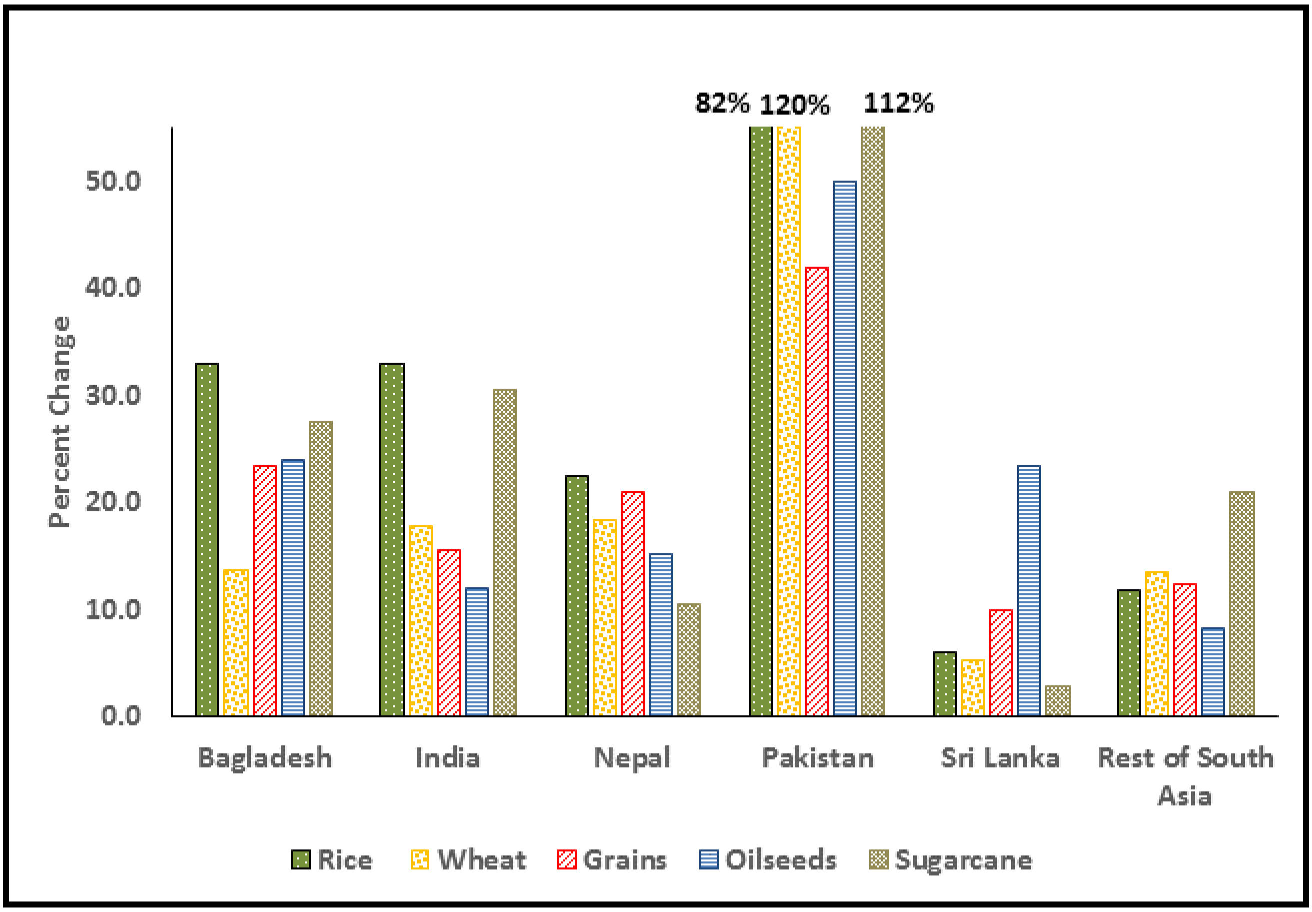


Figure 15. Percent change in crop price across South Asia due to water scarcity and climate-induced crop yield changes (figures of rice, wheat, sugar crops in Pakistan are out of scale)

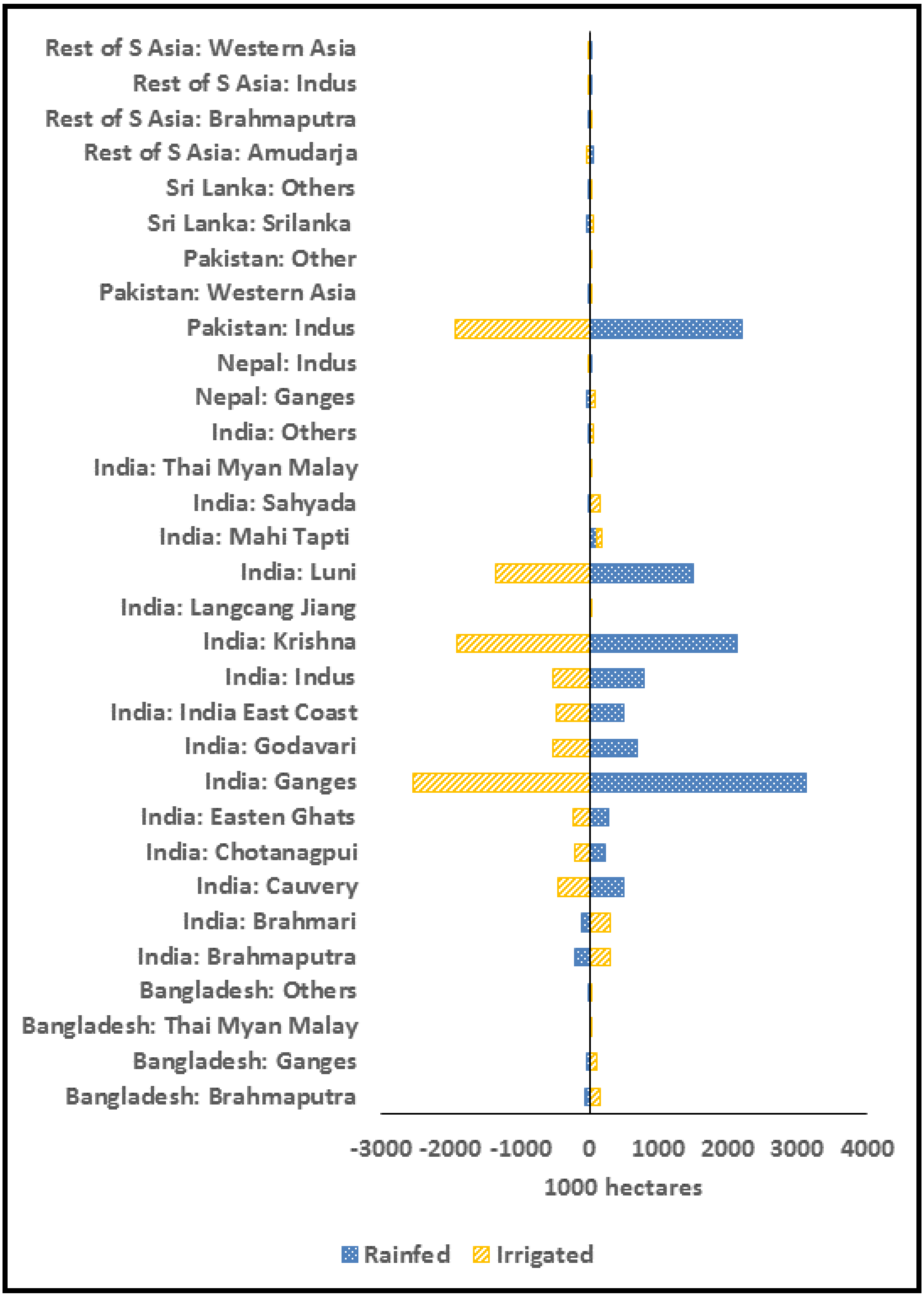


Figure 16. Percent change in the mix of irrigated and rainfed harvested areas due to climate-induced crop yield changes and water scarcity in South Asia

