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Groundwater Governance in Pakistan: From Colossal Development to Neglected Management

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Received: 13 September 2020; Accepted: 23 October 2020; Published: 27 October 2020



Abstract: Groundwater is playing an essential role in expanding irrigated agriculture in many parts of the world. Pakistan is the third-largest user of groundwater for irrigation in the world. The surface water supplies are sufficient to irrigate 27% of the area, whereas the remaining 73% is directly or indirectly irrigated using groundwater. The Punjab province uses more than 90% of the total groundwater abstraction. Currently, 1.2 million private tubewells are working in the country, out of which 85% are in Punjab, 6.4% are in Sindh, 3.8% are in Khyber-Pakhtunkhwa, and 4.8% are in Baluchistan. The total groundwater extraction in Pakistan is about 60 billion m³. The access to groundwater has helped farmers in securing food for the increasing population. However, unchecked groundwater exploitation has created severe environmental problems. These include rapidly falling groundwater levels in the irrigated areas and increased soil salinization problems. The groundwater levels in more than 50% of the irrigated areas of Punjab have dropped below 6 m, resulting in increased pumping cost and degraded groundwater quality. Despite hectic efforts, about 21% of the irrigated area is affected by different levels of salinity. The country has introduced numerous laws and regulations for the sustainable use and management of groundwater resources, but the success has so far been limited. Besides less respect for the law, unavailability of needed data and information, lack of political will and institutional arrangements are the primary reasons for poor groundwater management. Pakistan needs to revisit its strategies to make them adaptable to local conditions. An integrated water resource management approach that brings together relevant government departments, political leadership, knowledge institutions, and other stakeholders could be an attractive option.

Keywords: groundwater governance; soil salinity; irrigated areas; groundwater levels; Pakistan

1. Introduction

Groundwater irrigation plays a vital role in boosting agricultural production and livelihoods of rural communities in many parts of the world. For example, the area in South Asia equipped for irrigation has tripled since 1950 [1]. India, Pakistan, and Bangladesh are the largest groundwater users in South Asia, with an estimated annual extraction of about 320 billion m³ (bm³) (India = 230 bm³; Pakistan = 60 bm³; Bangladesh = 30 bm³) [2–4]. More than 85% is used for agricultural purposes, compared to 40% in the rest of the world [1,5]. These three countries irrigate 48 million ha (mha) using groundwater, approximately 42% of the global groundwater-fed cropland [6]. Diminishing surface water supplies and the desire to expand the irrigated area to produce more food for the ever-increasing population are the major factors behind this intensive groundwater use. Furthermore, supply-driven policies of the governments and subsidized energy and pumps have exacerbated the use of groundwater for agriculture in these countries [7,8].

Dwindling surface water supplies due to declining storage capacities and growing climate change concerns have threatened the future of irrigated agriculture, which produces about 90% of the total grains in Pakistan [9,10]. The arid and semi-arid conditions prevailing in most parts of the country

make irrigation mandatory for sustainable crop production, as the evapotranspiration is high and rainfall is meager and unreliable [11]. More than 75% of this rainfall is received during the monsoon season (July–September). The contribution of rain to agricultural irrigation is about 30 bm^3 , which is only sufficient to meet 15% of the crop water requirements and the remaining 85% is met through irrigation [12]. The scarcity and unreliability of surface water supplies left farmers with no other option than to abstract groundwater to fulfill irrigation water demands, regardless of its quality and the pumping cost [3].

The surface water availability in the Indus basin is 820 mm/ha/year, assuming a total canal supply of 130 bm^3 and a serving area of 16 mha. This water availability is far lower than the evapotranspiration requirements to support a year-round basin-wide intensive cropping system practiced in the Indus basin. This shortfall in surface water supplies is met through the exploitation of groundwater. Groundwater has played a crucial role in thwarting water shortages and ensuring food security for the rising population. The access to groundwater has helped farmers to cope with the vagaries of surface supplies, diversify cropping patterns, and transform uncertain crop yields into more sustained crop production. However, the on-going unregulated and unplanned groundwater abstraction is endangering the future of irrigated agriculture in the country. In many irrigated areas, groundwater levels are falling, resulting in increased pumping costs, and deteriorating groundwater quality. This situation has made groundwater inaccessible for smallholder farmers. Besides, soil salinity problems in irrigated areas are expanding, and many areas are under threat.

Despite the crucial role groundwater plays in improving agricultural production and economic growth, its governance has not received the needed attention. In the absence of an effective management policy, it has become a pumping arms race; the person with the biggest pump usually wins. Presently, groundwater withdrawals exceed renewals and are turning this boon into a looming disaster [10–14]. Since two-thirds of the rural population are directly or indirectly dependent on groundwater for their food security and livelihood, country need to take critical steps to protect the rights of smallholder farmers. One of the major bottlenecks in the management of groundwater is the lack of sufficient data, and vigorous analysis of the available data to comprehensively understand the dynamics of groundwater use in agriculture and its impacts on the socio-economic conditions of the farmers and environment. This paper reviews the historical development of groundwater use patterns and examines the challenges of groundwater governance in large river basins such as the Indus basin. The paper also reviews different strategies that have been used in different countries for managing groundwater and analyzes why these solutions did not work in the Indus basin. The outcomes of this paper will be equally applicable for groundwater management in other river basins, such as the Yellow River basin of China and Ganges-Brahmaputra basin in India and Bangladesh.

2. The Indus Basin

Agriculture is an essential pillar of Pakistan's economy, because it contributes about 20% of the gross national product (GDP) and employs 44% of the total labor force. More than 80% of the population directly or indirectly depends on agriculture to earn their living. The arable agricultural resource base is about 22 mha, 27% of the total land area. About 16 mha are irrigated, and 6 mha are rain-fed. The irrigated area produces more than 90% of the entire agricultural and livestock productions. The irrigated lands are located in the areas between different rivers of the Indus basin [15]. The climate in most parts of the country favors two cropping seasons in a year: the winter growing season (November–April), and the summer growing season (May–October). More than 85% of farms are smallholders (0.5–5.0 ha). Therefore, crops are selected, to a small degree, to serve the farmers' household consumption and for livestock. The principal crops include wheat, rice, cotton, sugarcane, fruits, vegetables, and pulses. The crop yields are far below their demonstrated potential. In addition to water scarcity and poor irrigation management practices, lack of necessary inputs such as fertilizer and pesticides are primary reasons for the low yields.

The extensive contiguous Indus Basin Irrigation System (IBIS) irrigates about 16 mha of land. The value of agricultural output of the IBIS grows at an average annual rate of approximately 3% [16]. After the Indus Basin Water Treaty of 1960, the exclusive rights of three eastern Rivers (the Ravi, the Beas, and the Sutlej) were given to India, while the three western rivers (the Chenab, the Jhelum, and the Indus,) were given to Pakistan (Figure 1) [17]. The Indus River and its tributaries, on average, bring 190 km^3 of water annually. This includes 179 km^3 from the three western rivers and 11 km^3 from the three eastern rivers. Most of this, about 130 km^3 , is diverted for irrigation. About 50 km^3 flows to the sea, and 10 km^3 is the system losses (e.g., evaporation, seepage, and spills during floods) [18,19].

