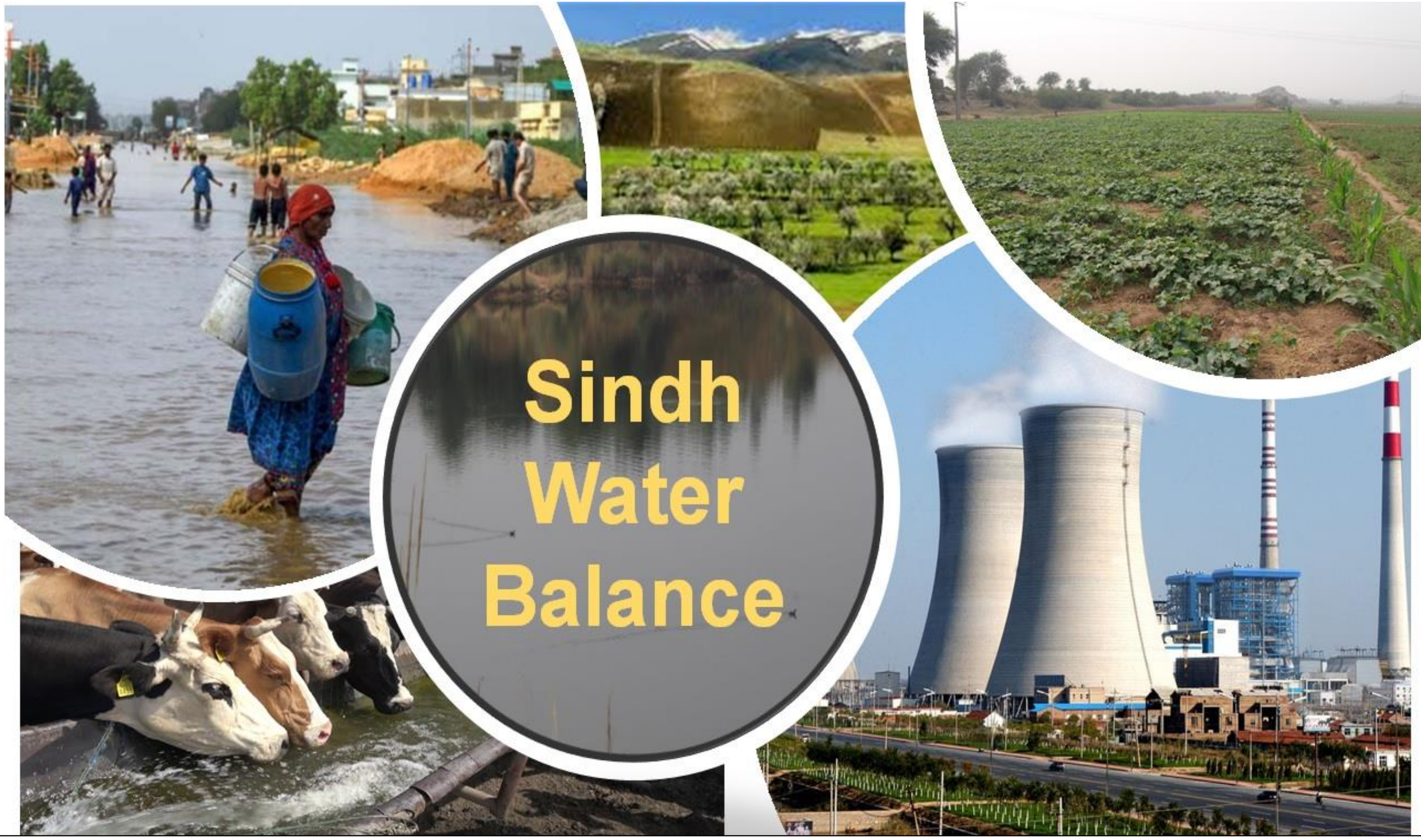
SINDH WATER BALANCE



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LIST OF ABBREVIATIONS

Word	**Abbreviation**
AMSL	Above Mean Sea Level
AWBs	Area Water Boards
BCM	Billion Cubic Meter
CCA	Culturable Command Area
CPEC	China Pakistan Economic Corridor
CWR	Crop Water Requirement
EEflux	Earth Engine Evapotranspiration Flux
ET	Evapotranspiration
FAO	Food and Agriculture Organization
FOs	Farmers' Organizations
GCA	Gross Command Area
GW	Groundwater
GWT	Groundwater Table
IBIS	Indus Basin Irrigation System
IRSA	Indus River System Authority
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
Kg	Kilogram
Km	Kilometer
l/c/d	Liters Per Capita Per Day
l/s	Liters per Second
LBOD	Left Bank Outfall Drain
MAF	Million Acres Feet
METRIC	Mapping ET at High Resolution Internalized Calibration
MHa	Million Hectare
Mm	Millimeter
NDC	Natural Disasters Consortium
NDP	National Drainage Program
NPIW	National Program for Improvement of Watercourses
PARC	Pakistan Agricultural Research Council
PMD	Pakistan Meteorological Department
Ppm	Parts per Million
RBOD	Right Bank Outfall Drain
RS	Remote Sensing
SDGs	Sustainable Development Goals
SID	Sindh Irrigation Department

SIDA	Sindh Irrigation and Drainage Authority
SWI	Standardized Water-Level Index
SWOT	Strengths, Weaknesses, Opportunities, And Threats
UC	Union Council
WHO	World Health Organization

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EXECUTIVE SUMMARY

This study was conducted by the US Pakistan Center for Advanced Studies in Water (USPCASW) in collaboration with the Water Sector Improvement Project (WSIP). The purpose of this study was to assess the water resources of Sindh using secondary data and give policy recommendations that will help in efficiently managing the municipal, industrial, irrigation/agriculture, and environmental needs. The goal of this study is to have policy reforms in the Sindh water sector for sustainable and equitable water distribution among various users. The key findings of the study, including satellite-based crop water use, provide mathematically sound data essential for developing knowledge-based policies and recommendations for efficient water use to manage available water resources.

Reports of previous studies were consulted to comprehend the current state of water resources in the province. Information regarding water availability from different sources and use by various stakeholders was summarized in this report. For annual and seasonal (*Kharif* and *Rabi*) river flow availability and variability, 21 years of historical flows (1998-1999 to 2018-2019) were analyzed and presented using time-series inflow data. Based on annual inflows at the Guddu Barrage, three flow scenarios—minimum (2001-2002), maximum (2010-2011), and average (2017-2018)—were developed considering them to be the representative of dry, wet, and average years' weather conditions, respectively. The annual runoff (based on 21-year record) has an average of 65.19 MAF, with 70-85 % of flows occurring in the *Kharif* season. During the *Kharif* season, the water availability was found to be sufficient, but conveyance losses were also more. The losses were calculated by comparing the quantum of water at upstream and downstream ends of a reach during a particular season. Besides high flows during the *Kharif* season, the canal withdrawals need to be checked and managed to ensure the availability of water at the farm levels. The conveyance losses in the Sukkur-Kotri reach during the study period were found to be more (1.3 times) than in the Guddu-Sukkur reach, which need to be managed since they may cause shortfalls in the environmental flows down Kotri barrage especially during the low flow periods.

For crop water use and requirement, a more precise assessment was carried out for 2017-2019 period using high-resolution time-series satellite images, water inflows, and weather data for major crops at canal command levels. Literature-based water demand estimates indicated 93-95%, 2%–3%, 2% utilization in agriculture, domestic, and for industrial use, respectively, whereas, water requirement for ecology and environmental flows was unaccounted for. However, our analysis for the recent year (2018-2019) estimated lower consumption by all types of vegetation grown in the area—around 80% of the total water available at the canal command level, including canal diversions and total precipitation. The remaining amount may presumably be lost during the delivery to the farms or at the farm level.

The consumptive water use of the Rohri canal (originating from Sukkur Barrage) command area was found to be more than the authorized flows. In additional to the authorized flows, 2.49 MAF water was consumed to fulfil the agricultural demand under current cropping patterns and intensities. As advocated in the national water policy, the current water productivity and means to further raise it needs to be investigated to address this gap. The Kalri Baghar (KB) Feeder canal (Kotri Barrage) had maximum surplus water, i.e. 1.0 MAF more than the agricultural and municipal demands, during all three growing seasons of *Rabi* 2017-2018, *Kharif* 2018, and *Rabi* 2018-2019. The inflows and outflows of the Beghari canal (Guddu Barrage) CCA were balanced well where only 0.07 MAF inflows remained as surplus. Water management and planning is needed for balanced flows to meet the consumptive water demands of all 14 canals culturable command areas (CCAs) by redistributing water between and within CCAs. Within CCAs, head-tail inequities are a significant issue.

Sindh water balance study for an average water year (2018-2019) revealed consumptions of 33.8 MAF, 1.19 MAF, 0.45 MAF, and 0.22 MAF by agriculture, domestic users, industries, and livestock, respectively. Down Kotri water availability was 1.76 MAF. The conveyance losses along the river reaches were 6.69 MAF, whereas, a considerable amount of 5.69 MAF was attributed to unaccounted losses.

The domestic water demand in 2050 will rise to 2.66 MAF, with urban need almost three times the rural demand. Projected water demands for crops are not easy to ascertain. There is a need for decision-makers to come up with the most preferred policy environment to improve incomes to farmers, raise productivity, etc. All within the boundaries of what are key physical limits to growth: available land and available water (including water that may be somewhat reclaimed through conservation measures; i.e., reducing losses). Reliable projections regarding industrial water use were not available, and therefore, the future industrial need could not be precisely estimated.

Many studies have predicted a shortfall of water by 32% in 2025 in the Indus River (Qureshi, 2011). This shortage causing food insecurity and other water-related issues in the country will affect the Sindh province more due to its location at the river’s tail end. Population rise, rapid urbanization, poor socio-economic conditions, ineffective water management, and climate change will increase pressure on the available water resources (Planning Commission Report, 2013). The rising population will demand more food, but at the same time, agriculture water share will be under pressure due to the rising demand of other competing users. To combat this situation, there is an urgent need to adopt integrated water resource management (IWRM) as a basis for decision-makers to make informed political decisions by recognizing all the competing uses. Since agriculture is the largest user of water among all sectors, effective water management in this sector will have the most significant impact.

Based on the review of literature, secondary data analysis, and satellite data derived information, three categories of actions are identified— 1) planning, research, and development actions, 2) corrective actions, and 3) preventive actions. The recommendations presented under these categories will form the basis for discussions to develop policy reforms for the water sector. Some important recommendations are as follows;

- Knowledge-based water management strategies should be developed by the government, giving due considerations to economic, social, and environmental factors.
- Environmental consideration should also be given importance in allocations. The post-Tarbela below Kotri flows have declined substantially that need to be checked and managed.
- Impact of climate change should be given paramount consideration in all water-related policies and decision-making.
- Provincial water policy should be developed, incorporating provincial requirements besides conforming to the national policy.
- Water should not be treated as a free commodity. Introduce irrigation tariffs, privatize water giving water rights to the user, and allow water trading among users. This intervention will reduce water losses and optimize its use.
- Based on water availability, economic considerations, and population needs, future development plans should be developed, and subsequently, the water allocations among users are decided.
- Water allocations are available at the provincial level, whereas water inter and intra sector water allocations are also needed for water resources management within the province. For example, in agriculture, water allocations should be done at the CCA level based on actual crop water requirements. If water is supplied to the crops per their requirements, then excess water can fulfill the water demands of other sectors. Therefore, a provincial water policy should be developed, incorporating provincial requirements besides conforming to the national policy.
- The current irrigation practices are water-intensive and should be replaced by advanced water-efficient irrigation technology.
- The crop water productivity in Pakistan is low as compared to other regions of the world. Increasing this productivity will also decrease agriculture water demand.
- Inefficient agricultural practices, seepage, evaporation, and other losses are not precisely estimated. Scientific investigations through mathematical modeling and ground-truthing are needed for this purpose.
- Practices leading to recycling and conservation should be promoted, including rainwater harvesting.
- New technologies, equipment, and infrastructure that help to reduce wasteful use of water should be implemented.
- The impaired water bodies due to pollution are limiting water availability, which, if not regulated by enforcing the law, may become unmanageable with increasing population and industrial units. In this regard, a comprehensive water quality assessment of the region is needed as a first step, after which water quality standards should be established consistent with the sustainable development goal 6.

- Secondary datasets are limited in space and time, calling for a detailed study supported by primary data to precisely calculate water availability and demand with continual updating. A comprehensive standardized geospatial database for the water sector is needed, which will be easy to update and shared among different departments.
- Extensive studies for longer historical flows and consumptions are needed to derive new water allocations plans, which will be more representative of the actual demands at the canal command level.

PART I: BACKGROUND PAPER

SINDH WATER BALANCE

1 Introduction

The major water users in the country are agriculture, domestic, industrial, and environmental sectors. Not only is the demand for these competing users changing with time due to population growth, but the water supply is also being affected owing to increased hydro-variability around the globe due to the changing climate. The goal of our study is to come up with recommendations for policy reforms in the water sector for sustainable and equitable water distribution among various users. This report summarizes the key findings of the study. This water balance study for the Sindh province aims to identify knowledge gaps and suggest policy recommendations. Water balancing is comparing inputs, outputs, and changes in the storage of water in a system.

2 Objectives

The primary objective of this study is to assess the water resources of Sindh using secondary data that will help to manage municipal, industrial, irrigation/agriculture, and environmental needs with sustainable utilization.

3 Scope of the Study

Following is the itemized scope of the work.

1. The water balance was assessed in the 14 canal culturable command areas (CCAs) of Sindh. The analysis was based on inflow and outflow data from secondary sources such as statistical reports, Sindh Irrigation and Drainage Authority (SIDA), and Sindh Irrigation Department (SID). Projected values of the population data were used to calculate future demands. For historical data, the Bureau of Statistics (BoS) were contacted.
2. Seasonal and annual water inflow variabilities at the Guddu, Sukkur, and Kotri Barrages were assessed (low, high, and average flows) for the post-Tarbela period.
3. Various water resources (groundwater, natural, and artificial reservoirs) and their contribution towards Sindh's water quantum were studied through a literature survey.
4. Crop water requirement for major crops was estimated for two *Rabi* seasons (2017-2018 & 2018-2019) and one *Kharif* season (2018). Consumptive water use in all 14 CCAs was also assessed for the same period. This analysis utilized weather data and crop data statistics supplemented by satellite data.
5. Consumptive water use for low (2001-2002) and high (2010-2011) flows was estimated and surplus and deficit water amounts were calculated. The study years catered varying inflows and demands scenarios with changing weather parameters.
6. Current and future sectoral water demand was estimated other than crop requirements. The other sectors included livestock and municipal. Relatively large uncertainties with regards to future industrial uses and environmental needs could not allow us to ascertain their precise demands. For water balance model, literature based approximate values were utilized.
7. The water balance of Sind's water resources for the recent year (2018-2019) study is presented.
8. Suggestions are given for the sustainable water distribution among CCAs for existing irrigation practices. Further recommendations are provided in the policy recommendation section for the adoption of efficient water use and improved water management technologies.

9. Based on this study, appropriate recommendations for sustainable and equitable water distribution in different sectors are made to manage available water resources efficiently.

4 Methodology

The water requirements of municipal, industry, agriculture, and environment were identified through secondary data supplemented by satellite-derived information. Since this study is based on secondary data, the accuracy of the analysis is mainly dependent on the completeness of the data acquired.

4.1 Itemized Framework of the Study

Following is the itemized framework of the study. However, the detailed methodology is presented in the accompanying Technical Paper (Part II of this report).

1. The study of various water resources and their contribution were analyzed, appropriate assumptions were made, and study limitations were identified.
2. Historical flows (Guddu inflows and Kotri outflows from 1998-1999 to 2018-2019) were studied, and trends identified.
3. Based on Guddu inflows (1998-1999 to 2018-2019), low, average, and high flow periods were ascertained.
4. Domestic water requirements at the district level with future projections were estimated using per capita water requirements found in the literature.
5. Industrial and environmental water demands were reported from the literature.
6. Future domestic water demands were derived from the projected values of the historical data using population growth models. For future agricultural, industrial, and environmental water demands, literature was searched.
7. Losses/gains along the river reaches (Guddu-Sukkur and Sukkur-Kotri) were calculated.
8. Sindh water balance was assessed balancing the inflows (including Guddu inflows and rainwater) with the consumptive water use at the province level for low and high flows.
9. A more detailed Sindh agriculture water balance was assessed for the most recent years, balancing the inflows and outflows within 14 canal command areas. From the most recent years under study, two *Rabi* seasons (2017-2018 and 2018-2019) and one *Kharif* season (2018) were studied to present water balancing schemes. For evapotranspiration (ET), satellite data were processed. Crop water requirements and actual ET values of major crops (wheat, rice, cotton, and sugarcane) at different growth stages were estimated. This report presents total crop water requirement (CWR) and average actual ET on a seasonal basis.

