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Intersectoral Water Allocation in the Indus Basin-Under Different Management Policies

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The Indus River supports the world's largest contiguous irrigation system, the Indus Basin Irrigation System (IBIS), which accounts for most of Pakistan's freshwater consumption. At the same time, domestic and industrial water demands are growing rapidly and environmental water needs remain unmet. This paper uses a hydro-agro-economic model, the Indus Basin Model Revised - Multi Year (IBMR-MY) to evaluate intersectoral water allocation in Pakistan's Indus Basin under different surface water allocation and groundwater regulation polices. Modeling results indicate that more flexible surface water allocation policies can lead to substantial improvements in agricultural profits and also impact hydropower profits, but will have little impact on domestic and industrial water use benefits. Moreover, average flows to the Arabian Sea show no significant changes under this setting, which suggests that the optimal water use through flexible allocation policies will not necessarily jeopardize the flow for environment. We find that improving water allocation flexibility in irrigation will thus not only be crucial for improving agricultural outcomes in Pakistan, but also for sustained domestic, industrial and hydropower generation as well as environmental outcomes.

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I. INTRODUCTION

Growing population, increasing urbanization and industrialization result in increasing demand for water across all water-using sectors, including domestic, industrial and agricultural uses as well as hydropower production (Chawla et al, 2012). This results in rapidly growing, intersectoral competition for water resources, which is particularly important in developing countries, such as Pakistan, where both economic and population growth are fairly rapid. The Indus Basin is the backbone of Pakistan's economy. It supports approximately 90 percent of all food grown in the country through the Indus Basin Irrigation System (IBIS) and provides important energy production services (hydropower) as well as domestic and industrial water supply. To meet this growing demand, the basin has two major multi-purpose storage reservoirs, Mangla and Tarbela, 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 (Yu et al, 2103). All infrastructures were originally designed to provide reliable irrigation water supply for the agricultural sector. Historically, domestic and industrial (D&I) water uses were supplied by groundwater, especially in Punjab province (GOP, 2002). But declining water tables and degrading water quality, especially in urban areas (NESPAK, 1991), have led to government calls for the regulation of groundwater abstractions (GOP, 2009) and the substitution of groundwater use for D&I needs with cleaner surface (canal) water. These developments will further fuel intersectoral water competition, as expressed by the Pakistan Water Sector Strategy: "*…as development proceeds and the population as well as country's economy grow, competition for water resources will become a major concern*" (GOP, 2002).

Previous studies have documented the challenges of intersectoral water transfers in developing countries (Rosegrant and Ringler, 1998; Meinzen-Dick and Appasamy, 2002; Molle and Berkoff, 2006 and Mustafa et al, 2013). Rosegrant and Ringler (1998) report that the severity of economic impacts of water transfers out of irrigated agriculture will depend on the relative economic strength of the sector, and the linkages between the area of origin and destination of the water. Molle and Berkoff (2006) suggest that intersectoral water transfers from agriculture to the D&I sector usually follow the "path of least political-economic resistance." In the case of Pakistan, Mustafa et al. (2013) suggest that how to share water more equally among different sectors might be more critical than how to increase supply or decrease demand. Most previous Indus water resource studies primarily focused on agricultural water uses (Briscoe and Qamar, 2006; Yu et al, 2013), while studies on domestic and industrial water uses related to water quality and public health issues (Rahman et al, 1997; van der Hoek et al, 2002; Azizullah et al, 2011; Nasir et al, 2012) due to the low share of D&I water use and its predominant reliance on groundwater.

According to the Government of Pakistan (GOP, 2002) D&I demand was 4.3 million acre-feet (MAF, 1 MAF = 1.234 billion cubic meter) in 2002, including 3.2 MAF for domestic and 1.1 MAF for industrial water uses, with expected increases to 12.1 MAF by 2025. Hussain et al. (2011) use a water balance method to show that by as early as 2015, gaps between supply and demand of domestic and industrial water can reach 4.5 and 0.4 MAF, respectively. Azad (2003) provides a detailed study of water resources management in Sindh province estimating a D&I demand increase of 2.4 MAF by 2025. Suttinon et al. (2009) and Bhatti and Nasu (2010) use data analysis and simple economic models to evaluate D&I water use growth trends to 2030 under different socio-economic scenarios.

No study up to now, based on our knowledge, assessed the impact of increasing intersectoral water transfers out of agriculture on Pakistan's agricultural economy. This paper uses a hydro-agro-economic model to evaluate the current intersectoral water allocation under different surface water (allocation) and groundwater (regulation) polices. Results of this study provide insights into policy for enhanced intersectoral water allocation.

2. DOMESTIC AND INDUSTRIAL WATER USE PROFITS

The IBMR-MY is a multi-year extension of the Indus Basin Model Revised (IBMR) (Duloy and O'Mara, 1984; Ahmad et al, 1990; NESPAK, 2013). The model was originally designed to allocate water to achieve maximum agricultural profits in the basin subject to physical and institutional constraints. Recent updates (Yu et al. 2013, Yang et al. 2013a and Yang et al. 2013b) have resulted in inclusion of hydropower benefits. IBMR-MY is a hydro-agro-economic model that covers the four key provinces in Pakistan's Indus Basin: Khyber Pakhtunkhwa (KPK), Punjab, Sindh and Balochistan. It uses agro-climatic zones (ACZs, Figure 1) as basic spatial units for agricultural production. The water supply of each ACZ is provided by canals (located inside ACZs) that intake water from the Indus basin as well as zonal groundwater pumping. Input data include agronomic data (crop yield, crop water requirements and labor and tractor needs); economic data (crop price, price elasticity and wage, etc); a resources inventory (available land area, labor force and tractors); and irrigation systems and water data (streamflow, canal capacity and field efficiency). Primary model outputs include gross profits from agricultural production, farm cost, and surface and groundwater usage at ACZ level that can be aggregated to the provincial and basinwide levels. Livestock is indirectly considered through fodder production and no international trade is incorporated.