The IBIS consists of the perennial rivers, a network of unlined canals, and distribution channels. It is a supply-based system, and water is delivered to farmers weekly in a pre-determined quantity based on their landholding. The delivery efficiency of the irrigation system is low, ranging from 35% to 40% from the canal head to the crop root zone. The existing water storage capacity is 30 days of Indus River runoff, very low compared to 900 days for the Colorado and Murray Darling rivers, 500 days for the Orange River in South Africa, and 120–220 days for the Peninsular Rivers in India [20].

Increasing siltation will decrease the existing storage capacity of Pakistan by 57% by 2025. The Pakistan Water Sector Strategy estimates that the country will be required to increase its storage capacity by 22 km^3 by 2025 to meet the projected annual water demand of 165 km^3 [21]. Over the last 50 years, Pakistan has failed miserably in the development of new water storages and related infrastructure, due to increasing financial and environmental concerns. Under the present socio-economic and political circumstances, it will remain a challenge in the coming years. Therefore, groundwater-based irrigation will be crucial for food security and the economic development of the country.

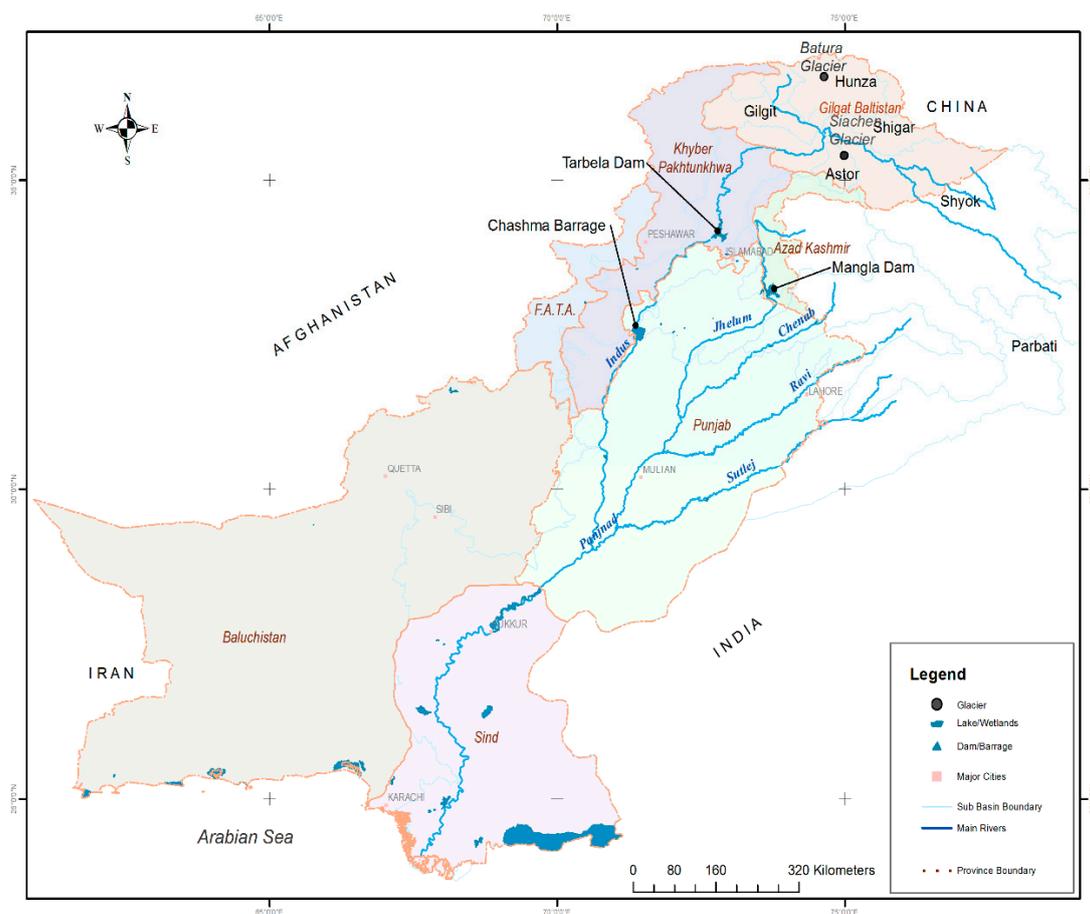


Figure 1. Map of Pakistan with provincial boundaries (Not at exact scale).

3. Groundwater Development in Pakistan

Pakistan is the third-largest user of groundwater, consuming about 9% of the global groundwater abstraction and occupying 4.6% of the total groundwater-irrigated area of the world [13,22]. The extensive use of groundwater in the country started in the 1960s, when 16,700 drainage wells with a discharge capacity of 0.80 m³/sec were installed under the government-funded Salinity Control and Reclamation Projects (SCARPs). The SCARP tubewells were installed to control water-logging and salinity problems in 2.6 mha of the irrigated lands [7]. Due to low salinity (1–2 dS/m), the pumped groundwater was released into the canal system to solve disposal problems and to increase irrigation supplies at the farmgate.

The demonstration of the SCARP model motivated farmers to install their own tubewells, resulting in the massive development of private tubewells, i.e., from merely 30,000 in 1960 to over 1.2 million in 2018. Out of these, more than 90% are only working in the Punjab province. During this period, the irrigated area in Punjab was almost doubled (from 8.6 to 16 mha), and the groundwater contribution to the overall irrigation water supply at the farmgate increased from 8% to 75% [15,23]. The remaining 4.4% are in Sindh, 1.8% are in Khyber Pakhtunkhwa (KPK), and 3.8% are in Baluchistan. In Punjab, the canal system contributes to more than 80% of the total groundwater recharge; therefore, canal systems have become more of a recharge process than an efficient water supply system [24].

The shallow depth and better quality of groundwater favored the massive development of private tubewells in Punjab. In Punjab, only 23% of the area has poor groundwater quality, compared to 78% in Sindh [19]. For this reason, the development of private tubewells in Sindh remains limited. In Baluchistan, groundwater levels are deep, and turbine/submersible pumps are needed to run these tubewells. The average installation cost of a deep electric tubewell (>20 m) is USD 10,000, compared to USD 1000 for a shallow tubewell (<5 m). Increasing energy prices have made it very expensive to extract groundwater from deeper depths using electric tubewells. The installation and operational cost of deep electric tubewells are beyond the capacity of poor farmers.

In Pakistan, the cost of pumping 1000 cubic meters of water from a shallow tubewell is USD 4.5, compared to USD 15 from a deep tubewell [25]. Of course, these costs are affected by varying energy prices. In the Baluchistan province, electricity is subsidized to make the groundwater pumping from deeper depths affordable for smallholder farmers. However, evidence exists that the primary beneficiaries of this subsidy are still large landholders who own deeper wells. The provision of subsidized electricity has further compounded the problem of groundwater overdraft in many parts of Baluchistan [3,26].

Figure 2 shows that about 85% of the tubewells in the Punjab province are diesel operated, and the remaining 15% are electric. Over the last 20 years, electric tubewells have increased from 12% in 2000 to 16% in 2018 [15]. Farmers prefer diesel tubewells due to low installation and operational costs compared to electric tubewells. Moreover, diesel tubewells are more convenient for small and fragmented landholders. Most of the diesel tubewells have a capacity of 0.030 m³/sec and use Chinese pumps of 10–12 hp. The total groundwater potential of Pakistan is about 68 km³, out of which 60 km³ is currently exploited [23,25]. This indicates that the groundwater resource is almost exhausted, because the remaining groundwater is in the regions where it is not easy to abstract due to economic and technical reasons [3]. Most of the groundwater pumped for irrigation is the water “recharged” from the irrigation network and farmer fields. Due to this inter-connectivity, assessing the total available water resources needs much caution [26,27].