5 Crop Water Requirement

Crop water requirements for all major crops for all 14 CCAs were calculated using the reference ET (ETr) acquired from Ahmad (2004) (refer Fig 5 for processing details). The average actual water use by these crops during their different growth phases were calculated with the help of crop calendar, crops masks, and METRIC-EEFLUX ET product based on Landsat data. Tables 1 – 6 present crop specific details. The same information is provided in the graphical form in Annexure E.

Table 1: Crop Water Requirement of Wheat in Sindh

Source	Canal	CWR (mm)
Guddu Barrage	Beghari Sindh Feeder Canal	450
	Desert & Pat Feeder Canal	459
	Ghotki Feeder Canal	430
Sukkur Barrage	North West Canal	454
	Rice Canal	448
	Dadu Canal	470
	Nara Canal	532
	Khairpur East Feeder	471
	Rohri Canal	455
	Khairpur West Feeder	448
Kotri Barrage	KB Feeder	450
	Pinyari Canal	449
	Fulleli Canal	452

Table 2. Average Actual ET of Wheat in Sindh Canals during *Rabi* 2017-2018 and 2018-19

Source	Canal	Actual ET 2017-18 (mm)	Actual ET 2018-19 (mm)
Guddu Barrage	Beghari Sindh Feeder Canal	434	475
	Desert Feeder Canal	355	499
	Pat Feeder	355	499
	Ghotki Feeder Canal	380	407
Sukkur Barrage	North West Canal	430	378
	Rice Canal	408	380
	Dadu Canal	307	408
	Nara Canal	465	439
	Khairpur East Feeder	309	390
	Rohri Canal	377	396
	Khairpur West Feeder	411	397
Kotri Barrage	KB Feeder	342	316
	Pinyari Canal	294	281
	Fulleli Canal	286	275

Table 3: Crop Water Requirement of Cotton in Sindh

Source	Canal	CWR (mm)
Guddu Barrage	Ghotki Feeder Canal	864
	Dadu Canal	817
Sukkur Barrage	Nara Canal	775
	Khairpur East Feeder	908
	Rohri Canal	853
	Khairpur West Feeder	885

Table 4: Average Actual ET of Cotton in Sindh Canals during *Kharif* 2018

Source	Canal	Actual ET (mm)
Guddu Barrage	Ghotki Feeder Canal	611
	Dadu Canal	410
Sukkur Barrage	Nara Canal	593
	Khairpur East Feeder	566
	Rohri Canal	601
	Khairpur West Feeder	645

Table 5: CWR and Average Actual ET of Rice in Sindh during *Kharif* 2018

Source	Canal	CWR (mm)	Actual ET (mm)
Guddu Barrage	Beghari Sindh Feeder Canal	931	560
	Desert Feeder Canal	950	561
Sukkur Barrage	North West Canal	937	566
	Rice Canal	921	561
	Dadu Canal	929	475
Kotri Barrage	KB Feeder	893	549
	Pinyari Canal	893	629
	Fulleli Canal	888	617

Table 6: CWR and Average Actual ET of Sugarcane in Sindh during *Kharif* 2018

Source	Canal	CWR (mm)	Actual ET (mm)
Guddu Barrage	Ghotki Feeder Canal	1707	836
Sukkur Barrage	Dadu Canal	1742	822
	Nara Canal	1693	855
	Khairpur East Feeder	1794	921
	Rohri Canal	1764	881
	Khairpur West Feeder	1756	975
Kotri Barrage	KB Feeder	1632	828
	Pinyari Canal	1647	877
	Fulleli Canal	1647	875

6 Water Balance of Sindh

Developing a Sindh water balance model using secondary data was very challenging. Many models were found in the literature (Young et al., 2019; Laghari et al., 2012; Hussain et al., 2011), but these were either at the country level or for some other part of the country. Also, some of these models are based on data not consistent in time. Water availability and demand both are variable in time and space, and data from different periods can be misleading. In this study agricultural, livestock, and domestic water uses were calculated along with the river conveyance losses. However, the industrial water use was calculated based on estimates provided in the literature.

Table 7 presents the current water balance of Sindh. The temporal changes in both supply and demand values will render variable water balances in different years. The water availability in 2018-2019 was close to the average flows, and therefore, this can be considered as the water balance for an average year. The balanced surplus amount of 5.69 MAF is presumably the unaccounted water losses, including groundwater recharge and irrigation escapes (surplus from watercourses, surface drains, irrigation surplus) which need further investigation. Even with water inflows more than the outflows, the environmental flows as per water accord were not recorded down Kotri Barrage. With increasing future demand, the water consumption will increase by all water users, and the environmental flows are expected to be compromised even more. Therefore, there is a need to reduce losses at all levels. Furthermore, water allocations should be done as per the crop water requirement so that the water wastage can be minimized.

Table 7: Sindh Water Balance for 2018-2019 Water Year

Water Inflows/Outflows	**MAF**
Water Inflows	
Guddu Inflows	48.40
Rainwater	1.40
Total Inflows (A)	**49.80**
Water Outflows	
Agriculture (crop)	33.80
Domestic	1.19
Industrial	0.45
Livestock	0.22
Total Consumption by the Users (B)	**35.66**
Conveyance Losses	
Kharif (Guddu-Sukkur Reach)	3.87
Rabi (Guddu-Sukkur Reach)	1.05
Kharif (Sukkur-Kotri Reach)	1.58
Rabi (Sukkur-Kotri Reach)	0.19
Total River Losses (C)	**6.69**
Down Kotri Flows (D)	**1.76**
Balance = Inflows (A) - Outflows (B+C+D)	**5.69**

7 Future Water Demand

Population increase and urbanization will raise water demand. How much, where, and when these changes will be substantial, are some questions that need to be answered. Researchers gave different values of demand rise, but all are convinced that this demand will increase in all high, normal, and low scenarios. Intergovernmental Panel on Climate Change (IPCC) special report on global warming (October 2018) also indicated that even limiting global warming to 1.5°C (staying within a total carbon budget) would intensify the frequency of extreme weathers, the risk to water supply and food security, rising sea levels, diminishing Arctic sea ice, and loss of ecosystems, among other impacts (IPCC, 2018). These impacts will be more significant in developing countries that will limit the supply of sufficient water to meet the rising demand for water from competing users.

Based on current projections of temperature and precipitation data, water shortages and shortfalls are expected in Pakistan that will cause increased water demands not only for human consumption but also for its agriculture to sustain. Many recent studies (Amir & Habib, 2015; Bhutto et al., 2019) have identified the increased demand in different sectors besides a clear gap between the current and future water availability.

In the coming years, Sindh will experience demographic changes. The urban-rural water per capita demand will change due to various reasons such as improved living standards, rural migrations to cities, etc. Besides population growth, urbanization will increase from 50% to 64% in 2025 (Bhutto et al., 2019), and the demand projections based on current urban/rural dynamics will no longer be valid.

Industrial reforms and improvement in the energy sector will also improve the industrial sector, which will have a direct impact on its water demand. It is also expected that industries will come back to Pakistan from Bangladesh and South Africa, and new units are planned in the coming years within the industrial zones of the megacities (Amir & Habib, 2015). With the development of the industrial sector, water demand will also rise. Predicting exact industrial demand is not straight forward since there are many factors on which industrial development depends, such as political stability in the country, law and order situation, uninterrupted power and water supply, government policies, etc. On the other hand, industrial growth may also affect the quality of water resources by discharging untreated waste and hence reducing the availability of good quality water. Based on the review of the industrial growth estimates, the industrial demand will be doubled from 2025 to 2050 with no consideration of the impact of China Pakistan Economic Corridor (CPEC) on the industrial growth, which will make this rise even higher (Amir & Habib, 2015). CPEC will not only impact the industrial demand, but it may cause a transition from rural-based to an urban-based economy.

Population growth and urbanization will not only need additional water for domestic and industrial use but will necessitate an increase in agricultural production as well. Around a 50% increase in irrigation water requirement was predicted in 2003 by 2025 with no change in irrigation practices asking for an additional 21.3 MAF to maintain the balance between supply and demand of agriculture products. A similar increase was predicted at that time in the municipal and industrial water requirements, where about an additional 2.4 MAF water need was estimated (Azad et al., 2003).

It is evident that if other sectors demand increases, the water availability for agriculture will be reduced. The additional domestic and industrial demands may call for a reduction in irrigation water that may be challenging for water managers. Climate change will also play its part in increasing the crop water requirement. Estimates of Pakistan Meteorological Department (PMD) show an increase in this requirement by 11%, 19%, and 29% for temperature rises of 1°C, 2°C, and

3°C, respectively (Amir & Habib, 2015). The same study indicated that the overall demand for water in Sindh would go up by 7 MAF, 12 MAF, and 22 MAF, respectively, for 1°C, 2°C, and 3°C rise in temperatures.

The need for environmental flows is also expected to increase. By 2025, about 5 MAF will be needed for this purpose, which will increase to 7.5 MAF in 2050 (Amir & Habib, 2015). The environmental flows of 2050 are not likely to be achieved if the demands of other sectors are required to be met first. The reduced flows may damage the river ecosystem by altering water quality, temperature, and sediment dynamics.

For meeting the water requirements of all water users in 2025, an additional 23.7 MAF (21.3+2.4 MAF) of water would be required (Amir & Habib, 2015). The additional requirement would need to be met through surface water resources if groundwater resources are not developed in the province. Since the groundwater use in Sindh is limited, sustainable water use with conservation practices will be a significant factor in ensuring water availability for increasing demands.

8 Issues And Challenges

Through the literature review, various issues were identified, mostly in the agricultural sector. Since agriculture takes a considerable share of water, its impact on water dynamics is more significant as well. The water challenges, in the context of the Sindh province water need, are briefly discussed here.

8.1 System Losses

Transmission or conveyance losses through system leakages are some significant problems faced by the Indus Basin Irrigation System (IBIS) and drinking water distribution systems. The IBIS losses account for 41% of the total water derived from the river. A major part of these losses (around 40% of the total) is lost through watercourses, which are the tertiary channels serving at the farms level. Crops consume only about 60% of the withdrawn water applied to fields, and rest is lost to evaporation. The significant portion of available groundwater recharge (74%–80%) is lost as non-beneficial evaporation. Two major canal rehabilitation programs focusing on watercourse improvements—National Program for Improvement of Watercourses (NPIW) and Sindh On-Farm Water Management Project (SOFWMP) — are reported to have positive impacts through the increased cultivated area and reduced salinity.

8.2 Salinity and Water Logging

Salinity and waterlogging are accounting for 50% of the land that rises to 70% after the monsoon season (van Steenbergen, Basharat, & Lashari, 2015). An increase in the irrigation area, besides the rising groundwater table, is causing an increase in the soil salinity in Sindh (Azad et al., 2003). Problems of salinity and waterlogging are impairing soil quality and turning fertile land unsuitable for agricultural activities. Waterlogging is reducing crop yield by shortening the maturity period of crops (van Steenbergen, Basharat, & Lashari, 2015).

8.3 Over Irrigation

Overwatering of crops can also cause salinity and waterlogging problems. This was evident after the drought of 1999–2002 in which waterlogging was reduced, and crop yields were not affected (van Steenbergen, Basharat, & Lashari, 2015). Over irrigation leads to evaporation losses and water loss to groundwater, rivers, or surface drains (Young et al., 2019).

8.4 Groundwater Use

Along the left bank of the Indus River, there are some pockets of good quality groundwater. On the one hand, groundwater is overly exploited due to its cheap and quick availability. On the other hand, in some places, it is underutilized even when its quality is suitable for irrigation purposes. Possible reasons are high irrigation allocations and cost involved in developing and extracting groundwater. High irrigation allocations, as in the Rice canal, also give no incentives for farmers to use groundwater (van Steenbergen, Basharat, & Lashari, 2015). Groundwater management and regulations are also lacking in the country (Young et al., 2019).

Groundwater quality is not good in Sindh, and around 78% of groundwater is saline in the province. The groundwater resources are substantially impaired. The threat to shallow groundwater is municipal and industrial untreated waste disposal (especially toxic effluent). Seawater intrusion is another threat to groundwater resources (Azad, Rasheed, and Memon, 2003). The salinity levels found in the literature for Pakistan vary widely from 1000 to more than 3000 ppm. However, due to limited data availability and quality, the actual status of groundwater is difficult to comprehend.

8.5 Water Intensive Crops

In Sindh, a higher proportion of the irrigated area is being cultivated with water-intensive crops such as rice and sugarcane. Rice crop does not only need a massive amount of water but causes higher evaporative losses compared to other crops. Sugarcane in the province is being cultivated all year round, demanding a significant share of water. At some places, sugarcane is sown in the later months of the year or around the *Kharif* season to achieve higher yields. This practice requires a longer time to harvest and demanding additional quantities of water and fertilizer.

8.6 Low Crop Water Productivity

In Pakistan, crop production per unit of irrigation water is very low—rather lowest in the world (Qureshi, 2011). Mostly the crops grown in the region have low water productivity when compared with international standards. For example, in Pakistan, the productivity of cereal is 0.13 kg/m^3 of water, whereas it is 1.56 kg/m^3 in the USA, 0.82 kg/m^3 in China, and 0.39 kg/m^3 in India. Water-intensive crops and inferior conventional irrigation methods are responsible for low water productivity.

8.7 Higher per Capita Withdrawals

In developing countries, 20 to 30 liters of water per person per day is considered adequate for basic human needs. In contrast to that, the water demand is set for a much higher per capita consumption rate. Although the rural per capita rate (45 l/day) is a little bit more than the rate mentioned above, the urban per capita rate is much higher with 120 l/day. Higher rates demand more withdrawals than adequate that end up in wastages.

8.8 Surface Water Quality Issue

Water pollution is further limiting the available freshwater stock. The inadequate treatment capacity of municipal and industrial effluent, agricultural runoff flushing fertilizers and pesticides, waste dumping into the waterbodies are some of the major causes of water pollution. In Indus irrigated agriculture fields and urban industrial and commercial areas, the water quality is typically not fit for drinking.

8.9 Environmental Issues

Pakistan's ecosystems and environmental resources are under immense pressure due to the increase in withdrawals, pollution, urbanization, and agriculture. Soon, environmental degradation is likely to get worse, causing a decline in urban water security (Young et al., 2019). Young et al. (2019) further mentioned that no agreed environmental flow regime exists for the Indus River. The reductions are substantial, especially during *Rabi* or low flow seasons, and are environmentally unsustainable. Withdrawals are kept high during drought years with low system inflows, causing a high level of water stress affecting the environment. Since inter-annual variability of water availability is expected to increase, supply limits will more frequently constrain withdrawals causing high environmental stress. Some of the reported important consequences of the impaired environment are; Indus delta degradation, biodiversity loss, diminishing fish stocks, and destruction of important ecosystems of the Indus Basin.

8.10 Social Issues

Researchers have pointed out the possibility of social unrest due to the major gap in supply and demand affecting both the rural and urban populations. Issues and conflicts in growing urban centers are emerging in South Asia due to extreme stresses on water demand caused by temperature rises.

8.11 Infrastructure and Management Gaps

Water supply, sanitation, irrigation, and drainage services have infrastructure gaps. The water distribution network is outdated and poorly maintained with leaky pipes causing waterlogging. According to a recent World Bank report, the additional yield expected from new reservoirs would not be substantial to justify their high financial cost. The same report indicated an increase in the future water demand that would exceed supply if available storage remains the same with no improvement in demand management. Even if environmental flows are disregarded, this supply-demand gap will still increase.

