Irrigation and Agriculture System in the Indus Basin

The Indus basin in Pakistan is one of the most intensively irrigated regions in the world. The human control of water, essential for agricultural production in the arid plains, is through large dams and canals operated with entrenched rules of allocation and deliveries. The current infrastructure and its institutions of water control have evolved over the 19th and 20th century, and the existing system has become plagued with practices skewing irrigation benefits to powerful actors, sub-optimal operations, and low crop production on farms. Degrading infrastructure, un-regulated use of groundwater, and salinization and water logging are also affecting agricultural production. With high population growth, the system needs changes in order to continue to meet the growing demands of food and water. New initiatives at federal and provincial levels (including reform in governance and transparency in operations) and provision of new on-farm technologies are being implemented.

System Components

Following the human-technical-environmental systems framework[1], human, technical, environmental, institutional, and knowledge components are identified by italics. A full table of system components is shown in Appendix A.

Farmers cultivate *arable land* to obtain *agricultural produce* on farms in the Indus basin of Pakistan. Farmers use irrigation for agriculture in regions where rainfall is insufficient for growing crops, and water in *rivers and lakes* and water in *aquifers* is used for irrigation. The Indus river and its tributaries in Pakistan have a mean annual runoff of approximately 172 billion cubic meters (BCM), and ~75% (130 BMC) on average are withdrawn into canals for irrigation[2]. Water in rivers transport *sediment* that gets distributed during floods and enriches arable land, and water and *sediment* sustain *ecosystems* on land, in river deltas[3], and in coastal waters. High content of *salts* in soil and water, however, affect soil fertility and *ecosystems*.

The irrigation system in the Indus basin has largescale infrastructure managed by *State irrigation officials*. The produced crops include wheat, rice, sugar cane, cotton, pulses and many fruits and vegetables. Most of the agricultural produce is used by *domestic consumers,* but some is exported to *foreign consumers*. For example, Pakistan exported rice worth approximately $2.3 billion (9.5% of exports), and cotton and fabric products over $10 billion (43% of exports) in 2019[4].

Surface water irrigation is carried out with *reservoirs, barrages, and canals* to store, direct, and convey water from rivers and lakes to farms. There are 3 major reservoirs, 18 barrages, 12 inter-river link canals, and 45 major canals in the Indus basin in Pakistan. The canals network is hierarchical, with the major canals branching into 4000 distributaries, and further branching into 107,000 watercourses delivering water to farms[2]. The inter-connected system is controlled by a hierarchy of federal, provincial and district level state irrigation officials. In some regions, *pumps* are used to extract

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groundwater in aquifers. Farmers irrigate fields mostly with flood irrigation techniques that use more water than the water requirement of the crops. Some farms have deployed *on-farm irrigation equipment* such as sprinklers and drips, but their use remains low in the region due to costs and maintenance issues and due to availability of low-cost water from the canals and/or unregulated ground water from *pumps*.

Agricultural produce markets provide the economic incentives for agricultural production to farmers and provide food and products to consumers. Crop production in Pakistan accounted for 6.8% (and the total agricultural sector accounted for 19.3%) of the national GDP in 2019[5]. *Water policies, regulations and management* are in the jurisdiction of the federal and provincial governments who formulate rules for using water in rivers and lakes and water in aquifers for agriculture (along with industrial and domestic use). State irrigation officials formulate *surface water allocations and schedules* known as *entitlements* that delineate volumetric shares and timing of water supply for each canal command (area irrigated by a canal)[6]. The *Water rates and taxation policies* impact profitability for farmers and influence their cropping decisions and choice of on-farm practices and technologies.

Water table depth provides information about the extent of groundwater present in an aquifer and needs monitoring for regulating its use. *Canal delivery performance* includes reliability (likelihood of receiving irrigation water at scheduled time), efficiency (fraction of diverted water delivered to farms as some amount is lost due to seepage) and other measures. The *canal delivery performance* is affected by sediment accumulation, type of materials used for canal construction, and by operation procedures used by state irrigation officials. *Soil moisture and salinity levels* indicate build-up of salts and water logging that result over time due to repeated cycles of irrigation and fertilizer use and inadequate drainage of farm lands. The specific *crop production techniques* employed by farmers impact seasonal crop yields as well as long-term land fertility, and proper *on-farm irrigation techniques* help in maintaining normal salt and water balance in plant root zones.

