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An Introduction to the IBMR – A Hydro-Economic Model for Climate Change Impact Assessment in Pakistan's Indus River Basin

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Abstract
The Indus Basin Model Revised (IBMR) is a hydro-agro-economic optimization model for agricultural investment planning across Pakistan's Indus Basin provinces. This study describes an update and modification of the model--called IBMR-2012--that reflects the current agro-economic conditions in Pakistan for the purpose of evaluating the impact of climate change on water allocation and food security. Results of hydro-climatic parameter sensitivity and basin-wide and provincial level climate change impacts on crop productions are presented. We show that compared to Punjab, Sindh faces both significantly larger climate change impacts on agriculture and higher uncertainty regarding climate change impacts in the future.

Keywords: Indus Basin Model Revised, Pakistan, water allocation, GCM uncertainty, climate

Introduction

Pakistan relies on the largest contiguous irrigation system in the world, known as the Indus Basin Irrigation System (IBIS), for its basic agricultural production and water supply for all sectors of the economy. The basin that supports this irrigation system consists of the Indus River mainstream and its major tributaries--the Kabul, Jhelum, Chenab, Ravi, and Sutlej rivers--(Figure 1) which flow through four provinces: Khyber Pakhtunkhwa (KPK), Punjab (PUNJAB), Sindh (SIND) and Balochistan (BLCH) in Pakistan. The basin has two major multi-purpose storage reservoirs, 19 barrages, 12 inter-river link canals, 45 major irrigation canal commands (covering over 18 million hectares), and over 120,000 watercourses delivering water to farms and other productive uses. Annual river flows are about 146 million acre-feet (MAF, 1 MAF equals 1.234 km^3), of which about 106 MAF of water are diverted from the river system to canals annually (COMSATS, 2003). The total length of the canals is about 60,000 km, with communal watercourses, farm channels and field ditches running another 1.8 million km. These canals operate in tandem with vast and growing groundwater extraction from private tubewells.

The IBIS is the backbone of the country's agricultural economy, and provides 90% of the food production in the country (Qureshi, 2011). Pakistan's GDP in 2009 was US $161.819 billion with a contribution by agriculture of 21.5% (WB, 2012). Seventy percent of the country's export earnings and 54% of labor force employment occur are within IBIS (Yu et al, 2013). The intensity of local and regional conflicts over water availability are constantly increasing due to population growth and increasing water demands (Kahlown and Majeed, 2003).

Duloy and O'Mara (1984) developed the first version of the Indus Basin Model (IBM) as a research tool for investigating water-related projects and agricultural policies in IBIS. A more streamlined version of the IBMR model ('R' was added for "revised") was developed in 1988 by the World Bank's Development Research Center and the Water and Power Development Authority (WAPDA) of Pakistan. The IBMR uses the General Algebraic Modeling System (GAMS) to solve the water allocation for IBIS with a linear or non-linear format (Ahmad et al, 1990). The World Bank and WAPDA updated IBMR in 2002 using 1999-2000 input data, and, at that time, they updated the modeling structure to incorporate the 1991 Inter-provincial Water Allocation Accord signed by the four provinces.

Several recent studies, notably the World Bank study *Pakistan's Water Economy: Running Dry* (Briscoe and Qamar, 2006), have focused global attention on Indus water resource issues. To assess the impacts of climate risks and alternative climate change adaptation options on water and agricultural production in the basin, the World Bank and WAPDA found it necessary to further update the IBMR. Particularly, the new update aims at analyzing the inter-relationships among climate, water, and agriculture in Pakistan. A better understanding of these linkages will help to guide the prioritization and planning of future investments in these sectors. This paper presents the latest updates of the IBMR using the 2008-2009 hydrologic and production year as the baseline (named IBMR-2012). The paper then proceeds with hydro-climatic sensitivity analyses to assess which model parameters as well as which Pakistan provinces are most sensitive to climate change. The following sections describe the modified model structure, new input data, and sensitivity analyses of hydro-climate related parameters as well as results of climate change impact assessment.

Literature Review on Indus Basin Modeling

This study follows a long legacy of research and planning for the Indus Basin in Pakistan. The first version of the Indus Basin Model, developed by Duloy and O'Mara (1984), included farm production functions for different cropping technologies in the canal command areas and was based on a detailed rural household survey conducted in 1978. The analysis also linked hydrologic inflows and routing with irrigation systems, and thereby showed where efficiencies could be gained in water allocation.

WAPDA started the next major basin analysis, known as the *Water Sector Investment Planning Study* (WSIPS), in the late 1980s and focused on mid-term (10 year) development alternatives (WAPDA, 1990). This study drew upon a farm survey in 1988 to update farm production technologies and functions by canal command in the IBMR. The WSIPS used the model to evaluate a range of investment portfolios: no change, minimum investment, a basic plan (75 billion Pakistan Rs.) that optimized net economic profits subject to a capital constraint, and a maximum plan if additional investment funds were available. A detailed guide to the IBMR was written by Ahmad et al. (1990). Ahmad and Kutcher (1992) applied this IBMR and evaluated environmental (surface water and groundwater, both fresh and saline) considerations of different irrigation plans. This study noted the following emerging water and food challenges in their report: slowing crop yield growth, increasing water scarcity, deteriorating infrastructure, extensive waterlogging and salinity, and the high cost of drainage for canal command areas.

They also used the IBMR to examine the sources of salinity in groundwater and buildup in soils after optimized water allocation under varied water management policies. Various projects and programs later used the IBMR to show, for example, the impact of Kalabagh Dam (Ahmad et al, 1986); to assess waterlogging and salinity under different scenarios of crop yields and tubewell investment levels in Sindh province (Rehman and Rehman, 1993); and to identify salinity management alternatives for the Rechna Doab region of Punjab (Rehman et al, 1997).

Moreover, a joint WAPDA-U.S. Environmental Protection Agency team used the IBMR model to study *Complex River Basin Management in a Changing Global Climate: A National Assessment*, analyzing General Circulation Model (GCM) climate scenarios along with WAPDA development alternatives in the late 1980s (Wescoat and Leichenko, 1992). They ran the model with two different water allocation rules: 100% of historical water allocations (i.e. fixed delivery) and 80% of historical allocations, assuming that the remainder would be used outside irrigated agriculture. This early study showed that the impact of climate change can reduce the net economic profits of the minimum investment plan studied by 40% to 100%. This earlier work also demonstrated that, with some exceptions, the Indus basin irrigation baseline values seemed relatively robust under different future climate conditions.

The 2002 IBMR update used 1999-2000 input data for the baseline. This IBMR-2002 was applied to evaluate the effects of raising the Mangla Dam (Alam and Olsthoorn, 2011). As this literature review shows, the IBMR has been effectively used for critical water-related investment analysis. A further update of the IBMR, with new input data and an updated modeling structure (corresponding to the current hydro-agro-economic conditions in Pakistan) would thus have great potential to help decision-makers understand the impact of climate change and water governance changes on the agricultural sector in Pakistan.