8.12 Up-stream Water Development Projects

Sindh, being the lower riparian region of the Indus River system, is the most vulnerable province to economic, social, and environmental impacts of the upstream water development projects. The shrinking Indus delta is being presented as proof of low water availability in the deltaic region.

8.13 Impaired Natural Drainage System

The natural drainage system has been impaired and disrupted, especially in the urban areas of the province due to unplanned landuse changes. Sindh being the lower riparian, with relatively flat topography, has the most altered drainage network with blockages. The problem of drainage gets further aggravated, increasing the risk of flooding and sea intrusion in the Indus delta due to inadequate artificial drainage infrastructure of Left Bank Outfall Drainage (LBOD).

8.14 Operation and Maintenance of IBIS

The IBIS is also said to be less productive due to inadequate operation and maintenance of the system. Other issues with the canal irrigation system are institutional uncertainties and, most importantly, the absence of the future vision. Lack of funds may be one of the reasons since irrigation tax (*Abiana*) collection, to cover operation and maintenance costs, is also not very efficient. In essence, only 20% of total Abiana is recovered. The irrigation reform's main objectives included the improved tax collection and enhanced water supplies, through Farmers' Organizations (FOs), which have not been successfully achieved.

8.15 Direct Outlets (DO) From Canals

More than 100 direct outlets (DOs) are present in Sindh, mostly in the Nara and Rohri CCAs. Granting DOs to the farm owners has been criticized in the past since these are politically based decisions. The chief minister has the liberty to grant special permission based on the irrigation needs of a landowner applying for a DO. One objection to this process is that the rights of the downstream users are disregarded while granting DOs to the influential landowners who are many times drawing more water than sanctioned—ranging from 4 to over 30 times of its approved quantity.

8.16 Sedimentation of Reservoirs

The river water diversions are decreasing due to the sedimentation of the upstream reservoirs. The storage capacity of a reservoir also decreases due to sedimentation. Mangla and Tarbela reservoirs have reduced their capacities by about 30% of their designed storages.

8.17 Institutional Structures of Water Control and Management

There are multiple agencies for irrigation management, including Sindh Irrigation and Drainage Authority (SIDA), Area Water Boards (AWBs), Farmers' Organizations (FOs), and Sindh Irrigation Department. Institutional changes may involve transition risks and uncertainty regarding water control management. Moreover, farmers and local communities felt distanced from the routine management and operations of the canal distribution network due to the introduction of centralization and bureaucratization of irrigation management practices.

8.18 Ineffective Policies

The problem with the national water and other policies has always been their failure in achieving their perceived objectives. Lack of institutional mechanisms, enabling legislation, and economic incentives were said to be some of the reasons behind their ineffectiveness. Other concerns were regarding the absence of a periodic review mechanism needed in the context of changing national and international scenarios, even if the direction of these policies was correct.

8.19 Institutional Capacity and Governance Issue

Finally, yet importantly, institutional capacity and governance are the most important components that can bring about enormous positive changes in the system. Many problems in the country stem from inadequate legal framework for water. There exist an inadequate policy framework and lack of policy implementation with unclear, incomplete, and overlapping institutional mandate. The water organizations lack the institutional capacity to perform their mandated responsibilities at all levels with ineffective inter-sectoral water allocation planning.

Water theft or illegal water tapping from the system is also said to be a problem causing conflicts between upper and lower riparians. In Pakistan, no licensing system for water entitlements exists, other than the *warabandi* system. *Warabandi* is a usual practice for canal water distribution among farmers. *Warabandi* may also create disputes among users if not based on water efficiency and equity. Moreover, no regulations exist for water consumed by cities or industries. Lack of water rights and non-existence of needed regulation to delegate these rights are also causing abusive water use. Increased conflicts over water between provinces and sectors are also creating less resilience to increase drought severity. In the 1990s, the World Bank proposed the water market by privatizing canal waters and giving water rights to their users to trade water and handing management responsibilities over to irrigation users at canal level under its National Drainage Program, but it was not turned out to be a successful venture.

9 Recommendations

A comprehensive set of measures for the efficient management and development of water resources is needed focusing on the integrated water resource management (IWRM) principles. The IWRM approach realizes the need to introduce appropriate policy reforms, corrective and preventive actions, and research- and knowledge-based planning, development interventions to introduce more efficient, effective, and sustainable water infrastructure and management systems in the province. The following recommendations, split into four classes (not mutually exclusive), are put forward in this regard.

9.1 Planning, Research, and Development Actions

i. Effective water management and inter-sectoral water allocation planning should be done engaging all water users in the decision-making process.

ii. Strengthen water data management, modeling, and forecasting for quantitative assessment of water use among industrial, domestic, and agricultural sectors from surface and groundwater sources, leaving the provision of environmental flows. There is a need to develop a comprehensive mathematical model of Indus Basin, taking into account climate change.

iii. Improvement in the water delivery systems by up-gradating the system will reduce system losses and water theft. For improved operations, modernization of infrastructure is required by improving flow control structures and installing real-time data monitoring systems (Young et al., 2019).

iv. Water infrastructures, including Sukkur Barrage and its canal network, need improvement to maintain their efficiencies and reduce the risks associated with the aging structures.

v. Continuous monitoring and assessment of surface and groundwater are needed for their quality, quantity, withdrawal, recharge, etc.

vi. National and international exchange of experience and expertise should be promoted through bilateral or multilateral organizations.

vii. A detailed study supported by primary data is needed to calculate precise water availability vs. its demand.

viii. Promote the recycling of water at all levels.

ix. Introduce bio saline agriculture using saline water and desalination of saline water.

x. Introduce higher-value crops over wheat and sugarcane (Young et al., 2019).

xi. Manage forest and rangeland to combat climate change.

xii. Promote rainwater harvesting and hill torrent management. New storage facilities, such as small storage ponds, delayed actions, or check dams, will help to manage increasing variations in the seasonal flows due to climate change, to store floodwater, and to control sediments.

xiii. Wherever feasible, in irrigation system management, non-engineering solutions should be given preference on engineering solutions damaging to the environment.

9.2 Corrective Actions

i. Combat with waterlogging and salinity. Equitable and reasonable water allocation will discourage over-irrigation that may reduce waterlogging and salinity. This is evident from the fact that during the drought of 1999-2002, waterlogging was reduced without affecting the crop yield (van Steenbergen, Basharat, & Lashari, 2015).

ii. For food security and accelerated economic growth of the country, it is necessary to substantially increase crop water productivity, which is quite low in Sindh (Young et al., 2019). Low crop productivity and water wastages demand to utilize the available water efficiently and carefully and introducing high-efficiency and innovative irrigation systems (PARC, nd).

iii. Overall, water losses are enormous, which needs to checked and reduced.

iv. There is a dire need to improve the natural drainage network or introduce an artificial drainage system. An efficient drainage system will not only reduce the water logging problem but will also lessen the chances of flooding.

v. Strengthen participatory water management through water users' associations. The main problems faced by the FOs are lack of capacity, limited authority, and absence of enforcement powers (OXFAM, 2016).

vi. Restore degraded lakes and wetlands.

vii. Revisit reservoirs' standard operating procedures based on improved modeling.

viii. Improve drinking water supply schemes.

ix. Reduce water pollution and regulate discharges by enforcing the law.

9.3 Preventive Actions

i. Channel lining is needed to reduce system losses. The lining of the canals and watercourses is especially required where groundwater is saline or waterlogging exists.

ii. Avoid over-irrigation and introduce efficient irrigation techniques.

iii. Water should not be treated as a free commodity. Introduce irrigation tariffs, privatize water giving water rights to the user, and allow water trading among users. This intervention will reduce water losses and optimize its use.

iv. Based on water availability, decide whether to develop future agriculture development plans or not?

v. Water metering is required to discourage wastage.

9.4 Policy Reforms

i. Significant reforms and investments are needed in the agricultural sector for reductions in losses and improvements in water productivity (Young, 2019).

ii. Legislations are required for groundwater use for sustainable groundwater management. Limiting the abstraction to the safe yield is a must in this context.

iii. The impact of climate change should be given paramount consideration in all water-related policies and decision-making.

iv. A conflict resolution mechanism needs to be implemented to ensure equitable and fair water distribution and manage disputes.

v. Water quality-based standards should be developed to manage nonpoint pollution and to restore impaired water bodies, especially the endangered wetlands.

vi. Demand management can enhance water availability. Market-based forces to convert water from social good to socio-economic good will help in this regard. Water pricing and privatization policies by regional water utilities need to be introduced.

vii. The provincial government should identify the key policy issues and formulate its provincial water policy to guide future water management by setting clear legal and institutional reforms. An effective policy is needed in this regard that is other than just a standard toolbox garnished with inspirational jargon, but with no implementation capacity.

Last but not least, despite finding engineering solutions to every problem, a culture of out-of-the-box thinking environment should be promoted and supported at all decision-making levels. A high-level brainstorming of multidisciplinary visionary think-tanks comprising diverse interest groups and stakeholders should routinely be conducted focusing IWRM concepts on exploring sustainable, innovative, practical, and cost-effective solutions with the least environmental cost. Inviting young water researchers and students to be part of this exercise will help to build a strong team of future water experts and problem solvers.

PART II: TECHNICAL PAPER

SINDH WATER BALANCE

1 DESCRIPTION OF SINDH PROVINCE

1.1 Population

Sindh is the second most populated province of Pakistan. According to the 2017 Population Census, the population of Sindh is about 48 million (25 million in urban and 23 million in rural areas), accounting for 23% of the country's total population (Pakistan Bureau of Statistics, 2017). A drastic change in demographics of the province is expected in the future as a result of improving the life expectancy rate and expanding cities due to migration from rural areas (Zaidi and Zafar, 2018).

1.2 Location

Area wise Sindh province is the third largest province of Pakistan which is located between 23^{o} 35′ and 28^{o} 30′ North latitudes and 66^{o} 42′ and 71^{o} 01′ East longitudes. It is bordered by the Punjab province on North, Balochistan province on its West, India in East, and the Arabian Sea in its South. The province is situated in the lower Indus basin (Fig 1). The area of the province is about 140,900 km^{2}, which is 17.7% of the total area of Pakistan. There are 29 districts in the province (Pakistan Bureau of Statistics, 2017).

1.3 Physical Features and Topography

The topography of Sindh is relatively flat as compared to other regions of the country. The maximum and minimum elevations are one (01) meter above mean sea level (AMSL) (near the deltaic region) and around 2150 meters AMSL (at Kirthar Mountains, Dadu District), respectively[1]. Sindh has a coastal belt (270 km long) along the Arabian Sea in the South, Indus River delta (southern region), deserts (Pat and Thar in the eastern part), fertile plains along the Indus River, hills (Halar, Suleman, Kirthar, and Aravalli), and marine rocks (Karoonjhar). Agricultural lands mostly occupy the Indus River floodplains. Some forests are also present along the left and right banks of the Indus River and in the deltaic regions (mangrove forests). The forest area is somewhat unique due to less rainfall and subtropical location (Sindh Forest Department, nd).

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[1]. These elevations are derived from satellite-based SRTM Digital Elevation Model (courtesy to Mr. Rao Zahid Khalil)

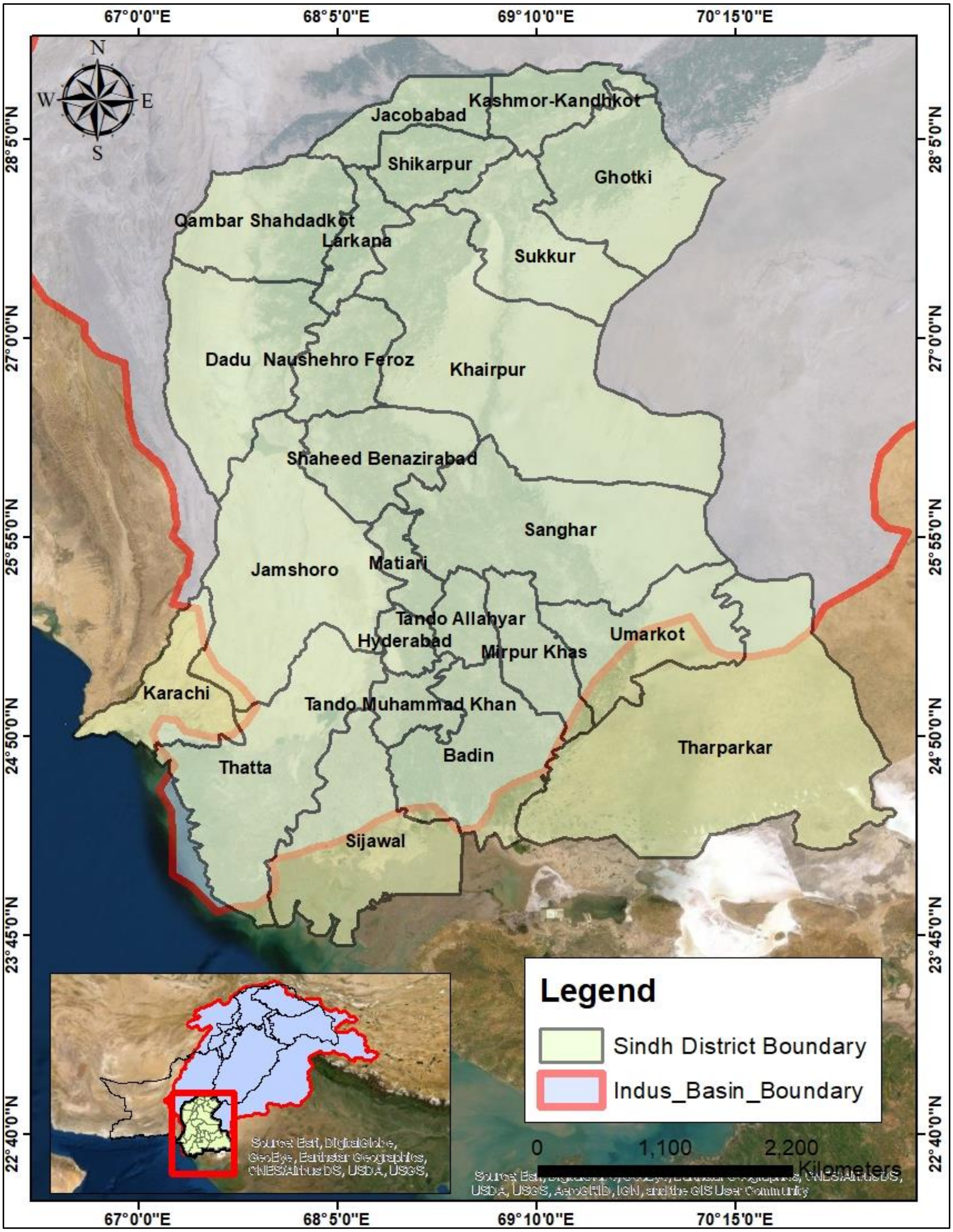


Figure 1: Study Area—The Sindh Province

1.4 Climate and Weather

Sindh is categorized as an arid region, as most of its areas received less than 140 - 200 mm of annual rainfall (Azadet al., 2003; Muslehuddinet al., 2005). In parts of the lower Indus Basin, the average rainfall is even less than 100 mm (Planning Commission, 2012). There are two significant sources of rainfall in Pakistan: the monsoons and the western disturbances. The average annual rainfall is around 178 mm, which mostly occurs during the monsoon months of July and August. The contribution of rain is relatively low as compared to the canal and groundwater in most of the canal command areas of Sindh.

Hottest months are from May to August when temperatures are exceeding 46° Celsius (°C). During the cold months of December and January, the minimum average temperature may drop to 2°C (Tahir & Aslam, 2010). In recent years, due to changes and shifting in the weather patterns, incidences of floods, droughts, and heatwaves are frequent. In the last five years, monthly rainfall varied from as low as one (01) mm to a high of 217.2 mm in 2015 in the Badin district. Overall the rain is scarce, erratic, and unpredictable (Azad et al., 2003). Average rainfalls and temperatures recorded at Pakistan meteorological department (PMD) weather stations in Sindh during 2014 - 2018 are presented in Table 1. Annexure A is provided at the end of this report for further weather and climate-related data and information.