The existing irrigation infrastructure in the Indus basin has expanded over two centuries (since the mid 1800s during British rule) to the present as the world's largest, contiguous system. The system was mostly built with state-of-the art *hydrological sciences and engineering* knowledge of the 19th and 20th century[7].

Interactions

Interactions between the three sets of material components (human, technical, and environmental components) in the context of the non-material components (institutions and knowledge) are organized here into pathways focused on key interactions. See Figure 2 for a full interaction matrix. Figure 3 illustrates the pathway of interactions for each subsection.

a) Irrigation Institutions

The Indus river flows through the entire length of Pakistan, stretching from the Himalayas to the Makran coast of the Arabian Sea, and connects with the provinces of Khyber Pakhtunkhwa (KPK), Punjab, Sindh and Baluchistan. The plains of Pakistan's Indus basin are arid with annual average rainfall ranging from 102 to 600 mm[2]. The Indus river and its tributaries however, provide large inflows of water, and have given rise to fertile arable land. The human control of diverting and using this water from the rivers has enabled agricultural production in the region for over five millennia[8]. The modern system has connected reservoirs, barrages, and canals that store, regulate and convey water for irrigation for farmers (Fig. 2, box 2-1a). The existing system spreads water over 44.5 million contiguous acres with a network of over 160,000 km of water channels[2]. This infrastructure requires technical knowledge and expertise from irrigation officials (Fig. 2, box 2-1b), and cannot be operated independently at local level by farmers. The irrigation officials establish water policies and regulations (Fig. 2, box 1-1d) usually based on national and state-level water policies.

The canal entitlements are established every six months for two cropping seasons of Kharif (summer) and Rabi (winter). The water quantity and time of delivery at the farm-level is conducted through a rotating schedule, called *warabandi*, throughout the cropping season for farmers. The warabandi is a proxy to a water right, and is the *right to time* (during which the outlet to a farm is open for water flow)[6]. Timely and adequate irrigation from canals is needed for maximum yield of crops (Fig. 2, box 2-3a) that ultimately impacts revenues, therefore some farmers influence irrigation officials for favorable volume and timing of canal deliveries thereby affecting other farmers (Fig. 2, box 1-1b) [9,10].

Farmers that receive inadequate and unreliable supplies are not able to achieve maximum possible crop yields and suffer revenue losses. The pressure from some farmers also distorts the enforcement of rules[11]. While irrigation officials implement water policies and conduct operation of the canals, and levy fines, they sometimes do so unevenly (Fig. 2, box 1-1c), whereby only violations of some farmers are fined, while some other farmers are not penalized. This variation in observance and enforcement of rules contributes to inequality in productivity, and incomes, and overall social well-being.

b) **Low water and land productivity**

Farms in the Indus basin produce surplus (rather than engaging in subsistence agriculture), and consumers and farmers interact through markets (Fig. 2, box 1-1a). Economic incentives drive farmers to cultivate arable land (Fig.2, box 1-3a), and farmers use irrigation technologies to apply water to fields (Fig.2, box 1-2b). The on-farm irrigation technology affects water and fertilizer use efficiency and yield (Fig. 2, 2-3b), and farmers obtain agricultural produce on their farms (Fig. 2, box 1-3b). The average production of crops per unit of land and water used is comparatively lower in the Indus basin than other regions. For instance, the yield of wheat in California (USA) and in Punjab (India) is higher than the yield in Punjab (Pakistan). Reports show that it is 2 tons/hectare in Pakistan, whereas it is 4 tons/hectare and 7 tons/hectare in India and

California respectively. Similarly, for water, the wheat yield is 0.5 kg/m^3 in Pakistan, whereas it is 0.8 kg/m^3, and 1 kg/m^3 in India and California respectively[6].

The on-farm irrigation methods and equipment imposes costs on farmers (Fig. 2, box 2-1f), and most farms use flood irrigation techniques that are cheap but use much more water than is needed by crops. Sprinkler and drips are more efficient but also cost more.