The IBMR Modeling structure

The IBMR is a hydro-agro-economic model using agro-climatic zones (ACZ, Figure 1) as basic spatial units. The overall model objective is to maximize the sum of zonal consumer and producer surpluses (CPS), which are the net economic profits for the entire Indus Basin. The IBMR-2012 models CPS using a supply-demand relationship. Since CPS has a non-linear format, the IBMR-2012 uses a piece-wise linear programming approach to solve this objective function. Although the modeled prices may fluctuate between zero and the intercept of the demand curve, this is unlikely to happen in reality, and so prices are given upper and lower bounds. It is assumed that, outside of these bounds, inter-zonal trade will exist. However, the model does not actually simulate such trade. The IBMR also does not consider international trade explicitly but does account for the prices of international exports and imports and adjusts production accordingly.

The four provinces currently modeled contain one or more ACZs that represent a consistent cropping pattern, land characteristics and climatic conditions. The model includes 12 ACZs. A node-link system is used to represent the river (supply node)-canal (demand node) network, and this node-link system provides surface water to each ACZ. Agricultural production and consumption is simulated at the ACZ level. Each ACZ consists of one or more canal command areas (CCAs, Figure 1) based on the canal water diversions. In some cases, one CCA can contribute water to two ACZs. Therefore, each CCA has been further divided into four subareas based on the proportion of water provided by canals (Ahmad et al, 1990). This hierarchal structure of the IBMR-2012 is provided in Table 1.

In the IBMR, the residual moisture in the root zone is explicitly modeled and represents a potential source of water for crops. Crop water needs are met from precipitation, canals, groundwater wells (mostly shallow), and soil moisture in the root zone (also known as “sub-irrigation”). An evaporation parameter in the model is used to define the "sub-irrigation" water available to plants. The IBMR assumes that 60% of the evaporation from shallow groundwater can be absorbed by crops (Ahmad et al, 1990 and Ahmad and Kutcher, 1992) and the remainder is lost as evaporation to the atmosphere. Therefore, although evaporation is a “water loss” from a water balance perspective, part of that “water loss” from shallow groundwater is used by crops which are “water gains” from a crop perspective. This water balance at the ACZ level is graphically depicted in Figure 3. This figure also demonstrates how surface and groundwater interact.

The IBMR-2012 input and output data and the key equations are described as follows.

<u>Input data</u>

The input data of IBMR-2012 can be categorized as 1) agronomic and livestock data, 2) economic data, 3) resources inventory, and 4) irrigation systems and water data.

Agronomic and Livestock Data

Agronomic data is the information about the crop activities in the basin. The required inputs include: crop growing period, labor, crop water needs (which will be altered in the climate change impact assessment to represent temperature change), fertilizer use, draft power requirements, yield and also by-products (such as straw and seed) convert factors. There are 14 irrigated crops in the IBMR-2012: basmati rice, other irrigated rice, cotton, rabi season fodder, gram, maize, mustard and rapeseed, kharif season fodder, sugarcane, wheat, orchard, potatoes, onions and chilies. Livestock data include labor and feed requirements of each animal type. It also contains conversion factors to determine the products of these animals: meat and milk. The IBMR-2012 includes three types of livestock: bullocks, cows and buffaloes.

Economic Data

Economic data include the estimated demand for each crop and livestock product, the market prices for all commodities, the fixed production cost for meat and orchards, and the price elasticities for different commodities. The practice of farm families, particularly of smaller farms, to consume a large proportion of their agricultural output cannot be ignored and is incorporated into the IBMR-2012 as on-farm consumption (acting like a constraint in the model to secure minimal crop production in each ACZ). Once ACZ consumption requirements are met, the remaining production is available to the market. Therefore, the demand for commodities in the IBMR-2012 is the residual of production less on-farm consumption.

Resources Inventory

Resource inventory data refer to all resources with the exception of water. These resources include: agricultural workers, tractors, private tubewells, households, animals and total available irrigated area (cropped land). The farm population is used to compute labor availability. This IBMR-2012 version replaced all animal draft with tractors, reflecting economic development in the country.

Irrigation Systems and Water Data

Water input data include surface water inflow, rainfall, historical canal diversions, evaporation and sub-irrigation, and private and public tubewell pumping. Fifty year inflow records from the nine tributaries (Indus, Chenab, Jhelum, Harro, Kabul, Ravi, Soan, Sutlej, and Swat) are also used. In the modeling analysis, different exceedance probabilities of inflows are used to assess their effects on basin agricultural production. The baseline run uses the 50%

exceedance probability which equals 132 MAF annually. The total live reservoir storage in the model is 11.5 MAF. Four reservoirs are used in the current model structure: Mangla, Tarbela, Chashma and Chotiari. When modeling the irrigation system, the basic unit is the CCA. All data on these commands are aggregated to the level of the agricultural model (i.e. ACZ).

Equations

In total, 20 equations are used to optimize the complex processes related to water allocation and economic activities. These equations can be categorized into six classes: 1) objective function, 2) economic equations, 3) water balance equations, 4) canal equations, 5) crop equations and 6) livestock equations. Only four critical equations are explained here, others can be found in Ahmad et al. (1990) and Yu et al. (2013).

The objective function of the IBMR-2012 is to maximize the net economic profits for the entire basin given in equation (1). The objective function is only for the agriculture sector and does not include hydropower production or municipal and industrial water consumption. All items are summed across the agriculture commodity, groundwater type (saline or fresh), and the ACZs.

$$CPS = \sum_Z \sum_G \sum_C Price_{Z,G,C} \times Production_{Z,G,C} - \sum_Z \sum_G Cost_{Z,G} - \sum_Z \sum_C Import_{Z,C} - \sum Slackvariables + \sum_Z \sum_C Export_{Z,C} + \sum_M \sum_N WaterValue_{M,N} \quad (1)$$

where Z is the index for ACZ, G is the index for groundwater type, C is the index for crop, M is the index for month and N is the index for node or reservoir. *Price* × *Production* is the total gross benefit from crop and livestock production and *Cost* is the total cost of production. *Import* is the total cost for importing crops and *Export* is the total benefit for exporting crops. Import and export prices are different from the market price that is used to calculate gross crop benefit. Import and export quantities are constrained in the model to prevent ACZs to export all crop production for maximal benefit or import all demand for minimal cost. *WaterValue* is the value of water flow to the sea or stored in reservoirs. The model uses this item to address the hedging intention of multi-year operation of reservoirs and also the ecological value of water flow to the Arabian Sea. The *Slackvariables* in the objective function represent a penalty for insufficient water in the network flow model or insufficient production to satisfy on-farm consumption. In reality, in cases where there is a shortfall of irrigation water, production does not necessarily stop. This variable thus prevents infeasibilities at low-flow conditions, and imposes penalties on the objective value. This also means that the objective value does not necessarily reflect the real basin-wide net economic profits that would be observed under these water shortfall conditions.

