CGE-W: an Integrated Modeling Framework for Analyzing Water-Economy Links Applied to Pakistan

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Abstract. This paper describes a linked model system consisting of a dynamic economywide Computable General Equilibrium (CGE) model and a regional water system model (RWSM). The combined CGE-W model is applied to Pakistan to analyze the economywide impacts of changes in water resources in the Indus river basin, focusing on water "shocks" such as droughts. The CGE-W model is regionally disaggregated with a number of crops and includes the impacts of water stress on agricultural productivity. The RWSM model applied to Pakistan (RWSM-Pak) is a new water basin simulation model that starts from the Indus Basin Model Revised (IBMR) for Pakistan first developed by the World Bank. RWSM-Pak is designed to manage the water system (reservoirs and canal system) under different scenarios of river flows and competing demands (provided by the CGE model). The CGE model is disaggregated to incorporate water demand and the impact of water shortages on crops. Both models simulate long-run economic growth and changes in water resources, supporting analysis of long-run climate change scenarios, and are designed to work together as an integrated model system. The CGE-W model framework combines the strengths of the component economic and water models, without having to make compromises typical of water models that incorporate simple economics or economic models that include water in a simplified manner. To illustrate the use of the model system, we present empirical results for four climate change scenarios and analyze the economic benefits of adding a new dam to the system.

Index Terms: CGE model, climate change, Pakistan, water basin model

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1 Introduction

Dramatic impacts of climate change are likely to be felt through changes in the water system of the planet. Changes in droughts and floods, as well as changes in the seasonality and intensity of precipitation, might disrupt the most fragile agricultural economies. There are numerous studies of the impacts of climate change on both water resources and agriculture.[1] In a country like Pakistan, which is water limited and relies heavily on irrigated agriculture (Briscoe and Qamar, 2005a), the water system is much more complex than can be considered by economic models that incorporate water in a simple manner. Water basin models, on the other hand, track only the direct effects of climate change on the water system and fail to encompass the repercussions on the broader

[1] Reviewed in the Intergovernmental Panel on Climate Change Fourth Assessment Report Working Group II (Parry et al. 2007)

economy. We need to integrate our knowledge of the entire economic system and its links to water systems to consider the challenges posed by climate change. The goal is to link economic and water models, drawing on the strengths of both approaches without having to compromise by either specifying a simplified treatment of water in an economic model or simplified economics in a water model.

The first section briefly surveys earlier water models and economic models that explicitly include water, indicating their shortcomings in studying this class of problems. We then present the Computable General Equilibrium - Water (CGE-W) model framework, which integrates separate water and economic models in a consistent system. Finally, we present results of the application of a CGE-W model of Pakistan, which includes a CGE model and a river basin model of the Indus Valley.

2 History of Water and Economic models

Water system practitioners and economists have a long history of borrowing from each other in their models. Economists recognize that water shortages are important and have tried to capture the impacts in economic models in a stylized manner. Water practitioners have carried out numerous cost-benefit analyses of water projects, with simple models of the economic impact of water availability. There is tension between these two approaches, since the “stylization” of water in economic models and economics in water models do not satisfy either economists or water modelers.

An early example of a CGE model incorporating water is the work by Berck et al. (1990) on the San Joaquin Valley in California. The model considers water as a production factor and incorporates specifications of different fixed land-water technology across crops. Water is allocated by solving a linear programming problem to choose the optimal land-water technology at the bottom of a nested production function within the CGE simulation model. The study analyzes the effects of reducing water input to agriculture on the aggregate Valley economy. Goodman (2000), Dwyer et al. (2005), Diao et al. (2008) and Wattanakuljarus (2006) incorporate water as an factor input in sectoral CES production functions in single-country models, while Berrittella et al. (2007) and Calzadilla et al. (2010) do so in multi-country models. The principal shortcoming of all these models is that water is considered as a yearly flow, thus ignoring the seasonal character of water supply as well as the mechanics of its distribution. Such a model would, for example, be inadequate to measure the impact of a dam whose operation focuses on sub-periods within a year (monthly or finer). A partial answer to this problem is provided by Strzepek et al. (2008) and Robinson et al. (2008), which treat non-substitutable land-water bundles in two-season crop production, using a linear-programming technology for land and water at the bottom of a nested production function, and so incorporate two periods for the Nile flow in Egypt. This approach however would be inadequate for other countries with more complex hydrological systems like Pakistan.

Water basin planners have long incorporated measures of economics in their models to value the effects of proposed water system investments in dams or irrigation systems for cost-benefit analysis (e.g. Hufschmidt & Fiering 1966). An early practical examples at the basin scale is the MIT work on the Rio Colorado in Argentina, described in Major & Lenton (1979), where an optimization model is used for screening relevant projects and a simulation model is used to refine the cost-benefit analysis. These models only incorporate sectors directly affected by water (e.g., agriculture, hydropower) and so only cover part of the economy and cannot capture the indirect effects of water investments (e.g., new dams) across the economy.