The agricultural produce provides revenue to farmers, and nutrition sources and products to consumers (Fig. 2, box 3-1a), and these benefits drive consumers and farmers to interact through markets (Fig.2, box 1-1a).

c) Groundwater Use

In regions where canal reliability is low due to deferred maintenance (Fig. 2 box2-2c), and as timely and adequate irrigation is needed for achieving maximum yield (Fig. 2, box 2-3a), famers install and operate pumps (Fig. 2, box 1-2a) and abstract groundwater from aquifers for irrigation (Fig. 2, box 1-3c). Pumps provide reliable, on-demand water to irrigators (Fig. 2, box 2-1c). Since pumping is not regulated or controlled in the Indus basin, pumping has expanded considerably over the last several decades to meet irrigation needs (Fig. 2 box2-3a)[2]. Government statistics show over a million tubewells (groundwater wells with pumps) in Punjab province alone[12]. In a region with extensive canal network, this expansion of pumping highlights issues with the canal system and the advantages to farmers. Some of the expansion of pumping has also been in areas where there are no water courses.

Pumping consumes energy (Fig.2, box 2-2b)[13]. 88% of the pumps run on diesel in Punjab, and the rest run on electricity[12]. Pumps also impose maintenance costs on farmers (Fig.2, item 2, 1, v), in addition to fuel costs, and that increases the costs of production and reduces profitability.

While pumps provide reliable supplies, pumping reduces stored groundwater (Fig. 2, box 2-3d), and if there is excessive pumping with inadequate recharge, depletion of aquifers can occur. The groundwater conditions are heterogenous in the basin. In some north eastern parts of Punjab, the water table has declined by 5 meters over an 11 year period (between 1999 and 2009)[14].

d) Degrading infrastructure

The Indus and its tributaries are one of the heavier silt-bearing rivers in the world. The river waters annually carry about 0.435 BCM of sediment[6], and irrigation infrastructure is greatly affected. As the reservoirs, barrages, and canals store, regulate, and convey water for irrigation for farmers (Fig. 2, box 2-1a), the sediment is built up in reservoirs and reduces storage capacity over time (Fig. 2, box 3-2a). This limits the ability for controlling water as the stored volume in reservoirs determines releases for canals (Fig. 2, box 2-2a) in each season. The combined storage capacity for major reservoirs was over 15 Million Acre-Feet (MAF), or 18.5 BCM, in 1975, and it is projected to decline to 10.4 MAF by 2025[6]. In addition to reservoirs, the sediment is also built up in canals and reduces conveyance capacity and performance over time[15] (Fig. 2, box 3-2b).

The reservoirs, barrages, and canals impose maintenance costs on irrigation officials (Fig. 2, box 2-1d), and as irrigation officials build, operate and maintain irrigation infrastructure (Fig. 2, box 1-2c), they require state funds for necessary maintenance. The state governments, however, struggle with insufficient funds for such activities because the farm owners form political coalitions for keeping water rates and land taxation low (Fig. 2, box 1-1e). The water charges (reportedly $1.5/ acre) are insufficient to cover the costs of service provision[16]. Deferred infrastructure maintenance reduces reliability of surface deliveries (Fig. 2, box 2-2c). As the performance degrades overall in the system, some farm owners influence irrigation officials for favorable volume and timing of canal deliveries thereby affecting other farmers (Fig.2, box 1-1b), and ensuring necessary irrigation supplies for production in their own farms.

The significant backlog of deferred maintenance is a growing challenge in the region[6].

e) Water logging and salinity

The reservoirs, barrages, and canals store, regulate, and convey water for irrigation to farmers (Fig. 2, box 2-1a), and once the water reaches the farms, farmers use irrigation technologies to apply water to fields (Fig. 2, box 1-2b) and obtain agricultural produce on farms (Fig. 2, box 1-3b).

The agricultural production over time affects soil fertility of arable land and salt content in soils (Fig. 2, box3-3a) depending on the types of crops grown and the specific cultivation techniques that are used. Farmers using improper irrigation and fertilization practices cause an increase in soil salinity and water logging (Fig. 2, box1-3d). The water logged and saline soil degrades farm land and reduces farmer livelihoods (Fig. 2, box 3-1b).

The salts in the Indus basin come from different origins. There are fossil salts deposits in the plains that occur at various locations, and while most of the deposits are in deeper substrata, some salts get mobilized due to pumping of deep groundwater. The irrigation waters from the upper Indus basin bring in salts. The incoming water is of low salinity (200-300 parts per million), however, the high volume of irrigation implies a significant salt import. Historically, the salts were transported to the sea. But with large-scale distribution of water by canals over the land area, water flow to the sea has declined. It is estimated that approximately 1.5 - 2.5 tones of salt per hectare per year are added to the irrigated lands[17]. The lower part of the basin is of marine origin, formed through geologic processes of coastal accretion, and marine salts are strongly present at shallow depths[17]. Groundwater quality in the lower basin (in the Sindh province) is highly saline in most of the irrigation areas[18].