To evaluate the economic impact of intersectoral water allocation and transfers, we add domestic and industrial water demand functions into the objective function following Jenkins et al (2003), Brozovic et al. (2007) and Wan et al (2012). For this study, we use a utility function approach. This utility function is adopted from the demand curve of domestic water supply and is affected by changes in water price, the price elasticity of water demand and total water uses (which are a function of both population and per capita water usage). We use a multi-variable linear regression to fit a linear function for this utility equation as follows:

$$D_i = \alpha_{0i} + \alpha_{1i} \times D\_water\ use_i + \alpha_{2i} \times D\_elasticity_i + \alpha_{3i} \times D\_water\ price_i \quad (1)$$

where *i* represent the index for different municipalities considered, α_0 is the constant in the linear function, α_1, α_2 and α_3 represent the coefficients for total domestic water use, price elasticity and domestic water price, respectively. Following Ringler et al. (2006), a similar utility function for industrial water profits is also a linear fitted function, as follows:

$$I_{ig} = \beta_{0ig} + \beta_{1ig} \times I\_water\ use_{ig} + \beta_{2ig} \times I\_elasticity_i + \beta_{3ig} \times I\_water\ price_i \quad (2)$$

where *i* represent the index for different municipalities and *g* represent the index of different industrial groups. Four major industrial groups are considered in this study: textile, chemical, paper and food. β_{1i}, β_{2i} and β_{3i} represent coefficients for total industrial water use, price elasticity and industrial water price, respectively, for these four groups.

The nine most populated municipalities in the basin are selected for analysis (Table 1). Domestic and industrial water uses in equations (1) and (2) are decision variables determined by the model. Elasticities from estimated values by Nauges and Whittington (2010) are used for the price elasticity of water demand. Price data were obtained from municipalities' utility company websites and previous studies (Karachi Water & Sewerage Board, 2013; Rawalpindi Development Authority, 2013 and Rauf and Siddiqi, 2008). Lahore, Rawalpindi and Karachi report "Rupee (Rs.) per volume" water prices which were used for this study. Information for other municipalities, which either have a "flat rate" water price or no price data available use the price information from the nearest municipality with volume-based charges (Table 1). The modified objective function is presented in equation (3):

$$Basinwide\ Profit = \sum_Z \sum_G \sum_C Price_{Z,G,C} \times Crop\ Production_{Z,G,C} - \sum_Z \sum_G Crop\ Cost_{Z,G} + \sum_N Energy\ price \times Hydropower_N + \sum_I D\&I\ Profit_I - \sum Slackvariables \quad (3)$$

where *Z* is the index for ACZ, *G* is the index for groundwater type, *C* is the index for crop, *I* is the index for municipality and *N* is the index for reservoir. *Price* × *Production* is the total gross profits from irrigated crop production, *Cost* is the total cost of irrigated crop production, *D&I profits* are the sum of domestic and industrial water use profits (i.e. "$\sum D_i + I_{ig}$"), *Energy price* × *Hydropower* denotes profits from hydropower generation and *Slackvariables* represent the penalty of insufficient water in the model or insufficient production to satisfy minimal consumption. This objective function drives the optimization of intersectoral water allocation in different surface and groundwater management scenarios that are described in the following.

3. SCENARIO SET UP

Surface Water Allocation Policies

The 1991 interprovincial Indus Water Apportionment Accord between the four provinces sharing the lower Indus River defines the water allocation to each province but allows intra-provincial freedom of canal allocations. This Accord is enforced by the Indus River System Authority (IRSA). Table 2 presents details on water sharing among the provinces (Blackmore and Hasan 2005) in the Accord. Paragraph 14 (b) of the Accord specifies that actual average system uses for the period of 1977-82 form the guideline for developing future regulation patterns. These ten-day uses would also be adjusted proportionally to correspond to the indicated seasonal allocations of the different canal systems, and would form the basis for sharing shortages and surpluses. Additional river supplies, including flood supplies and future storage, would need to be distributed as follows: 37 percent each to Punjab and Sindh, 12 percent to Balochistan and 14 percent to KPK (Table 2). The need for certain minimum flows to the Arabian Sea to control for seawater intrusion was recognized and set at 10 MAF (Blackmore and Hasan 2005).

In our model, we use historical, long-term average (1991-2000) canal-level water diversions to represent this water allocation policy. This “IRSA-rule” (IRSA-RUL) water allocation policy assumes that the actual observed canal diversion follow IRSA rules and use the historical average as a basis. We allow for a 20% deviation from the base for each canal to give the model limited flexibility for optimization under varying hydrological and climatic conditions. This setting is more restricted compared to other settings since it does not allow for ful, intra-provincial optimization of water allocation.

Since 2003, the following rules are strictly enforced by IRSA using a 10-day schedule (Imam and Lohani, 2012):

- *Tier I*

Water Availability < Para 14b; use exact Para 14b allocation for KPK and Balochistan. The deficit (= Water Availability – Para14b) is shared by Punjab and Sindh using a 52% and 48% proportion (see also Table 2).

- *Tier II*

Water Availability > Para14b but < Para 2, protect actual average system use; balance as per Para 2.

- *Tier III*

Water Availability > Para 2; use Para 2, the surplus (= Water Availability – Para2) will be balanced as per Para 4

We define this three tier formulation as our second water allocation policy: “IRSA-optimization” (IRSA-OPT). Under this setting, provinces have the freedom within their shares to allocate province-wise and period-wise among water uses based on the specific available water volume.