Table 1: Precipitation and Temperature in Various Districts of Sindh (2014-2018)

Districts	Min Monthly Precipitation mm	Max Monthly Precipitation mm	Min Monthly Temp °C	Max Monthly Temp °C
Badin	0.8	217.2	6.3	41.8
Dadu	1.0	133.0	4.3	47.1
Hyderabad	0.4	131.8	9.2	43.0
Jacobabad	1.0	53.0	6.5	45.6
Karachi	0.3	96.9	9.9	38.7
Larkana	1.0	73.3	7.3	45.5
Mirpurkhas	1.8	119.5	7.3	41.8
Nawabshah	1.0	73.1	5.9	45.7
Sukkur	0.1	101.0	6.7	45.0
Thatta	1.2	123.8	8.7	39.1

Data acquired from the Pakistan Meteorological Department (2019)

1.5 Water Availability

1.5.1 Indus River

The primary source of surface water for the province is the Indus River. The River supplies water to its users through the canal system. Huge water losses are present at different levels of this system, including transmission and farm-level losses. The average losses from canals, watercourses, and fields are generally computed as 21%, 40%, and 25%, respectively. The overall irrigation efficiency is 36 % (Azad et al., 2003). System losses in IBIS corresponding to canal supplies ranged from 67 to 68 MAF during the post - Tarbela period or about 64% of the IBIS waters (Randhawa, 2002). However, inconsistent values of the losses were found throughout the literature.

1.5.2 Groundwater

Different agencies have made estimates of groundwater resources at different times, which vary significantly. The estimated groundwater resources vary between 13 MAF to 16.2 MAF with a safe yield ranging between 4.4 MAF to 8.1 MAF (Azad et al., 2003). Lashari and Mahesar (2012) estimated groundwater availability as 5 MAF. In Sindh, the groundwater use is minimal due to unavailability of good quality groundwater. Groundwater is mostly saline, and waterlogged areas are around 50% and 70% before and after the monsoon season, respectively, and a significant portion of groundwater recharge (70%-80%) is lost as non-beneficial evaporation. (van Steenbergen et al., 2015).

According to a 2002 report, more than half (57%) of the area, with a water table less than three (03) meters, is affected by waterlogging (Randhawa, 2002), which has further increased since then. Good quality groundwater is present along the left bank of the Indus River in a strip. Some other areas also have some fresh groundwater pockets. Reliable and accurate estimates of groundwater use in the province are not available. Data provided by FAO (Azad et al., 2003) show a gradual increase in the number of tube-wells. The same report indicated around 53,862 tube-wells in the province (public: 12,038 and private: 41,824 or higher as estimated by unofficial sources) (Azad et al., 2003). Sindh Irrigation Department identified 3933 freshwater tube-wells and 2255 saline water tube-wells. During 2009-2010 to 2015-2016 installation of private tube-wells (153 to 178) became more popular than public tube-wells (5 to none) (Pakistan Bureau of Statistics, 2017a). The main purpose of many public tube-wells was to drain saline water (Azad et al., 2003).

1.5.3 Rainfall

The average rainfall in the province is low and does not contribute significantly to crop use (Azad et al., 2003). Many regions in the Sindh province were under 'moderate to severe' drought conditions due to no or meager rains and continued dry conditions, which prevailed since July 2018 till the recent monsoon rainfalls of 2019 (Pakistan Meteorological Department, 2018).

However, there exists a potential of conserving flashy floods from the hill torrents of high magnitudes, which occur in a short duration. The hill torrents in Pakistan have a total development potential of about 17 MAF, out of which 5 MAF has already been safeguarded by various interventions such as dispersion/diversion structures, delay action dams, reservoirs, and retaining walls (Dawn, 2004). Around 0.72 MAF of potential water available in the Rod-Kohi areas of Sindh (1.36 MA) (Asif et al., 2014)). Some local studies identified presence of the natural depression with water storage potential. The storage capacity of these natural reservoirs can further be enhanced (Soomro, 2019).

1.5.4 Wetlands

Out of 19 wetlands of international importance (Ramsar Sites), there are 10 in Sindh (including Hub dam, which is in both Sindh and Balochistan provinces) (Siyal, 2019). Major canals or their seepage and rainfall feed these wetlands (Azad et al., 2003). The major lakes of the province are Manchar, Keenjhar, and Haleji. The province is also rich with water bodies.

1.5.5 Nais

Besides Indus, there are hill drains, which are known as Nais. The two well-known Nais are Nai-Bran and Nai-Gaj.

1.6 Drainage

Left Bank Outfall Drain (LBOD) and Right Bank Outfall Drain (RBOD) crossing on either side of the Indus River were constructed to drain out the agricultural effluents into the Arabian Sea. Not only these two drains, but there are significant number of drains in the entire province which drains to the Arabian Sea (Tahir and Aslam, 2010). More detail on the Sindh drainage system can be found in a report prepared by the Sindh Irrigation and Drainage Authority (SIDA) (Sindh Irrigation and Drainage Authority, 2012).

1.7 Seasonality of Flows

Both water availability and demand fluctuate over time (Laghari et al., 2012). Water availability in the Indus River is extremely seasonal due to flow variability throughout the year. From June to September (90 to 120 days period), around 85% of the annual flows occur.

After the 1991 Water Accord to 2019, inflows at Guddu varied between 131.1 MAF (max) and 43.4 MAF (min) with an average of 87.7 MAF. Within the same period, the average *Kharif* (summer) and *Rabi* (winter) inflows at Guddu were 72.4 MAF and 15.4 MAF, respectively. The average outflow to the sea below Kotri was 36.3 MAF varying between lows of 0.7 MAF in 2000-2001 and highs of 91.8 MAF in 1994-95 (Azad et al., 2003). The high and low inflows from 2004 to 2019 at Guddu were 103.27 MAF (2010-2011) and 43.63 MAF (2001-2002), respectively, with an average of 65.19 MAF. These high and low values relate to the flood year of 2010-2011 and the drought year of 2001-2002, respectively. In 2018-2019, *Kharif* and *Rabi* flows at Guddu were 36.91 MAF and 12.24 MAF, respectively, and the annual outflow to the sea below Kotri was only 1.76 MAF. The estimates also show a decrease in the river flows in 2018-2019 from the previous several years. Unavailability of the flow records beyond 1998 was the reason for the break up of the flow statistics into two time periods—1991-2003 (found in the literature and 2004-2019—analyzed by the authors.

1.8 Water Share under Water Accord 1991

The Federal Government and provinces agreed upon the 1991 Accord on the Apportionment of surface water among the provinces. Under this Accord, Sindh's share is 48.76 MAF—33.94 MAF in *Kharif* and, 14.82 MAF in *Rabi*. To check sea intrusion, minimum escape below Kotri was recognized as 10 MAF. However, the actual supplies to the province are mainly dependent on the system's water availability. In the past, the *Rabi* supplies have been short of the allocations during drought years due to low water availability in the upstream reservoirs (Azad et al., Rasheed, & Memon, 2003).

Many researchers emphasized the reevaluation of the Accord with the changing scenarios. Some researchers also identified some shortfalls of the accord (Hassan et al. 2019).

1.9 Agriculture

1.9.1 Major Crops

Sindh is mostly an agriculture province. There are two cropping seasons: the *Kharif* or summer season (April to September) and the *Rabi* or winter season (October to March). The primary field crops in Sindh—wheat, cotton, rice, and sugarcane, occupy 68 % of the total cropped area (Lashari and Mahesar, 2012). The major horticultural crops are mangos, bananas, dates, and chilies (Lashari and Mahesar, 2012). Annual cropping intensities vary significantly across canal commands (Mirani et al., 2003).

1.9.2 Irrigation

Irrigation work in Sindh is centuries old. Besides canal irrigation, tube-wells and wells also irrigate some areas. The groundwater of good and marginal quality has been utilized in some areas for irrigation purposes.

1.9.2.1 Indus Basin Irrigation System

Sindh agriculture depends mostly on the Indus water supplied through the canal system due to low mean annual rainfall. Groundwater quality is also impaired in many areas of Sindh, making it unsuitable for agriculture. There are three main barrages to fulfill the water demand for agriculture—Guddu, Sukkur, and Kotri barrages off shooting 14 canals. The Guddu Barrage is built near the Sindh Punjab border, where the Indus enters the Sindh province. Sukkur barrage is the oldest barrage situated across the River Indus, about 483 km North-East of Karachi. The most downstream is Kotri Barrage, located 4.8 km North of Hyderabad City. The canal system mainly supplies water to crops, but it also provides water for humans, livestock, fishery, and navigation (PCMU-WSIP, 2016). Figure 2 illustrates the 14 canal command areas of IBIS.

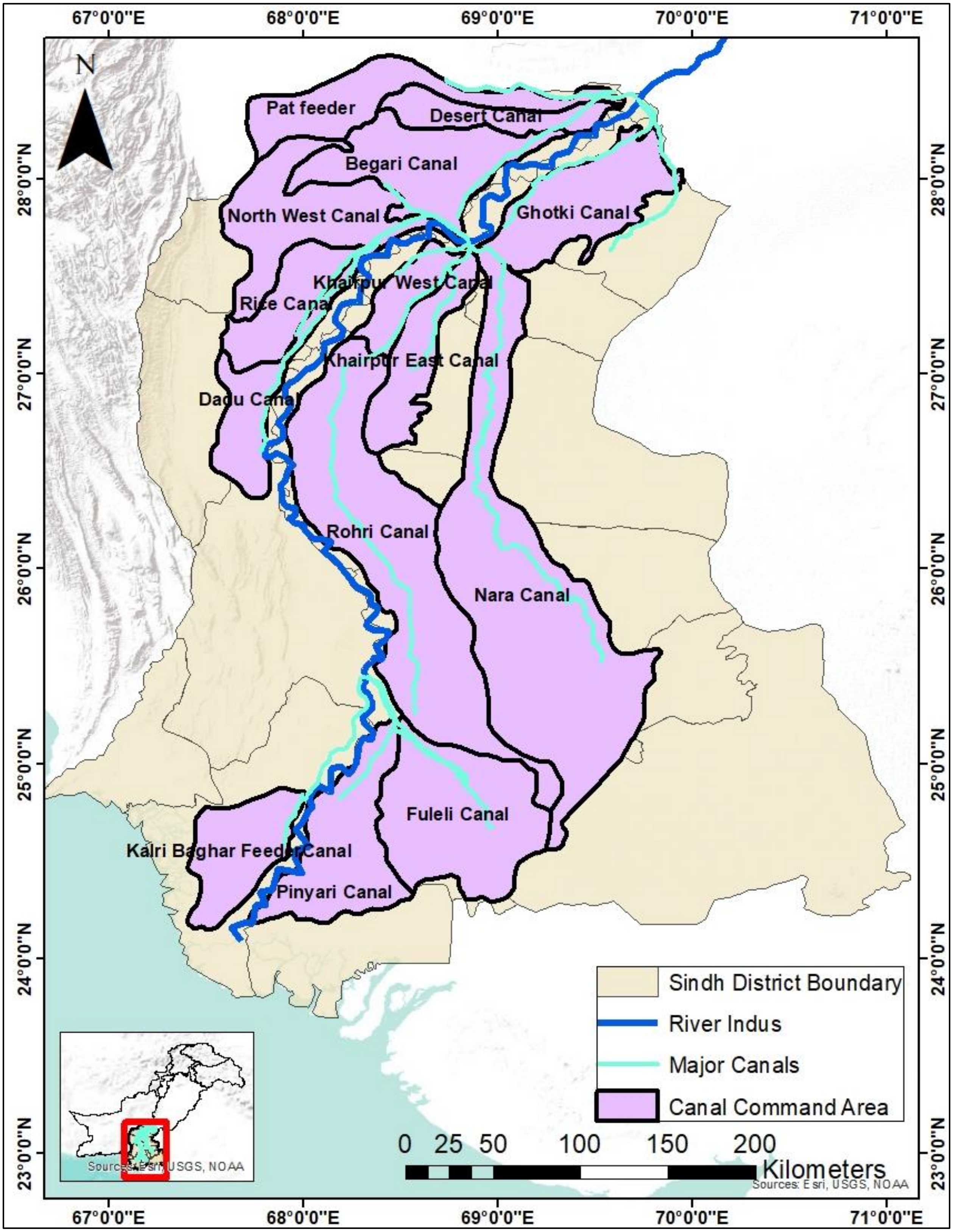


Figure 2: Sindh Canal Command Area

1.9.2.2 Other Sources

In addition to IBIS, groundwater also irrigates a small cultivated area. Major irrigated area of around 78% is underlain with saline or brackish water, which is unsuitable for agriculture (Azad et al., 2003). Canal seepage, poor irrigation management, and lack of drainage facilities have raised the groundwater table in the Indus Basin, which used to be about 12 meters in depth before the introduction of the irrigation system in Sindh, which has caused salinity (Chaudhary, 2012). About 4.3 MAF groundwater utilization for irrigation is estimated on an annual basis, which is mainly recharged from canal diversions (Azad et al., 2003). However, the exact information regarding groundwater use and extent in the Sindh province is not available. The fresh or marginal quality groundwater is mixed with canal water and used for irrigation (Tahir and Aslam, 2010). However, the groundwater contribution in total crop water requirement is minimal (PCMU-WSIP, 2016). Figure 3 illustrates the comparison between the canal irrigated and groundwater irrigated areas in Sindh.

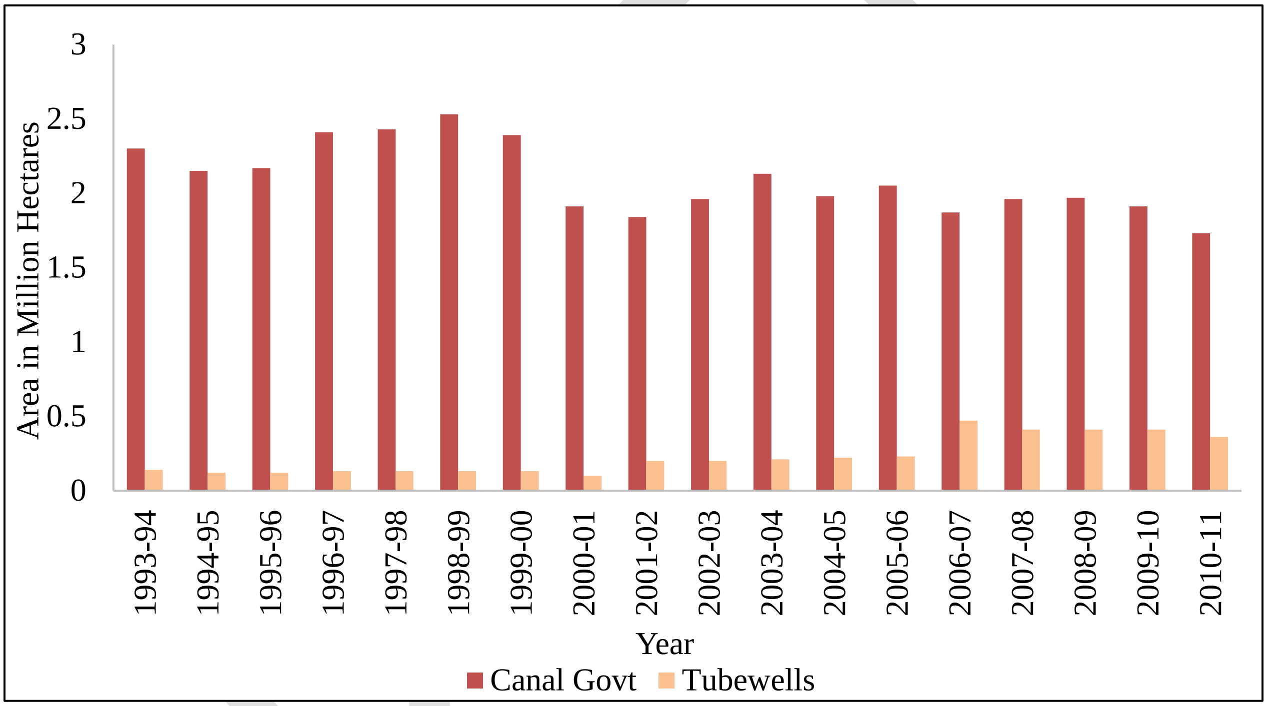


Figure 3: Area Irrigated by Different Water Sources in the Sindh Province
(Data source: http://www.pbs.gov.pk/content/table-4-area-irrigated-different-sources)

Lashari and Mahesar (2012) compared the wheat areas irrigated in canal command and rainfed, which indicated a minimal amount of area irrigated by rainwater as compared to the area fed by canal irrigation. Also, the wheat yield in the rainfed area was found to be much less than the irrigated yield.