In sum, some economic models incorporate water in a stylized manner, but inadequately represent the physical properties and management of river basins, and some water models include economic valuation of water, but are too stylized and inadequately represent indirect effects. The philosophy of the CGE-W model framework is to integrate a disaggregated CGE model which does not include water explicitly with a water-basin model that does not incorporate an economic model. The two models are designed to communicate dynamically, even though they operate with different time steps (annual for the CGE model, typically monthly for the water model). The CGE-W model framework combines the strengths of the component economic and water models, without having to make compromises typical of water models that incorporate simple economics or economic models that include water in a simplified manner.

3 The CGE-W Framework Applied to Pakistan

3.1 The CGE-W Framework

The CGE-W model of Pakistan consists of a CGE model of Pakistan, a water demand module, the Regional Water System Model for Pakistan (RWSM-Pak), and a water stress module. Figure 1 presents the schematics of how the system of models operates year by year. We describe the steps in detail in Section 3.4 below, after describing the component models. All the component models in this implementation of the CGE-W framework are coded in the General Algebraic Model Solver (GAMS), which allows for integrated solution of the suite of models. In principle, the linking of the models can be done within GAMS, but individual component models could be on other computer languages (e.g., Fortran or Matlab) since GAMS allows calling other programs from within a GAMS program.

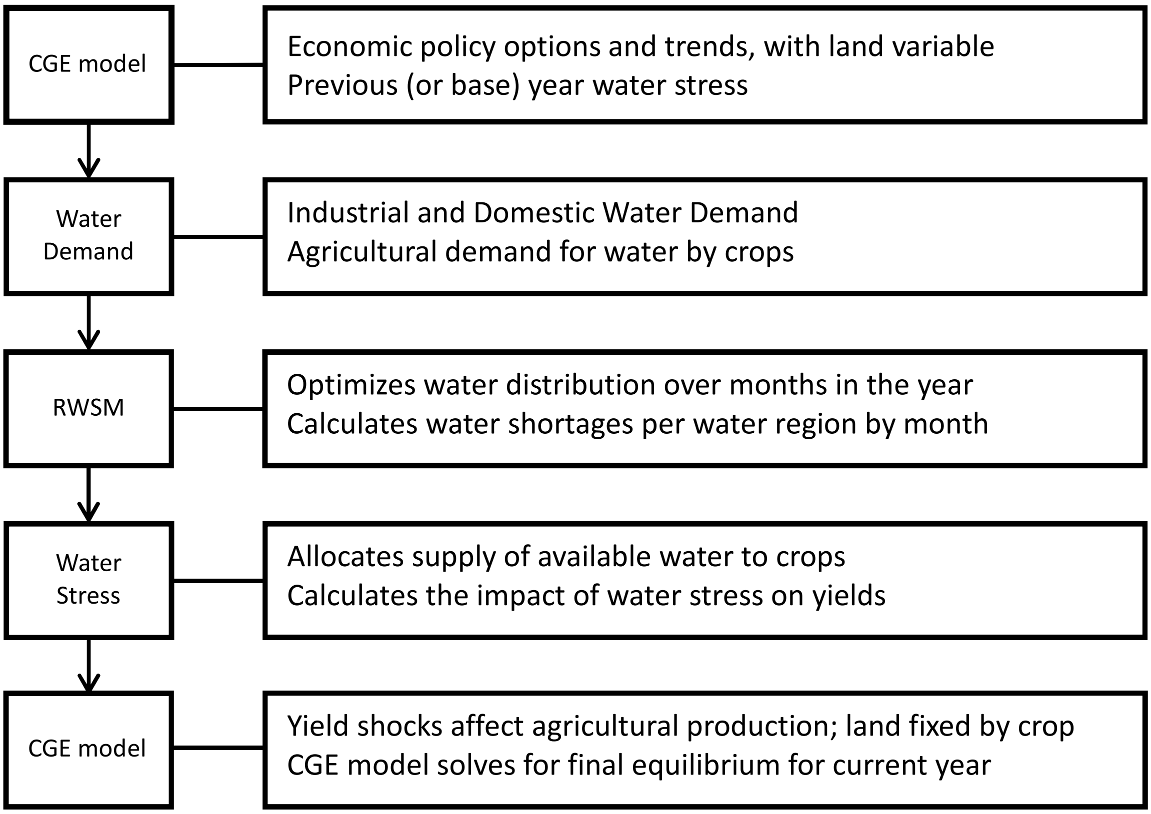

Figure 1. The CGE-W framework: operation of the system of models in a given year.