Canals distribute water over land (Fig. 2, box 2-3b), and water seepage from canals recharges aquifers (Fig. 2, box 2-3c). Unlined canals lose significant fraction of water. It is estimated that up to 30-40% of the water is lost in the canal network due to seepage[17]. The recharge process increases water in the aquifers, and high water table can lead to water logging (Fig. 2, box 3-3b).

It is estimated that roughly over 1 million acres (largely in Sindh province) are lost due to water logging and salinization in the Indus basin[17].

If the challenges (discussed above) are not addressed, then large-scale irrigation, and consequently, large-scale agricultural production may not remain possible in the Indus basin in the coming decades.

Interventions

This section identifies ways in which different interveners can act to modify interactions in the system. Figure 4 provides a complete intervention matrix.

Potential interveners in the irrigation and agriculture system include the *Federal government of Pakistan, Ministry of Water Resources, Indus River System Authority (IRSA), Government of Punjab, Government of Sindh, Government of Khyber Pakhtunkhwa (KPK), Government of Baluchistan, Punjab Irrigation Department (PID), Punjab Agriculture Department, Sindh Irrigation and Drainage Authority (SIDA).*

This section summarizes four different types of potential interventions: increasing transparency in irrigation operations, improving forecasting and allocations scheduling, modernizing on-farm irrigation equipment, regulating groundwater use, and distributed systems for storage for irrigation.

a) Increasing transparency in irrigation operations

Increasing transparency in operations, and publicly reporting important information of water deliveries can advance institutional reform and enhance equity. In recent years, there have been efforts to establish electronic measurement and monitoring systems and open information platforms.

The Punjab Irrigation Department (PID) has set up a Program Monitoring and Implement Unit for Canal Operations and Discharge Data in Irrigation and Power Department (PMIU). The initiative conducts various field operations and also runs a digital platform where information of canal entitlements and deliveries are provided, and where complaints related to irrigation supplies can be filed[19]. These projects aim to enhance equity by increasing operations transparency and by making reporting of irregularities more accessible and widely available to farmers. Studies show that providing information alone will not fully address issues of institutional reform[20], however, greater public scrutiny and information access can limit unlawful distortions in distribution of water.

b) Improved forecasting and allocations scheduling

Improved seasonal forecasting and allocations for canals can enhance reliability and help farmers obtain higher production by planning their farming activities accordingly. The federal agencies (Indus River System Authority and Ministry of Water Resources) and provincial irrigation departments cooperate in and coordinate planning activities.

Reliability is by definition a measure of how well the actual irrigation deliveries match with planned (scheduled) deliveries. Recent studies have shown that canal entitlements and deliveries do not repeatedly match in some cases, and there is great potential to enhance reliability by improving quality of forecasts, and improving seasonal entitlement planning process[21]. Similarly, at the water course levels (where water is scheduled and provided on a rotational basis), there is potential for improvement with better planning processes thereby enhancing reliability.

In some on-going efforts, in cooperation with the Ministry of Water Resources, the Indus River System Authority (IRSA), Punjab Irrigation Department, and Sindh Irrigation and Drainage Authority, new and improved modeling and forecasting systems have been developed and demonstrated[22], but adoption and implementation is still needed for such efforts to initiate performance change.

c) Modern On-farm irrigation systems

The on-farm water management (OFWM) practices include land leveling, water course lining, and use of new technologies such as drips, sprinklers, and soil sensors. Enhancing on-farm productivity will require investments in OFWM[6] as well as extension services for farmers' training. Drip and sprinkler irrigation have been piloted in the past, but wide scale adoption has not yet occurred. This is largely due to continued availability of water at low rates, and comparatively higher costs for the on-farm equipment as compared to flood irrigation alternative.