1.9.3 Irrigation Water Management Agencies

The leading irrigation water management authorities in Sindh are the Indus River System Authority (IRSA), Sindh Irrigation and Drainage Authority (SIDA), and Sindh Irrigation Department (SID). The Farmer Organizations (FO) are responsible for the operation and management of distributaries and minors and to collect water charges in the areas of AWBs.

1.10 Industrial Water

The total requirement of water in major cities of Sindh is supplied by either various water supply schemes or truck supplies. Groundwater is also used in industries that have access to good quality and quantity of water.

1.11 Domestic Water

Major cities have water supply schemes, whereas the rural population primarily uses canal water and groundwater where it is fit to drink. According to a survey conducted by the Natural Disasters Consortium (NDC), one-fourth of the population does not have access to improved water sources. Around 28% depend on underdeveloped drinking water sources (NDC, January 2019).

1.12 Livestock Water Use

Another issue is the unavailability of drinking water for livestock. Livestock water need is fulfilled through available water supplies. In some rural areas of the province, the availability of drinking water for livestock has some issues (NDC, January 2019).

1.13 Water Pollution

Increasing water pollution—due to untreated or partially treated domestic and industrial effluent, agricultural runoffs carrying traces of pesticides and fertilizers, and urban waste and runoffs— is also reducing the availability of useable water by impairing the freshwater sources. Managing the quality of water resources is not an easy task. Even in the advanced countries where piped discharges are fairly regulated under the discharge permits, the non-point pollution is not well-managed and is impairing water bodies to a considerable extent.

1.14 Climate Change

Pakistan is 8th among the countries most affected by climate change, with 145 extreme weather-related events during 1998-2017 (Germanwatch, 2018). Within Pakistan, Sindh is the province most hit by extreme weather events caused by climate change. The extreme events, including floods and droughts, have caused monetary losses, shortage of food, and loss of human lives. A few examples in the recent decade are massive floods of 2010 and 2011 and drought of 1999-2002. According to the National Disaster Management Authority, districts of Sukkur, Khairpur, Sanghar, Umerkot, Badin, Tharparkar, Kachho, and Kohistan areas of Districts Thatta, Jamshoro, and Dadu are frequently hit by drought.

Climate change is not only expected to alter the water dynamics in Pakistan in the future, but it is already impacting Sindh in the form of sea-level rise, heat waves, droughts, and floods. (Amir & Habib, 2015). Variability in water availability and demand will increase with changes in the climate. The changing climate will impact water availability differently in both short- and long-terms. In the short-term, water availability will increase but will eventually deplete the ice reserves feeding the Indus River. Low flows in the River will lead to less water availability in the longer-run.

2 METHODOLOGY

The estimation of water requirements for domestic, industry, environment, and agriculture use is essential for improved planning and allocation of water resources among competing sectors. The purpose of this water balance study is to understand the current and future trends in water availability to develop sustainable water budgeting of the Sindh province to manage its water resources efficiently. Water balance exercise is balancing the inflows and outflows and is based on the law of conservation of mass applied to the water cycle. Equation 3.1 presents the main variables of water balance in a region within a given time.

(Canal Inflow – Seepage) + (Rainfall – Percolation) + Groundwater – Evapotranspiration – Domestic and Industrial Consumption= Change in Storage **Eq. 3.1**

In the above equation, change in storage includes initial abstraction and change in soil moisture and surface retention. Whereas, in our case, we assumed that there is no change in storage.

This study is based on secondary data, but during the literature survey, it was also found that many of the terms required for the water balance studies contained no, ambiguous, or inconsistent data. To some extent, data gaps were managed and supplemented by remote sensing data. Some measured data were used directly to calculate water balance variables, such as canal water volumes and per capita water requirement. However, most water monitoring data required some form of analysis before being inputted into this report.

2.1 Methodological Framework

A generic methodological flowchart is shown in Fig 4. A detailed description is provided in the subsequent sections.

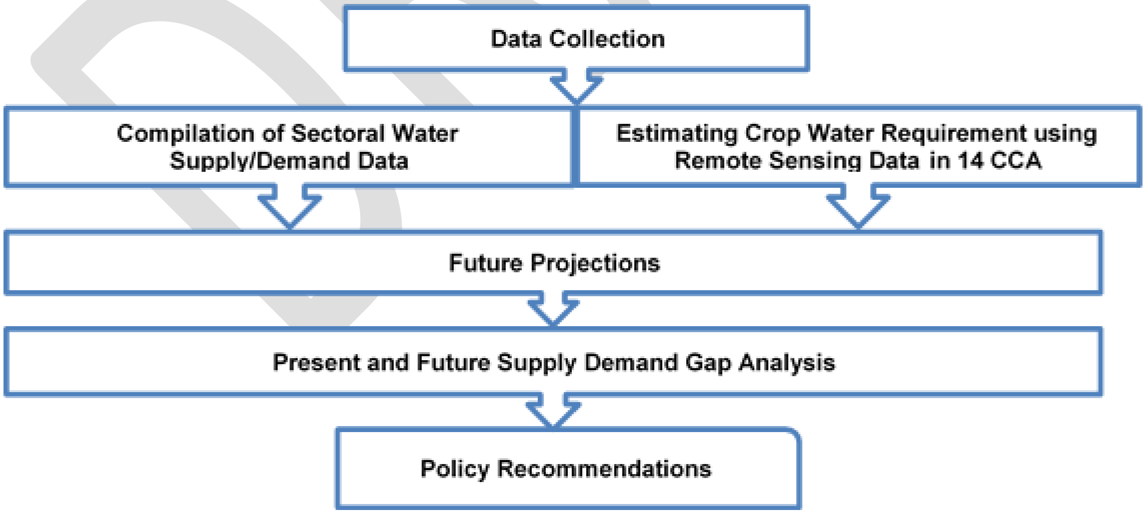


Figure 4: Methodological Flowchart

2.2 Data Collection and Entry

Study data were collected from various sources, including published reports, government statistics, government agencies, personal communication with experts, and satellite data portals. A summary of data and their sources, other than the published reports, is presented in Table 2.

Table 2: Study Data Sources

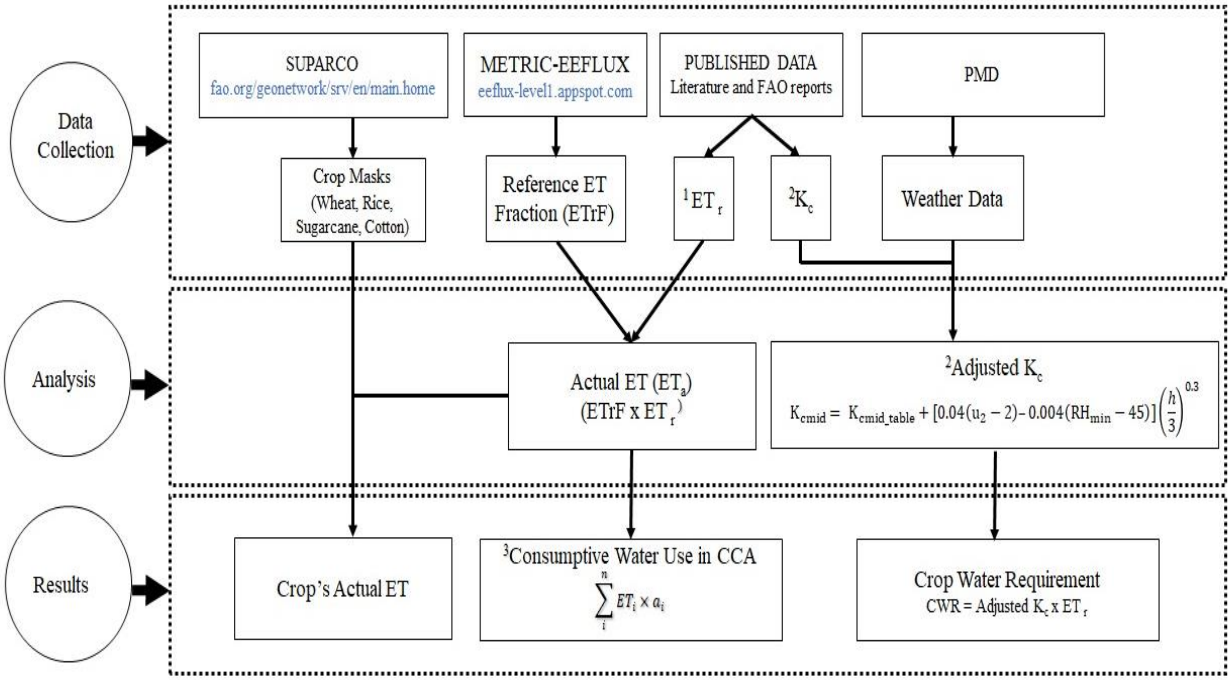
SN	Description	Source
1	Climate data	Pakistan Meteorological Department (PMD) and Drainage and Reclamation Institute of Pakistan (DRIP) Tandojam
2	Population/ Census	Census Bureau of Pakistan
3	Agricultural Statistics	Pakistan Bureau of statistics and Crop Reporting Service Center, Hyderabad
4	Canal Water Flows	Sindh Irrigation Department (SID)/Sindh Irrigation Drainage Authority (SIDA)
6	GIS Shapefiles of Canal Command Areas	Water Sector Improvement Project (WSIP)
7	Evapotranspiration	METRIC-EEFLUX (https://eeflux-level1.appspot.com/)
8	Crop Calendar	Agriculture Research Institute, Tandojam.

2.3 Assessment Methods

The data were analyzed for each category of water users—agriculture, industrial, and domestic. Environmental water demand was also assessed, particularly in the perspective of down Kotri barrage water availability to maintain the ecology and to control seawater intrusion in the deltaic region of Sindh.

2.3.1 Agriculture Water Assessment

Agriculture water use in terms of actual ET or consumptive water was estimated using satellite data. Actual ET is the measure of water used by the crops. In our study, actual ET was estimated using freely available Landsat satellite data products from the Earth Engine Evapotranspiration Flux (EEflux) based on the METRIC (Mapping Evapo-Transpiration at high Resolution with Internalized Calibration) method. The methodology is used to calculate water consumption in 14 canal command areas (CCA) and average actual ET of major crops grown in Sindh during the *Rabi* seasons of 2017-2018 and 2018-2019 and *Kharif* season of 2018. Fig 5 illustrates the steps involved in estimating CWR, water consumption in each CCA, and the average actual ET of the major crops.



[1] Ahmad, S. (2004). Water Balance and Evapotranspiration Of the Country's Water Resources Assistance Strategy By the World Bank

[2] Allen et al. (1998). FAO Irrigation and Drainage Paper No. 56 Crop Evapotranspiration

[3] Where 'n' is the total pixel count, 'a' is the area of pixel of Landsat ET image

Figure 5: Methodological Flowchart for Estimating Actual ET, Water Consumption and CWR

2.3.1.1 Assumptions

1. For estimating wheat CWR, the tail and head regions of Nara and Rohri canal commands are assumed to have the same growing periods.
2. For periods where cloud-free images were not available, images before and after that period were interpolated and used in the analysis.
3. The study period was from Oct 2017 to Apr 2019. The effective precipitation of the monsoon season 2017 was not considered. However, it might have impacted the soil moisture present at *Rabi* 2017-2018.

2.3.2 Livestock Water Use Assessment

Various methods were found in the literature to assess water use by livestock. These methods give a wide range of estimates for the same livestock product. In this study, livestock drinking water use is included only, and water required for producing animal products is not counted and considered as industrial water.

The daily water intake varies with types of animals and their sex, breed, size, growth stages, etc. Weather parameters such as temperature, relative humidity, and air temperature also affect the water consumption rate (Ward and McKague, 2007). Water quality and management practices also influence animal water intake. The process of water consumed by the individual species takes place within the system and, therefore, the consumed water is not lost from it, instead returned as urine or fecal moisture deposited on the soil or vegetation from which it might infiltrate or evaporate. Another rule of thumb described by the Food and Agriculture Organization (FAO) is a rough estimate of livestock water demand as 15 % of irrigated crop ET—33% of rain-grown crops and 68% of permanent pastures and rangelands (Doreau et al., 2012).

In this study, a factsheet on water requirements of livestock by Ward and McKague (2007) is used along with the recent official livestock statistics of Sindh (2018). The factsheet is prepared for Ontario, Canada, which is a colder region than the study area. Therefore, actual water demands may be higher than the estimated values.

2.3.3 Domestic and Industrial Water Assessment

A literature survey was done on domestic and industrial water demand relevant to Sindh. Wherever data could be found, demand was estimated using the best available data. Major urban cities have water supply schemes, and water is supplied through pipes to the residential and industrial areas. The drinking sources for the rural population are canal water and groundwater.

Domestic water is the billed amount of water used in the residential areas for indoor and outdoor activities including drinking, cooking, bathing and washing, sanitation, and gardening, and others. Water demand in all sectors is in close relation with population growth, but domestic water demand can be directly estimated by multiplying the total population with the per capita water consumption. Per capita consumption rate is also variable and depends on various factors other than the seasonal and regional variations. Urban and rural water demands also differ. Improved living standards and availability of water distribution systems with piped connections in houses also increase this demand. Therefore, urban lifestyle water demand is much higher than the rural demand. In this study, per capita 'water access' values of 45 liters per capita per day (l/c/d) in rural areas and 120 l/c/d in urban areas as defined in the National Drinking Water Policy document were used (Amir and Habib, 2015). The per capita values were multiplied with the future population to calculate future demand.

The industrial water is used in processes to transform lower value or raw materials into usable items of commercial value and the development of power (other than hydroelectric power) (Amir and Habib, 2015). Industrial water does not include agricultural use.

2.3.4 Environmental Water Need Assessment

Environmental flows are required to sustain freshwater and estuarine ecosystems. Due to irrigation water diversions at various structures on the River, the flows have decreased. Water Accord of 1991 has identified the required environmental flows downstream Kotri Barrage. Multiple studies were found in the literature that challenged these values as well. The scope of this study is not to analyze the legitimacy of the Accord, but to assess the presence of the Accord defined flows since 1991 using historical downstream Kotri flow data.

2.4 Future Projections

It is highly likely that the water demand of all users will increase in the future due to population growth, urbanization, and hydroclimate changes. The increase in demand will become a severe issue if the current inefficient water management practices prevail in the future as well.

2.4.1 Future Population Estimate

Exponential population growth was assumed for the next three decades. Equation 3.2 was used to estimate the future population assuming a constant growth rate.

$$\mathbf{P = P_o\, e^{rt}} \qquad \textbf{Eq. 3.2}$$

Where:

P_o = Population in 2017 (Sindh population from 2017 census = 48 million)

P = Population in future (2025, 2030, and 2050)

r = Annual growth rate in Sindh (= 2.41%) from 2017 census

t = number of years between current and future populations (8, 13, and 33 years, respectively, for 2025, 2030 and 2050)

2.5 SWOT Analysis

The SWOT (strengths, weaknesses, opportunities, and threats) analysis was employed to optimize the measures for sustainable water resources. The SWOT analysis included the following steps.

1. Current situational analysis.
2. Analysis of the external environment based on threats and opportunities.
3. Analysis of the internal system based on strengths and weaknesses.
4. Measures/ actions to minimize weaknesses and threats that are putting pressure on the available water resources.
5. Possible measures to convert weaknesses and strengths into threats and opportunities wherever possible.

3 RESULTS AND DISCUSSIONS

This section presents the results derived from the water balance study done for the Sindh province. The inputs and outputs of water for different uses were assessed in this study. Water use of each water sector selected for this study is discussed in the subsequent sections. The assessment also took into account the present water demand and future change in this demand due to an increase in population. Literature-based water demand estimates indicate 93-95%, 2%–3%, 2% utilization in agriculture, domestic, and industrial use, respectively, whereas, water requirement for ecology and environmental flows was unaccounted for (Amir & Habib, 2015). However, our analysis for the recent year (2018-2019) estimates lower utilization (around 80% of the total water available at the CCA level including canal diversions and precipitation) by the agricultural sector.