3.2 The IFPRI Standard CGE Model of Pakistan

CGE models simulate the operation of market economies, specifying the behavior of all relevant "agents" (e.g., producers, households, government) as they interact across markets. They are "complete" models in that they take account of all economic activity in the specified economy. The social accounting matrix (SAM) framework on which these models are based is also complete, taking account of all real and monetized flows in the economy and specifying "balance" in the economic accounts of every agent in the model. Every agent must exactly balance receipts and expenditures, and all markets must clear, with supply exactly equaling demand for all factors and commodities.

In CGE models, producers sell output and purchase factor inputs, with total sales exactly equaling total payments (e.g., payments to factors of production, including value-added and intermediate-input costs). Producers are assumed to maximize profits subject to technology (production functions) and prices of inputs. The first-order conditions for profit maximization essentially define the factor demands and output supply behavior of producers. Households receive income and purchase commodities. Their income from all sources must exactly equal their expenditures. Commodity demand is determined by assuming that consumers maximize utility subject to their income constraints and commodity prices.

CGE models operate by generating the “circular flow” of income and expenditure, tracing all income flows by source and destination: sales revenue to factor payments from producers to households across factor markets; household expenditures from income for commodities across commodity markets; and hence sales revenue back to producers. They solve for simultaneous equilibrium in all commodity and factor markets, yielding equilibrium commodity and factor prices that “clear” these markets.

A CGE model is a “deep” structural model in the sense that it specifies: (1) the actors (producers, households), (2) their motivation (profit maximization, utility maximization), (3) technological constraints (production functions), (4) the signals they respond to (input and output prices), and (5) the institutional structure in which they operate (competitive markets), and finally (6) “system constraints” that include supply-demand balance across all product and factor markets. The deep structural characteristics of CGE models, their grounding in general equilibrium theory, and their consistent and complete SAM data base provide a framework that captures direct and indirect market interactions, incorporates general equilibrium welfare analysis, and supports exploration of scenarios that include changes in policy, behavior and technology at the level of micro agents.

The IFPRI CGE model of Pakistan is based on a SAM developed by Dorosh et al. (2006) and updated by Debowicz et al. (2012). This model includes agricultural detail that allows for a good representation of water shocks on the economy, as well as disaggregated labor and household categories to capture distributional impacts of policies. The model code starts from a new version of the IFPRI standard CGE model (Löfgren, Harris and Robinson, 2001). The shock due to water stress is defined as the ratio of crop yields for the current year compared to the base year. The base year data define the equilibrium of the water system in 2007-2008. In the first run of the CGE model in each year, the external water shock is assumed fixed from the previous year, so farmers anticipate the same level of water stress as in the previous year.

3.3 The Regional Water System Model for Pakistan

RWSM-Pak is a classic water basin management model, but does not include any economic measures. The model covers only the Indus basin, which represents more than 90% of agricultural production in Pakistan. It is largely inspired by the original Indus Basin Model Revised, IBMR (Ahmad et al. 1990; recently updated by Yu et al. 2013). It models the six main rivers of the Indus basin flowing through Pakistan and providing irrigation water—from East to West: the Sutlej, the Ravi, the Chenab, the Jhelum, the Indus and the Kabul—as well as the main dams in the system: Tarbela, Mangla, Chasma and Chotiari. The water is routed through the forty-seven nodes of the Indus system in Pakistan. These nodes include reservoirs, link canals between rivers and barrages for irrigation outlets. Inflows, precipitations, runoff and crop water need data are generated externally by a climate model downscaled to Pakistan using historic data. The routing model takes into account river routing time, reservoir evaporation and link canal capacity.