The cost function contains all the costs for crop and livestock production in each ACZ as shown in equation (2).

$$Cost_{Z,G} = \sum_Z \sum_C \sum_S \sum_W \left(FERT_{Z,C,S,M} + MISCCT_{Z,C,S,M} + SEEDP_{Z,C,S,M} + TW_{Z,C,S,M} + TRACTOR_{Z,C,S,M}\right) + \sum_Z \sum_G \sum_A Animal_{Z,G,A} + \sum_Z \sum_{SEA} PP_{Z,SEA} + \sum_Z \sum_G \sum_M Labor_{Z,G,M} \quad (2)$$

where *S* is the index for cropping sequence (e.g. standard, late or early planting), *W* is the index for water application (e.g. standard, light or heavy stress while stress application require less water and labor and produce less output), *A* is the index for different animals (cow bullock and buffalo) and *SEA* is the index for season (rabi and kharif). *FERT* is the cost of fertilizer, *MISCCT* are miscellaneous costs like insecticides and herbicides, *SEEDP* is the cost of seed, *TW* is the energy cost for groundwater pumping, *TRACTOR* is the cost for operating tractors, *Animal* is the fixed cost for livestock, *PP* is the cost for purchased protein concentrates for animals and *Labor* is the cost for hiring labor.

Water balances in the river network and root zone are the essential mass balances in the IBMR. The surface water balance is related to the river routing process in the IBMR. The following equation (3) describes the entire river network monthly water balance at each node.

$$\sum_I Inflow_I^M + \sum_N RIVERD_N \times TRIB_N^M + \sum_N RIVERC_N \times TRIB_N^{M-1} + \sum_N RIVERB_N \times F_N^M + \sum_N RIVERC_N \times F_N^{M-1} + \sum_N RCONT_N^{M-1} - RCONT_N^M + Prec_N^M + Evap_N^M - \sum_N CANALDIV_N^M + SlackWater_N^M = 0 \quad (3)$$

where *I* is the index for inflow node. *Inflow* is the streamflow, *RIVERD* is the routing coefficient for tributaries, *TRIB* is the tributaries' flow, *RIVERC* is the routing coefficient for the previous month, *RIVERB* is the routing coefficient for the mainstream, *F* is the mainstream flow, *RCONT* is the monthly reservoir storage, *Prec* is the rainfall on the reservoir surface, *EVAP* is the evaporation loss from the reservoir surface, *CANALDIV* is the canal diversion and *SlackWater* is the slack surface water (one of the slack variables in the objective function) needed at nodes.

The root zone water balance at each ACZ in IBMR is the relationship between the total available water in the root zone and the total crop water requirements as shown in Figure 2. The following equation (4) describes this balance.

$$Max\left[\left(WNR_{Z,G,C,S,W}^M - SUBIRRI_{Z,G}^M * LAND_{Z,G,C,S,W}^M\right), 0\right] \times X_{Z,G,C,S,W}^M \leq TW_{Z,G}^M + GWT_{Z,G}^M + WDIVRZ_{Z,G}^M + SlackRWater_{Z,G} \quad (4)$$

where *WNR* is the water requirement from crops, *SUBIRRI* is the sub-irrigation, *X* is the cropped area, *TW* is the total private tubewell pumping, *GWT* is total public tubewell pumping, *WDIVRZ* is the surface water diversion and *SlackRWater* is the slack root zone water, which is one of the slack variables in the objective function.

Major Constraints

Three major constraints are applied in the IBMR. 1) canal capacity: The physical canal capacity is used as the upper boundary of canal water diversions in the model. 2) provincial historical diversion accord: Maintaining the 1991 Inter-provincial Water Allocation Accord is another constraint in the model. This water sharing agreement specifies how much water needs to be delivered to each province. In order to consider this accord in the IBMR-2012, the actual monthly canal diversions from 1991 to 2000 (after the Accord) are averaged and utilized as the constraint itself ("DIVACRD"). In this study, a 20% deviation from the monthly canal diversion was allowed, that is, each canal command diversion can range from 0.8–1.2 times the historical, long-term average value (while maintaining the physical constraints in the system). This is the same setting followed by WAPDA (1990). 3) reservoir operation rule: No complex operation rules have been applied to these reservoirs. Monthly upper and lower boundaries of reservoir storage are the only constraints. This is acceptable given that the model operates on a single-year basis. This constraint affects surface water routing and avoids reservoir drawdown to nil at the end of the year.

Output data

The output data from the IBMR contains a great deal of information. The first output is values in the objective function. Key outputs include gross profit from agricultural production, farm cost, agricultural imports and exports, the economic value of water in reservoirs and the flow to the sea. The slack values can also be assessed. Non-zero slack values signify water stress in the model run. Cropped areas of different crops in each ACZ are one of the major agricultural outputs. The model provides detailed information for every combination of cropping sequence and water application of crop outputs. For example, production can be summed across ACZs or provinces or from seasonal to annual. The results are also provided for each ACZ with different groundwater types (fresh and saline). Resources used, such as labor and fertilizer (both quantity and cost), are also calculated for each ACZ. Hydropower generation from reservoirs is a by-product from the model. The final major output from the IBMR-2012 is the surface water and groundwater balance for each ACZ.

Model baseline and climate change impact settings

Model baseline and diagnosis

The baseline setting uses the agronomic, economic and resources inventory input data from 2008 to 2009. The 50% exceedance probability is used as inflow and long-term average rainfall and crop water requirements as hydro-climatic inputs. This section presents the baseline performance of the IBMR. Table 2 shows the major outputs from the model. The basin-wide net profit from agriculture is 2,850,099 million PRs. (USD $35.62 billion where 1 USD = 80 PRs. in 2009). Punjab has the largest cropped area, production and profit, followed by Sindh. Surface and groundwater use across the provinces follows the 1991 Accord closely. Punjab diverts 59.9 MAF, Sindh diverts 44.1 MAF and other provinces divert 8.4 MAF. Punjab uses most groundwater, at about 53.2 MAF. Basmati rice, cotton, sugarcane and wheat generate the highest gross profit in Punjab. Other irrigated rice and cotton gross profit are highest in Sindh (Table 3). The primary production costs are hired labor, and tractor and fertilizer use (Table 4).

Given the complexity of the IBMR-2012 and the assumptions that it requires, we evaluate the model performance to increase confidence in the results of the simulations. The basin-wide net economic profits (USD $35.62 billion) is very close to Pakistan's agricultural GDP in 2009: USD $34.79 billion according to the World Development Indicators (WB, 2012). The government report "Agricultural Statistics of Pakistan 2008-2009" (MINFA, 2010) was used to compare the provincial level results. The results from IBMR-2012 are not expected to exactly match the observed values reported in MINFA (2010). The purpose of this comparison is to evaluate the ability of the model to provide a realistic representation of the hydro-agro-economic system. The primary agro-economic outputs of the IBMR, such as cropped area and crop production at the provincial level, were compared with observed values. Since KPK and BLCH cover a smaller proportion of the Indus River Basin, only Punjab and Sindh were selected for the comparison.