Finally, we want to test a basinwide (i.e. inter-provincial) optimization water allocation policy. This “BAS-OPT” policy allows water to be used based on the marginal value of water only and disregards the constraints of the provincial water sharing agreement. We use this setting to evaluate the potential of centralized optimization and results obtained from this setting are treated as an upper limit of the current system from a basinwide perspective. In sum, three surface water allocation policies are identified as: “IRSA-RUL,” “IRSA-OPT” and “BAS-OPT.”

Groundwater regulation policy

Historically, groundwater supplied the majority of domestic and industrial water uses in Pakistan for both urban and rural areas (GOP, 2002) and was also used to compensate for insufficient surface irrigation supplies, especially in Punjab. However, as described earlier, developments in both rural and urban areas for all purposes are putting pressure on groundwater resources. Most of the groundwater resources are already over exploited and the potential for further development of groundwater is therefore limited (Shahid, 2005).

To address groundwater management, two possible regulations are implemented. The first relates to maximum groundwater pumping. Previous studies suggested that the "safe yield" of groundwater pumping in the basin is about 50 MAF (Briscoe and Qamar, 2006; Qureshi, 2011; Yu et al, 2013). We run the model with or without this 50 MAF pumping cap. The second rule relates to D&I water uses. In the model, two D&I water source settings are applied: "D&I use groundwater only" for all municipalities, which is close to the current situation and "D&I use both surface and groundwater" for all municipalities which is more likely to be the situation in the future. For this, D&I water uses are linked with existing ACZs and canals in the original model structure based on their geographical locations. This linkage is summarized in Table 1. Results of these runs allow us to evaluate growing intersectoral water competition for both surface and groundwater.

Changing future water supply and demand

Pakistan's rapidly growing population suggests that intersectoral competition for water will grow considerably over the next decades. We therefore model this competition under changing water supply (due to climate change) and demand conditions (irrigated area expansion, population increase and technological change). According to Yu et al. (2013), changes in annual total streamflow might range from a reduction of 22% (temperature increase of 0.5^{o}C and precipitation decrease of 20%) to an increase of 26% (temperature increase 4.5^{o}C and precipitation increase of 20%) in the future. A non-parametric bootstrap streamflow generator is used to generate time series of streamflow for nine tributaries in the model. The bootstrap method is a simple but widely used method that can synthesize streamflow time series data from historical records while maintaining its statistical properties (Kim et al, 2004; Ndiritu, 2011).

We randomly choose one year from a 50-year historical record (1961-2010) and use the monthly streamflow of different tributaries from that chosen year as the synthesized streamflow. This procedure is repeated 30 times to generate a 30-year streamflow time series. Since these are real streamflow values, the spatial correlations among tributaries and the temporal characteristics among months are preserved. To generate future inflows, the same model is used but a parameter that represents the annual change rate is added into the model. This delta method is also widely used in hydrology or climate-related studies (Hamlet and Lettenmaier, 1999; Snover et al, 2003). To simulate a low-inflow future, the annual change rate is negative so that total system streamflow in the end year is a prescribed percentage of the original year. Using this generator, we generate three different streamflow time series: low supply (annual rate of change of -0.83% resulting in a 22% streamflow reduction after 30 years), medium supply (annual rate of change is 0%) and high supply (annual rate of change is 0.77% resulting in a 26%-increase in total streamflow over 30 years).

Water demand changes are driven by population increase for D&I water uses and by expansion of irrigated areas for agriculture. We assume three pathways for development: low, medium and high. For domestic and industrial water uses, we adopt Suttinon et al. (2009) who use a Cohort-component method to estimate that the 2030 population in Pakistan will be 2.02, 2.08 and 2.10 times the level of 2011 under low, medium and high development conditions, respectively. Similarly, industrial water uses in 2030, estimated by Input-Output table and water use per value of production, would be 0.61, 1.35 and 2.23 times 2011 levels under low, medium and high development conditions (Suttinon et al, 2009). For irrigation, we assume that the physically available crop area (which is connected with irrigation water use in a non-linear fashion in the model) of the IBIS can be expanded by 0%, 5% and 10% to represent low, medium and high development conditions, respectively. The future supply-demand uncertainty issue is addressed by joining these supply and demand change settings under alternative groundwater regulations. Figure 2 summarizes the scenarios simulated with the IBMR-MY.

4. RESULTS AND DISCUSSION

Impacts of surface water and groundwater policies

Current (2011) population, irrigated crop area and synthetic 30-year streamflow values (medium supply level) are used in the model to evaluate the effects of surface and groundwater policies. Basinwide sectoral profits (30 years average, maximum and minimum) are summarized in Table 3. D&I profits barely change across scenarios, which indicates that water uses in these two sectors have higher economic values, as expected. Hydropower profits are not affected by changes in groundwater regulations, but change slightly under changing surface allocation rules. When the model switches from the IRSA-RUL policy to IRSA-OPT or BAS-OPT policies, more hydropower profits are generated, especially in high-flow years. This is due to the flexibility of the system under the optimization framework.

Agricultural profits, on the other hand, are affected by both surface and groundwater policies. When the model switches from IRSA-RUL to IRSA-OPT or BAS-OPT water management, average agricultural profits increase by 2.5% and 5.0%, respectively. When D&I water sources switch from groundwater only to both surface and groundwater sourcing, average agricultural profits slightly increase, by 0.3% to 0.6%, depending on the surface allocation strategy. The reason for increased profits is the reduction in groundwater pumping cost for irrigation due to higher water tables as D&I draws more surface water. Table 4 presents the average annual groundwater drawdown rate under different scenarios. Groundwater drawdown rates are always lower when D&I use both surface and groundwater in Punjab and Sindh. The drawdown rate only increases in KPK and Balochistan under the BAS-OPT water allocation policy. However, in Punjab, more efficient surface water allocation also drives additional groundwater drawdown. The groundwater cap, on the other hand, has small negative effects on agricultural profits, as expected. Under IRSA-RUL, the groundwater cap results in average agricultural profit declines of about 0.15%. Under IRSA-OPT and BAS-OPT water allocation strategies adverse effects are eliminated. The agricultural profit decrease 0.02% and 0.01% in Table 3 first column under IRSA-OPT and BAS-OPT, respectively).