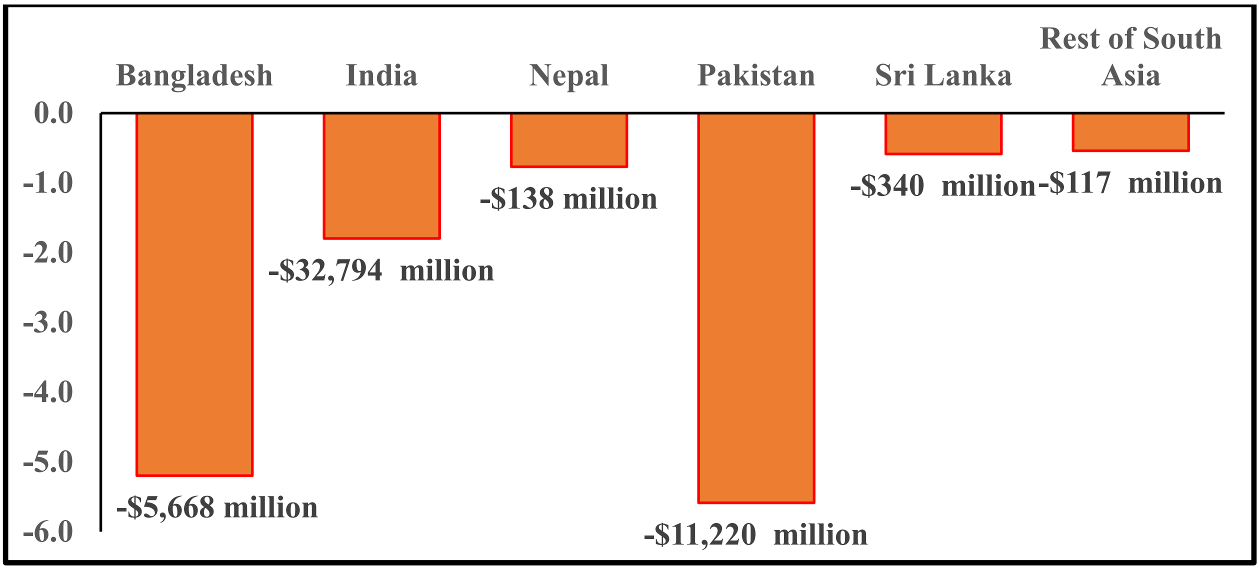


Figure 17. Percent change in GDP due to water scarcity and climate-induced crop yield changes (figures on the bars represent monetary values of changes at 2011 constant prices)

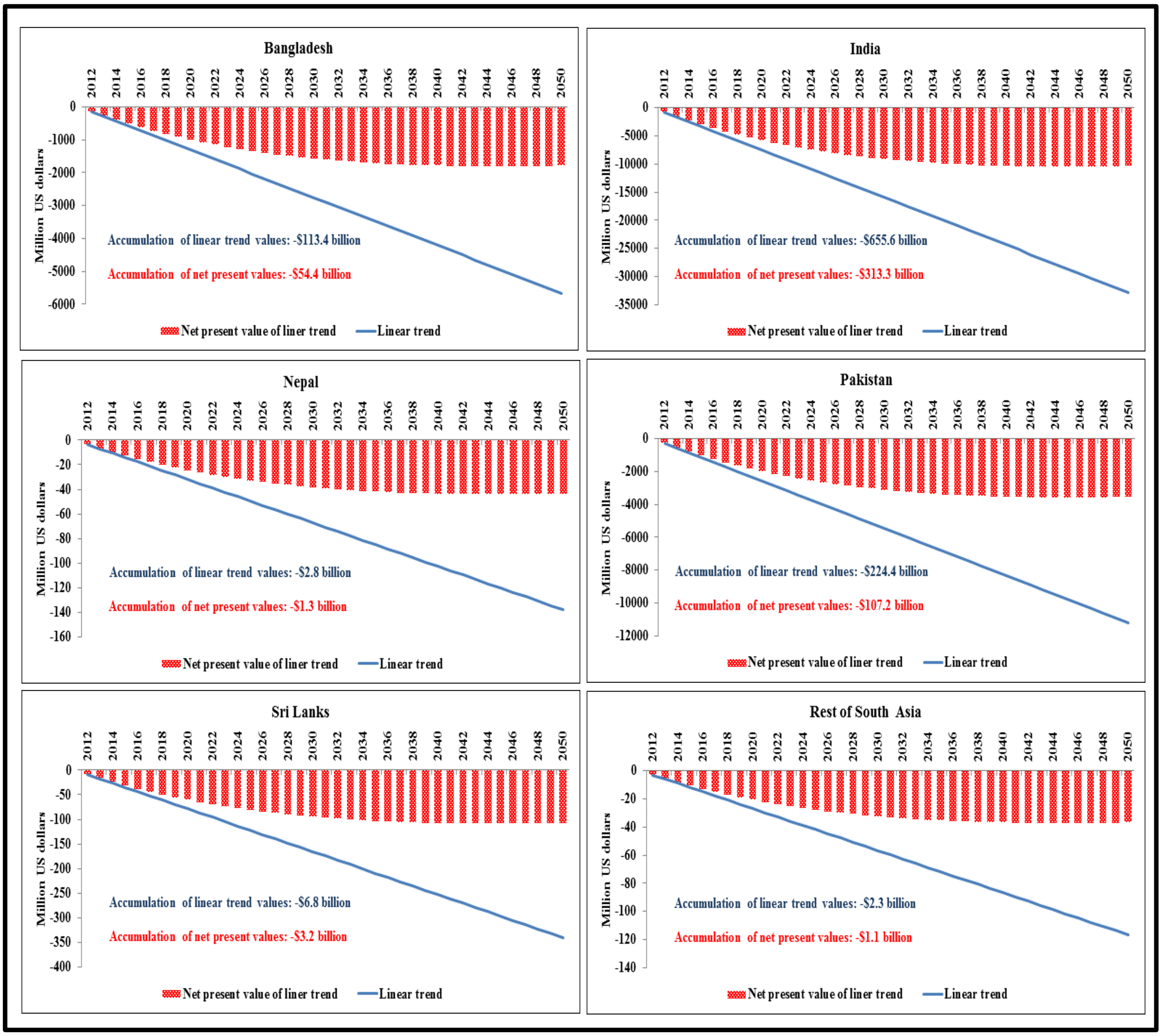


Figure 18. Percent change in GDP due to water scarcity and climate-induced crop yield changes (figures on the bars represent monetary values of changes at 2011 constant prices)