In Punjab, more than three million farmers are directly or indirectly benefiting from tubewells. On average, one in four farming families owns a small tubewell, whereas the others purchase water from their neighboring farmers through informal groundwater markets [28,29]. The investment in private tubewells in Punjab is estimated at USD 750 million. The unrestricted access to groundwater through these tubewells has helped farmers to increase their crop yields, diversify cropping patterns, and to cope with extreme events such as droughts. Farmers in many areas have started growing water-demanding crops such as rice and sugarcane due to better economic returns.

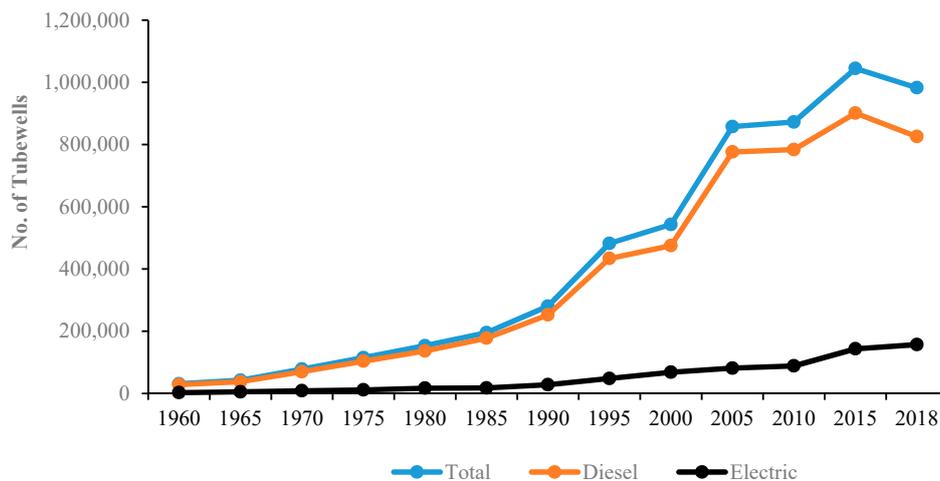


Figure 2. Temporal development of private tubewells in the Punjab province of Pakistan (Source: Punjab Agricultural Statistical Department).

The groundwater development was encouraged by easy access and acceptable groundwater quality and cropping patterns. In the rainfed and dry areas, groundwater is available at greater depths and in smaller quantities. Therefore, it was not affordable for smallholder farmers. In the canal command areas, groundwater is shallow and of much better quality due to excessive seepage from unlined canals and irrigation fields. Besides, irrigation water requirements are high due to high cropping intensities. This situation prompted farmers to install small tubewells to extract groundwater to feed their thirsty crops, especially rice and sugarcane. Therefore, in these areas (Figure 3, green bars), tubewell density increased. This situation not only helped farmers to expand the cultivated area for rice and sugarcane in these districts, but also increased crop yields by 50–100%. The overall impact of these developments was improved income for farms and a more secure livelihood for farmers. Groundwater also acts as a last resort for providing drinking water for humans and animals in the rural and desert areas of the country, especially during the low-rainfall years [3,28].

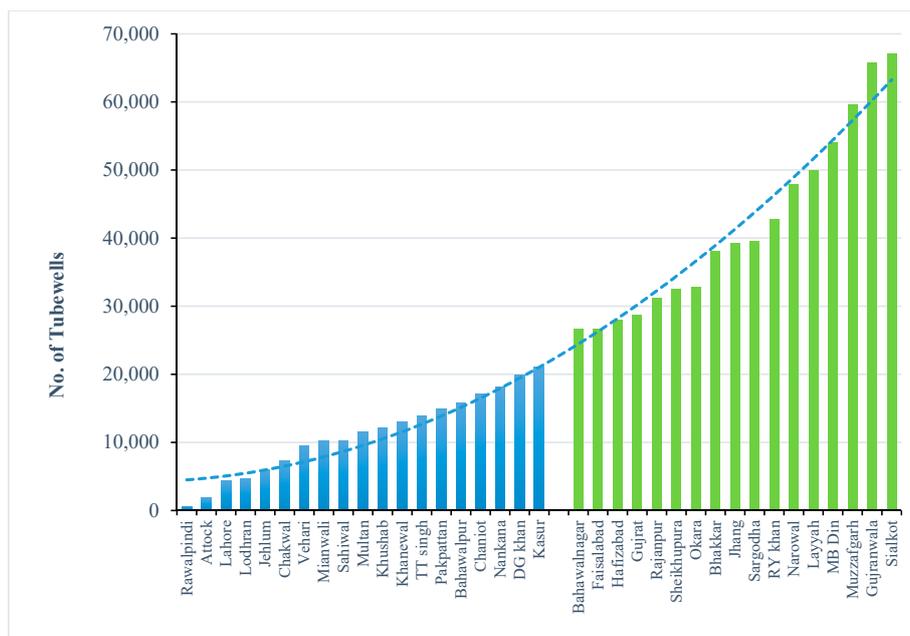


Figure 3. Number of tubewells in different districts in the Punjab Province of Pakistan (Source: Punjab Agricultural Statistical Department).

4. Patterns of Groundwater Use in Pakistan

The groundwater use patterns vary in different provinces. For example, groundwater use in Sindh province is minimal due to quality concerns. In the Khyber Pakhtunkhwa and Baluchistan provinces, groundwater exploitation is costly due to deeper depths and aquifer characteristics. In Punjab, the use of groundwater is widespread due to its existence at shallow depths and relatively good quality. The groundwater use in different parts of Punjab depends on many factors, such as cropping patterns, cropping intensity, agro-climatic conditions, and available groundwater quality. There are three distinct climatic zones in the Punjab province (Table 1). Upper Punjab has an average annual rainfall of above 500 mm (high rainfall zone), central Punjab receives 300–400 mm (medium rainfall zone), and lower Punjab has 100–150 mm rainfall (dry zone). The cropping patterns in these zones differ based on the availability of surface water and groundwater [19]. For high rainfall zones, groundwater use is low compared to small and medium rainfall zones, despite rice being a major crop grown in these areas. In the areas where wheat–cotton cropping rotation is more common, groundwater use is relatively small due to the lower water requirement of these crops. In the sugarcane and fodder-dominant areas, groundwater use is high due to high water demand.

Table 1. Cropping patterns, cropping intensity and groundwater quality in different agro-climatic zones.

Climatic Zones.	Rainfall (mm)	Cropping Intensity (%)	Cropping Pattern	Groundwater Quality ¹
Upper Punjab (High rainfall)	>500	130	Wheat–Fodder Wheat–Rice	Fit for irrigation
Central Punjab (Medium rainfall)	300–400	140	Wheat–Cotton Sugarcane Wheat–Fodder	Marginally fit for irrigation
Lower Punjab (Low rainfall)	100–150	150	Wheat–Cotton Sugarcane	Marginally too unfit for irrigation

¹: In Pakistan, water is considered fit for irrigation if $EC_w < 1.5 \text{ dS m}^{-1}$; $SAR = 10 \text{ mmol L}^{-1}$; $RSC = 2.5 \text{ meq L}^{-1}$; marginally fit for irrigation if EC_w ranges between $1.5\text{--}3.0 \text{ dS m}^{-1}$; $SAR = 10\text{--}18 \text{ mmol L}^{-1}$; $RSC = 2.5\text{--}5 \text{ meq L}^{-1}$ and unfit for irrigation if $EC_w > 3.0 \text{ dS m}^{-1}$; $SAR > 18 \text{ mmol L}^{-1}$; $RSC > 5 \text{ meq L}^{-1}$. EC_w is Electrical Conductivity of water, SAR is Sodium Adsorption Ratio and RSC is Residual Sodium Carbonate [30].