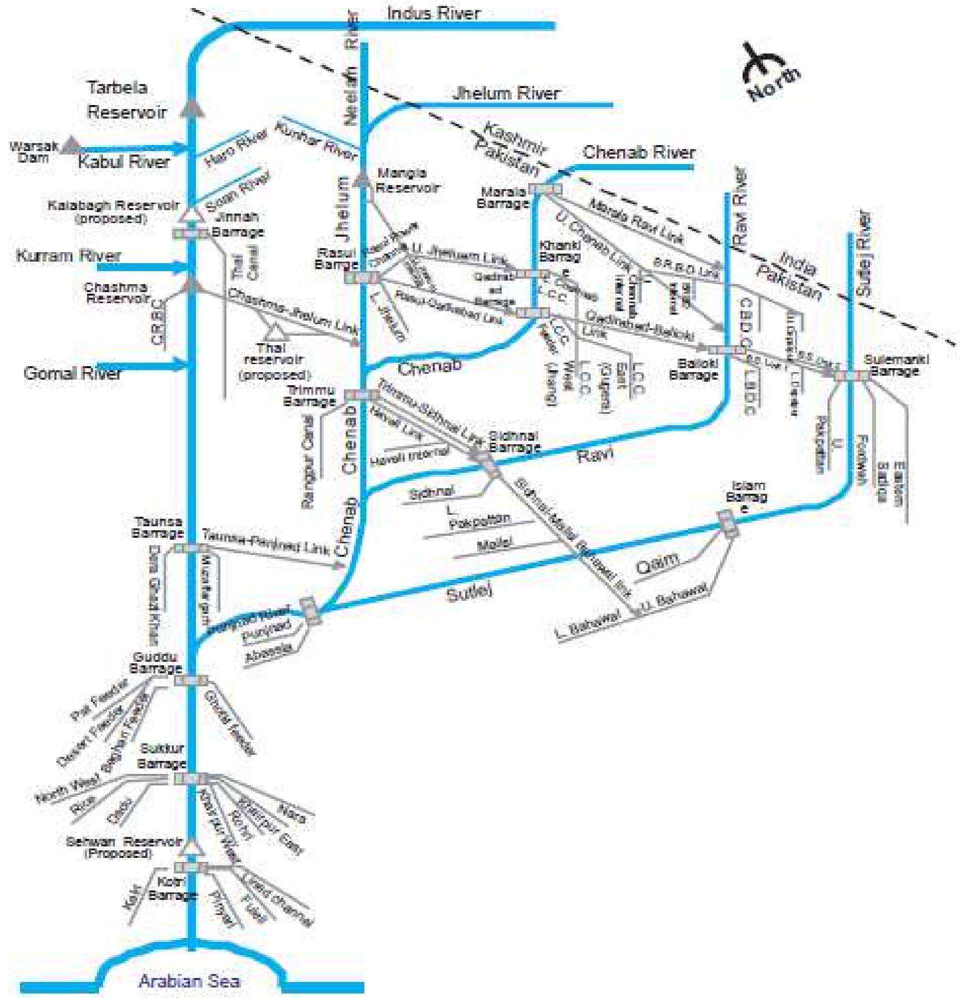

Figure 2 The Indus River basin and irrigation canals (Briscoe & Qamar, 2005b) as modeled in RWSM-Pak

The model disaggregates the forty-five main irrigation canals of the Pakistan Indus basin in twelve agro-economic areas, based on provinces and crops grown. Four of these zones are in Sindh, five in Punjab, two in Khyber-Pakhtunwa, and one in Balochistan. Three non water-stressed zones cover the rest of Pakistan. Agricultural land area, irrigation capacity and groundwater pumping are disaggregated to this level. Groundwater pumping is allowed only in non-saline groundwater areas—each zone is disaggregated in a fresh and a saline area, if relevant— , though we place a cap on maximal annual abstractions consistent with a sustainable yield for the Indus aquifer (fifty million acre-feet, as per Briscoe & Qamar, 2005 and Yu et al., 2013). RWSM-Pak assumes non-irrigation water is drawn from groundwater only.

The Water Accord of 1991, which reflects a highly sensitive political compromise, dictates the sharing of water between the four provinces, and that dams should be managed only for irrigation purpose(Briscoe & Qamar, 2005b). Implementing the Accord leads us to impose rule-based constraints on the simulated system. The objective function is constrained by these stringent rules on dam storage, while maximizing the water delivered to cultivated areas. However we do not constrain individual canal releases to follow historic patterns, as this is a usage not enshrined in provincial law. Eight million acre-feet of water are reserved as an outflow to keep the delta healthy, which is also mandated by the Water Accord.

3.4 Linking the Models

The CGE-W model is solved dynamically (Figure 1). First, the CGE model is solved for the year assuming exogenous trends on various parameters, yielding projected outputs by sector and allocation of land to crops. Water stress is set to the average of the previous three years, which sets harvest expectations for the allocation of land to the different crops.

The Water Demand module then calculates water demand for crops, industry, households, and livestock. Crop demand is for consumptive use given the nature of the crops; Industrial water demand is assumed to be linearly related to industrial GDP; livestock demand to livestock GDP; and household demand to aggregate household income.

RWSM-Pak uses these water demands, along with river flows provided by a hydrology model (or historical data) and climate parameters, to provide the monthly repartition of water amongst crops and regions given the objective function described above.