New services for measuring soil moisture are emerging that seek to enhance water use efficiency of flood irrigation methods. Pilot testing by the Agriculture Department in Punjab has shown water savings of up to 35%, energy use by up to 35%, and yield increase by 8% [23].

d) Regulation of groundwater use

The irrigation system in the Indus basin has emerged as a conjunctive (joint) irrigation system, wherein both surface water and groundwater are accessed by farmers. However, only the surface system of canals is governed and regulated, and groundwater extraction remains unregulated. The National Water Policy (approved in 2018 by the Federal Government of Pakistan) includes provisions for provincial governments (including governments of KPK, Baluchistan, Punjab, and Sindh) to institute monitoring efforts to determine sustainable groundwater potential, and to "enforce legislation and take regulatory measures"[24].

The management and control of water in the provinces is within the jurisdiction of each provincial government, and so far, coordinated rules for groundwater use have yet to emerge. Possible interventions for managing ground water use can include instituting tiered (based on volume) and sector-based fees for water pumping for agricultural, industrial, and domestic use.

e) Network restructuring with distributed storage

The Indus basin irrigation system requires storage to ensure water availability for cropping, as flows in the rivers are highly seasonal and unevenly distributed during the year. Large dams for storage are expensive, and due to heavy siltation, have a fixed life span. The risks associated with large dam failure (due to natural or even human targeted activity) are also greater. The construction of large reservoirs has proven challenging over the past thirty years in Pakistan, and remains contentious due to inter-provincial disputes regarding control of irrigation water. The question of water storage should therefore be approached with new perspectives for the 21st century – with its attendant issues of climate change (that will bring more variability in water supply) and continued population growth (that continues to place demands for food and water in the region). While previous developments expanded a centralized system with few large storages, new developments need to include smaller, distributed systems.

Some projects such as the National Program for Enhancing Command Area of Small and Mini Dams in Barani Areas are emerging – in which farm ponds constructed in rainfed areas, along with solar powered pumping systems are used with laser land leveling to grow fruit, pulses and fodder[25].

In a country where population growth puts increasing pressures for food production and livelihoods, sustainable changes in water control and use and in farming practices are needed. Institutional reforms for increasing fairness and efficiency, regulation of a joint surface and groundwater irrigation system, and shift to new farm-scale technologies for enhancing water and land productivity can put the system on a better trajectory of development. Additionally, re-considering the irrigation system from its historical inter-connected, supply-based architecture, to a new structure that includes distributed storage and demand-based conveyance may lend adaptability and resilience for an uncertain future with climate change.

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Components, Interactions, and Interventions

Human components	Technical components	Environmental components
H1. Farmers (irrigators) H2. Irrigation (state) officials H3. Consumers (domestic and foreign)	T1. Reservoirs T2. Water diversion structures T3. Canals T4. Pumps T5. On-farm irrigation equipment	E1. Agricultural produce on farms E2. Arable land E3. Rivers and lakes E4. Aquifers E5. Sediment E6. Salts E7. Ecosystems
Institutional components	**Knowledge components**	
I1. Agricultural produce markets I2. Surface water allocations and schedules I3. Water policies, regulations & management I4. Water rates and taxation policies	K1. Water table depth K2. Canal delivery performance K3. Soil moisture and salinity level K4. Crop production techniques K5. On-farm irrigation techniques K6. Hydrological science and engineering	

Figure 1. Components in the Indus Basin Irrigation and Agriculture System.

Knowledge
Institutions

	1. Human	2. Technical	3. Environmental
1. Human	(1-1a) Consumers and farmers interact through markets (1-1b) Some farmers influence irrigation officials for favorable volume and timing of canal deliveries thereby affecting other farmers; (1-1c) Irrigation officials implement water policies and levy fines but sometimes do so unevenly (1-1d) Irrigation officials establish policies and regulations (1-1e) Farmers form political coalitions for keeping water rates and taxation low	(1-2a) Farmers install and operate pumps (1-2b) Farmers use irrigation technologies to apply water to fields. (1-2c) Irrigation officials build, operate, and maintain irrigation infrastructure	(1-3a) Farmers cultivate arable land (1-3b) Farmers obtain agricultural produce on farms (1-3c) Farmers pump groundwater for irrigation (1-3d) Farmers with improper irrigation and fertilization practices cause an increase in soil salinity and water logging
2. Technical	(2-1a) Reservoirs, barrages, and canals store, direct, and convey water for farmers (2-1b) Irrigation infrastructure requires technical expertise for operation (2-1c) Pumps provide on-demand water to irrigators (2-1d) Reservoirs, barrages, and canals impose maintenance costs for irrigation officials (2-1e) Pumps impose operations costs on farmers (2-1f) On-farm irrigation imposes maintenance costs on farmers.	(2-2a) Stored volume in reservoirs determines releases for canals (2-2b) Pumping consumes energy (2-2c) Deferred infrastructure maintenance decreases reliability of surface deliveries	(2-3a) Timely and adequate irrigation is needed for maximum yield. (2-3b) Canals distribute water over land (2-3e) Canals' seepage recharges aquifers (2-3d) Pumping extracts groundwater (2-3e) on-farm irrigation technology affects water and fertilizer use efficiency
3. Environmental	(3-1a) Agricultural produce provide revenue to farmers, and nutrition sources and products to consumers (3-1b) Water logged and saline soil degrades land and reduces farmer livelihoods	(3-2a) Sediment builds up in reservoirs and reduces storage capacity (3-2b) Sediment builds up in canals and reduces conveyance capacity and degrades performance	(3-3a) Agricultural production affects salts in soil and fertility of arable land (3-3b) Saline and water logged soil reduces yield and degrades land fertility