During the last 50 years, agriculture in Pakistan has changed from surface water to largely groundwater-fed irrigation. The increasing trend of groundwater use has played a pivotal role in enhancing the irrigated area and improving crop yields. Figure 4 shows that between 1960 and 2015, the area irrigated exclusively with canal water has reduced by 38% (from 8.59 to 5.37 mha), whereas the area irrigated by groundwater has increased by 390% (from 2.9 to 14.3 mha). This includes areas where groundwater is used both in isolation or in conjunction with the canal water.

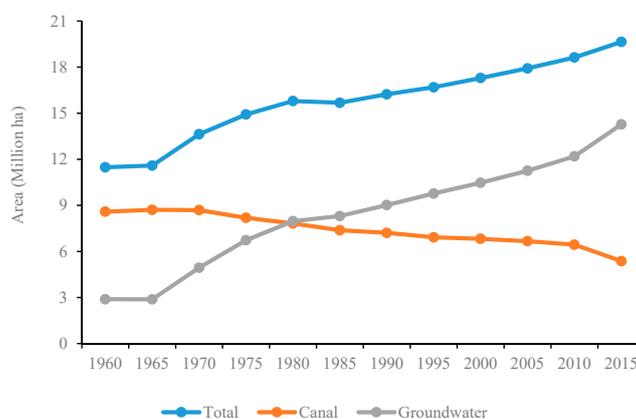


Figure 4. Groundwater use patterns in Pakistan (Source: Pakistan Statistical Bureau).

Until 1980, groundwater was only supplementing surface water supplies because the area under cultivation was less, and the need for irrigation water was rather conservative. After this period, farmers started extensive exploitation of groundwater to increase the cultivated area of wheat and other cash crops such as rice and sugarcane. During the period 1980–2017, the cultivated area of wheat, rice, and sugarcane increased by 33%, 42%, and 37%, respectively (Figure 5). The expansion in the areas of water-intensive crops (i.e., sugarcane and rice) was only possible due to the accessibility of groundwater, as the surface water supplies remained mostly unchanged or even started declining in many areas. Due to the expansion in the cropped area, the total production of these three crops almost tripled from 1980 to 2017. Today, Pakistan produces about 26 million tons of wheat, in comparison to 8.7 million tons in 1980 [24,31]. As the production of these crops is more than domestic consumption, a sizable proportion is exported.

In Punjab, more than 75% of the farmers mix groundwater with the surface water (conjunctive water use) to increase irrigation supplies and dilute salts [26]. However, in the areas where the groundwater is of acceptable quality for irrigation (head-reaches of canals), farmers also use groundwater alone for irrigation without mixing it with the canal water. Due to deficient and erratic canal supplies at the tail-reaches of the canal system, farmers also started using groundwater in isolation without considering its quality. However, this venture did not continue for long as they soon realized that their land was becoming salinized.

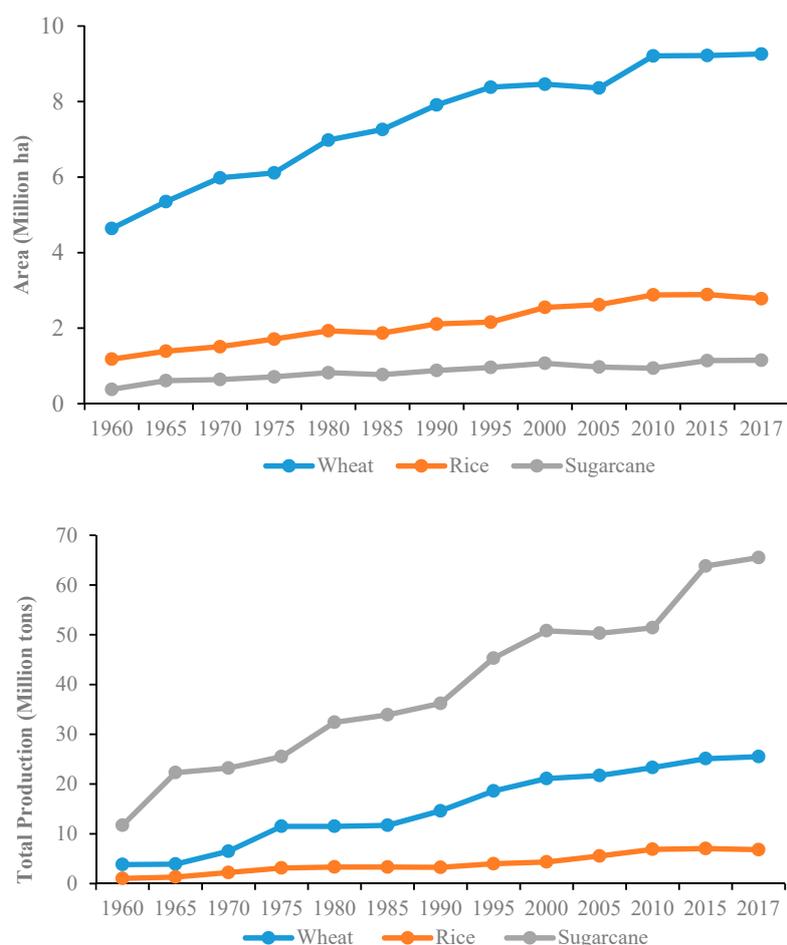


Figure 5. Development of cultivated area and production of three major crops in Pakistan (Source: Punjab Agricultural Statistical Department).

Figure 6 shows that, on average, 24% of the cultivated area is irrigated by canal water alone. About 23% of the total cultivated area is irrigated solely by groundwater, and the remaining 53% is irrigated through conjunctive use of surface water and groundwater. This means that 76% of the

cultivated area in Punjab is directly or indirectly dependent on groundwater to meet its irrigation demand. The area irrigated by canal water has decreased by about 0.40 mha during the last 20 years. In contrast, the area irrigated by groundwater alone has remained unchanged with small variations between different years. Noticeably, an additional 1.3 mha has adopted conjunctive use in Punjab over the last 20 years.

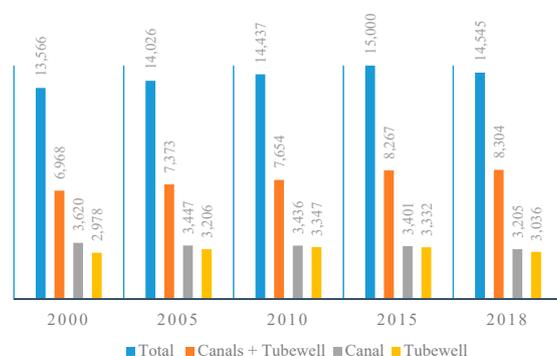


Figure 6. Area irrigated ('000' ha) by different modes of irrigation in the Punjab province (Source: Punjab Irrigation Department).

The sustainable production of major crops such as wheat, rice, and sugarcane is mainly dependent on the unlimited supply of groundwater. These three crops consume more than 80% of the total groundwater abstracted in Punjab. The availability of groundwater has transformed the trends of uncertain crop yields to a more stable and increased crop production. Farmers who have access to both surface water and groundwater earn five times more than those restricted to surface water supplies only [32].