The coefficients of determination (R^2) of cropped areas among 14 crops between the IBMR baseline run and MINFA data for 2009 were 0.98 for both Punjab and Sindh. The total cropped area in Punjab is 32.38 million acres from the IBMR while MINFA data show 33.84

million acres in 2009 and the root mean-square-error (RMSE) is 0.95 million acres. The total cropped area in Sindh is 8.13 million acres from the IBMR while MINFA data show 7.06 million acres in 2009 and the RMSE is 0.63 million acres. The R^2 of crop production among 14 crops are 0.99 for both Punjab and Sindh. Crop production in Punjab is 65.37 and 73.42 million tons in the IBMR and the MINFA data, respectively. Crop production in Sindh is 24.91 and 23.84 million tons in the IBMR and the MINFA data, respectively. RMSEs for crop production are 1.97 and 0.76 million tons in Punjab and Sindh, respectively. These results show that the model represents cropped area and production well. Although the absolute values might be different, the relative cropped pattern (proportion of each crop in area and production) are similar to the observations.

Climate change impact setting

Liniger et al. (1998) suggested that 90% of the lowland flow of the Indus River originates from the western Himalaya mountain areas. However, several studies have shown that this region might have a different response to the impact of climate change compared to other regions in the world (Archer, 2003; Flowler and Archer, 2006; Kaab et al., 2012). Most of the studies point to a generally increasing annual temperature trend (based on historical data); however, for, the changes in precipitation, the studies show diverging trends. The uncertainty of future climate predictions (temperature and precipitation) will significantly affect the prediction of streamflow in the Indus River. Different studies predict different percentages of snow and glacier melt contribution (less than 40% to more than 60%) to the streamflow of the Upper Indus Basin (UIB) (Bookhagen and Burbank, 2010; Jeelani et al., 2012). Glacier-melt dominated rivers will be affected more by spring and summer temperature increase and snow melt dominated rivers will be affected more by winter precipitation and summer temperature. Combing all these uncertainties together, different studies suggest varying streamflow changes in the future. Akhtar et al. (2008) suggest an increasing trend in summer flows from the UIB under the SRES A2 scenario; with a 1^{o}C increase in temperature resulting in a 16%-increase in streamflow. Tahir et al. (2011) offered a similar conclusion but with a different magnitude (1^{o}C increase in temperature would result in a 33%-increase in streamflow). However, Immerzeel et al. (2010) showed decreasing summer flows in the Indus under the A1B scenario for 2046-2065 period.

Due to the large uncertainty about climate change impacts, this study applies the method proposed by Brown and Wilby (2012) that systematically evaluates the system's response (in our case: the Indus Basin Irrigation System) under a much wider range of future climate conditions.

This process is named the “climate response surface” construction. After the “climate response surface” has been created, we overlap 17 GCM (SRES A2 and A1B scenarios) used in Global Change Impact Study Centre reports (Islam et al., 2009a and 2009b) to evaluate the uncertainty from GCM predictions. By overlapping GCM projections with climate response surfaces, this method can visualize the GCM uncertainty and demonstrate the robustness of the system response to climate information.

Results and discussion

Sensitivities of hydro-climate related parameters

Conducting sensitivities of hydro-climate related parameters is critical for climate change impact assessment since the IBMR-2012 is not a physically-based model which can directly use future climate input (temperature and precipitation from GCMs) for modeling results. We test several hydro-climate related parameters in this section.

Changes in Inflows

Inflow is one of the most important inputs in the IBMR-2012. Therefore, different exceedance probabilities are used to test the relative impact of changes in inflows on modeling results. The baseline run used the 50% exceedance probability of historical inflow record, which is 132 MAF annually. The results of the IBMR-2012 output are shown as a tornado diagram in Figure 3. When inflow changes from 92.8 to 201 MAF (90% to 10% exceedance probability), the low flow shows a larger impact on the objective value. Basin-wide net profits decrease 68% (912 billion PRs.) under 92.8 MAF annual inflows, but only increase 0.1% (2,852 billion PRs.) under 201 MAF. This is because the Accord caps the amount of water that can be used by the provinces. The total cost value shows the largest difference. Under the low flow condition, slack surface water is necessary to satisfy the Accord, and this slack value penalizes the basin-wide net profit. Power generation shows a positive relationship with inflow as expected. The lowest inflow will result in 13 billion kilowatt hour (BKWH) annually and the highest inflow can generate 24 BKWH in a year.

The provincial results show that under low flow conditions, Punjab has lower net profit and cropped area losses compared to Sindh in both absolute value and percentage terms. The profit difference in Punjab is 34.6 billion PRs. and 38.7 billion PRs. in Sindh. The area difference is 0.85 million acres in Punjab and 1.48 million acres in Sindh. Canal diversions show larger changes in Punjab than Sindh. The difference in Punjab is 16 MAF and 5 MAF in Sindh. The reason for this difference is that more groundwater is pumped in Punjab. Punjab will pump 7 MAF more under the low-flow compared to the high-flow scenario, while Sindh only pumps 1 MAF more.

Changes in Crop Water Requirements

Increasing temperatures are expected to increase evaporative demand from crops and soils, which would tend to increase the amount of water required to achieve a given level of plant production (Brown and Hansen, 2008). The crop water requirement parameters in the IBMR are based on theoretical consumptive requirements, survey data and model experiments of water balances of the entire basin (Ahmad et al., 1990). A local study by Naheed and Rasul (2010) provided data to establish a relationship between crop water requirement and air temperature change. Based on the FAO Penman-Monteith method (Allen et al., 1998), Naheed and Rasul (2010) estimated the reference crop evapotranspiration under different air temperature increases (+1, 2, and 3^{o}C) in northern and southern Pakistan. It is assumed that crop phenology and management will remain the same under different air temperature conditions. Based on these findings, our sensitivity analysis increases crop water requirements by 2.5%, 5%, 10%, 15%, 20%, 25%, 30% and 35%, respectively. These changes correspond to air temperature increases of 1^{o}C, 2^{o}C, 3^{o}C, 4^{o}C, 4.5^{o}C, 5.5^{o}C, 6^{o}C, 6.5^{o}C. Note that the analysis does not include direct yield impacts from higher temperatures. Results are given in Figure 4.