Chapter 5: Exploring the energy-water-food-climate nexus for the Indian Economy in 2050

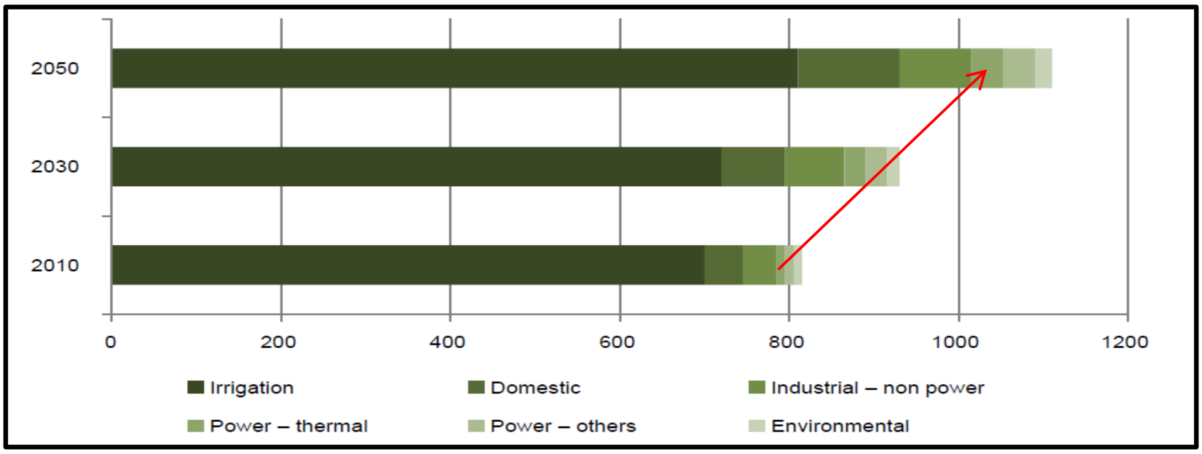
5.1. Introduction

The economy of India is expected to face serious water supply challenges over the coming decades. Population growth, coupled with economic growth of nearly 7% per year until 2050 will translate into strong growth in demand for water, if India continues to use water as usual. Currently, India does not use its water resources efficiently. Water use efficiency (WUE) in irrigated agriculture in India (the second world largest irrigated crop producer, following China) is just about 38% [1]. The corresponding figures for US, UK, and Australia are 55, 77, and 71% [1]. We already explained potential of irrigation WUE and its impact on India's economies in Chapter 4 although industry's share to total water use in India is relatively small, rising water demand for industrial works will intensify competition with other usages. With trend of rapid economic growth, it is envisaged that indusial water demand will also rise three folds of 2010 by 2050 (Central Water Commission, 2008). Water use efficiency in industrial uses is also low in India. For example, India was producing $7.5 industrial products per cubic meter of water in 2001 [2]. The corresponding figures for Brazil, Argentina, and South Korea were $23.4, $30, and $95.6 in the same year [2]. Among major industries, thermal power plant's share to total industrial water use is the highest, accounted 88% (CSE, 2012). The water use efficiency of Indian thermal power plants is - low as well. For example, the Center for Science and Environment (CSE) argues that water use by Indian once through wet cooling coal power plants on average is 8 times higher than the water use by modern wet cooling thermal power plants [2]. In view of the availability of water smart cooling technologies and financially stable corporate structure, thermal power generation sector has more advantage compared with other sectors to improve water use efficiency in short run.

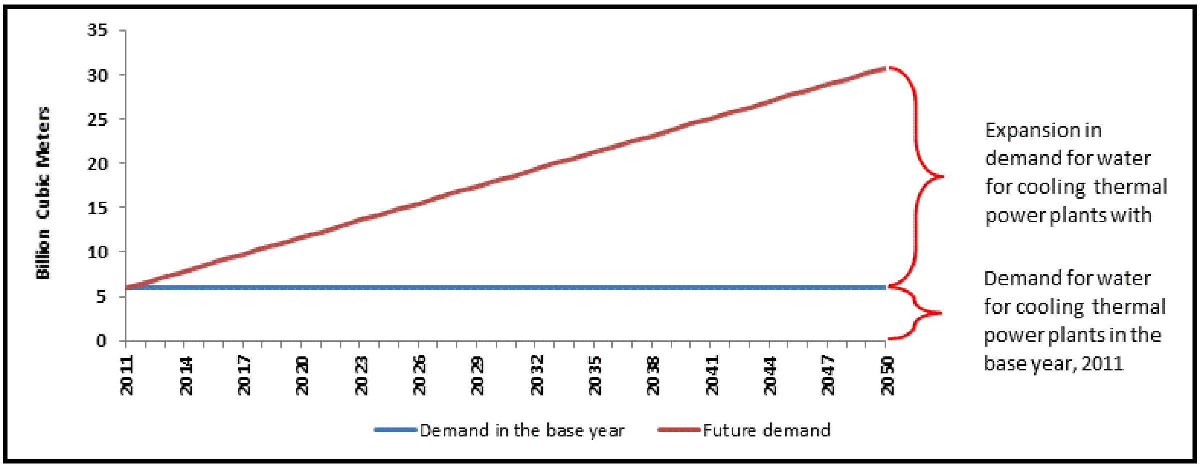
By improving water efficiency in power plants India can minimize growth in the demand for water. This chapter examines water saving in electricity generation – a major water using sector in India.

5.2. Water saving in electricity generation

A recent study conducted by the Institute for Global Environmental Strategies (IGES) shows that the electricity sector's claim on total available water could grow from 4% to more than 10% in India in 2050, if the use of wet cooling technologies persists [3]. This research indicates that water demand for cooling thermal power plants will increase from about 6 billion cubic meter in 2011 to about 31 billion cubic meter in 2050 (for details see Figure 1). Water-saving, dry cooling technologies (e.g. water smart closed dry loop and dry closed loop technologies), are available to cut significantly demand of thermal power plants for water. This means that India can save significant amount of water by adopting these water smart cooling technologies. This could help India to better manage risks of future water scarcity due to climate change. But, this requires significant investment and must be done at the time of construction of new power plants. Producing electricity using dry cooling technologies increases production costs of electricity because the new technologies are more capital intensive. In addition, dry cooling power plants are less energy efficient and hence use more fuels and generate extra GHGs emissions compared to the wet cooled generators. Hence, while water-saving dry cooling technologies could significantly cut demand for water and help India to mitigate future water scarcity, they are costly and significantly increase demand for capital, an essential input for economic growth. In this chapter, we study costs and benefits of adopting dry cooling technologies for the economy of India. To accomplish this task we used the GTAP-BIO-W model explained in chapter 2.



India's Water demand by major uses (Source: IGES)



India's Water demand for cooling thermal power plants

Figure 1: Projected water demand for cooling thermal power plants 2011-2050

5.3. Research method and experimental design

If India continues to use old type of wet cooling thermal plants, demand for water for electricity generation will increase as the economy grows in future. To estimate future demand for water to cool down thermal power plants we relied on the research developed by the IGES [3]. The IGES projected the electricity installed capacity by the type of generator and by river basins until 2050. It also provided data on water used for cooling power plants. We used this information to estimate demand for water for wet cooling power plants in 2050 by river basin. The results presented in Figure 2 in percent change compared with the base year (2011). This figure shows that demand for water for cooling thermal power plants increases significantly in Brahmani (by 1,622%), Eastern Ghats (1,600%), Krishna (447%) and many other river basins by significantly large percentage changes.