3.1 Seasonal and Annual Water Inflow Variability

3.1.1 Sindh Province River Inflows

To estimate the average surface water availability in the Indus System in the Sindh province, river inflows measured at the Guddu Barrage were used in the study. In this study, 21 years of post-Tarbela historical flows (1998-1999 to 2018-2019) are analyzed. Based on annual inflows at the Guddu Barrage (Fig 6), three flow scenarios—minimum (2001-2002), maximum (2010-2011), and average (2017-2018)—were developed considering them to be representative of dry, wet, and average years' weather conditions, respectively. IBIS is operated on a 10-day time step, therefore, annual and seasonal data (*Kharif/Rabi*) are derived from the 10-daily data. Also, in the 1991 Water Accord, the water allocations are based on seasonal as well as 10-daily basis.

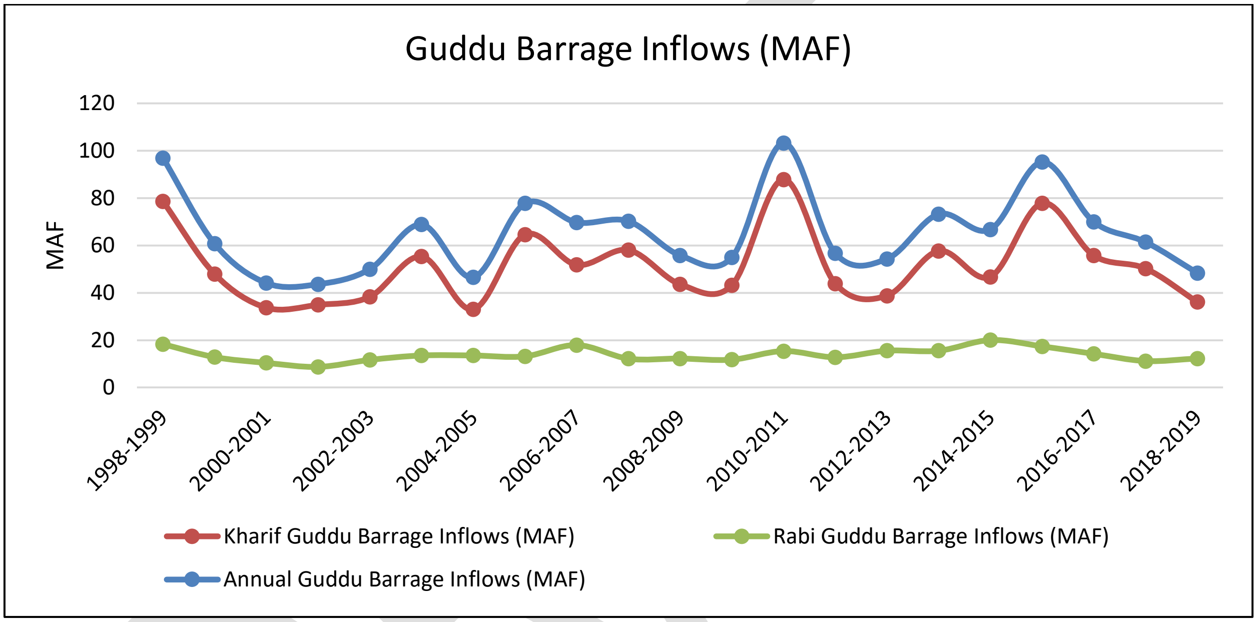


Figure 6: 10-daily Inflows at the Guddu Barrage

The annual runoff (based on 21-year record) has an average of 65.19 MAF, with 70-85 % of the flows occurring in the *Kharif* season (Table 3). The mean annual inflows of 65.19 MAF with a standard deviation of 17.1 MAF indicates that the 1991 Accord allocated amount of 48.76 MAF and greater than this value were available 83 % of the time. The lowest and the highest mean annual flows values were 43.63 MAF (2001-2002) and 103.27 MAF (2010-2011), respectively. It is noteworthy that the highest flow had a contribution from the 2010 super flood. The minimum flow with a 10% probability was 96.96 MAF occurred in 1998-1999.

Table 3: Indus River Inflows at Guddu Barrage (1998-1999 to 2018-2019)

	Minimum (MAF)	Average (MAF)	Maximum (MAF)
Kharif	33.02	51.35	87.87
Rabi	8.72	13.84	20.72
Total	**43.63**	**65.19**	**103.27**

The mean annual inflow volumes for the Indus River at the Sukkur and Kotri Barrages were also calculated as 51.7 MAF, and 24 MAF, respectively, from the 21-year (1998-1999 to 2018-2019) flow records. The mean annual escape down Kotri Barrage to the Arabian Sea was 13.8 MAF. Thus, on average, Sindh utilized 51.4 MAF (Guddu inflow – Kotri outflow) of river flows (including losses) annually from the Indus River.

Hydrographs for minimum (dry), maximum (wet), and average scenarios are presented in Fig 7 for inflows at the Guddu Barrage on a 10-daily basis. In Figure 7, the 21-year record of daily flows (1998-1998 to 2018-2019) indicates that all three scenarios followed the same trend of the river rising around May with flood peaks mostly occurring in August. After August, the river starts to recede. The wet year of the study period (2010-2011) shows a significant 10-daily flood peak of 1,011,536 cusecs in mid-August 2010, which is mainly due to the super flood of 2010.

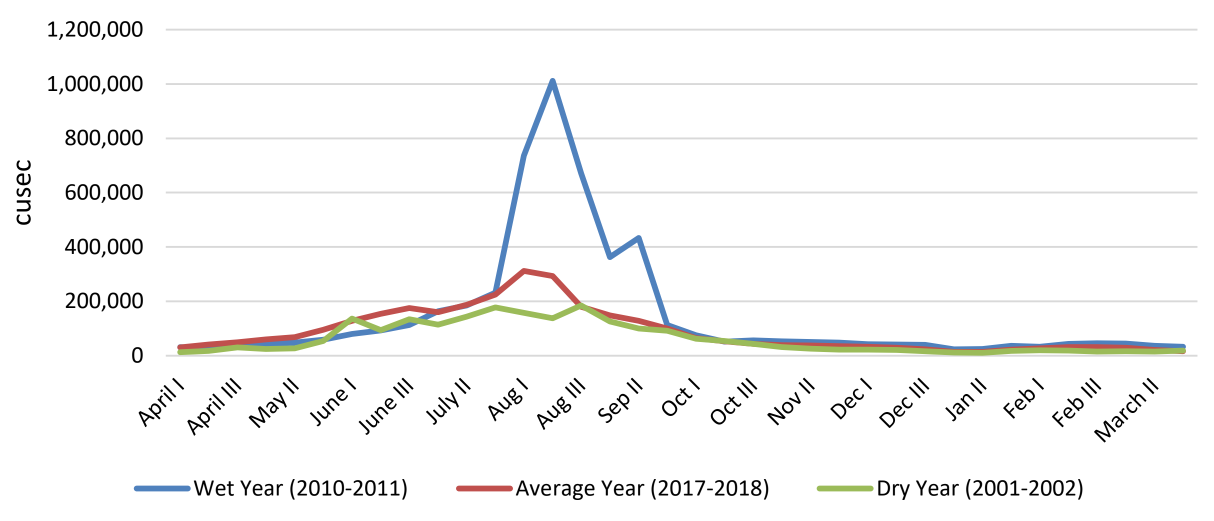


Figure 7: 10-daily Inflows Hydrographs at Guddu for Dry (2001-2002) and Wet (2010-2011) Years and Average (2017-2018)

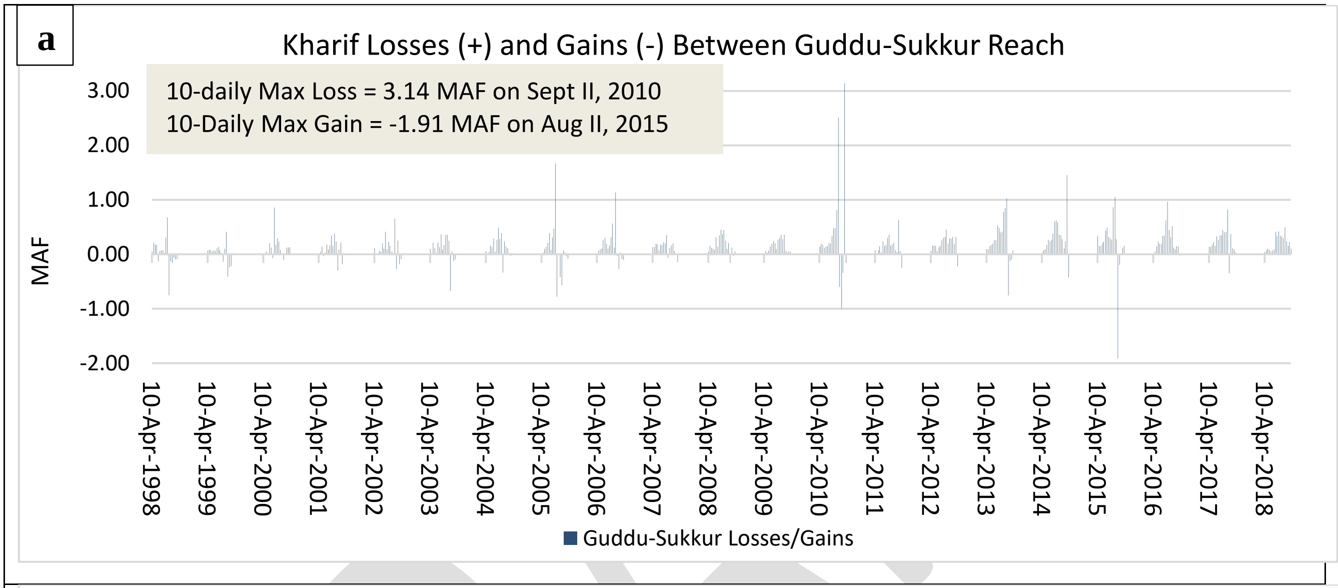
3.2 Losses / Gains in River Reaches

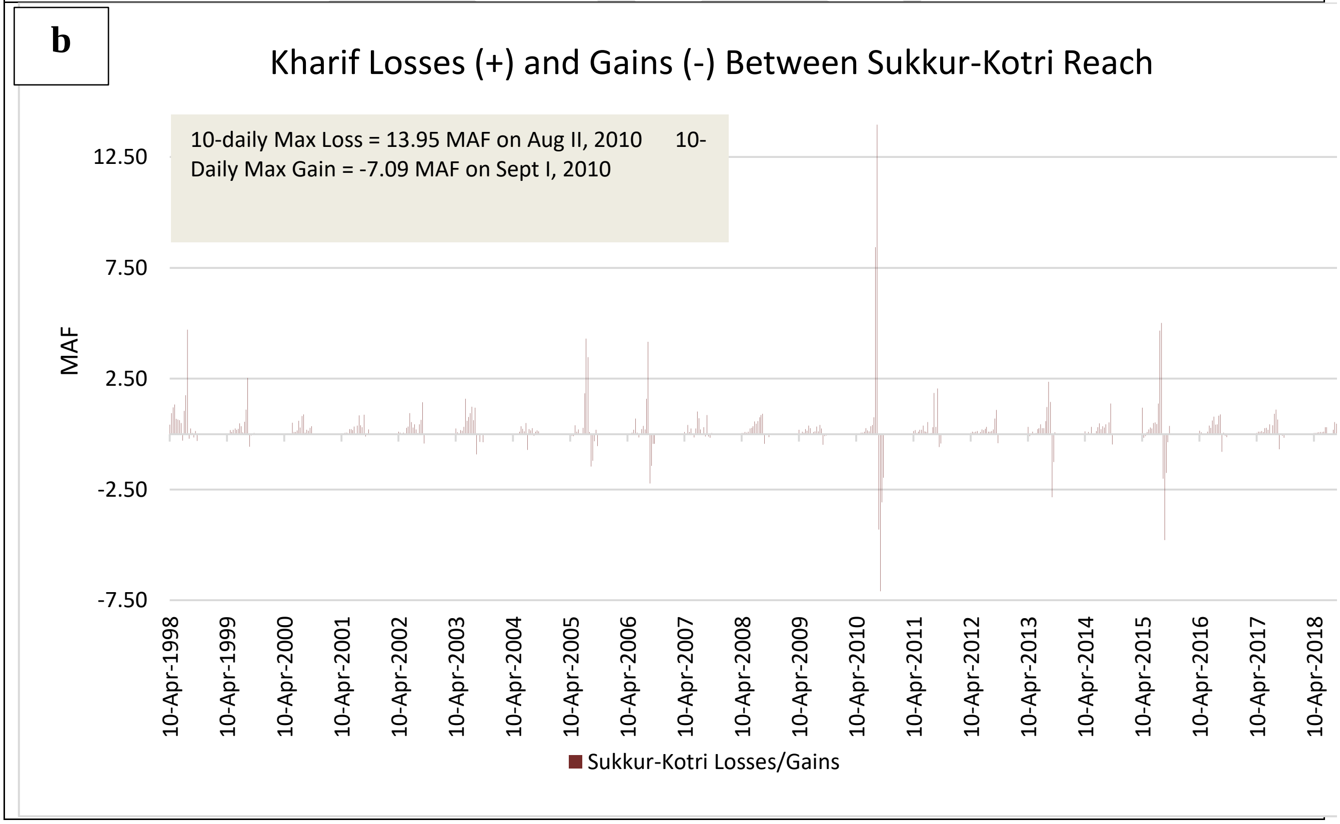
The river water losses and gains were calculated along the Guddu-Sukkur, and Sukkur-Kotri reaches at 10-daily, seasonal (*Kharif* and *Rabi*), and annual basis for the entire study period (1998-1999 to 2018-2019) (Figs 8-a, b, c, and d). Exceptionally large losses (13.38 MAF during *Kharif* 1998) have been observed in the Sukkur-Kotri reach. After balancing the losses and gains for the entire study period, both river reaches were found to lose water with mean annual values of 3.66 MAF and 4.85 MAF, respectively, along Guddu-Sukkur and Sukkur-Kotri reaches.

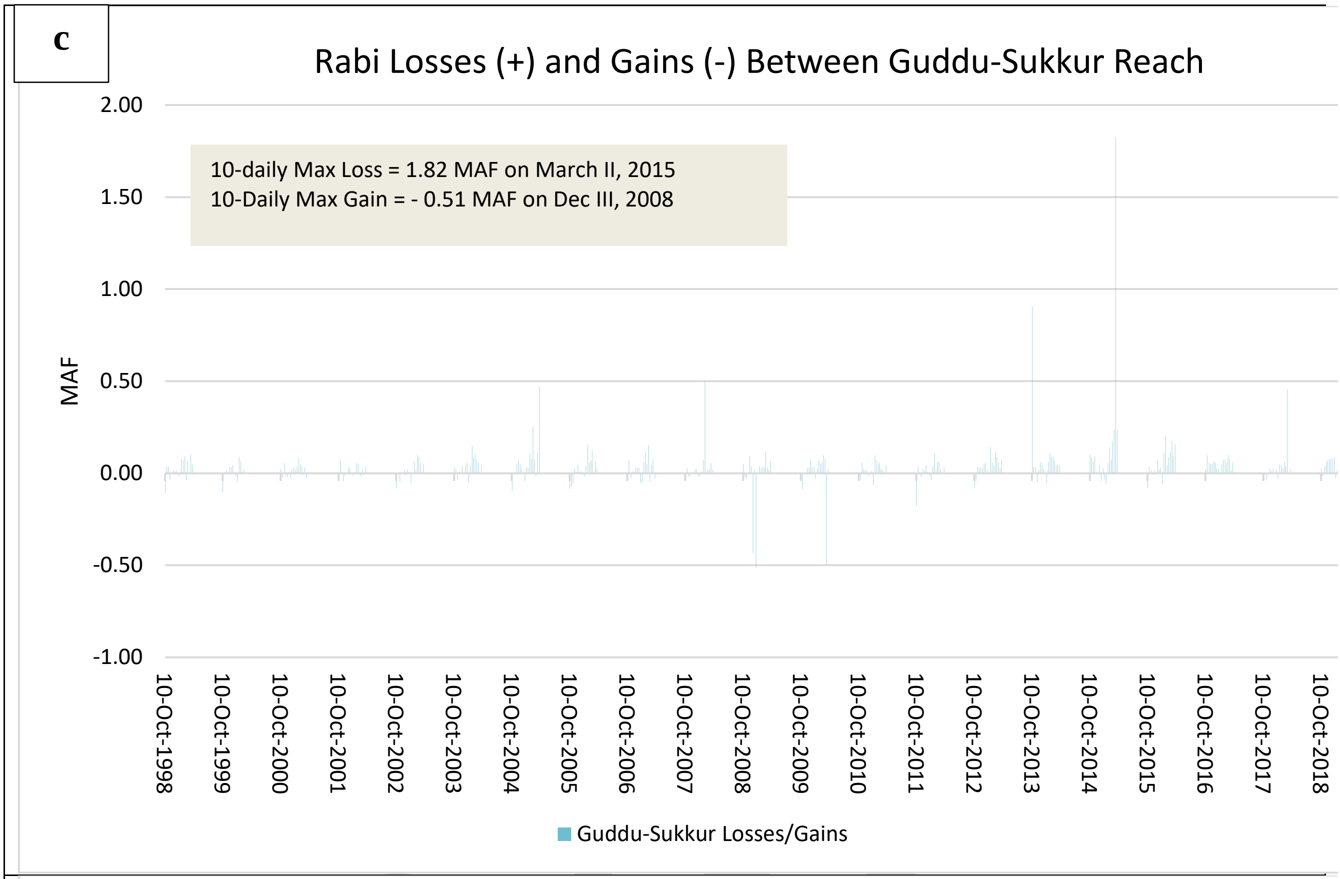
In the dry year (2001-2002), no gains were estimated in any of the two reaches. The total losses during this year were 1.77 MAF in the Guddu-Sukkur reach and 4.65 MAF in the Sukkur-Kotri reach. In the flood year of 2010-2011, both the losses (8.33 MAF) and gains (4.1 MAF) were high in the Sukkur-Kotri reach. In the same year, the *Kharif* losses (7.01 MAF) were the highest in the study period along the Guddu-Sukkur reach as well.