Figure 3 shows the effects of surface and groundwater policies on actual D&I water uses. This figure first demonstrates that although the profits from D&I are stable throughout all runs (Table 3), the average D&I water sources differ by scenario. Under more flexible water allocation mechanisms, D&I uses more groundwater and thus less surface water. This is because under more flexible water allocation mechanisms, water can be used more profitably in irrigated agriculture, and the additional profit gain in irrigated agriculture is larger than the additional pumping cost to supply D&I purposes. When groundwater is capped at 50 MAF, surface water use increases slightly (e.g. 0.1 MAF for IRSA-RUL and IRSA-OPT and no change for BAS-OPT), as expected.

Water uses for environmental purposes can also be treated as another "sector" in the intersectoral water allocation analysis. Various methods have been used to quantify environmental water demands, such as minimum flow requirements or the natural flow regime method (Poff et al, 1997; Richter et al, 2003). Such environmental demands can then be added into the modeling framework using methods like agent-based modeling (Yang et al. 2009; Yang et al. 2012). In this study, we evaluate changes in flows to the Arabian Sea as a result of alternative management strategies. Results are shown in Figure 4. Flows to the Arabian Sea are lowest under IRSA-OPT, as more water (an additional 6 MAF per year) is delivered to KPK and Balochistan based on the 2003 implementation of the agreement. However, flows are never less than 10 MAF, again based on the agreement. Under BAS-OPT, on the other hand, flow to the Arabian Sea slightly dips to less than 10 MAF under low-flow years. However, average flows to the Arabian Sea show no significant changes under this setting, which suggests that the optimal water use through flexible allocation policies will not necessarily jeopardize flow for the environment.

Impacts of water supply and demand uncertainties

In this section, we focus on impacts of changing water supply and demand on intersectoral water allocation and profits. We assume that surface water allocation will follow the IRSA-RUL policy, as real optimization is not yet used in the IBIS, and either both surface and groundwater or only groundwater is available for D&I water uses. Table 5 presents basinwide profits under different runs and also the percentage change from the "baseline." The baseline is defined as the IRSA-RUL policy with both surface and groundwater for D&I water uses and historic water supply and demand.

Domestic water use benefits show a monotonic increase when demand grows regardless of water supply and source changes, indicating the high value of domestic water uses. Hydropower profits, on the other hand, change monotonically with changes in supply regardless of changes in demand. On the other hand, agriculture and industries are affected by changes in both supply and demand. Agricultural profit changes range from +3.9% (under high supply with high demand) to -1.2% (under low supply and low demand). Agricultural profits are always lower under a groundwater cap. Industrial profits change substantially with demand growth when groundwater is not regulated. When groundwater is capped at 50 MAF, both water supply and demand changes affect industrial profits. In that case, larger water supplies will result in higher industrial profits. This result indicates that industrial water use profits will become more sensitive to water supply changes when groundwater is regulated.

Figure 5 shows changes in actual water uses for domestic and industrial purposes under different water supply and demand changes. Figure 5(a) shows that demand changes will affect both surface and groundwater uses for domestic purposes when groundwater pumping is not restricted. When demand increases, groundwater extractions increase. Figure 5(b) confirms that industrial water use is primarily affected by demand growth. A cap on groundwater and changing supplies has limited effects.

5. CONCLUSION

The Indus Basin is the backbone of Pakistan's economy. It supports the country's economy and water uses. The rapidly growing population in the country will put growing pressures on intersectoral competition for scarce water resources. This paper uses a hydro-agro-economic model, the Indus Basin Model Revised – Multi Year, to evaluate both current and potential future intersectoral water allocation under different surface water allocation and groundwater regulation polices.

Modeling results indicate that changes in surface water policies will affect hydropower profits only slightly; changes in production are largely driven by changes in water supply. For agriculture, on the other hand, increased flexibility in canal water allocation within and across provinces can substantially improve agricultural profits. Groundwater regulation, through setting an abstraction limit, while important for sustainable water use in the country, can negatively affect agricultural profits. A better representation of groundwater in the model is needed to reflect the costs and benefits of unregulated abstractions (see below). D&I water use benefits are largely unaffected by surface water and groundwater policies due to their higher economic values. Flow to the Arabian Sea is most reduced under the IRSA-OPT allocation mechanisms as surplus flows are allocated to Balochistan and KPK.

Water supply and demand changes out to 2040 will result in changes in agricultural profits ranging from plus 3.9% to minus 1.2%. Future domestic water use profits are only affected by demand changes while hydropower profits are affected by supply changes. Industrial water use profits will, in general, change with demand but changes in supply matter if groundwater abstractions are capped.

Estimated domestic and industrial water uses are of the same magnitude as previous studies (GDP, 2002; Suttinon et al, 2009) under both current and future conditions, which provide some confidence about the results.