The Water Stress module then allocates water among crops in an area, given the economic value of the crop. We use the FAO Ky approach (Doorenbos & Kassam, 1979) to measure water stress using a multiplicative approach to include seasonality of water stress impacts (Hanks, 1974; Jensen, 1968; Raes, Geerts, Kipkorir, Wellens, & Sahli, 2006). Because optimizing total value of production given fixed prices leads to a tendency for specializing in high-value crops, we include a measure of risk aversion for farmers in the objective function, which preserves a diversified production structure even in case of a drought. The stress model produces a measure of yield stress for every crop—both irrigated and rainfed—in each of the twelve agro-ecological zones, which is then aggregated to the provincial level to match the regions in the CGE model.

Finally, the new yield shocks are calculated and applied to the CGE model, which is solved a second time for the final equilibrium, but now assuming that the allocation of land to crops is fixed since farmers cannot change their decisions after planting. This solution yields all economic variables, including quantities and prices of outputs and inputs, and all income flows. We then move to the next year, update various parameters on trend and start the process again.

4 Simulation Results

The CGE-W model for Pakistan is run dynamically from 2008 to 2050. Water shortages affect only the agricultural sectors in the model, ignoring hydropower and floods.[2] The impact is modeled as a shock on total factor productivity of the production functions for crops, proportional to the shock in actual yields.

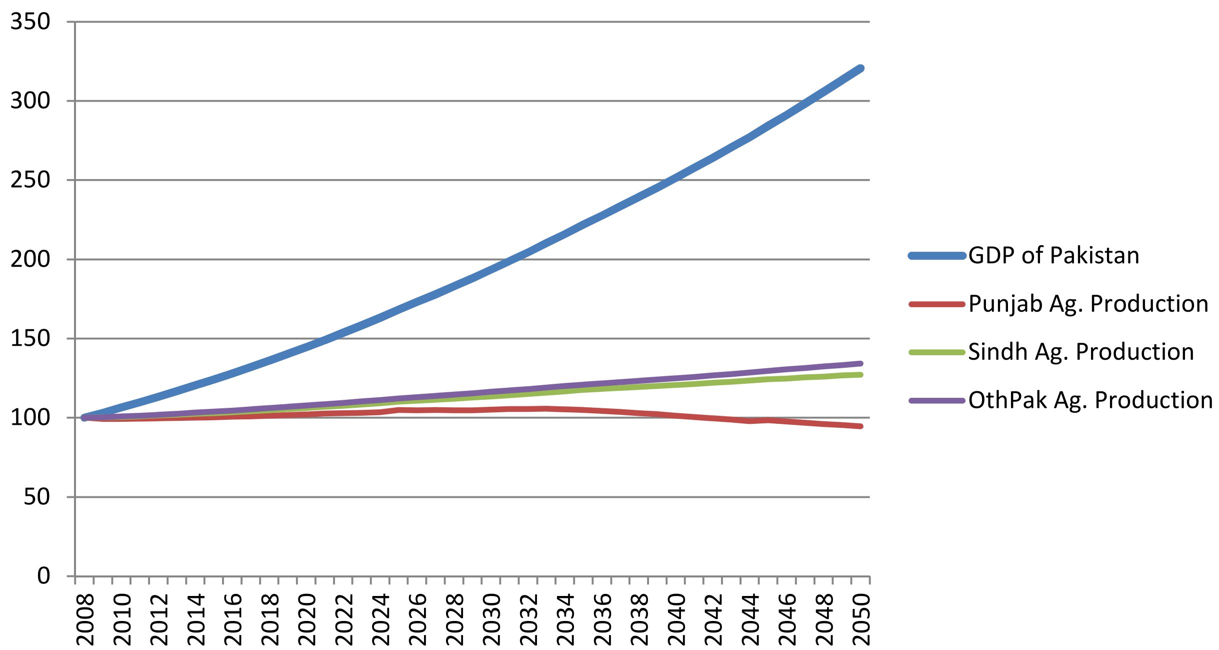

Figure 3. Baseline projections from CGE-W, base 100 in 2008. GDP and Agricultural production

Figure 2 describes GDP and agricultural production for the base scenario in the two main provinces of Pakistan (Punjab and Sindh) and in the rest of the country. In the base in 2008, 63% of production comes from Punjab, 20% from Sindh and 17% from the rest of Pakistan. Most of the production in Punjab and Sindh is irrigated by the Indus Basin River system, while agriculture is rainfed in most of the rest of Pakistan. For the base scenario, we specify a growth rate of the economy of about 3% per year.[3] There is no increase in agricultural land. Under these assumptions, Sindhi agricultural produc-

[2] We plan to introduce hydropower and flood impact in future versions of the model.

[3] The calibration of the growth rate is essentially done by specifying exogenous rates of total factor productivity growth. Labor force growth is also exogenous, while growth of the capital stock is endogenous, determined by aggregate annual savings and investment.

tion increases steadily, while Punjabi production increases slightly until 2035 and then decreases slightly due to the pressure of rising industrial and domestic water demand on already stressed water supplies. Agricultural commodity prices increase in real terms, sometimes sharply for the most water-intensive crops (rice in particular).