Figure 2. Interaction matrix for the irrigation and agriculture systems.

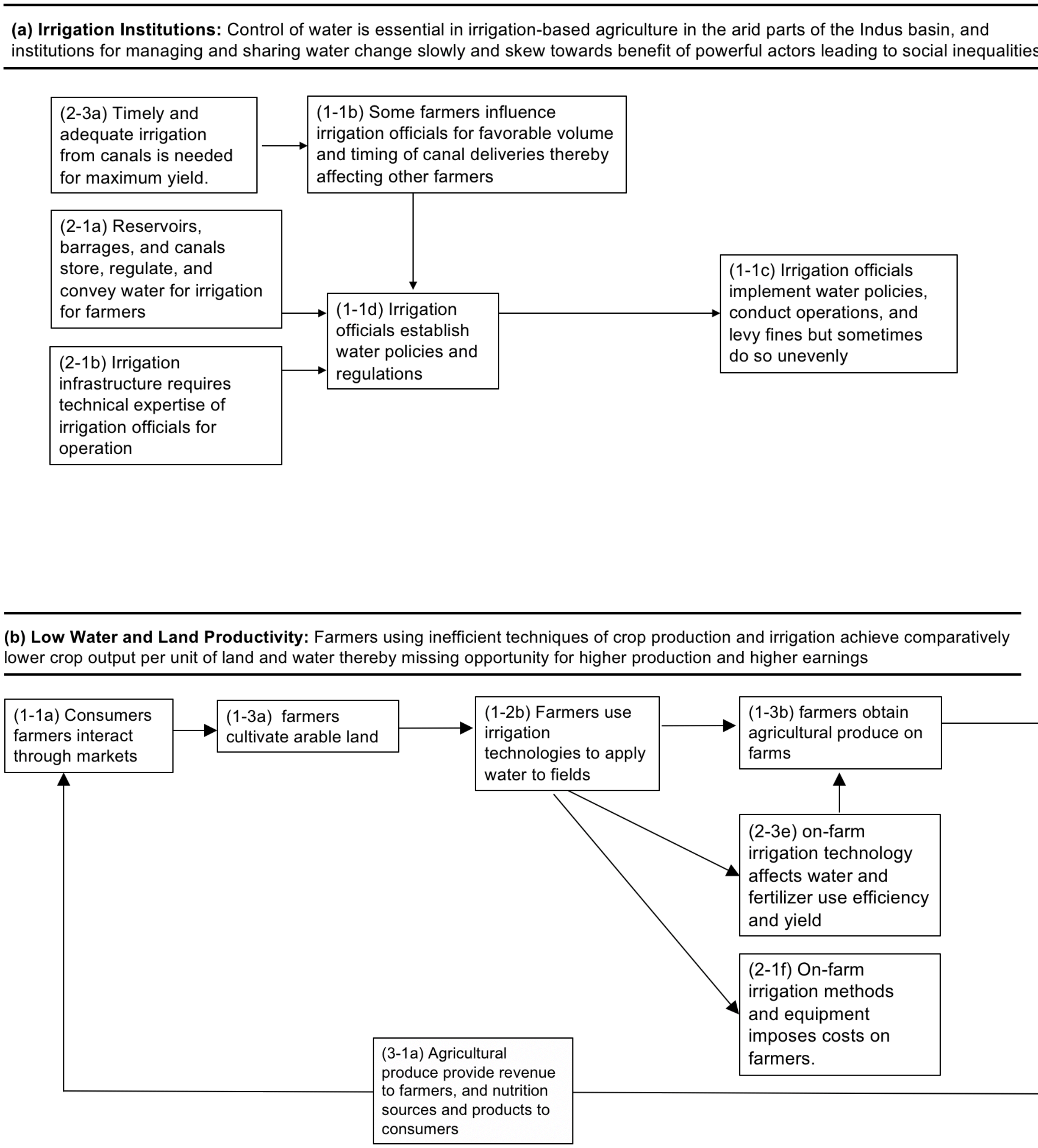
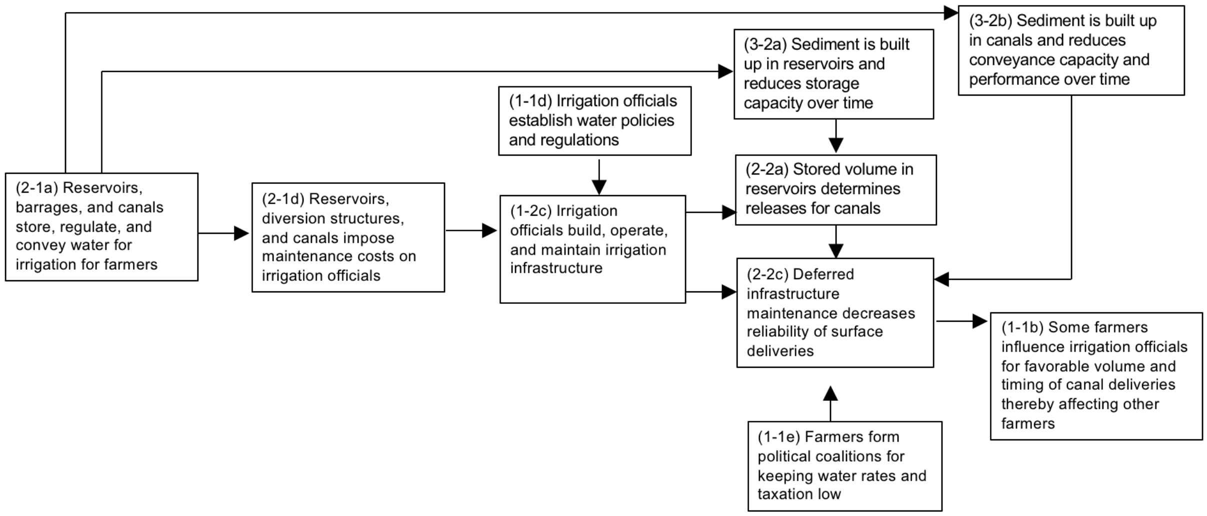