Figure 7 illustrates that, on average, 31% of the sugarcane area is irrigated by canal water, followed by 23% for wheat and 12% for rice. The remaining cultivated areas of sugarcane and wheat crops are irrigated using groundwater. For both crops, 52% of the cultivated area is irrigated through conjunctive use of surface water and groundwater. About 26% of the wheat area used groundwater alone, followed by 17% for the sugarcane. For the rice crop, only 12% area was irrigated by canal water, and the remaining 88% was irrigated using groundwater (57% through conjunctive use of groundwater and surface water) and 31% by groundwater alone. This situation indicates the vital role of groundwater in enhancing agricultural production in the country. Without groundwater, production levels of three major cash crops cannot be sustained, with severe consequences for the food security and socio-economic development of the country.

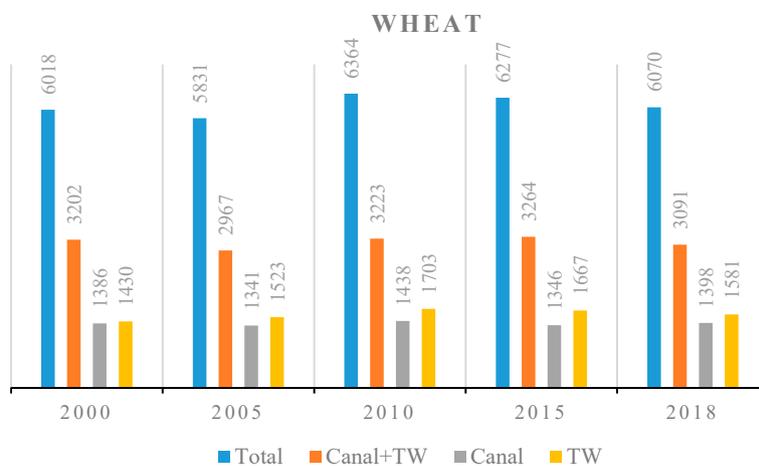


Figure 7. Cont.

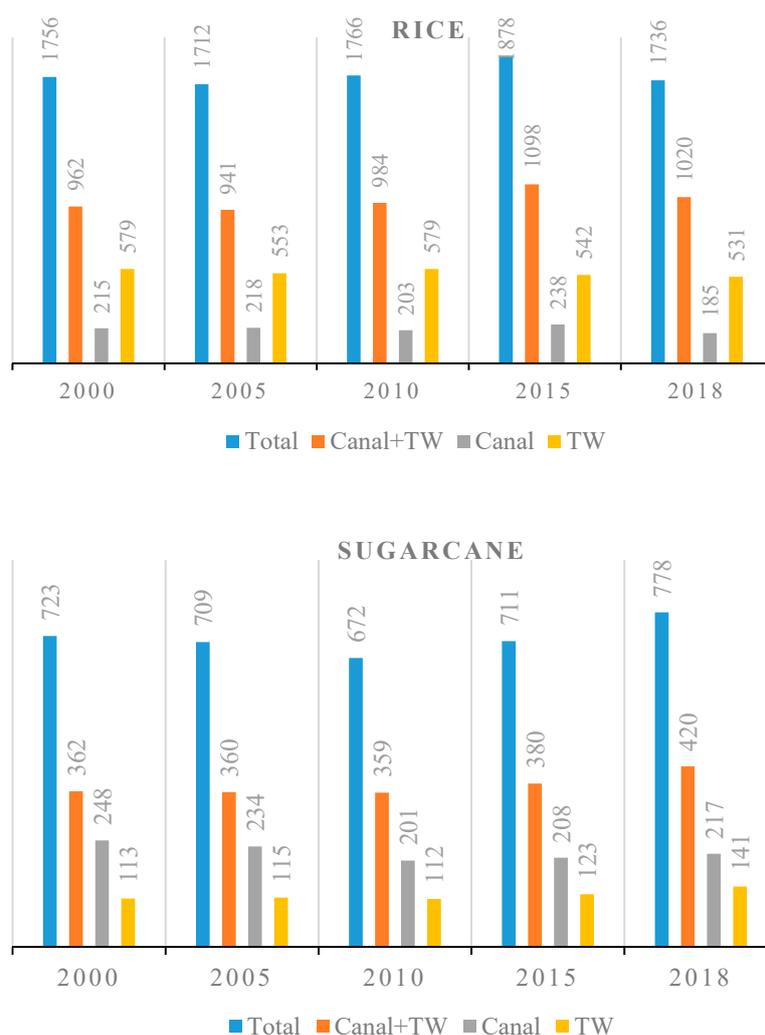


Figure 7. Area of three major crops irrigated (‘000’ ha) by different modes of irrigation in Punjab (TW = Tubewell) (Source: Punjab Irrigation Department).

5. Environmental Impacts of Groundwater Development in Pakistan

The benefits harnessed by farmers through excessive use of groundwater for irrigation came with a considerable environmental cost. The unregulated groundwater exploitation resulted in an excessive lowering of groundwater levels in irrigated areas of Punjab and Baluchistan provinces. Figure 8 depicts declining trends in the groundwater levels over time in Punjab. During the period 2008–2018, the area with a groundwater table between 0–150 cm decreased by 35%, whereas the area below 600 cm depth has increased by about 15%. At present, 50% of the total cultivated area in Punjab has a groundwater table depth below 600 cm. Therefore, many farmers have deepened boreholes and installed higher capacity pumps, because the efficiency of small pumps decreases significantly below a depth of 500 cm. This situation has led to increased irrigation requirements of crops, due to the cessation of groundwater contribution to plants through the capillary rise. Due to the geo-morphological conditions of KPK, salinity problems are also less severe in this province.

In the Baluchistan province, the situation is even more challenging because groundwater tables are declining at a rate of 2 to 3 m annually. In the absence of effective management measures, the smallholder farmers in 15% of the area in Punjab and 20% in Baluchistan may lose access to groundwater by 2025 [14,24]. The changes in groundwater levels are less pronounced in Sindh, owing to restricted exploitation due to quality concerns. In Khyber Pakhtunkhwa (KPK), the situation is also better due to a surplus canal water supply and less dependence on groundwater.

The declining groundwater levels are also responsible for the deterioration of groundwater quality. The quality of shallow groundwater in Punjab is below 1000 parts per million (ppm) because of consistent seepage from the irrigation system. The deep groundwater is generally found between the areas of any two major canals, whereas the fresh and shallow groundwater is confined to a small strip along the main channels. Besides salinity, higher contents of fluoride (7–12 mg/L) and arsenic (50 µg/L) have also been found in the irrigated areas, owing to the disposal of untreated wastewater into the water bodies [33]. The problems of groundwater quality are not limited to salinity but also to higher levels of sodium, and to a lesser extent, of chloride, magnesium, and potassium. In Punjab, 70% of the tubewells extract saline-sodic water. The irrigation with this water is turning irrigated lands into saline-sodic soils [33].