The baseline scenario assumes historic average flows, and so does not represent dry and wet years. In the next scenario, we reproduce the inflow conditions from 1966-1967 to 2007-2008, which include wet and dry periods, as compiled by the Water and Power Development Authority (WAPDA) of the Government of Pakistan. Figures 4, 5 and 6 present the evolution of GDP and of agricultural production under a historic scenario compared to the base, as well as the same scenarios with the building of the Basha dam.

The impact of droughts range up to 0.6 percent loss in GDP (in 2044), while a wet year may increase GDP by 0.22 percent (in 2040). Most of the impact of droughts is born by Punjab rather than Sindh. Sindh is indeed irrigated by the Indus, which is currently slightly under-exploited in terms of quantity, and the Water Accord of 1991 (signed between Pakistan's then-four provinces to share the water) allocates a higher portion -- compared to the historic repartition -- to Sindh for its agricultural development.

The addition of the Basha dam (6 million acre-feet of storage in the upper Indus river valley, upstream of Tarbela [see figure 2]) improves the GDP by 0.1 percent per year in the next decade, up to 0.3 percent in dry years in the 2040s.[4] Again, most of the benefits of the dam go to Punjab with increases of agricultural production by 5% on average at the end of the 2040s compared to the baseline, while Sindh production goes up only 1% compared to the baseline. The Basha dam basically provides supplemental water for Punjab in a water-constrained environment (if Sindhi production does rise in the baseline, Punjabi production does not).

[4] We do not take into account the cost of building the dam in this analysis. Conceptually, the dam appears on the Indus on the first day of the 2009 water year. The model as implemented here measures benefits, but does not consider costs. Moreover we do not consider dam silting, which is likely to reduce storage over the years.

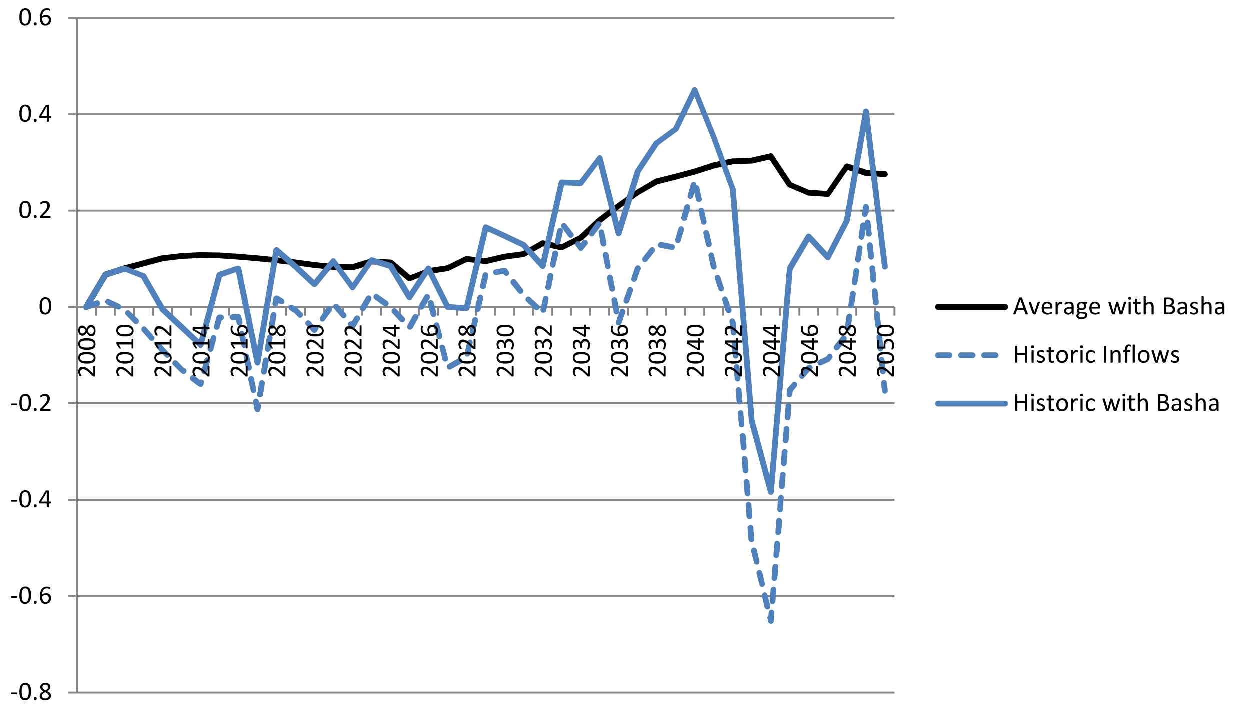

Figure 4. GDP fluctuations from the base with historic inflows and the construction of Basha dam (in percentage)