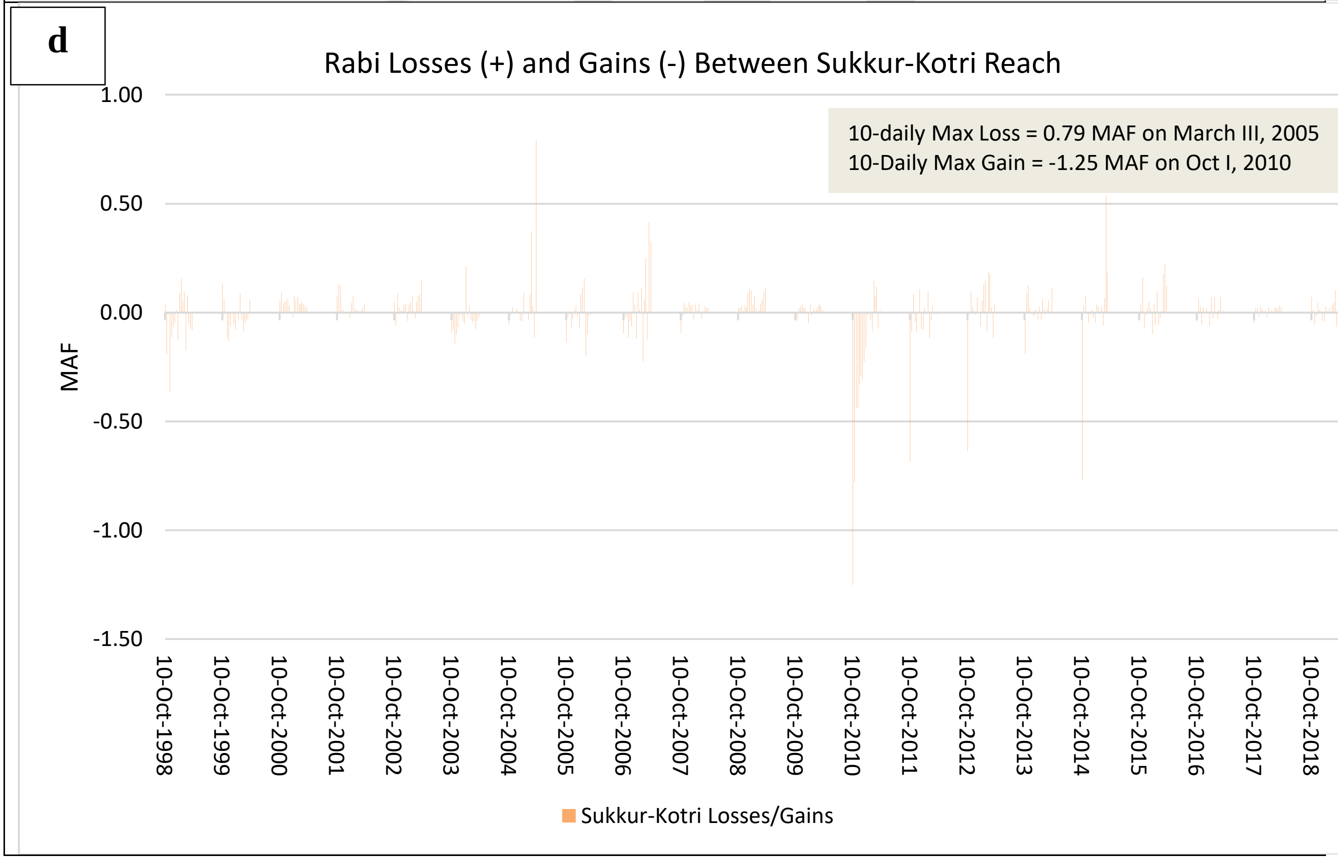
In 12 out of 21 years, the losses between the Sukkur and Kotri reach, being the longer reach, were more than between the Guddu and Sukkur barrages. Not only this, but total losses in the Sukkur-Kotri reach during the study period were much higher (132.6 %) than in the Guddu-Sukkur reach, which need to be investigated and checked since these losses reduce the availability of environmental flows down Kotri Barrage.

On average, the losses were more in the *Kharif* seasons and significantly low in the *Rabi* seasons. One reason may be the difference in the availability of water between the two seasons, and another is the contribution of evaporation in the summer months. These losses and gains may be considered as groundwater water recharges and discharges, but assuming entire *Kharif* losses as ground-water recharge will not be justifiable due to high evaporation rate in summers.






c
Rabi Losses (+) and Gains (-) Between Guddu-Sukkur Reach
10-daily Max Loss = 1.82 MAF on March II, 2015
10-Daily Max Gain = - 0.51 MAF on Dec III, 2008
MAF
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
10-Oct-1998
10-Oct-1999
10-Oct-2000
10-Oct-2001
10-Oct-2002
10-Oct-2003
10-Oct-2004
10-Oct-2005
10-Oct-2006
10-Oct-2007
10-Oct-2008
10-Oct-2009
10-Oct-2010
10-Oct-2011
10-Oct-2012
10-Oct-2013
10-Oct-2014
10-Oct-2015
10-Oct-2016
10-Oct-2017
10-Oct-2018
Guddu-Sukkur Losses/Gains


d
Rabi Losses (+) and Gains (-) Between Sukkur-Kotri Reach
10-daily Max Loss = 0.79 MAF on March III, 2005
10-Daily Max Gain = -1.25 MAF on Oct I, 2010
MAF
1.00
0.50
0.00
-0.50
-1.00
-1.50
10-Oct-1998
10-Oct-1999
10-Oct-2000
10-Oct-2001
10-Oct-2002
10-Oct-2003
10-Oct-2004
10-Oct-2005
10-Oct-2006
10-Oct-2007
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10-Oct-2009
10-Oct-2010
10-Oct-2011
10-Oct-2012
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10-Oct-2016
10-Oct-2017
10-Oct-2018
Sukkur-Kotri Losses/Gains

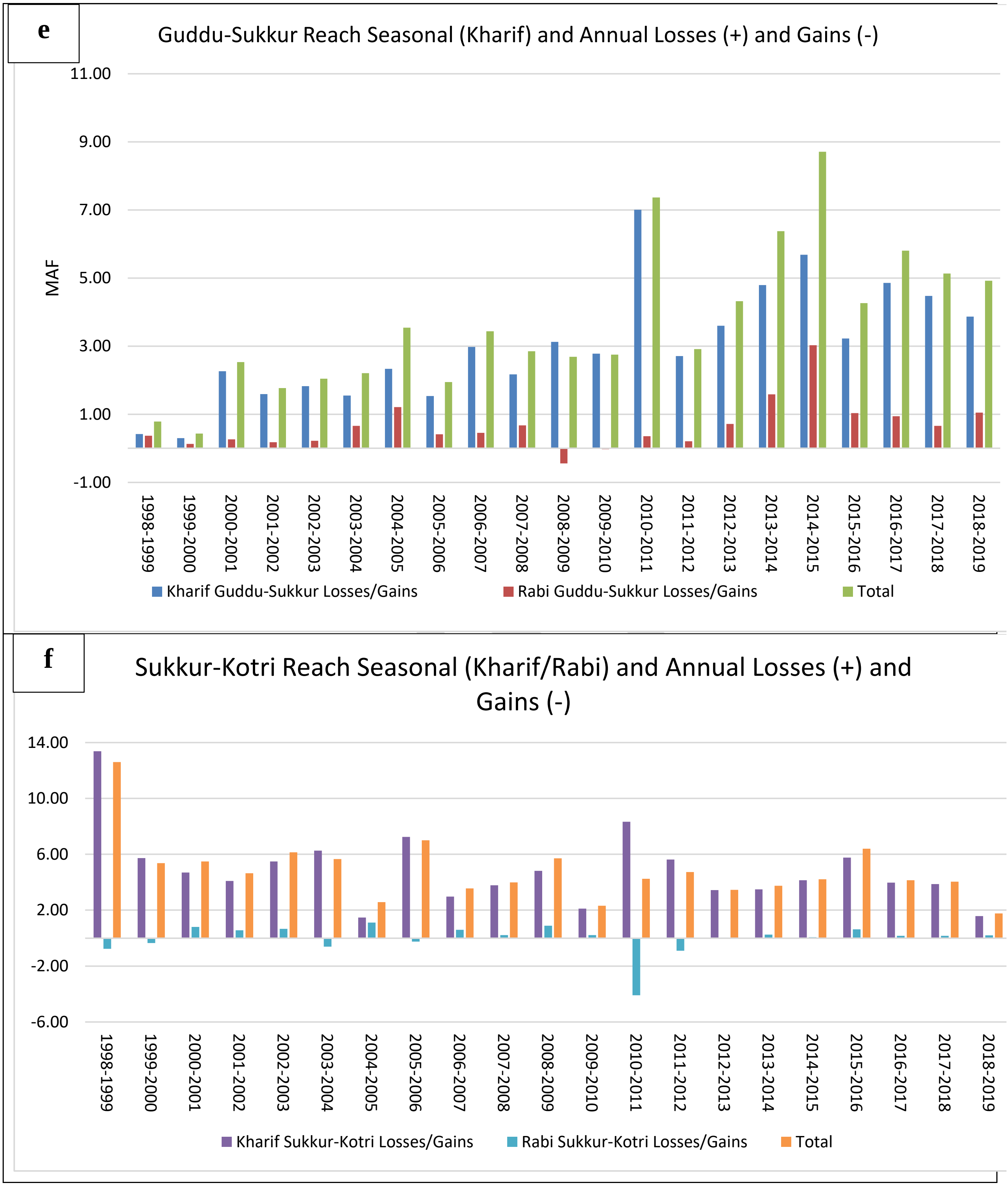

Figure 8: Gains and Losses in the River Reaches

3.3 Water Demand for Major Crops

Agriculture is the backbone of the economy of the province. In Sindh, the total gross command area (GCA) is around 6 MHa (calculated from GIS shapefiles). The availability of water for agriculture use was approximated to the canal supplied water, and therefore, the canal water available for each command area during the *Rabi* and *Kharif* seasons were considered as water inputs. At some places, tube-wells are used for irrigating the crops mostly during the canal water shortfalls, but in Sindh, the majority of the agricultural practices are based on canal water. While balancing the water for the agriculture sector, the groundwater was not considered as an additional water supply assuming that groundwater is recharged either through seepages of canal water or by rainfall, which was already accounted for.

A recent World Bank report also identified the errors in water balance studies by double-counting surface withdrawals in groundwater totals, which are nothing but canal and surface seeps into the aquifers (Young et al., 2019). The distinction between surface water and groundwater is not definite, and most of the groundwater is replenished through surface water (Laghari et al., 2012). Therefore, groundwater withdrawal is simply the water leaked from the canal system. All over Pakistan, around 70% of the groundwater withdrawal is in actual canal leakage and irrigation drainage, and the remaining amount is supplemented by recharge from rain and river water (Laghari et al., 2012). For the Sindh province, with lower rains, this share is expected to be even more than 70%. Therefore, adding groundwater will be double-counting of the available canal and rain waters. This assumption is not only reasonable in the given scenario but has value in our case where reliable data on the extent of groundwater use in the province is not available.

3.3.1 Consumptive Water Use

Tables 4, 5 and 6 presents consumptive water use, calculated from actual ET, along with culturable command areas (CCA), authorized flows, and precipitation volumes for all CCA. The information provided in these tables is helpful to calculate surplus or deficit waters in all CCAs during the study period. Maps on average actual ET in each CCA are provided in Annexure D.

Table 4: Authorized Canal Flows and Water Consumption during *Rabi* 2017-2018

Source	Canal	CCA[1] (MHa)	Authorized Canal Volume[2] (MAF)	Precipitation[3] (MAF)	Consumptive Use[4] (MAF)
Guddu Barrage	Beghari Sindh Feeder Canal	0.424	0.14	0.03	1.17
	Desert & Pat Feeder Canal	0.501	1.09	0.03	0.50
	Ghotki Feeder Canal	0.392	1.00	0.02	1.06
	Total	**1.317**	**2.23**	**0.08**	**2.73**
Sukkur Barrage	North West Canal	0.452	0.73	0.04	1.51
	Rice Canal	0.222	0.19	0.02	0.83
	Dadu Canal	0.235	0.65	0.02	0.60
	Nara Canal	1.002	2.30	0.02	2.97
	Khairpur East Feeder	0.240	0.37	0.01	0.52
	Rohri Canal	1.092	2.38	0.03	3.47
	Khairpur West Feeder	0.136	0.29	0.01	0.56
	Total	**3.379**	**6.91**	**0.15**	**10.46**
Kotri Barrage	KB Feeder	0.284	0.85	0.00	0.65
	Pinyari Canal	0.437	0.21	0.01	0.92
	Fulleli Canal	0.620	0.61	0.04	1.15
	Total	**1.341**	**1.67**	**0.05**	**2.72**
Sindh Barrages	**Grand Total**	**6.037**	**10.81**	**0.28**	**15.91**

[1] Calculated from CCAs shapefiles using ArcMap software.
[2] Obtained from the flow data.
[3] Obtained by interpolating the PMD weather data.
[4] Volume obtained tfrom remotely sensed actual ET

Table 5: Authorized Canal Flows and Water Consumption during *Kharif* 2018

Source	Canal	CCA (MHa)	Authorized Canal Volume (MAF)	Precipitation (MAF)	Consumptive Use (MAF)
Guddu Barrage	Beghari Sindh Feeder Canal	0.424	2.57	0.03	1.20
	Desert & Pat Feeder Canal	0.501	2.69	0.04	1.64
	Ghotki Feeder Canal	0.392	2.27	0.04	1.21
	Total	**1.317**	**7.53**	**0.11**	**4.05**
Sukkur Barrage	North West Canal	0.452	1.51	0.06	1.21
	Rice Canal	0.222	2.62	0.03	1.50
	Dadu Canal	0.235	0.93	0.01	0.36
	Nara Canal	1.002	3.88	0.46	3.26
	Khairpur East Feeder	0.240	0.54	0.03	0.54
	Rohri Canal	1.092	3.67	0.21	3.56
	Khairpur West Feeder	0.136	0.41	0.02	0.64
	Total	**3.379**	**13.6**	**0.82**	**11.1**
Kotri Barrage	KB Feeder	0.284	1.81	0.06	1.02
	Pinyari Canal	0.437	2.36	0.12	1.12
	Fulleli Canal	0.620	4.16	0.29	1.87
	Total	**1.341**	**8.30**	**0.47**	**4.00**
Sindh Barrages	**Grand Total**	**6.037**	**29.43**	**1.4**	**19.15**

Table 6: Authorized Canal Flows and Water Consumption during Rabi 2018-2019*

Source	Canal	CCA (MHa)	Authorized Canal Volume (MAF)	Consumptive Use (MAF)
Guddu Barrage	Beghari Sindh Feeder Canal	0.424	0.09	0.30
	Desert & Pat Feeder Canal	0.501	0.96	1.44
	Ghotki Feeder Canal	0.392	0.95	1.15
	Total	**1.317**	**2.00**	**2.89**
Sukkur Barrage	North West Canal	0.452	1.02	1.44
	Rice Canal	0.222	0.28	0.85
	Dadu Canal	0.235	0.64	0.48
	Nara Canal	1.002	2.34	2.37
	Khairpur East Feeder	0.240	0.31	0.64
	Rohri Canal	1.092	2.17	3.45
	Khairpur West Feeder	0.136	0.24	0.44
	Total	**3.379**	**7.00**	**9.67**
Kotri Barrage	KB Feeder	0.284	1.58	0.62
	Pinyari Canal	0.437	0.36	0.21
	Fulleli Canal	0.620	0.87	1.30
	Total	**1.341**	**2.80**	**2.13**
Sindh Barrages	**Grand Total**	**6.037**	**11.8**	**14.69**

*No precipitation was observed in Rabi 2018-19

3.4 Sindh Agriculture Water Balance

For agriculture water balance, the available water (inflows to the province at the Guddu Barrage plus rainfall) was compared with the total consumptive water use in the entire irrigated area of Sindh. The percent consumptive water use in Sindh was calculated for dry (2001-2002) and wet (2010-2011) years (Table 7). The consumptive water or actual ET was the quantum of water consumed by the entire vegetated area. The water consumed by the vegetation during the dry year is around 63.8 % of the amount consumed in the wet year. Since the wet year was a flood year which caused water inundated areas and the consumptive water used is actual ET, there is a possibility that this value is comprised more on evaporation than on transpiration through vegetation cover.