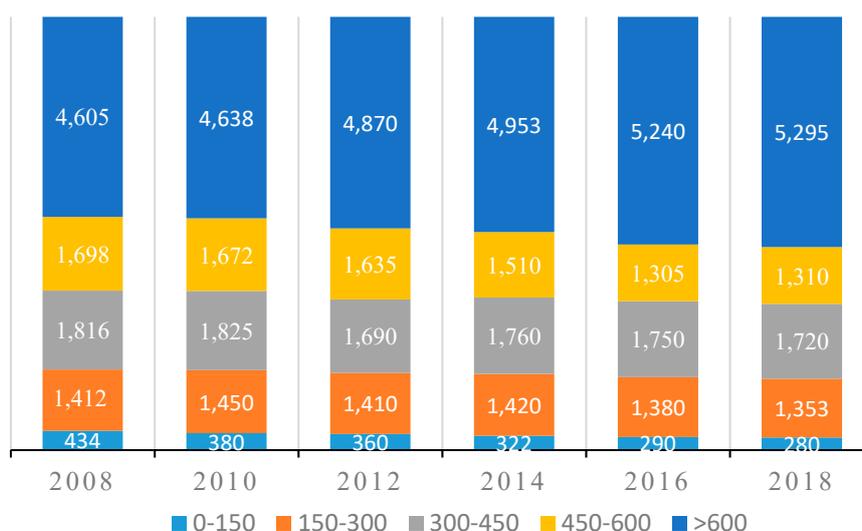


Figure 8. Temporal changes in groundwater table depths in the Punjab province (Source: SCARP Monitoring Organization).

The IBIS brings in about 33 million tons of salts every year. Of this, 16.4 million tons flows out to the sea, while the remaining 16.6 million tons are added to the irrigated lands. This means that, on average, one ton of salts is added to each hectare of land annually. Currently, about 4.5 mha of land is affected by soil salinity [34].

The extent of soil salinity is more significant in the tail-end areas of the canal system where poor-quality groundwater is used for irrigation. The lowering of groundwater table depths due to excessive pumping helped in the reduction in salinity in the irrigated areas in Punjab. Figure 9 indicates that during the period 1980–2002, the percentage of the area affected by salinity in Punjab reduced by 8% (from 14% to merely 6%). However, this was not the case in Sindh, where only a 4% decrease in the saline area was observed. Even today, about 43% of the area in the Sindh province is affected by different levels of salinity (25% is slightly saline, 7% moderately saline, and 11% strongly saline [34].

The inadequate drainage conditions and the presence of shallow and brackish groundwater are the major contributing factors for higher soil salinity conditions in the Sindh province [27]. The increase in the saline area in Baluchistan is due to the excessive use of brackish groundwater pumped from deeper aquifers. Alarming, the area under moderate-to-strong soil salinity has increased from 9% in 1980 to over 17% in 2002. This situation could be disastrous for Baluchistan because most of the salt-sensitive fruit crops are grown in this region. Increased soil salinity is hampering the production and quality of the fruit crops, rendering substantial economic losses to farmers and the country.

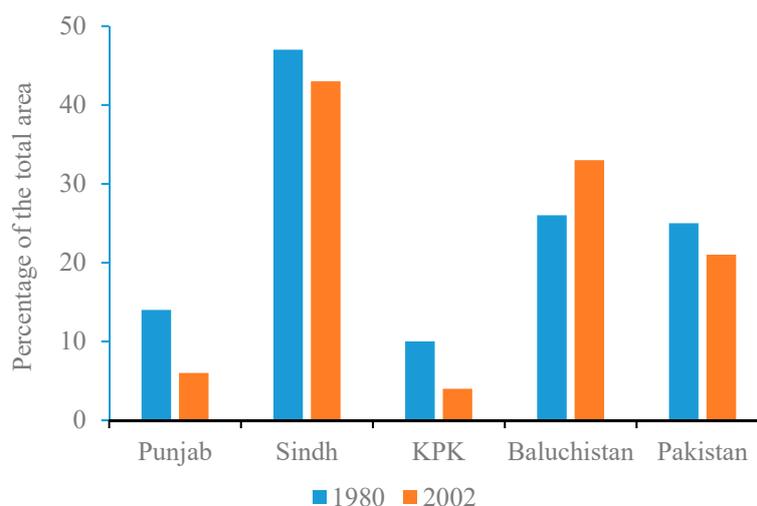


Figure 9. Percentage of the area affected by soil salinity in different provinces of Pakistan (Source: Water and Power Development Authority (WAPDA), 2007).

6. Challenges of Groundwater Governance in Pakistan

In the 1980s, problems of high groundwater tables and ensuing soil salinization due to capillary rise were considered as the major threats to agriculture. At that point, the focus of groundwater development was to control waterlogging and soil salinity problems. This objective was achieved through the installation of private tubewells in the irrigated areas. Energy subsidies and the inflow of small Chinese pumps provided the impetus for excessive groundwater development. Groundwater was presumed to be an unlimited resource, and there were no concerns about the over-exploitation of aquifers or deteriorations in groundwater quality. However, soon farmers started realizing that groundwater levels were falling, and the quality was degrading. The situation became worse in the tail-end areas of the canal commands where freshwater seepage from canals and rainfall was limited.

The performance of irrigation systems in Pakistan was considered weak due to the reduced involvement of farmers in the operational and management affairs [33,34]. In many other national irrigation systems, such as in Colombia, Argentina, Mexico, and even in Nepal, government agencies are responsible for operating dams and regulating river flows. In contrast, the distribution of water to farmlands in Pakistan is the responsibility of the farmers. In the late 1990s, the Government of Pakistan also embarked on far-reaching reforms to structure Provincial Irrigation Departments by establishing Provincial Irrigation and Drainage Authorities (PIDAs) at the provincial level to empower farmers and improve efficiency and sustainability. The PIDAs were established in 1997 with the assistance of the World Bank [35]. The PIDA act also defined groundwater extraction rights and empowered Water User Associations (WUAs) to monitor groundwater extraction in the canal command areas. In 2006, the provincial governments were also made responsible for evaluating the conditions of aquifers and developing strategies for their sustainable management. The PIDA act advocated demarcation of critical groundwater zones, licenses for tubewell installation in critical zones, and regular monitoring of pumping for all tubewells [36].

Notwithstanding all these efforts, the successful implementation of laws and policies remained a daunting challenge for the provincial governments due to a lack of the needed institutional capacity. As the government was keen to ensure food security for the poor rural communities, they continue allowing farmers to extract groundwater themselves. By doing so, local governments also moved away from accomplishing their responsibility of maintaining the surface supply system. During this process, the need for increasing the capacity of institutions to implement governing laws for the management of groundwater resources also did not receive due attention.

Although groundwater rights ordinances were introduced as early as 1978, and a permit system was launched in 1980, the direct management of large numbers of tubewells proved difficult due to

the socio-cultural realities. The permit system has proven successful in Australia, Oman, and other places where groundwater users are few, and governments are serious in upholding implemented laws. In countries such as China, India, and Pakistan, where the numbers of groundwater users are enormous and widely dispersed, managing permit systems to control groundwater exploitation becomes difficult, if not impossible [28,37–39]. Under similar conditions, even in Europe, the monitoring of groundwater abstraction by individual farmers has proved challenging [40].