When temperature changes from +1^{o}C to +6.5^{o}C (+2.5% to +35% of water requirement), the basin-wide agricultural net profits decrease 1% (2,829 billion PRs.) under +1^{o}C and decrease 52% (PRs. 1,379 billion) under +6.5^{o}C. This decrease in objective value is more or less linear with the temperature increases. The total cost shows the largest difference under +6.5^{o}C as the slack surface water variable acts as a penalty for the objective value. In general, temperature increases will negatively affect all IBMR outputs. Power generation will decrease about 10% (from 19.6 to 17.8 BKWH) under the highest temperature increase. This is because more water is needed to be released from reservoirs to satisfy crop water demands and as a result head (used for hydropower generation) will also decrease. The provincial results show that Punjab will have less agricultural profits and cropped area losses compared to Sindh in both absolute value and percentage terms. The profit difference in Punjab is 57.2 billion PRs. and 89.6 billion PRs. in

Sindh. The area difference is 1.58 million acres in Punjab and 2.88 million acre in Sindh. Canal diversions show larger increases in Sindh than Punjab in percentage terms but the absolute values are the same--an increase of 1 MAF in both provinces under +6.5^{o}C. More groundwater is available for pumping in Punjab than Sindh, which again is the reason why Punjab suffers less loss in net profits. Punjab will pump 31 MAF more under the highest temperature increase compared to the baseline, and Sindh will only pump 1 MAF more.

Other changes

Changes in inflows and crop water requirements are the two most sensitive hydro-climate related parameters in the IBMR-2012. We also test other parameters, such as the depth to groundwater, precipitation and the value of water flow to the sea (RVAL). The tested range for depth to groundwater is from a baseline value to positive 100% and the tested range for precipitation and RVAL is from positive to negative 40% compared to the baseline. None of these changes result in basin-wide agricultural net profit changes of more than 5% compared to the baseline. A basin-wide average depth to groundwater change from 15 ft to 30 ft will result in a decline in the objective value of 4%. This insensitivity is partly due to the fact that the unit pumping cost is not linked with depth to groundwater but only with the volume of groundwater pumped in the current modeling structure. An annual precipitation change from 150 mm to 300 mm will cause a less than 2% change in basin-wide net profits because rainfed area is not modeled. The change in RVAL results in less than a 0.5% change in basin-wide agricultural net profits given the physical infrastructure and Water Accord constraints embedded in the model.

Climate change impact assessment

Using the nine different inflows (changes from 92.8 to 201 MAF) and nine different temperatures (+1^{o}C to +6.5^{o}C), 81 outputs from the IBMR-2012 are used to construct the "climate response surface" of crop production for the entire basin, which is shown in Figure 5. The 17 GCM used in Islam et al, (2009a and 2009b) are overlaid on top of the "climate response surface" to show 1) the temporal changes suggested by GCMs and also 2) the uncertainty in different GCM predictions. The temperature and precipitation changes from GCMs are transferred into streamflow changes using the snow melt model applied in Yu et al (2013). The basin-wide result shows that under the normal and high flow situations (e. g. inflows larger than 130 MAF), the impact of temperature increase is not that significant. Under low flow situations (e. g. inflow less than 100 MAF), 1 ^{o}C will result in about 2% crop production decrease. When overlaid with 17 GCM results, it is clear that all GCMs project a trend of increasing temperature but the uncertainty of total inflow change (the expansion on x-axis) becomes wider over time. In general, GCMs project a -2% to -5% production decrease by 2020s (Figure 5a), a -2% to -8% decline by 2050s (Figure 5b) and -4% to -12% in 2080s (Figure 5c). The ensemble mean of 17 GCMs are also overlaid with the "climate response surface" in Figure 5d. This figure shows the difference between the A2 and A1B scenarios. The A1B scenarios usually predict lower inflow than the A2 scenarios. As a result, larger crop production declines were observed in the A1B scenario.

Figure 6 shows the "climate response surface" for different provinces. First, the shape of contour is different, indicating different provinces respond differently under climate change impacts. Second, the magnitude is much larger in Sindh than Punjab and other provinces. The most extreme condition (hot and dry) shows a more than 40% crop production decrease in Sindh, while declines in Punjab are only 5% and in other provinces 8%. Possible reasons for the lower declines in Punjab include larger use of (less saline) groundwater, higher crop yields in Punjab attracting more water, and higher temperatures in Sindh, the latter of which was not specifically studied in this model set-up. When overlaid with GCM predictions, the uncertainty of GCM results becomes critical. For the 2020s (Figure 6b), almost all GCMs predict a less than 3%-crop production decrease in Punjab and a less than 1%-decline in KPK and Balochistan. However, half of the GCMs predict more than a 5%-decrease and the reminder predict less than a 5%-decrease of crop production in Sindh. In the 2080s, GCM predictions show a range of crop production declines of 5% to 35% in Sindh but only a 1% to 5% drop in Punjab. The growing uncertainty makes taking costly policy and investment decisions difficult. For example, if a crop production decline of 10% by the 2080s is an accepted threshold above which policymakers would plan for early adaptation, Punjab would not need to invest in adaptation, while Sindh faces the difficult decision of spending money on adaptation policies or not because half of the GCM predictions suggest that declines are above the threshold. The "climate response surface" overlaid with GCM predictions approach can thus not only demonstrate the sensitivity of a system response to climate change but also indicate how GCM uncertainties will affect decision making.

Summary and Conclusions

An up-to-date Indus Basin Model Revised (IBMR-2012) is introduced in this paper. This hydro-agro-economic model is important to analyze inter-relationships among the climate, water, and agriculture sectors in the Indus River Basin in Pakistan. A better understanding of these linkages will help to guide the prioritization and planning of future investments in the basin.

The overall objective of the IBMR is to maximize the consumer and producer surplus (CPS) for the entire Indus Basin. The primary input data of the IBMR include agronomic, economic, hydro-climatic and institutional (Water Accord) data. Hydro-climate related parameter sensitivity analyses (a critical step in climate change impact assessment) indicate that stream inflows are the most sensitive hydro-climatic input in the model, followed by crop water requirements.

We show that Sindh faces both larger climate change impacts on agriculture and larger uncertainty regarding future climate outcomes for the province. Punjab can better deal with adverse climate change impacts due to its larger groundwater buffer, allowing it to compensate for some of the surface water declines.

Results of the “climate response surface” for the entire basin and different provinces show that if a threshold of acceptable crop production decrease is given (e. g. 10%), the growing uncertainty of GCM results over time will affect adaptation decision making differentially in Pakistan’s provinces. Particularly, Sindh will face a much larger dilemma than Punjab and other provinces on adaptation decisions aimed at likely conditions in the 2080s.

Policymakers in Sindh should accelerate investments in water- and crop-based adaptation strategies, such as expanding drip irrigation, which requires less (surface) water per unit of crop produced, as well as contemplate advanced seed technologies, particularly drought and heat-tolerant varieties of wheat given the larger adverse climate change impacts from water stress predicted for this province.