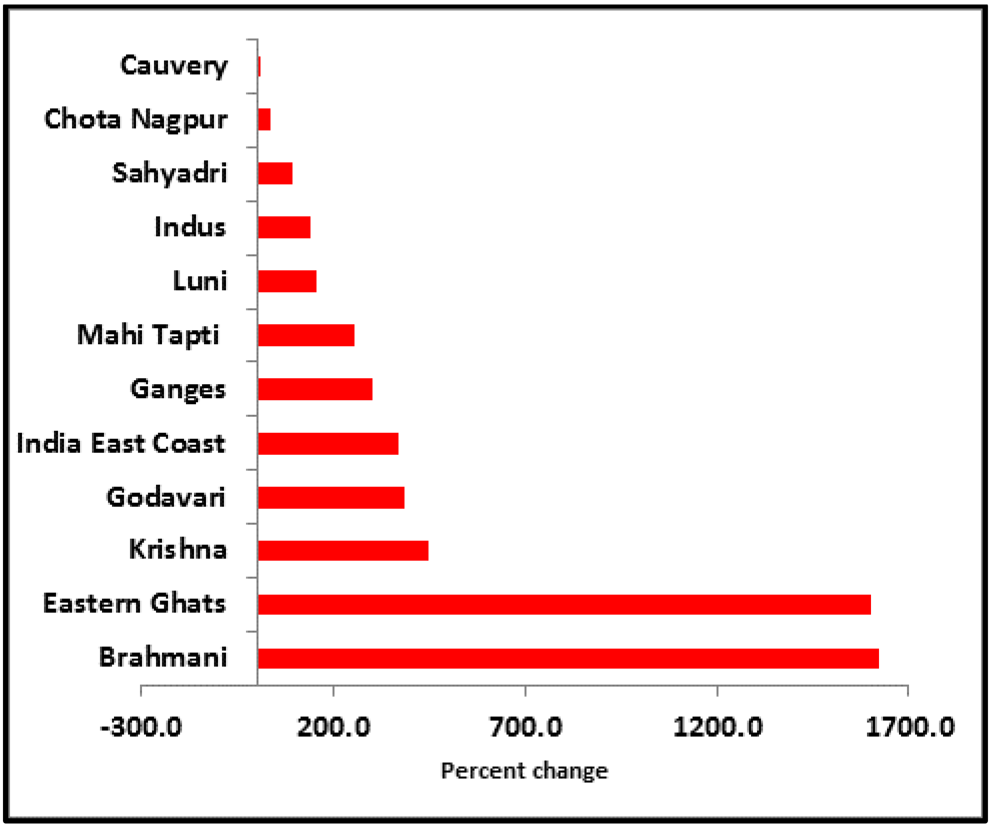


Figure 2: Expansion (%change) in water demand for cooling thermal power plants by river basin, 2011-2050

When supply of water is limited, the expansion in demand for water for cooling power plants increases the intensity of water scarcity. In the presence of water scarcity, the expansion in water demand for electricity may well lead to the reduction in water supply for irrigation, which is typically the residual claimant on water supplies. This possibility which is shown in Figure 3 indicates that water supply for irrigation goes down significantly in Eastern Ghats (-77%), Brahmani (-15%), India East Coast (-11%), and many other river basins.

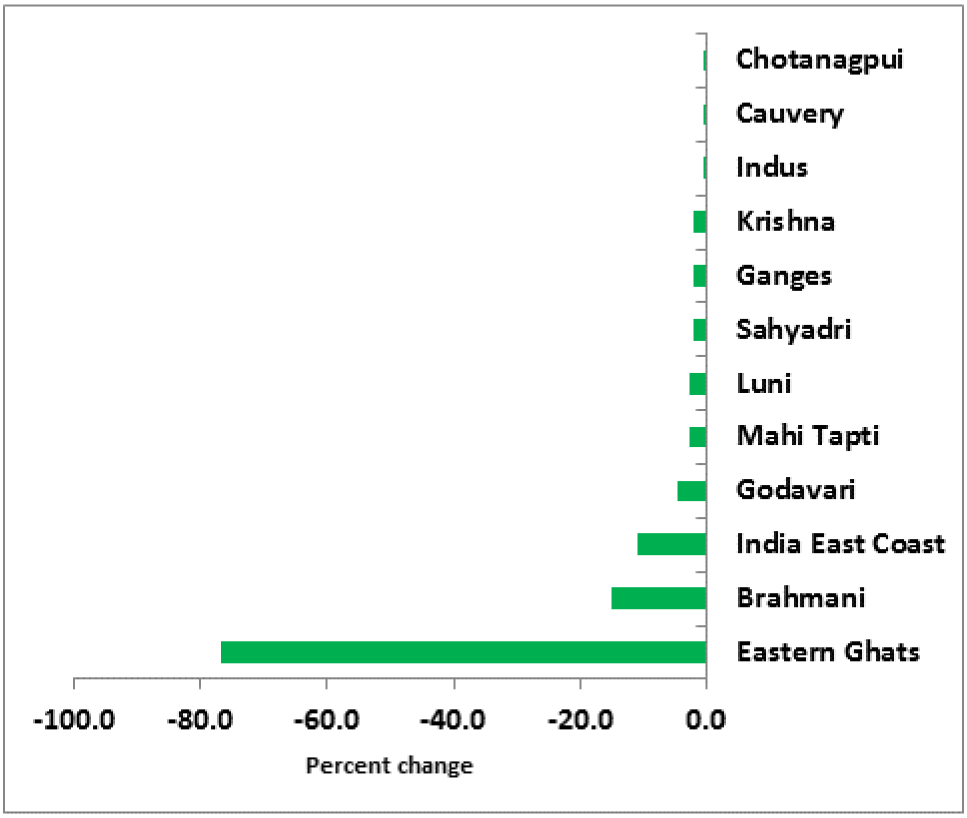


Figure 3: Reduction (%change) in water for irrigation due to electricity production using wet cooling generators by river basin, 2011-2050

To examine the consequences of the reduction in water supply for irrigation induced by the expansion in water demand for cooling thermal power plants we developed the following to experiments:

Experiment I. Water scarcity leads to reduction in available water for irrigation due to expansion in water demand for electricity production, if old type of wet-cooling technology is used

This experiment examines consequences for energy, water, land and food of expansion in water demand for cooling thermal power plants if India continues to use wet cooling technologies in future. To conduct this experiment, we took the following steps.

1. Expansion in demand for water for cooling power plants by river basin (presented in Figure 2) is considered as reduction in water supply for irrigation by river basin (presented in Figure 3).
2. The reduction in water supply for irrigation by river basin is introduced to the economy of India as exogenous shock in available water for irrigation, while we assume water supply remains unchanged for other economic activities.
3. The GTAP-BIO-W model is used to evaluate the consequences of projected irrigation shortfall due to expansion in water demand for electricity production on the overall performance of India's economy.

Experiment II. Reduced demand for water for cooling due to adoption of new dry cooling technologies under varying costs of new dry cooling technologies.