In many countries such as India and China, energy prices have been used as a surrogate for groundwater pricing, as a tool to manage groundwater. For example, in India, electricity is supplied for a limited time for the operation of agricultural tubewells. Learning from Indian experience, Pakistan has also tried many options for fixing energy prices for agrarian tubewells. During the 1980s, Pakistan moved from a flat tariff system to the actual billing system, and then to a combined flat and billing system [41]. The flat billing system helped in collecting revenue but failed to control groundwater abstraction. The flat tariff policy was also criticized by small farmers due to its ‘fixed cost’ even in cases of minimally or completely non-operational tubewells. These energy changing policies did not help in controlling groundwater over-draft, and groundwater extraction kept on rising because it was crucial to meet water demand [39]. One of the primary reasons for this failure was that, in Pakistan, only 15% of the total tubewells are powered using electricity [42]. Therefore, changing energy prices would have only a marginal effect on groundwater abstraction. Even in India, where a large proportion of tubewells are power-operated, a 25% increase in electricity prices only reduced 3% of groundwater abstraction [43]. Therefore, changing energy pricing policies prompted farmers to shift from electric to diesel pumps, resulting in little reduction in the actual groundwater abstraction [42].

For the successful management of groundwater resources, accurate and timely information on the discharge and recharge patterns is of vital importance. Based on these data, utilization strategies can be developed considering environmental and socio-economic aspects. This information is particularly essential for dry areas where discharge is usually very high compared to recharge, resulting in excessive lowering of groundwater levels [44]. Unfortunately, in Pakistan, the culture of measurement is non-existing because certain people benefit enormously from a lack of data and information. As a result, basins are over-drafted, creating problems of groundwater accessibility for smallholder farmers. It is, therefore, important that the rights of small users are protected because it can have severe economic impacts on their farms, including devaluing their lands. This situation also strengthens the perception that the problems of groundwater management in Pakistan are not due to the lack of regulations but are of more of a political nature [45].

Groundwater management in river basins is problematic because its use is mostly to supplement surface water supplies; therefore, a balance between recharge and discharge needs to be maintained. In the river basins, farmers prefer to use surface water for irrigation due to cost and quality reasons. Groundwater is used in the events where there are no surface flows, or when excessive amounts of water are needed to irrigate water-thirsty crops such as rice and sugarcane. Similar issues are faced by other large groundwater users such as China, India, and Bangladesh. Pakistan is also faced with the dilemma of the lack of coordination between different organizations with conflicting and overlapping roles and responsibilities. This situation requires institutional arrangements with clearly defined roles and responsibilities of concerned organizations. In addition to technical solutions, there is also a need to establish strong linkages between various organizations involved in the management of groundwater and surface water resources.

7. Improving Groundwater Governance in Pakistan

Like much of the developing world, Pakistan is also transforming fast from conventional agriculture to commercial farming, targeting higher yields and the cultivation of high-value crops. Increasing prices of agricultural commodities are attracting more people towards agriculture. Over the last few years, the production of primary crops such as rice, sugarcane, and wheat in Pakistan has surpassed the domestic demand. This excess production is exported to earn money from international

trade. To sustain this situation and further boost agricultural production, assured water supplies are imperative [46]. This means that the new water economy must be more flexible towards the reallocation of water for those who value it more than those who take it for granted.

The most challenging task is the management of groundwater quality because excessive pumping in the fresh groundwater areas may cause an intrusion of salty water from neighboring regions. Therefore, the management of aquifers requires a well-thought-out, pragmatic, patient, and persistent strategy. The fundamental element will be the substantial involvement of users and making significant investments in modernizing tools for water and agricultural management. The state must play an essential role in developing the required legislation and providing knowledge and decision support systems duly supported with relevant research feeding into the strategy, planning, designing, and implementation stages of the necessary actions. The efforts made in Pakistan to address the issue of groundwater governance and its implications are discussed below.

Under the PIDA act, farmer organizations (FOs) were given the responsibility of groundwater management. However, they restricted themselves only to canal operation. FOs' focus remained on the equitable distribution of canal water and collecting water fees from farmers, while the monitoring of groundwater within canal commands was ignored [47,48].

Despite a plethora of laws and regulations, their weak enforcement disappointed local groundwater users. The main lesson learned was that ordinances and laws are irrelevant if not correctly implemented with the involvement of groundwater users. This does not mean that regulation is less important. Moreover, this must be supported by a public awareness campaign to make farmers cautious of resource depletion and degradation. However, the main question remains; 'Who should organize farmers?'. Even the establishment of FOs in many other countries could not solve this issue. Limited success has been achieved in the areas where a smaller number of farmers are involved, and groundwater is the only shared source of water. However, this has not been the case in India and Pakistan, where numbers of farmers are large, and everybody has their own tubewell. In this case, controlling extraction from each tubewell becomes too difficult.

The canal water distribution system in Pakistan is characterized as 'protective irrigation', which is designed to distribute the little water available to the maximum number of users to prevent crop failure. The water allocation does not consider long-term impacts on environmental parameters such as soil salinity, drainage needs, changes in groundwater levels, and quality. Some of the potential measures which may help in improving groundwater governance are discussed below.

7.1. Revisiting Canal Water Allocations

The reforms in the canal water allocation process are also urgently needed to maximize the benefits of groundwater use for irrigation. Currently, groundwater is uniformly used in the head- and tail-reaches of canals. However, conventional wisdom suggests that farmers located at the head-reaches of the channel should use less groundwater than tail-end farmers because they have better access to surface water. This pattern of groundwater use causes waterlogging problems at the head-end and increasing soil salinity at the tail-end of the system, because farmers continue to use poor-quality groundwater for irrigation. One strategy for the judicious use of groundwater could be to allocate canal water supplies depending on cropping patterns, groundwater quality, and soil salinity levels. In the head-reaches of the canal system where groundwater availability is high, water allocations can be reduced to increase canal water supplies for the tail-reaches of the same canal [34]. The reduction in the canal water supplies for head-end farmers could be accommodated by providing them greater access to groundwater.

The implication of this approach might be that head-end farmers start pumping extra amounts of groundwater to maintain their profitable cropping patterns. Therefore, in the long-term, they might end up having salinity problems. On the other hand, tail-end farmers might also start changing their cropping patterns due to more freshwater availability. As freshwater will not be available in excess, they might end up pumping more groundwater. Therefore, integrating surface water and

groundwater management requires a comprehensive policy intervention regarding the cropping patterns and the maximum amount of groundwater that can be pumped by an individual farmer to ensure the sustainability of the system.

This stresses the need to involve farmers in the implementation of possible technical, scientific, institutional, and political tools for protecting the quality and quantity of water from key strategic aquifers. Policies should also be formulated for the economic transition of the population that currently depends on intensive irrigated agriculture to earn their living. This is essential to reduce pressure on groundwater resources and to create political space for direct management of the resource base.

7.2. Increasing Productivity of Groundwater Use

The groundwater use in most of the irrigated areas of the water-scarce regions is restricted to high-value crops due to less water demand, and higher financial returns to cover the energy and other operational costs of tubewells. In China, for example, more than 60% of cotton, vegetable, and oil crops are grown using groundwater [49]. Farmers in Andalusia in Spain apply only 3900 m³ per ha of groundwater compared to 5000 m³ per ha of surface water [50]. In contrast, Pakistan uses groundwater for growing water-intensive crops such as sugarcane and rice. More than 70% of the available groundwater resources are used to irrigate three crops, i.e., rice, sugarcane, and wheat. Therefore, by reducing 15–20% of the cultivated area of these crops, groundwater abstraction can be significantly reduced. This would also be a huge relief for its stressed energy sector. Considering the current groundwater situation, the country needs a serious debate on whether to grow rice and sugarcane or replace them with other less water-demanding and high-value crops to reduce stress on groundwater resources.