Several improvements could be added to the study. Some studies show that evapotranspiration can decline even when the mean temperature has risen. This is due to the decrease of the diurnal temperature range (Peterson et al, 1995 and Braganza et al, 2004). The linkage between temperature and crop water requirements can be improved with more detailed agronomic studies. The current single-year version of the IBMR-2012 can be modified into a multi-year version and groundwater simulations could be enhanced (e.g. allowing dynamic fresh and saline area changes). This improvement should be able to reflect the impact of climate change more accurately so as to evaluate the effect of the 1991 inter-provincial accord, which plays a critical role in the current water management scheme, under current and future climate conditions.

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Tables

Figures

Figure 1. The Indus River and IBMR model Agro-Climatic Zones and Canal Command Areas in Pakistan

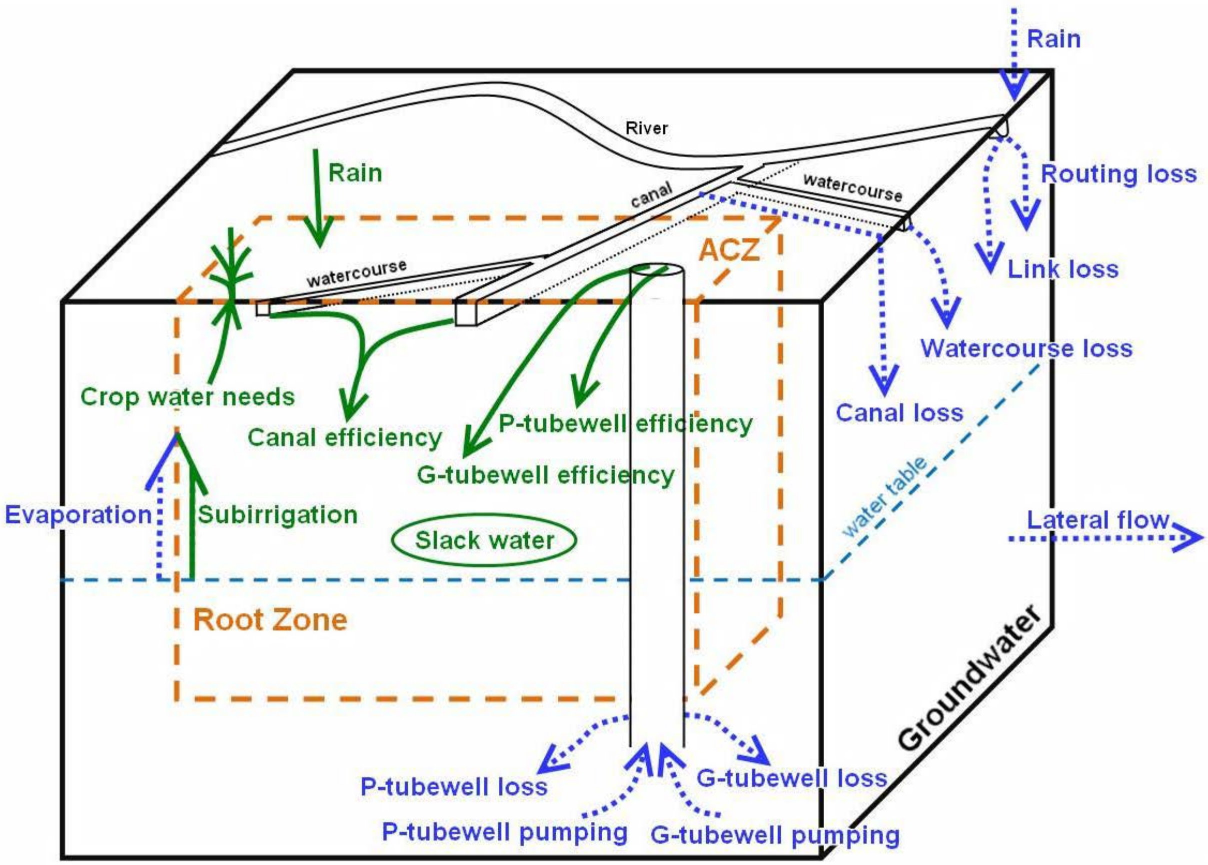

Figure 2. The water balance in the IBMR-2012.

Notes: The solid lines indicate the root zone water balance components which supply crop water requirement. The dotted lines represent the groundwater balance components that are tracked during the simulation runs. All water balance calculations are at the ACZ scale (dash zone) (Yu et al, 2013).

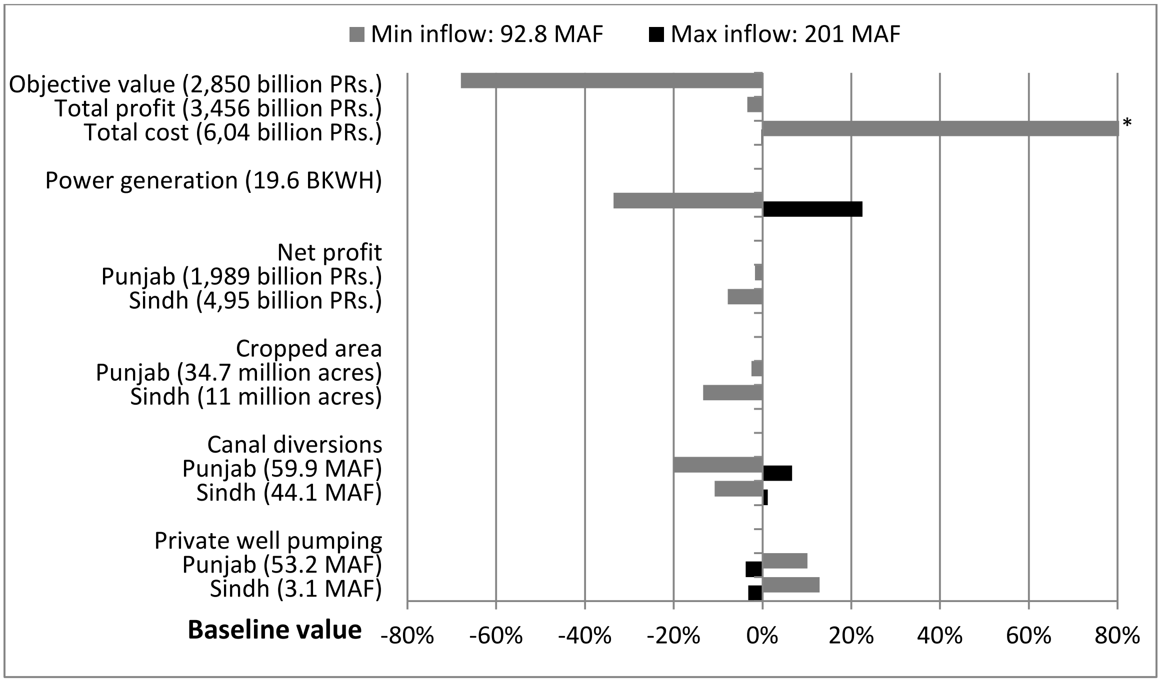

Figure 3. The impact of changes in inflow on IBMR - 2012 outputs.