This experiment examines the economy-wide costs of shifting to dry cooling technologies. If India shifts to dry cooling technologies to meet future demand for electricity, more water will be available for irrigation. However, building dry cooling power plants requires more capital compared to the wet cooling generators. Hence, less capital resources will be available to be used in other economic activates and that will lead to lower economic growth. This experiment analyses the gains and costs of using dry cooling power plants under varying adoption costs. To conduct this experiment we took the following steps:

i. From the first experiment we know the expansion in water for irrigation by river basin if India shifts to dry cooling technologies in future.

ii. The extra demand for capital is calculated for alternative capital intensity assumptions of dry cooling electricity.

iii. Finally, we used the results of the above steps and the GTAP-BIO-W model to evaluate the economy-wide impacts of build new dry cooling power plants for electricity production for the time period of 2011-2050.

In the rest of this chapter we analyze the simulation results of these two experiments. Before presenting the simulation results, it is important to note that the results obtained for the first experiments mentioned above could be different from the simulations results provided in Chapter 5. Here we only concentrate on water scarcity due to the expansion in water demand for cooling thermal power plants and that could be different for a the general water scarcity developed in Chapter 5.

5.4. Simulation results: *Experiment I*

5.4.1. Impacts on food production and price

The simulation results obtained from the first experiment indicates that water scarcity due to expansion in electricity water demand reduce India's food production by about $3,386 million in 2050 at 2011 prices (for details see Figure 4). Assuming a linear trend, the sum of losses in food production for the time period of 2011-2050 will be about $77.7 billion at 2011 prices. In chapter 5 we observed that India's food supply decreases by about $417.23 billion due to an overall water scarcity during the same time period. Hence, a large share of food lost (about 19%) due water scarcity is associated with water demand for cooling thermal power plants. As shown in Figure 5 water scarcity due to expansion in electricity supply negatively affect production of crops, livestock, and processed food item.

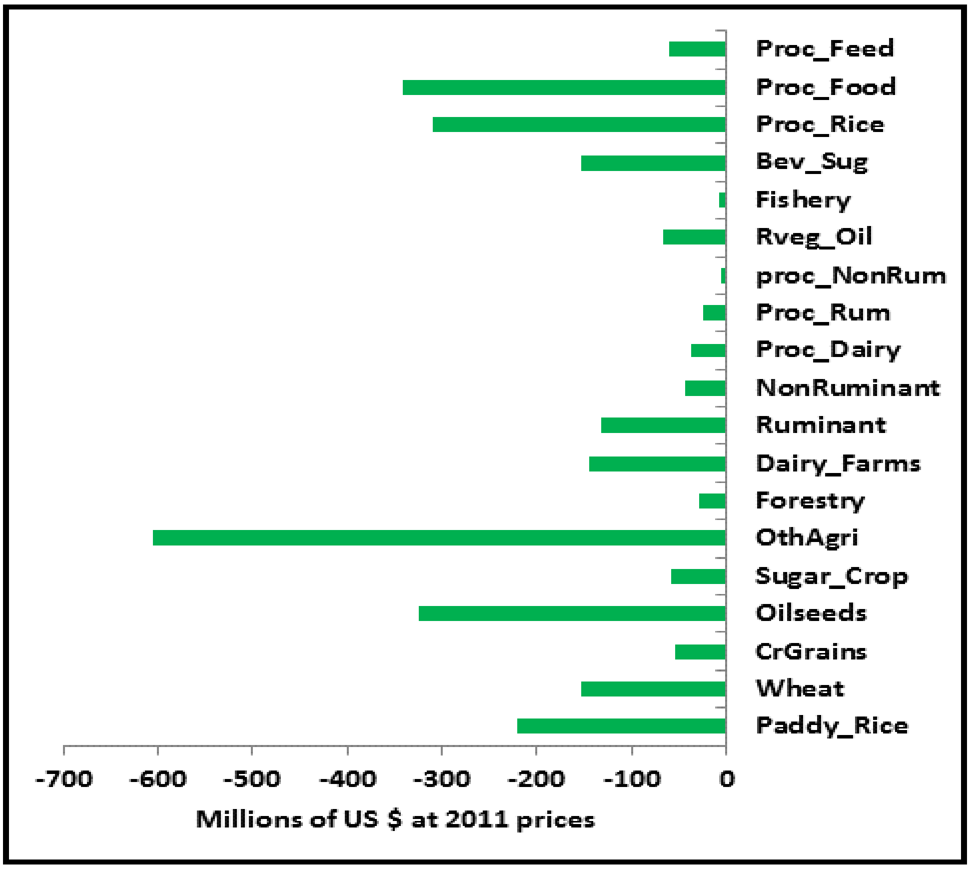


Figure 4: Reductions in food products in 2050 compared to the baseline due to expansion in water demand for cooling power plants (Other Agriculture (OthAgri) is downscaled by a factor of 0.5)

The impact of water scarcity due to the expansion in electricity water demand will translated to increase net food imports of India in 2050 by about $999.2 million (for details see Figure 5). Again assuming a linear trend, the sum of additional imported food during the time period of 2011-2050 will be about $19,983 billion at 2011 prices.