Future studies are suggested to focus on the linkage between a physically-based groundwater model or develop a more detailed groundwater component in the IBMR-MY. The IBMR-MY used in this study considers a dynamic water table where the depth to groundwater is changing year-by-year based on groundwater pumping. Pumping costs relate to both the volume of pumped groundwater and the depth of the water table. Finally, domestic, industrial and irrigation users can pump water and drainage wells are also linked. However, the real world groundwater condition in the Indus Basin is much more complex. For example, our model has simple lateral groundwater flow components, which are set as constants for each ACZ and were obtained from a previous model (Yu et al, 2013). Furthermore, dynamic changes between the fresh and saline groundwater zones are not included in the model. We thus assume that groundwater quality will remain the same throughout the modeling period. Finally, the model currently only allows for pumping (for productive uses) in freshwater areas. However, it is well known that farmers mix saline groundwater with fresh canal water for crop production due to insufficient canal water availability. To address these issues requires linking the IBMR-MY with a physically-based groundwater model or properly improving groundwater representation in the IBMR-MY. Previous physically-based or semi-physically-based groundwater modeling studies such as Ahmad et al. (2011) and Chandio et al. (2012) are limited to a local scale, such as one canal command area. Larger-scale groundwater studies are mostly limited to "data-analysis type" studies such as Amin (2004) due to the complexity to set up a model for basinwide scale. If a basinwide level physically-based or semi-physically-based groundwater model can be built, results should provide more detailed water table change under different conditions and benefit outcomes of this study.

This study is a novel effort in employing IBMR as a Multi-Year model (IBMR-MY). Future studies can employ a Multi-Year model to focus on the inclusion of structural changes in the Indus Basin (for instance, the incorporation of reservoirs) to understand these impact on water supply over a number of years, and to examine agricultural, domestic, industrial and hydropower benefits. Furthermore, the multi-year model could be modified to include the option of expanding the cropped area of orchard crops (for instance, mango, citrus, etc). This option could be incorporated to assess potential benefits (or costs) obtained from investments in orchard area expansion.

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ANNEX

Table 1. The basic information of domestic and industrial water uses for the nine municipalities modeled in IBMR-MY.

Municipalities	Estimated population in 2011	Domestic water price*	Industrial water price*	Linked ACZs	Linked canals
Karachi	13,205,339	23,135	38,776	SRWS	42-KAL
Lahore	7,129,609	8,840	11,592	PRW	02-CBD
Faisalabad	4,177,246	21,029	31,025	PSW	11-JHA
Multan	2,050,046	10,628	15,669	PCWW	17-SID
Rawalpindi	2,424,983	16,293	24,032	PSW	22-USW
Hyderabad	1,578,367	4,396	7,368	SCWN	39-ROH
Gujranwala	1,466,063	19,314	28,477	PRW	04-UC
Peshawar	1,439,205	39,330	65,920	KPKS	25-KAB
Islamabad	689,249	14,500	21,388	KPKS	22-USW

* Units for water price is Rs. per acre-feet; sources:

Sources: Population data-wikipedia; price data-Karachi water& sewerage board; Rawalpindi Development Authority; Rauf and Siddiqi (2008).

Table 2. Water apportionment across provinces according to the 1991 Water Accord

Province	Para 14b (1977-82 use)	Kharif – Para 2	Rabi – Para 2	Total Para 2	Para 4 (excess)
	MAF (%)	MAF (%)			%
Punjab	54.51 (53%)	37.07	18.87	55.94(49%)	37%
Sindh*	43.53 (42%)	33.94	14.82	48.76 (43%)	37%
KPK	3.05 (3%)	3.48	2.30	5.78 (5%)	14%
Balochistan	1.63 (2%)	2.85	1.02	3.87 (3%)	12%
Total	102.73 (100%)	77.34	37.01	114.35 (100%)	100%
Civil Canals** (KPK)		1.80	1.20	3.00	
Grand Total		79.14	38.21	117.35	

* Including already sanctioned Urban and Industrial uses for Metropolitan Karachi.

** Ungauged civil canals above rim stations.

Source: Blackmore and Hasan (2005)

Table 3. Basinwide sectoral profits under different surface and groundwater policies-30 year-average, maximum and minimum value

Profits (billion Rs.)		Agricultural			Domestic			Industrial			Hydropower		
		Mean	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
IRSA-RUL allocation policy													
D&I-GW	GW-no cap	4393	4640	4191	174	175	174	31	31	31	281	319	248
	GW- 50 cap	4384	4612	4189	175	175	175	30	31	26	280	319	248
D&I-SGW	GW-no cap	4414	4643	4227	174	175	174	31	31	31	281	319	248
	GW- 50 cap	4410	4637	4212	174	175	174	31	31	31	281	319	248
IRSA-OPT allocation policy													
D&I-GW	GW-no cap	4497	4744	4301	174	175	173	31	31	31	283	333	250
	GW- 50 cap	4496	4703	4299	175	175	175	31	31	23	283	332	249
D&I-SGW	GW-no cap	4515	4746	4326	175	175	175	31	31	31	283	334	249
	GW- 50 cap	4513	4748	4326	175	175	175	31	31	31	283	333	249
BAS-OPT allocation policy													
D&I-GW	GW-no cap	4608	4772	4467	175	175	175	31	31	31	282	332	249
	GW- 50 cap	4607	4772	4466	175	175	175	31	31	31	282	332	248
D&I-SGW	GW-no cap	4623	4772	4492	175	175	175	31	31	31	282	331	249
	GW- 50 cap	4623	4772	4495	175	175	175	31	31	31	282	331	249

* D&I-GW: Domestic and industrial water uses only use groundwater; D&I-SGW: Domestic and industrial water uses use both surface and groundwater; GW-no cap: no groundwater pumping cap; GW- 50 cap: basin-wide groundwater pumping is limited to 50 MAF. Note that profits listed in the table are affected by the penalty item in the objective function.