Notes: The results are percentage changes compared to baseline values for each item listed on the y-axis. (*the change of total cost compared to the baseline is +300%)

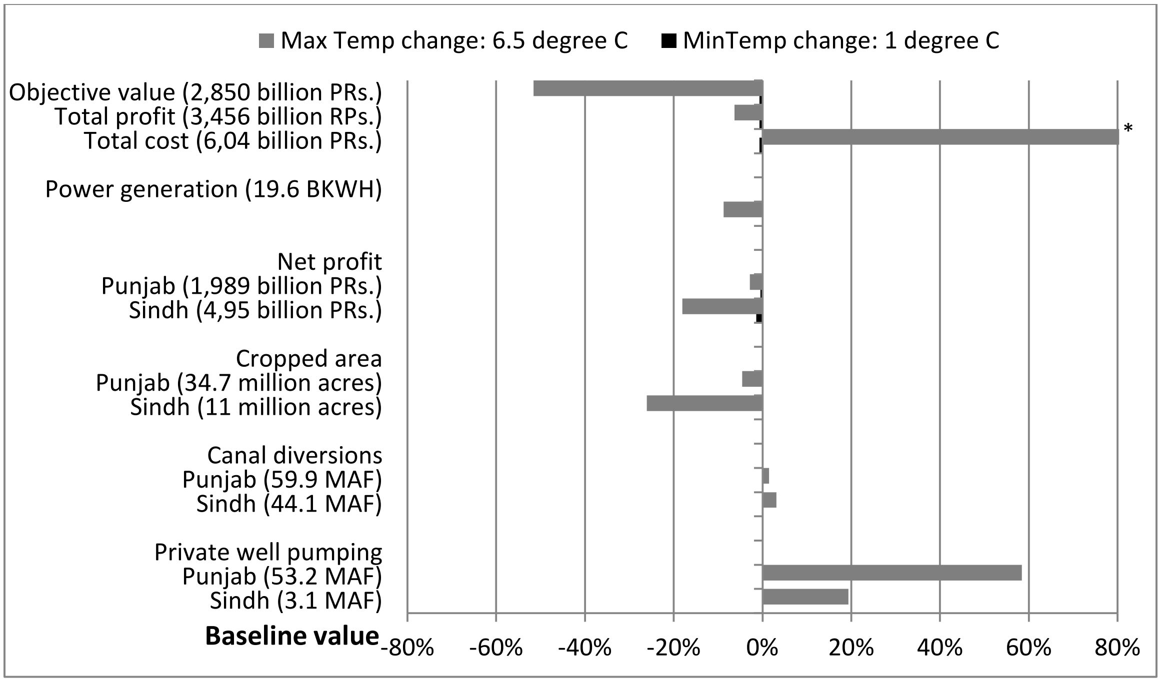

Figure 4. The impact of changes in temperature (crop water requirements) on IBMR-2012 outputs.
Notes: The results are percentage changes compared to baseline values for each item listed on the y-axis. (*the change of total cost compared to baseline is +207%)

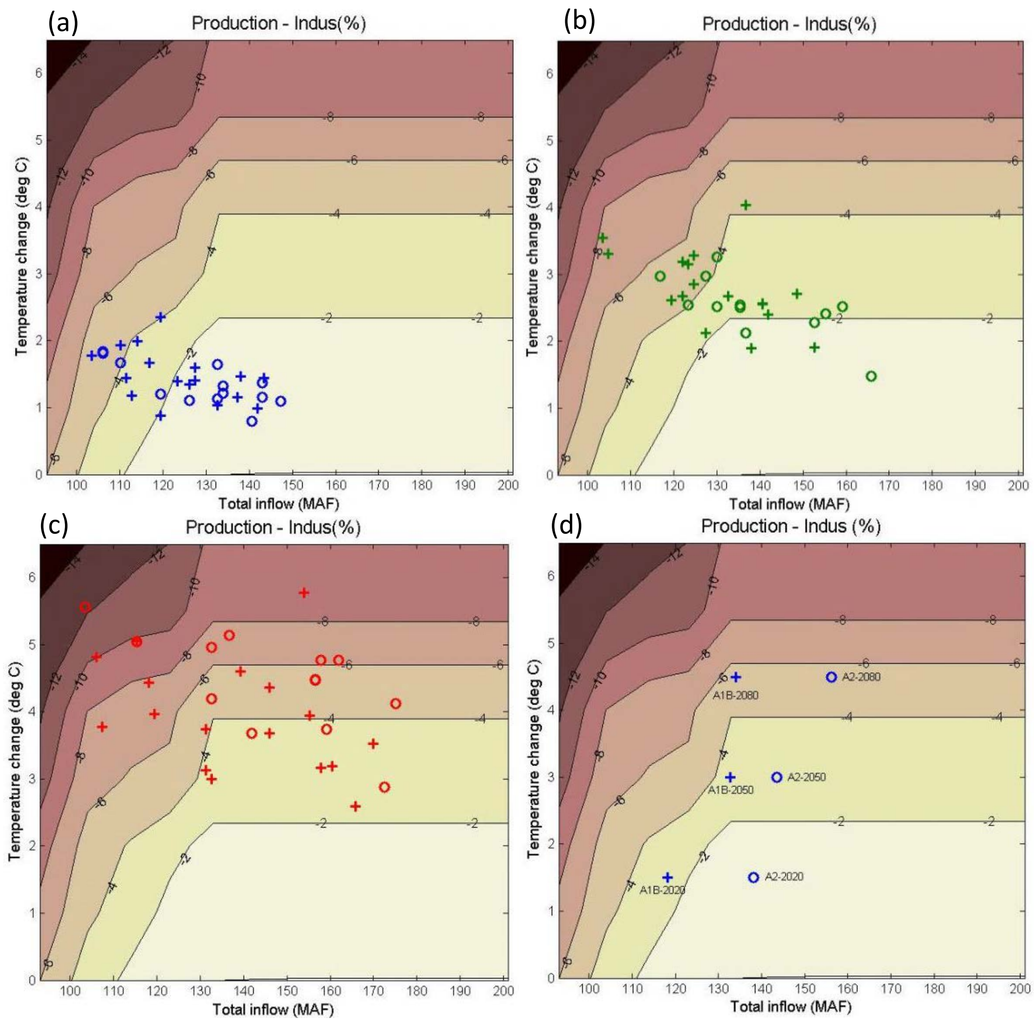

Figure 5. The basin-wide "climate response surface" of crop production changes (a) 2020s; (b) 2050s; (c) 2080s and (d) ensemble GCM mean.

Note: "**o**" represents A2 scenarios and "**+**" represents A1B scenarios.