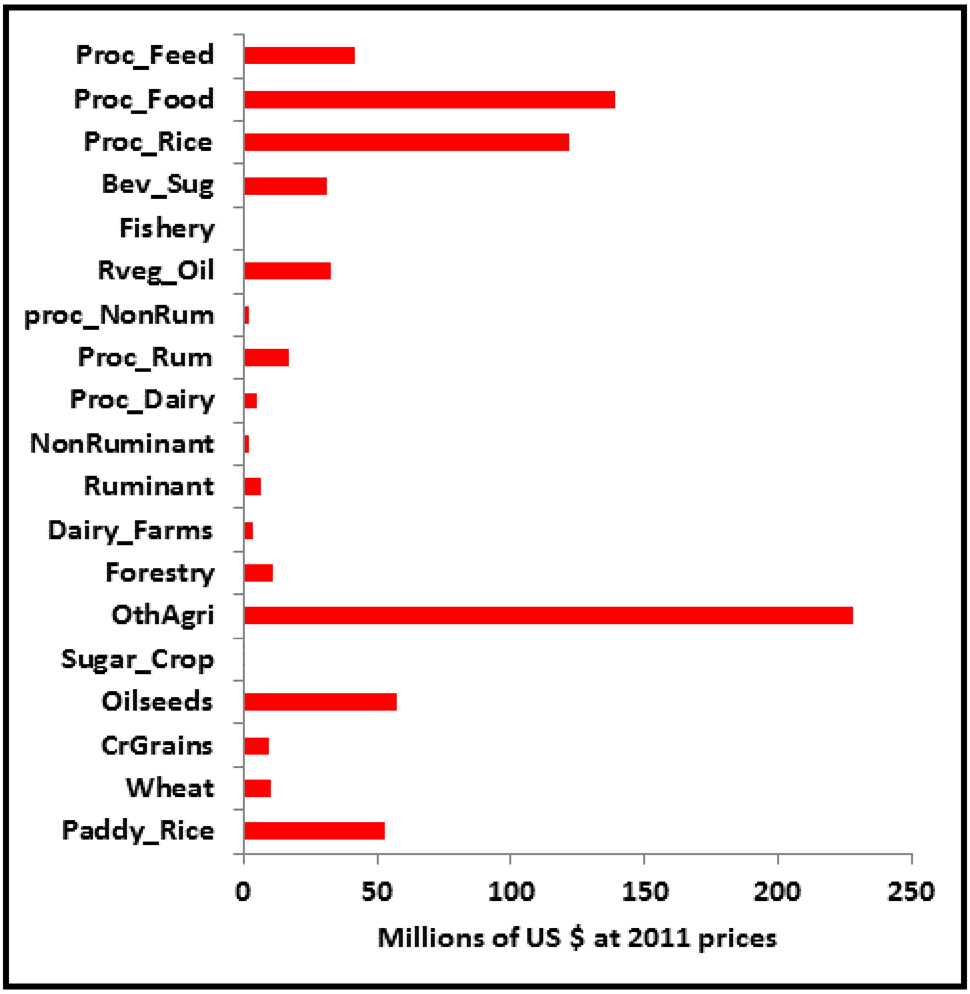


Figure 5: Increases in net imports of food products in 2050 compared to the baseline due to expansion in water demand for cooling power plants (Other Agriculture (OthAgri) is downscaled by a factor of 0.5)

In addition to reduction in outputs of food products and expansion in their net imports, the impact of water scarcity can lead to increase food prices. As shown in Figure 6 food prices increase up to 3.5% (for paddy rice and sugar crops) in 2050 due to expansion in electricity water demand. The increases in food prices are not very large.

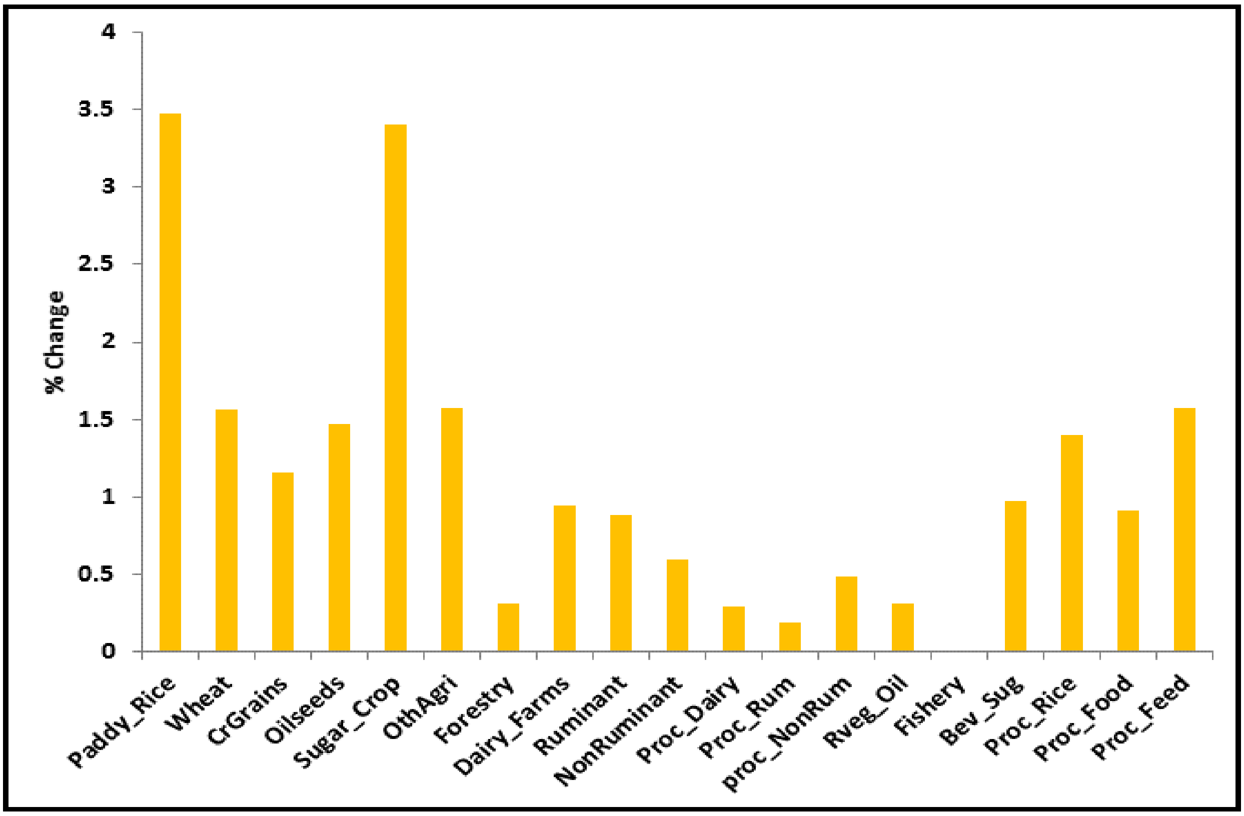


Figure 6: Price impacts of water scarcity due to expansion in water demand for cooling thermal power plans

5.4.2. Land use impacts

In chapter 4 we learned that an overall water scarcity could increase the demand for cropland by 1,540 thousand hectares at national level. The simulation results obtained from the experiment I indicates that water scarcity due to the expansion in demand for water for cooling power plants increases the demand for cropland by about 248.8 thousand hectares. We can therefore conclude that expansion in demand for cooling thermal power plants has a large share (about 16.2%) in induced land use changes due to water scarcity.

In chapter 4 we also observed that water scarcity can lead to expansion in rainfed agriculture. Water scarcity due to growth in demand for water for cooling thermal power plans generates a similar impact as shown in figure 7. This figure represents changes in irrigated and rainfed areas by river basin across India. This figure that major changes in the mix of rainfed and irrigated areas are expected to occur in India East Coast, Ganges, and Eastern Ghats.

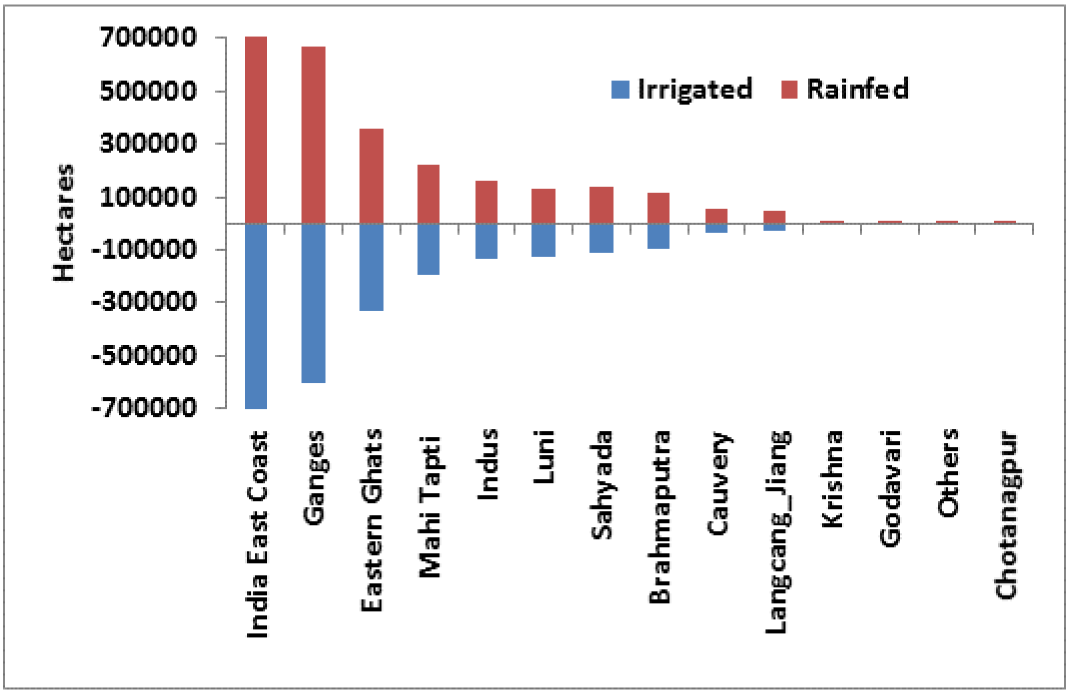


Figure 7: Land use impacts of water scarcity due to expansion in water demand for cooling thermal power plans, 2050 compared to 2011