Table 4. Provincial-level average annual groundwater drawdown rate under different surface and groundwater policies (in feet per year)

Groundwater drawdown rate (ft/year)			Punjab	Sindh	Others	Total
IRSA-RUL	D&I-GW	GW-no cap	7.1	0.2	2.6	9.9
		GW- 50 cap	6.6	-0.1	2.6	9.1
	D&I-SGW	GW-no cap	6.8	0.2	2.0	9.0
		GW- 50 cap	6.5	0.0	2.0	8.5
IRSA-OPT	D&I-GW	GW-no cap	7.7	-0.7	0.7	7.7
		GW- 50 cap	7.6	-0.8	0.5	7.3
	D&I-SGW	GW-no cap	7.5	-0.7	0.1	6.9
		GW- 50 cap	7.4	-0.7	0.1	6.8
BAS-OPT	D&I-GW	GW-no cap	4.8	0.2	2.8	7.8
		GW- 50 cap	4.8	0.2	2.7	7.7
	D&I-SGW	GW-no cap	4.5	0.3	2.1	6.9
		GW- 50 cap	4.5	0.3	2.1	6.9

*Others are KPK and Balochistan.

Table 5. Basinwide profit changes under different water supply and demand changes.

Profits (billion Rs.)	No GW Cap			GW 50 MAF Cap		
	Low supply	**Medium supply**	**High supply**	**Low supply**	**Medium supply**	**High supply**
Agricultural profits under current water supply and demand: 4414.3 billion Rs.						
Low demand	4376 (-0.9%)	4402 (-0.3%)	4430 (0.3%)	4361 (-1.2%)	4395 (-0.4%)	4428 (0.3%)
Medium demand	4458 (1.0%)	4485 (1.6%)	4489 (1.7%)	4432 (0.4%)	4465.3 (1.2%)	4473 (1.3%)
High demand	4524 (2.5%)	4553 (3.1%)	4585 (3.9%)	4491 (1.7%)	4529 (2.6%)	4558 (3.3%)
Domestic profits under current water supply and demand: 174.5 billion Rs.						
Low demand	400 (129%)	400 (129%)	400 (129%)	400 (129%)	400 (129%)	400 (129%)
Medium demand	413 (137%)	413 (137%)	413 (137%)	413 (137%)	413 (137%)	413 (137%)
High demand	418 (139%)	418 (139%)	418 (139%)	418 (139%)	418 (139%)	418 (139%)
Industrial profits under current water supply and demand: 31.1 billion Rs.						
Low demand	11 (-64%)	11 (-64%)	11 (-64%)	11 (-65%)	11 (-64%)	11 (-64%)
Medium demand	49 (57%)	49 (57%)	49 (58%)	46 (49%)	48 (55%)	48 (56%)
High demand	94 (202%)	94 (202%)	94 (202%)	86 (184%)	87 (190%)	90 (198%)
Hydropower profits under current water supply and demand: 280.9 billion Rs.						
Low demand	267 (-5.1%)	281 (0%)	296 (5.2%)	266 (-5.2%)	281 (-0.1%)	295 (5.1%)
Middle demand	267 (-5.1%)	281 (0%)	296 (5.2%)	266 (-5.3%)	280 (-0.2%)	295 (5.0%)
High demand	267 (-5.1%)	281 (0%)	296 (5.2%)	266 (-5.3%)	280 (-0.2%)	295 (5.0%)

Figure 1. The major cities and agro-climatic zones in the Indus Basin Model Revised – Multi Year.

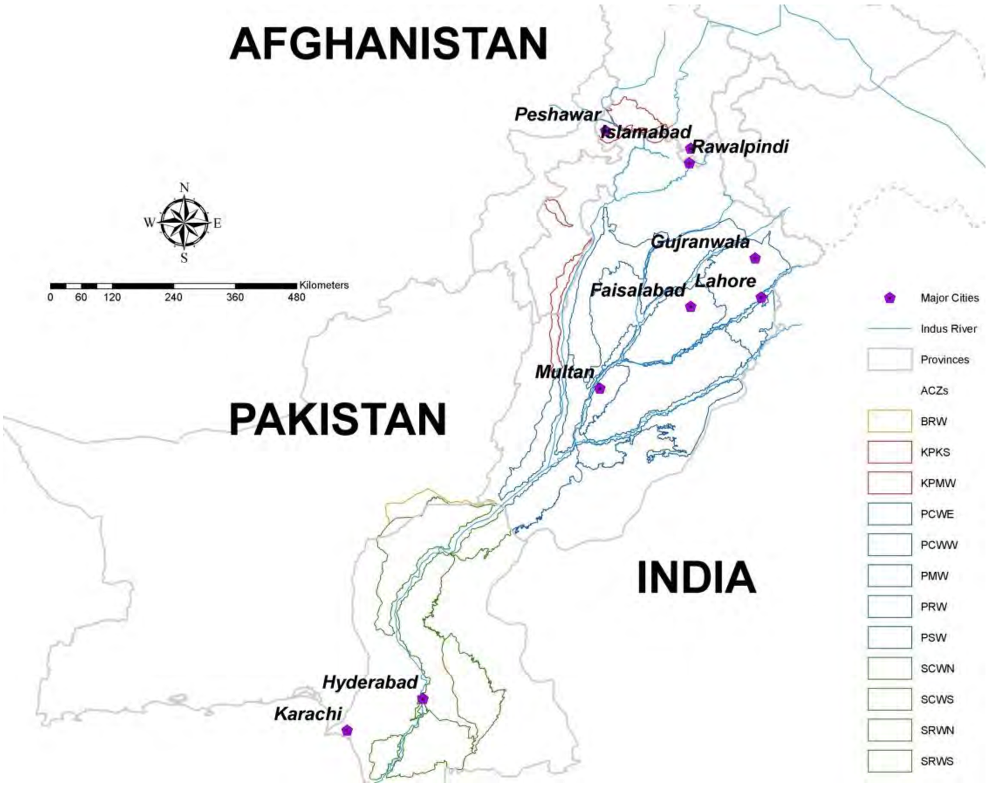


Figure 2. Summary of runs that been tested in this study.