Figure 3a. Pathways of interactions in the Indus Basin irrigation and agriculture system.

(c) Degrading Infrastructure : Storage infrastructure loses capacity due to sedimentation and canals require maintenance that is not fully conducted, leading to degraded performance. Large sunk costs in existing infrastructure inhibit investments for new interventions.



(d) Groundwater Use: Farmers operate pumps to access groundwater for meeting irrigation needs, but have to pay for operations and maintenance costs, and excessive pumping reduces groundwater stocks in aquifers and consumes energy

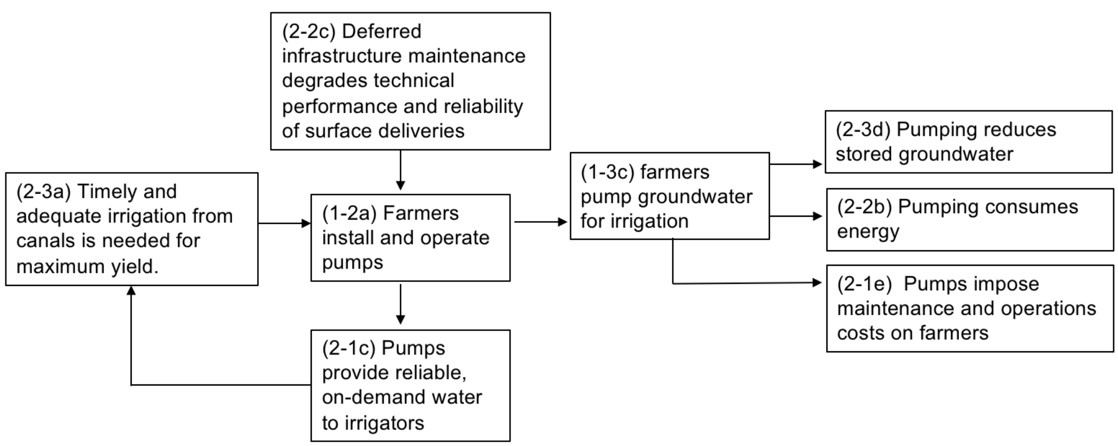


Figure 3b. Pathways of interactions in the Indus Basin irrigation and agriculture system.

(e) Water logging and salinity : Improper and repeated cycles of irrigation causes water logging and salinity destroying fertile arable land

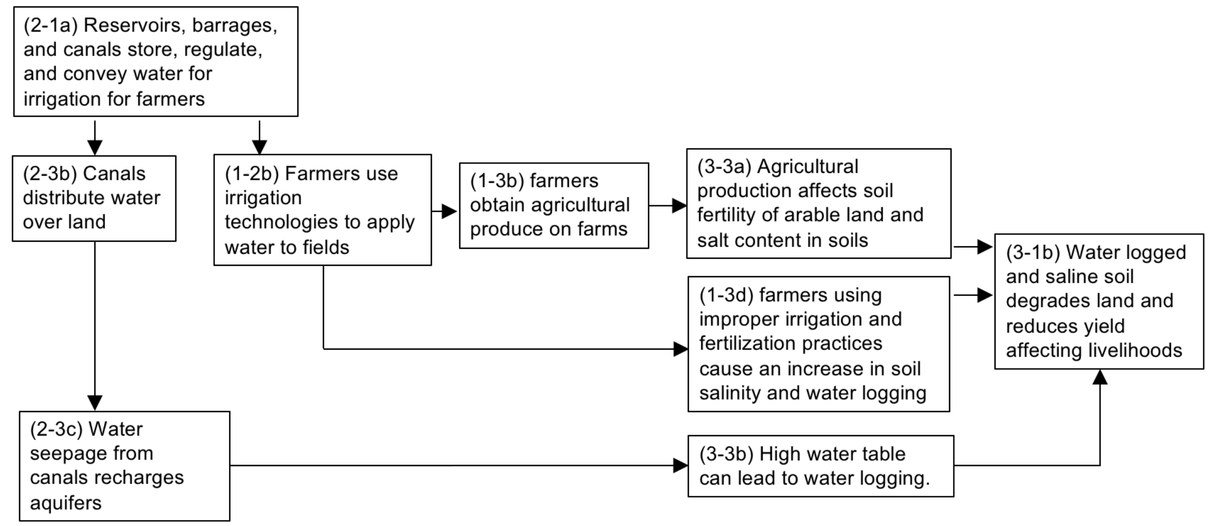


Figure 3c. Pathways of interactions in the Indus Basin irrigation and agriculture system.

Knowledge
Institutions

	1. Human	2. Technical	3. Environmental
1. Human	(1-1a) Increase transparency of irrigation deliveries with open information and ease of complaint filing (1-1b) Improve provincial and sub-provincial water forecasting and seasonal allocations scheduling (1-1c) Regulate groundwater pumping and canals as a conjunctive (joint) irrigation system	(1-2a) Implement efficient on-farm irrigation equipment (1-2b) Increase efficiency of groundwater pumps (for less energy consumption)	(1-3a) Strengthen extension services for farmers training for new cropping and irrigation techniques (1-3b) Provide low-cost services for monitoring soil conditions (1-3c) Monitor groundwater table depth
2. Technical		(2-2a) Deployment of efficient on-farm irrigation technologies (2-2b) Distributed networks for irrigation water storage and conveyance	(2-3a) Monitoring of groundwater table (2-3b) Subscription services for measuring farm soil moisture and salinity
3. Environmental			
	Interveners		
	Federal government of Pakistan, Ministry of Water Resources, Indus River System Authority (IRSA), Government of Punjab, Government of Sindh, Government of Khyber Pakhtunkhwa (KPK), Government of Baluchistan, Punjab Irrigation Department (PID), Punjab Agriculture Department, Sindh Irrigation and Drainage Authority (SIDA).		

Figure 4. Intervention matrix for the irrigation and agriculture system.