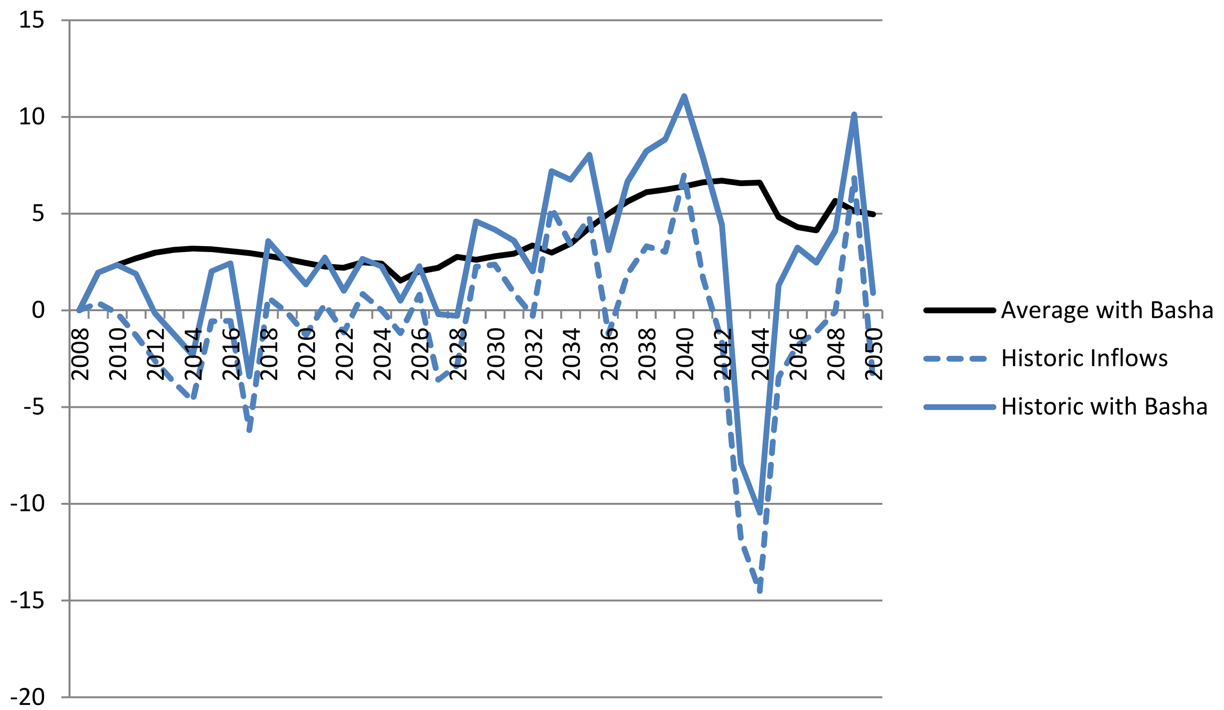

Figure 5. Punjab agricultural fluctuations from the base with historic inflows and the construction of Basha dam (in percentage)