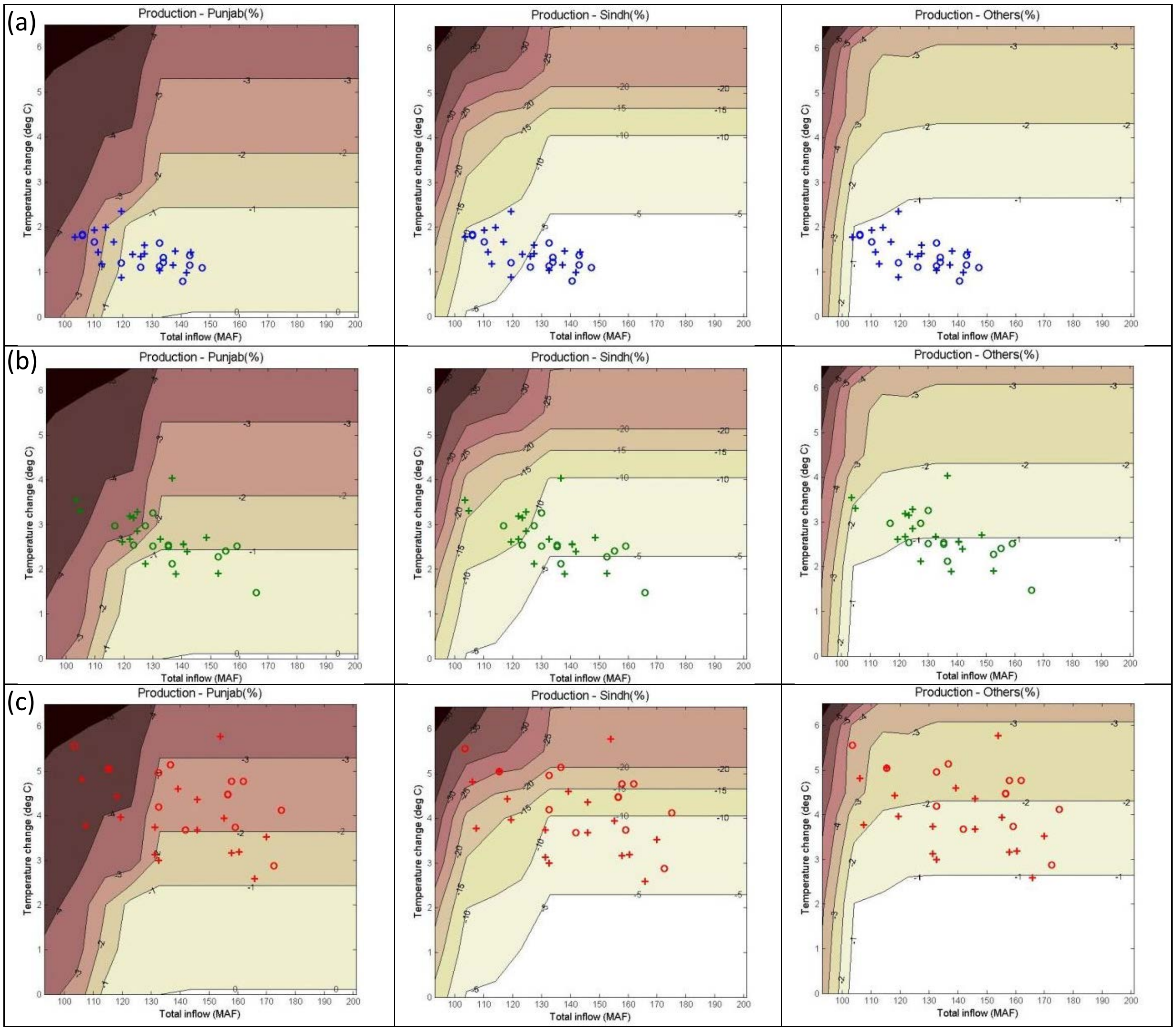

Figure 6. The “climate response surface” of crop production changes in Punjab, Sindh and other provinces (a) 2020s; (b) 2050s and (c) 2080s.

Note: “**o**” represents A2 scenarios and “+” represents A1B scenarios.

Table 1. The hierarchal structure in the IBMR-2012: provinces, ACZs, number of canals and cropped land.

Provinces	ACZ Name	Number of Canals	Available cropped land (million acres)
KPK	Khyber Pakhtunkhwa _kabul_swat (KPKS)	4	0.628
	Khyber Pakhtunkhwa _mixed_wheat (KPMW)	1	0.892
Punjab	Punjab_mixed_wheat (PMW)	2	3.876
	Punjab_cotton_wheat_west (PCWW)	4	3.177
	Punjab_cotton_wheat_east (PCWE)	10	8.556
	Punjab_sugarcane_wheat (PSW)	5	4.470
	Punjab_rice_wheat (PRW)	6	2.801
Sindh	Sindh_cotton_wheat_north (SCWN)	7	3.941
	Sindh_cotton_wheat_south (SCWS)	2	2.858
	Sindh_rice_wheat_north (SRWN)	5	3.208
	Sindh_rice_wheat_south (SRWS)	4	2.806
BLCH	Baluchistan_rice_wheat (BRW)	3	1.858

Table 2 Major IBMR-2012 outputs under baseline conditions

Provinces	Objective value (million PRs.)	Commodity total gross profit (million PRs.)	On-farm costs (million PRs.)	Cropped area (1000 acres)	Crop production (1000 tons)	Power generation (BKWH)
Pakistan	2,850,099	3,162,371	601,369	48,491	95,138	19.59
Punjab	-	2,430,117	440,965	34,734	65,374	-
Sindh	-	628,036	132,823	11,057	24,905	-
Others		104,218	27,582	2,701	4,859	-

Note: Others include KPK and BLCH

Table 3 Commodity gross profit breakdown for the baseline conditions (million PRs.)

Crops	Pakistan	Punjab	Sindh	Others
Basmati rice	749,694	749,694	0	0
Irrigated rice	170,466	27,733	108,530	34,204
Cotton	674,609	552,092	122,190	327
Gram	36,101	20,860	12,810	2,431
Maize	70,457	44,542	692	25,223
Mus+rap	2,574	1,923	7	645
Sugarcane	245,950	156,249	78,764	10,937
Wheat	418,049	377,301	35,080	5,669
Potato	111,421	108,316	682	2,424
Onion	56,891	18,360	37,187	1,344
Chili	35,674	17,685	17,962	27
Cow-milk	144,051	76,608	64,160	3,282
Buffalo-milk	446,434	278,755	149,973	17,706
All	3,162,371	2,430,117	628,036	104,218

Table 4 On-farm cost breakdown under baseline conditions (million PRs.)

Costs	Pakistan	Punjab	Sindh	Others
Seed	38,434	27,035	9,189	2,210
Labor	205,834	145,040	51,970	8,824
Miscellaneous	47,343	37,711	8,756	876
Protein	2,488	1,988	401	98
Fertilizer	120,082	79,972	33,261	6,849
Private well	45,930	42,942	2,530	458
Livestock	735	432	273	30
Tractor	140,524	105,844	26,442	8,238