The selection of appropriate crops such as sunflower, oil, fruit, and vegetable crops could help decrease water demand and increase farm incomes. Increased production of sunflower and oil crops could reduce the import bill, as Pakistan is spending about USD 2 billion annually on the import of cooking oil [48]. The selection of high-value crops could also increase the economic productivity of groundwater use. For example, groundwater users in Spain attain a financial return of USD 3.24 per m³, compared to USD 0.95 per m³ for surface water [51]. The economic productivity of peppers and tomatoes can be as high as USD 5.52 per m³ compared to only USD 0.25 per m³ for crops such as corn and cereals [52]. In the Jordan River Valley and Morocco, 75% of the horticultural crops are grown using groundwater, with an economic return of USD 16,000 per ha [38]. This shows that knowing the economics of groundwater use for irrigation is crucial for managing this resource.

7.3. Improving Water Use Efficiency

Despite technical advances, water use efficiency in Pakistan ranges between 35–40% [48]. Farmers mainly use flood methods of irrigation, and water application rates have no relevance to the crop water requirements.

Water conservation strategies, such as improved land leveling, zero tillage, and bed-furrow planting techniques have the potential to save a significant amount of water. Studies done in India, Pakistan, and Bangladesh have shown that up to 40% of water can be saved by bed-furrow planting compared to flood irrigation in wheat, cotton, and maize crops [53,54]. Similarly, the adoption of alternate wetting and drying methods of irrigation for rice can save a significant amount of water [55]. In the Pakistani context, where groundwater is the most significant contributor to meeting irrigation requirements of the rice crop, practicing these techniques can be of high relevance. The reduction in irrigation demands could help in reducing groundwater pumping and bringing a balance between recharge and discharge. For this purpose, the government should introduce policies and incentives for the private sector to invest in developing these technologies to make them affordable for small and medium farmers.

7.4. Improving Water Management

As discussed above, the delivery efficiency of the Indus system is only 36%, which means that much of the surface water is lost from the canal head to the crop root zone. This water loss is of particular concern in areas underlain with saline groundwater. Seepage in areas underlain with good quality groundwater, however, contributes to groundwater recharge. These seepage losses cause waterlogging and salinity in many areas. Pakistan has tested several on-farm water management strategies to control seepage losses. These included the lining of watercourses and canals, especially in the brackish groundwater quality areas. Despite these efforts, problems still widely persist in most of the irrigated lands. Due to its relatively flat topography, natural drainage in the Indus basin is minimal. Therefore, drainage water needs to be pumped away for safe disposal out of the irrigated areas. Pakistan's existing drainage network is inadequate, and most of it is in a state of disrepair. For the salt equilibrium in the fresh groundwater areas, it is crucial to know how much salt needs to be evacuated and where it should be stored or discharged [46].

Pakistan has a large water infrastructure base with an estimated replacement cost of about USD 60 billion [20]. Much of this infrastructure is operating beyond its designed life. Due to age and neglect, much of the water infrastructure is in poor shape, resulting in huge system losses and low performance in carrying water to the tail-reaches of the canal commands. Many elements of the vast hydraulic system are now reaching the end of their design lives and must be rejuvenated or replaced. There is an enormous backlog of deferred repair and maintenance. Recent irrigation and water supply "investments" have been for restoring poorly maintained systems, and not for the construction of new infrastructure. The services provided by this infrastructure are crucial for sustainable irrigated agriculture and the national well-being. However, these services can only be available if the structures are well maintained and they are replaced on time. Therefore, there is an urgent need to invest heavily in the rejuvenation of this system.

7.5. Policy Reforms

Like many developing countries, the provision of human and financial resources for groundwater management in Pakistan has remained very limited. Unlike the management of surface water resources, there has been a limited effort to manage aquifers that span beyond provincial administrative boundaries [56].

Institutional solutions to groundwater management have also proved far more complicated than was initially thought [57]. The government is usually under pressure to produce and secure food to feed the population and reduce poverty, especially in rural areas where more than 70% of the population lives. With significant investments in surface water and irrigation systems declining sharply, the development of the groundwater resources enabled the expansion of irrigated agriculture to continue. With many farm families now highly dependent on groundwater for their livelihoods, the national government was reluctant to implement the regulatory laws.

Considering the peculiarities of Pakistan's groundwater socio-ecology, a multi-dimensional approach is needed. The policy of providing subsidies for electrical tubewells needs to be reviewed; this subsidy is mainly benefiting large farmers who own deep electric tubewells. Moreover, farmers should be restricted to growing high-value fruit and vegetable crops with groundwater rather than continuing with growing traditional wheat and fodder crops through flood irrigation techniques.

In the groundwater stress areas, existing cropping patterns should be reviewed and replaced with the less water-consuming crops. There is a need to adopt different strategies for large commercial farmers and for poorer, smallholder farmers who are dependent on groundwater for protecting their livelihoods. Cropped areas in different agro-ecological zones should be allocated considering the country's food requirements and the availability of water resources.

8. Conclusions

Pakistan has immensely benefited from the extensive development of groundwater, as it has helped to achieve food security and protected livelihoods for millions of people living in the country. However, its unregulated and unplanned exploitation is replete with severe consequences, as the groundwater levels are falling in large tracts of irrigated land resulting in an increased cost of pumping and degraded quality of the pumped water. Irrigation with low-quality groundwater is responsible for exacerbating soil salinity problems in irrigated areas of the country. Currently, 21% of the total irrigated area is affected by different levels of salinity, threatening the future of irrigated agriculture, which is accountable for producing more than 90% of the total grains in the country. The Sindh province, where 22% of the total population of Pakistan lives, is the most hard-hit, with 43% of the area affected by salinity.

Pakistan must learn that the development of groundwater resources without proper planning and management strategies has backfired severely. Therefore, the country needs a legitimate discussion about whether to pump their aquifers to the maximum and face the consequences afterwards, or be more proactive now, and improve abstraction management to bring a balance between discharge and recharge. For effective groundwater management, Pakistan needs to introduce frameworks and instruments that are suitable for its conditions. Different strategies need to be presented for large commercial farmers and smallholder farmers dependent on groundwater for their livelihood.

Besides supply-side solutions, Pakistan also needs to work on demand-side solutions. Reducing the water demand for the agriculture sector through the introduction of innovative cultural and irrigation practices would be an attractive option. Pakistan also needs to make a significant push to establish and nurture a new set of institutions that can better understand the changing dynamics of water management and provide the required technical and policy support to manage increasingly scarce water resources. The adoption of an integrated water resources management (IWRM) approach that brings together concerned government departments, the private sector, the civil society, local political leadership, knowledge institutions, and other serious stakeholders could provide the needed platform for such a debate.

Author Contributions: A.S.Q. conceived the idea, collected, and analyzed the data, and drafted the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research receives no external funding.

Acknowledgments: This research is supported by the International Center for Biosaline Agriculture (ICBA) through its core funding. The agricultural extension and irrigation departments in Pakistan provided the time-series data for this work. I am thankful to Chris Perry for the review of an earlier version of this paper. I am also grateful to Khalid Mohtadullah, Ex (Member-Water) of the Water and Power Development Authority (WAPDA), for his comments and useful discussions during the writing of this article. I am thankful to the Pakistan Statistical Bureau and the Punjab Statistical Division for providing special permission to use their data for this work. The data on groundwater levels and quality were taken from the Salinity Control and Reclamation Program (SCARP), Directorate of WAPDA, through special permission. Their cooperation is also highly acknowledged.

Conflicts of Interest: The authors declare no conflict of interest.

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