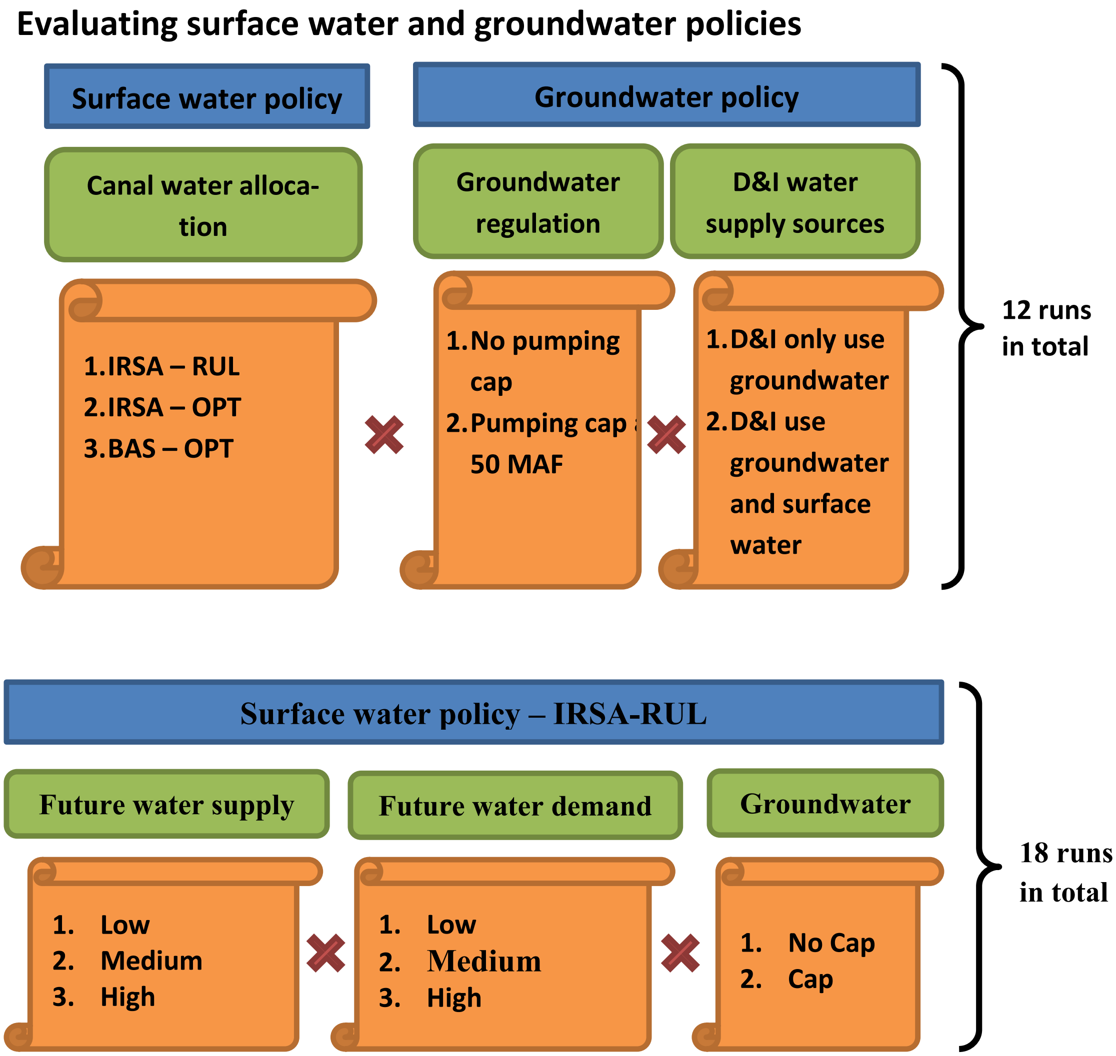


Figure 3. Average domestic and industrial water uses under different scenarios when both surface water and ground-water are available.

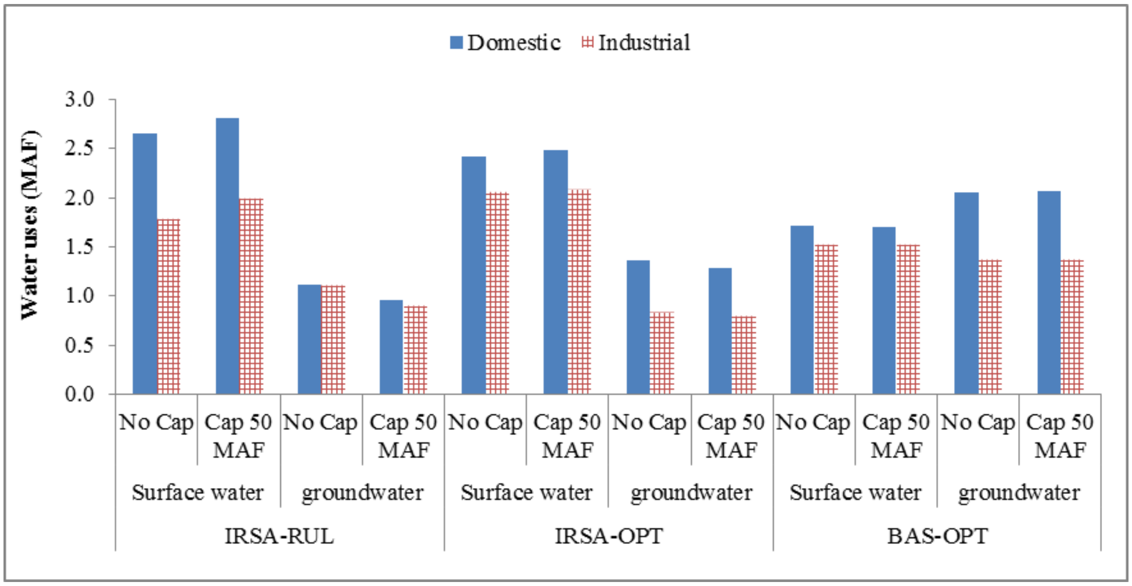


Figure 4. Flow to the Arabian Sea under different surface and groundwater policies