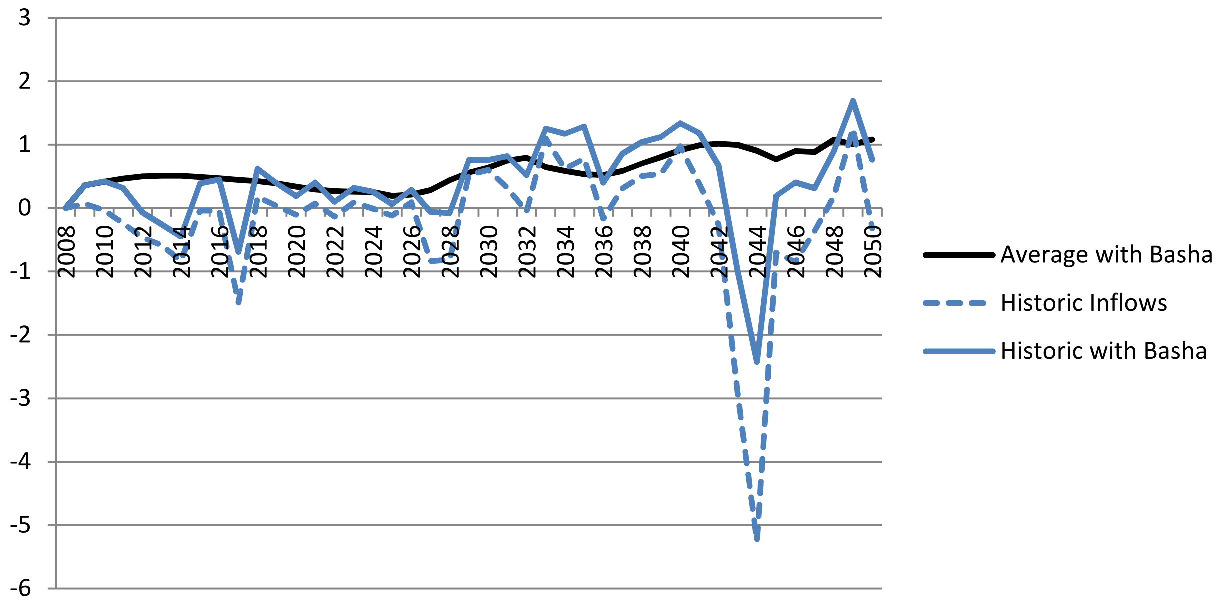

Figure 6. Sindh agricultural fluctuations from the base with historic inflows and the construction of Basha dam (in percentage)

Tables 1 and 2 show the implication of climate change for Pakistani GDP and agricultural production under four climate scenarios compared with the base.[5] Each scenario is built by adding the smoothed monthly variation from a 2008 base to the historic time series. Inflows are affected by runoff in the Himalayas, minor river inflows by runoff in Pakistan, rain by precipitation change, and crop water requirements by the change in evapotranspiration.

All climate scenarios produce similar negative impacts on the Pakistan water system, driven mostly by temperature change and increases in evapotranspiration. On average, climate impacts on irrigated agriculture cost about 0.3 points of GDP to Pakistan by 2050, and a 3 to 4 percent decrease in agricultural production compared to the historic baseline, with Punjab once again bearing the highest impact.

Basha dam, while providing some benefits compared to the historic baseline in the earlier timeframe, appears to completely mitigate this impact only until the 2030s (with the exception of the CSIRO B1 scenario, where the impact of climate with a dam remains positive by 2050).

[5] We are adding climate change using data from four different AR4 (Fourth Assessment Report) GCMs: CSIRO and MIROC, A1B and B1. CSIRO is based on a model produced by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) and MIROC on the Model for Interdisciplinary Research on Climate (MIROC), produced by the University of Tokyo's Center for Climate System Research (following the methodology of Jones & Thornton 2013). The two CSIRO scenarios have smaller but more evenly distributed precipitation increases. The two MIROC scenarios have greater increases on average.

Table 1. Average decadal GDP variation from no climate change/no dam scenario (in percent)

	2010s	2020s	2030s	2040s
MIROC A1B	-0.03	-0.11	-0.19	-0.32
MIROC A1B with Basha	0.05	0.01	0.00	-0.07
MIROC B1	-0.02	-0.10	-0.19	-0.30
MIROC B1 with Basha	0.06	0.02	0.00	-0.04
CSIRO A1B	-0.02	-0.07	-0.17	-0.34
CSIRO A1B with Basha	0.06	0.03	0.01	-0.08
CSIRO B1	-0.01	-0.04	-0.10	-0.20
CSIRO B1 with Basha	0.08	0.05	0.07	0.06

Table 2. Average decadal total Pakistan agricultural production variation from no climate change/no dam scenario (in percent)

	2010s	2020s	2030s	2040s
MIROC A1B	-0.60	-2.13	-2.93	-3.85
MIROC A1B with Basha	1.03	0.15	-0.12	-1.00
MIROC B1	-0.50	-1.96	-2.90	-3.59
MIROC B1 with Basha	1.10	0.29	-0.10	-0.52
CSIRO A1B	-0.47	-1.38	-2.73	-4.15
CSIRO A1B with Basha	1.27	0.57	0.06	-1.18
CSIRO B1	-0.23	-0.71	-1.55	-2.48
CSIRO B1 with Basha	1.56	0.88	1.07	0.58

5 Conclusion

CGE-W provides an integrated model framework to study intricate water resource problems under climate change and to track their implications as the damage and benefits spread across the economy. In Pakistan, it is clear that climate has a major impact on agricultural production, and model results indicate that the negative impact by 2050 can be largely mitigated by building the Basha dam on the Indus.

The CGE-W model provides a flexible consistent framework for linking separate water and economic models. The framework has been applied to Egypt, linking a CGE similar in structure to the Pakistan model to a completely different water basin management model.[6] The Egypt water model is similar in concept to the RWSM and is implemented in GAMS, which facilitated integration in the CGE-W framework. Planned future work using this framework includes the development of a hydro-electricity module and application to other countries.

[6] See Boehlert et al., 2013.

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