5.4.3. Economy wide impacts

The simulation results obtained from the first experiment indicate that the overall opportunity cost (welfare lost) of using wet cooling power plants is about \$3.3 billion in 2050. With a 3% discount rate, the net present value of welfare losses for the time period of 2011-2050 will be about \$31.6 billion at 2011 prices.

5.5. Simulation results: *Experiment II*

In the first experiment we examined the costs of water scarcity, if India continues to use old type of wet cooling for power plants with no technological progress in saving water in thermal plants. In the second experiment, we examine the benefits of water saving if India shifts to dry cooling power plants while we take into account the extra investment costs that India should pay for this shift.

While many generators in India use more than 6 cubic meters (1,585 gallons) of water per MWh of power, newer wet and dry cooling power plants use less water [4] as shown in figure 8. For example, this figure shows that dry cooling plants use only negligible amounts of water.

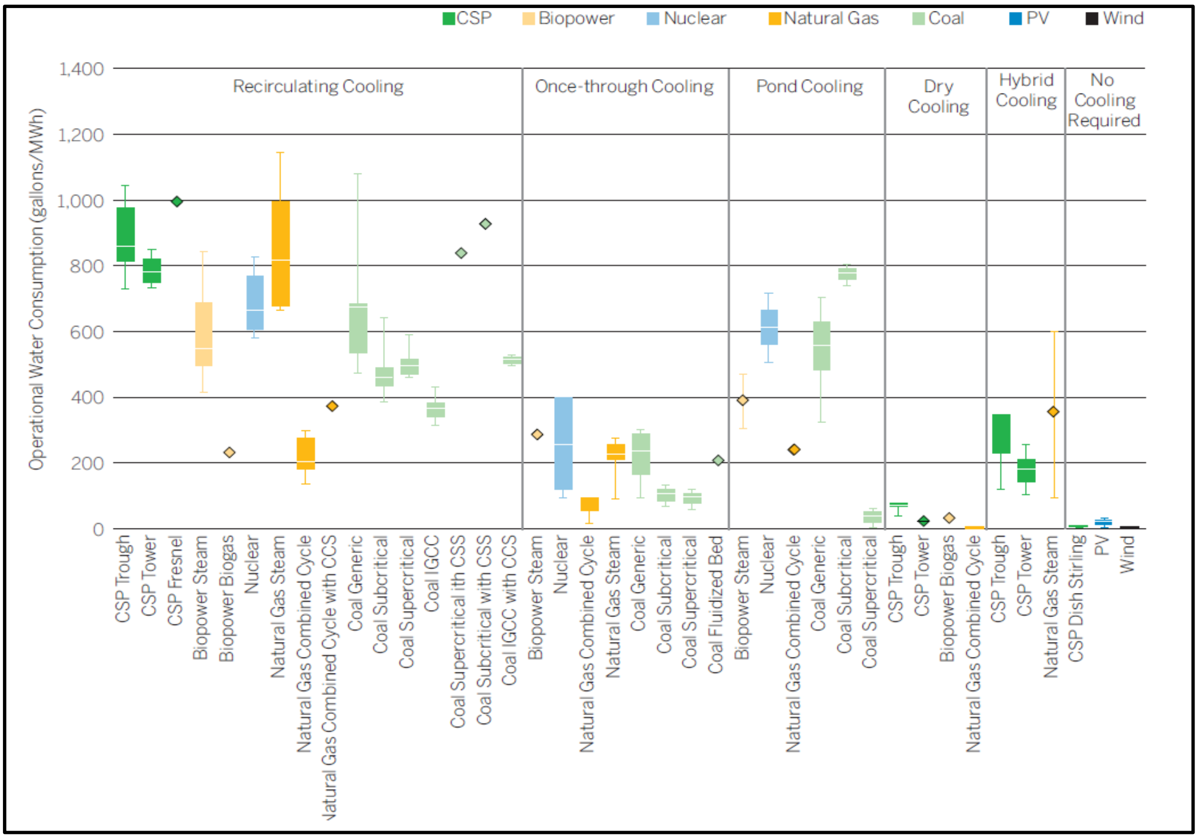


Figure 8: Water requirement for power generation, Source: World Bank [4]

Of course, if there is no extra cost to shift to the dry cooling generators, India could save lots of water and avoid welfare and production losses due to expansion in demand for cooling thermal power (a mirror image of experiment I). In that case the net gain in 2050 will be about $3.3 billion. However, the dry cooling power plants are more capital intensive and less energy efficient. This means that compared to the wet cooling technology extra amounts of capital are needed to switch to the dry cooling technology and drop the extra demand for cooling power plants for the same level of electricity production.

Now consider a case when switching to dry cooling power plants requires 2% more investment costs compared to the wet cooling technologies. In this case the economy gains from added water for irrigation due to water saving in power plants, but it needs more capital to produce electricity. Our simulation results indicate that in this case the net gain of switching to the dry cooling is about $1.3 billion for 2050. If the extra required investment goes up to 4%, then the net gain turns to -$.4 billion and for a 6% difference the net gain drops down to -$2 billion. This is higher than the cost of staying with wet cooling power plants (-$3.3 billion). We repeated this experiment for 8% and 10% and extra investment as well. As shown in Figure 9, from this analysis, we can conclude that the breakeven capital costs difference between the wet and dry cooling technologies is about 7.5% for economy of India. In other words, if switching to dry cooling boosts the cost of new capacity by about 7.5%, it would contribute to a decline in welfare, according to this analysis, which factors in the benefits of enhanced water availability for irrigated agriculture.