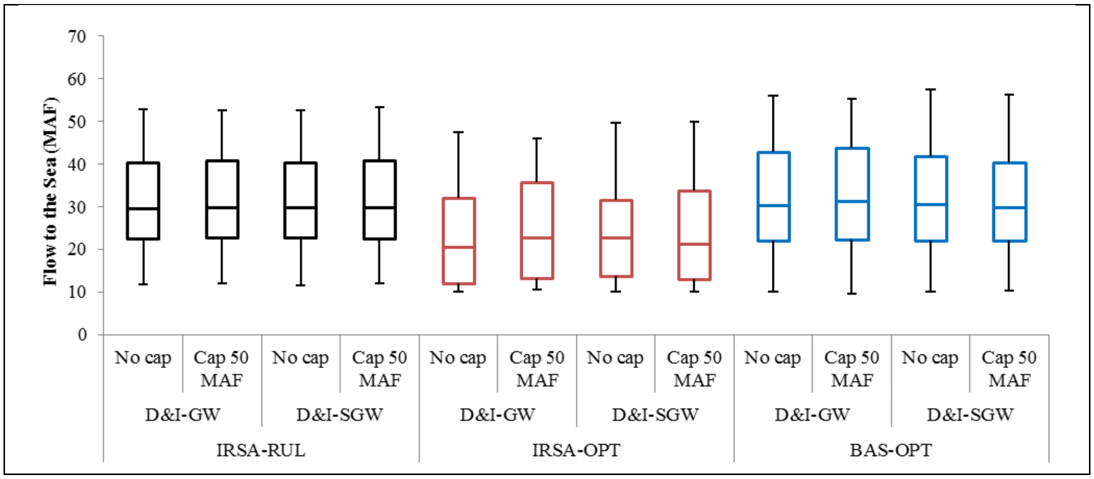
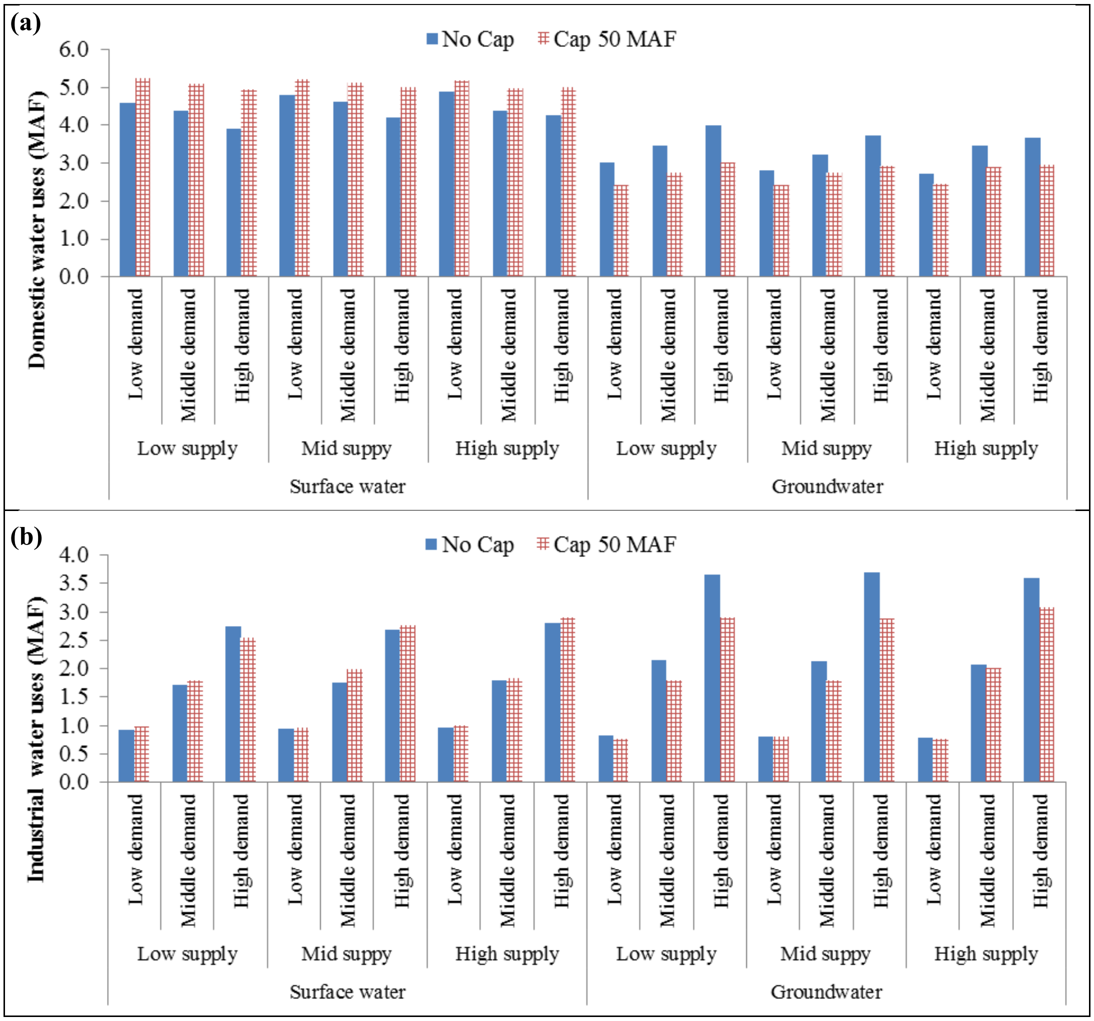


Figure 5. The (a) domestic and (b) industrial water uses under different water supply and demand changes



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