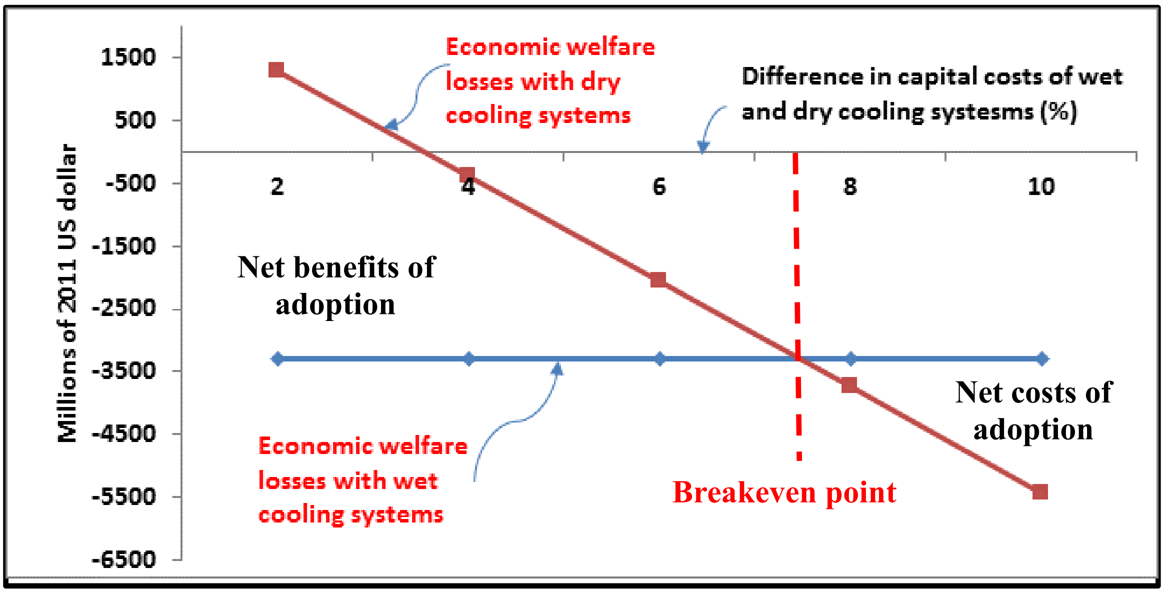


Figure 9. Breakeven capital cost differential between the wet and dry cooling technologies

If India shifts to dry cooling power plants to save water consumption, since dry cooling power plants are more capital intensive, then the demand for capital compared to other primary inputs goes up and therefore the price of capital versus labor will increases as shown in Figure 10. This figure shows that, when shifting to dry cooling does not need extra capital, the relative price of capital versus real wage rate (for unskilled labor) drops. However, when the shift to dry cooling is not free, then the relative price of capital goes up with the difference between capital costs of wet and dry cooling systems. This means than shifting to dry cooling could alter the relative price of primary inputs in favor of capital as is expected with a capital-intensive investment of this sort.

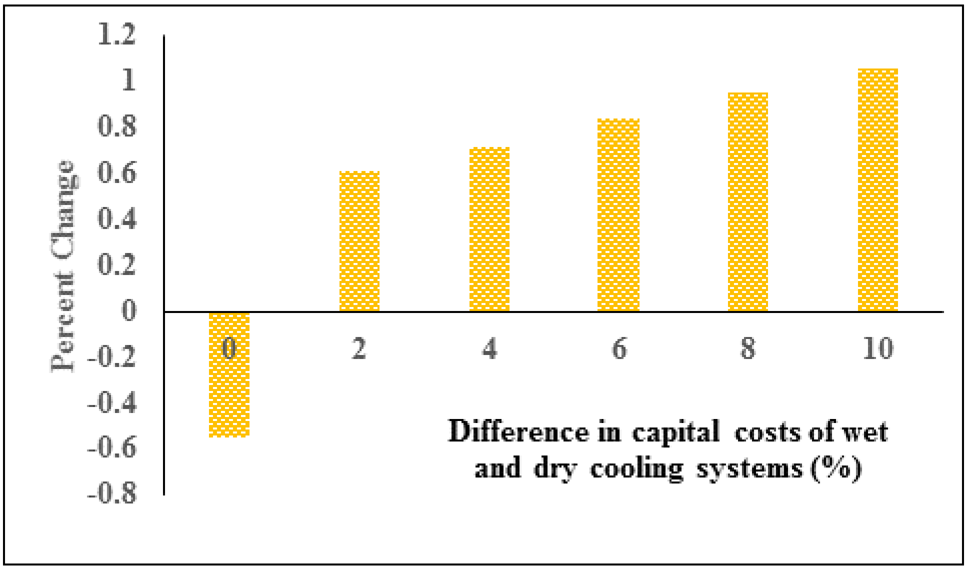


Figure 10: Change in relative price of capital versus unskilled labor due to shifting to dry cooling power generators in India

5.6. Conclusions

In this chapter, we first examined the impact of future expansion in demand for electricity in India on water scarcity and its economy wide impacts, if this county continues to use wet cooling thermal power plants. Then we analyzed the benefits of saving in water consumption by using dry cooling power generators which use small amount of water to run. From our analyses we learned the following.

- The increase in electricity production is likely to increase water scarcity in India,
- The share of electricity in overall water scarcity is large,
- The intensity of water scarcity is not uniform across river basins,
- Expansion in water demand for cooling thermal power plant will intensify water scarcity in Eastern Ghats, Brahmani, and India East Coast more than other river basins,
- The expansion in water scarcity due to expansion in supply of electricity could significantly harm crop outputs and food products through reduced water availability for irrigation,
- A large share of food lost due overall water scarcity is associated with water demand for cooling thermal power plants.
- In response to water scarcity, net imports of food will increase,
- While water scarcity increase net imports of crops and food products, these imports help to mitigate the consequences of water scarcity.
- Without trade the economy of India will suffer greater losses due to water scarcity,
- Dry cooling technologies could help to cut demand for water. However, dry cooling electricity generators need more capital.
- The breakeven capital cost differential between the wet and dry cooling technologies is about 7.5% for the economy of India. If dry cooling costs more than this additional increment, then this analysis suggests that the gains from additional water for agriculture are insufficient to justify this investment.
- Since building dry cooling power plants is more capital intensive than building the wet cooling generators, shifting towards dry cooling could change the relative prices of primary factors in favor of capital.

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6. Conclusions

This report shows how the prospects for development in South Asia are likely to be affected by the way in which water is used, especially for agriculture. The growth in demand for food will increase the demand for water, making it scarcer. If present levels of efficiency in water use and present policies for allocating water, are not changed this scarcity will be cause a decline in food production, an increased dependence on imports, higher food prices and a decline in GDP by 2050 relative to the case where there is no scarcity. These impacts will occur irrespective of any climate change. When the effects of climate are included to those of scarcity, the effects vary across river basins but the overall national impact on GDP and food prices is notably greater.

The results are tested for sensitivity by varying the level of water stress by +/- 50%. The effects on declines in GDP are generally small (ranging from practically zero to 6-7%), with the exception of Pakistan, where the range is +/-26%.

The case for some policy change to improve water use efficiency and take other measures to reduce water demand is therefore very strong and the potential for doing so is also clear. Measures to improve use of water in irrigation have been shown to be justified, after allowing for the costs of such implementing such measures. One possibility is for the finance for the programs to come from reductions in electricity subsidies to agriculture, a combination that has an overall positive impact on the economy. Another area where water scarcity can be reduced with significant macroeconomic and cross sectoral benefits is by reducing the demand for water for thermal cooling plants.

Further work is needed to evaluate these policy measures in greater detail. One aspect is in terms of the timing of any investments and the time profile of the benefits. Another is the distributional implications of the options and how they may be addressed. The third is a more spatially detailed assessment of where action will be most urgently needed to address water scarcity issues in the face of climate change.