Table 7: Agriculture Water Balance in Sindh for Dry and Wet Seasons during 1998-1999 to 2010-2019

	Season	Inflows at Guddu Barrage (MAF) (A)	Avg. Precipitation in CCA (MAF) (B)	Total Inflows (MAF) (A)+(B)	Water Consumption (actual ET) (MAF)	Water Consumption (%)
Dry Season	Kharif 2001	34.91	3.32	38.23	12.1	31.65
	Rabi 2001-2002	8.72	0.26	8.98	14.5	161.46
	Total	**43.63**	**3.58**	**47.21**	**26.6**	**56.34**
Wet Season	Kharif 2010	87.87	10.7	98.57	19.5	19.78
	Rabi 2010-2011	15.4	1.02	16.42	22.2	135.20
	Total	**103.27**	**10.7**	**114.99**	**41.7**	**36.26**

The surplus and deficit water flows for each CCA in Sindh were also calculated in this study (canal diversions + rainfall - consumptive water) (Fig 9). It was observed that the surplus flows are mostly available in the *Kharif* season, while deficit or negative flows were present to meet the consumptive demands during the *Rabi* seasons. The highest surplus flow of 2.0 MAF was observed in the Fuleli canal during the *Kharif* 2018 season. Based on this analysis, it was found that the highly productive CCA of Sindh, i.e., Rohri Canal, remained in deficit due to high consumptive demands throughout the *Rabi* and *Kharif* seasons. Through all CCAs and in all study seasons, the highest deficit value of -1.28 MAF was observed in the Rohri CCA during *Rabi* 2018-19.

This information is useful in managing the flows in such ways that a balance can be maintained by adjusting the flows in canals by reducing the surplus amounts and adding into the water deficit areas. Regulating the water flows according to the consumptive water need of a CCA can help in achieving an optimal water balance in the province.

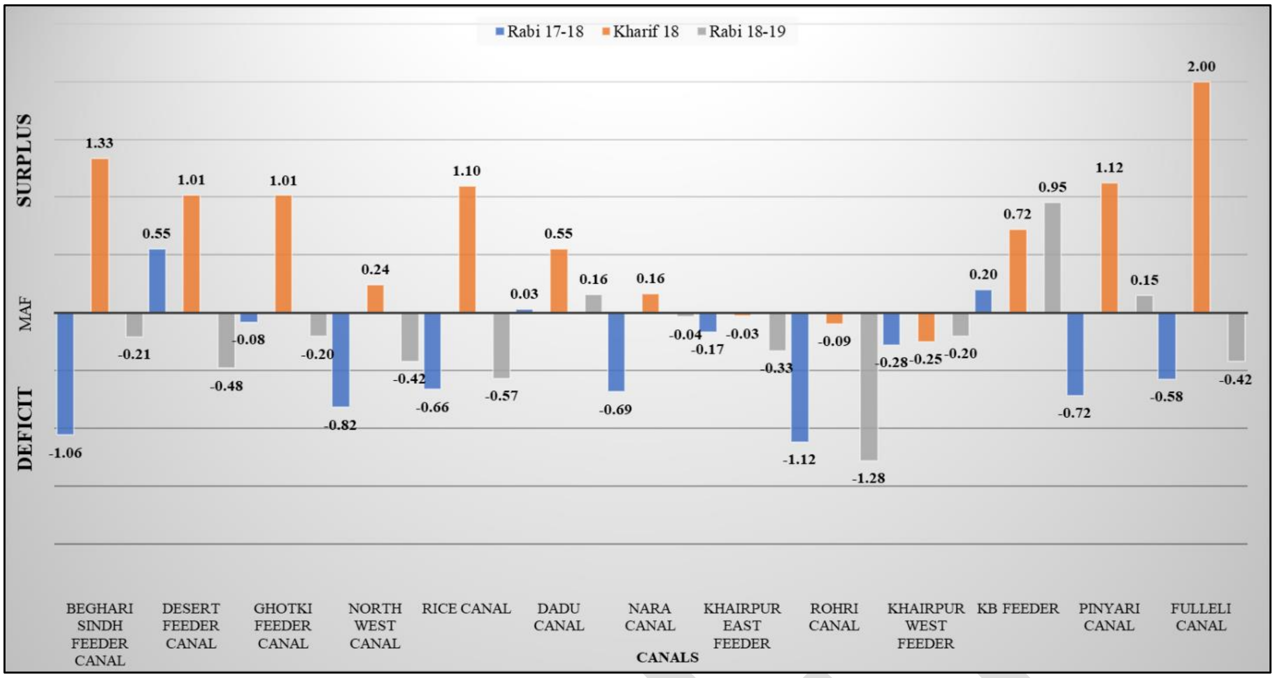

Figure 9: Surplus/Deficit Flows in Sindh CCA from *Rabi* 2017-18 to *Rabi* 2018-19

A water balance chart is shown in Fig 10, where the balance bars (in red color) present the reductions (negative values) or additions (positive values) in the canal flows during the entire study period. The Rohri canal remained in deficit during all study seasons and called for the highest water need (i.e., 2.49 MAF in addition to the authorized flows). KB Feeder canal had maximum surplus water during all three growing seasons (i.e., 1.87 MAF minus municipal demand of Karachi). Thus, water management and planning at the canal level is needed to distribute the balanced flows in order to meet the consumptive water demands of all 14 CCA. The inflows and outflows of the Beghari CCA were balanced well with 0.07 MAF surplus water than the authorized flows.

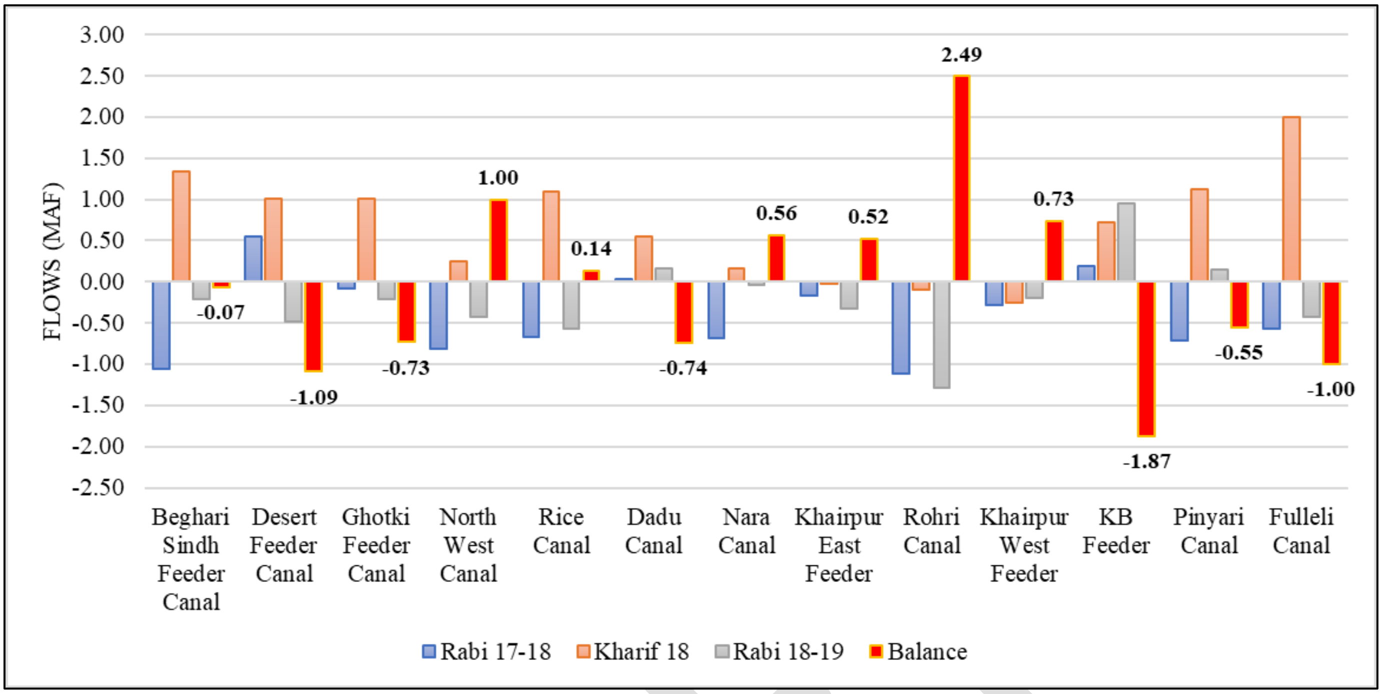

Figure 10: Agricultural Water Balance for Sindh Canals during *Rabi* 2017-18 to *Rabi* 2018-19

Balancing the consumptions and water use in the province can also indirectly identify the groundwater recharges and abstractions. Table 8 presents *Rabi* and *Kharif* groundwater recharges and discharges (or abstractions). It can be noted that during *Kharif*, the groundwater was being recharged, whereas, during the *Rabi* season, the deficit crop requirement was met by groundwater source.

Table 8: Groundwater Recharges and Abstractions

Season	Flows	Consumption	Recharge	%Water use	%Recharge
Kharif 2018	30.8	19.1	11.7	62.0	37.9
Rabi 2018-19	11.8	14.7	-2.9	124.5	*-24.5
Total	**42.6**	**33.8**	**8.8**	**79.4**	**20.6**

Flow, consumption, and recharge values are in MAF.
* negative value represents % abstraction of groundwater.

3.5 Livestock Water Demand

Water demand for livestock is calculated by multiplying the consumption rate (Ward & McKague, 2007) of each animal type to its population in Sindh (Livestock Statistics of Sindh). Table 9 presents the individual water demand for various animals found in the province. The overall consumption is low, with a value of 0.218 MAF.

Table 9: Water Requirement Estimates for Livestock

Dairy Cattle Type	**Average Typical Water Use (L/day)**	**Total Number of Animals**	**Water Required (L/day)**	**Water Required (L/year)**
Dairy calves (1-4 months)	9	1,723,422	15,510,798	5,661,441,270
Dairy heifers (5-24 months)	25	328,525	8,213,125	2,997,790,625
Milking cows	115	2,143,036	246,449,140	89,953,936,100
Dry cows	41	995,701	40,823,741	14,900,665,465
Total annual dairy cattle water requirements	**190**	**5,190,684**	**310,996,804**	**113,513,833,460**
Buffaloes Type	**Average Typical Water Use (L/day)**	**Total Number of Animals**	**Water Required (L/day)**	**Water Required (L/year)**
Feedlot cattle: backgrounder	25	3,363,195	84,079,875	30,689,154,375
Feedlot cattle: short keep	41	117,392	4,813,072	1,756,771,280
Lactating cows	55	3,051,119	167,811,545	61,251,213,925
Dry cows	38	808,459	30,721,442	11,213,326,330
Total annual Buffaloes water requirements	**159**	**7,340,165**	**287,425,934**	**104,910,465,910**
Sheep/Goats	**Average Typical Water Use (L/day)**	**Total Number of Animals**	**Water Required (L/day)**	**Water Required (L/year)**
Feeder lamb/Goat	4.4	4,827,680	21,241,792	7,753,254,080
Male Sheep/Goat	5.25	1,758,526	9,232,262	3,369,775,448
Lactating dairy ewe*/Goat	10.4	9,944,522	103,423,029	37,749,405,512
Total annual sheep/goats water requirements	**20.05**	**16,530,728**	**133,897,082**	**48,872,435,040**
Chicken, Hen, and Cocks	**Average Typical Water Use (L/1000 birds/day)**	**Total number/1000 birds**	**Water Required (L/day)**	**Water Required (L/year)**
Chicken, hen and cocks	**250**	**14,136**	**3,533,885**	**1,289,868,025**
Total annual water requirements (MAF)				**0.218 MAF**

Assumptions: 1) All the average typical water use (L/day) values are taken over a year once a day under the normal agricultural conditions in Ontario, Canada due to unavailability of consumption rates in the study area. Therefore, actual consumption in Sindh with higher temperatures is expected to be more than these estimates. 2) Water consumption is considered the same for all chicken types, i.e. laying hens, pullets, broiler breeders, and cocks.

3.6 Domestic or Municipal Water Requirement

Domestic water demand and supply in cities vary across different climatic, economic, and social conditions. The following sub-sections discuss the supply and demand scenarios of the province.

3.6.1 Supply

Urban cities in Sindh depend on surface water as their domestic water supply source, mainly consisting of the Indus River diversions (Amir & Habib, 2015). Groundwater quality in most of the province is not fit for drinking purposes due to high salinity and, therefore, its use is limited (Azad et al., 2003). Supplies from the canal system contribute to the drinking water needs of the rural population. Estimation of available water for domestic use is challenging to measure in a rural setup where canal inflows are used for both agriculture and domestic use.

Water supply schemes serve residential areas of Karachi, Hyderabad, and other cities through the pipe systems. At present, Karachi is allocated 1200 cusecs (34000 l/s) or 0.865 MAF per year from the Indus water through the Keenjhar Lake. Therefore, available water for combined domestic and industrial uses in Karachi is 0.865 MAF (without consideration of the losses). Leaky pipes and illegal tapping might have reduced the actual amount of water supplied to Karachi. According to a study, leakage losses and water thefts account for almost 30% of the total water supply of Karachi (Bhutto et al., 2019). The annual water demand in Karachi for domestic use for the 2017 population was estimated as 0.54 MAF, which is expected to increase to 0.67 in 2025. Adding industrial demand in domestic need will further increase this value. With current allocation, the demand will exceed the supply in the future. It is anticipated that around 600 cusecs of additional supply will be available through water supply system improvement and retrofitting. The supply to the city is expected to increase to 1.68 MAF (2320 l/s) from the Indus River in 2025 (Bhutto et al., 2019).

3.6.2 Demand

Population statistics and per capita water consumption are used to calculate the water demand of the province. There is a major difference between urban (120 l/day) and rural (45 l/d) per capita demands. The urbanization will change the urban-rural population ratio in the future, and hence the overall future water estimates based on current population growth rates in both urban and rural areas with their respective per capita demands will no longer be valid. However, in this study, no such change in the urban-rural dynamics is considered.

The current annual domestic water demand of the province is 1.19 MAF. With the increase in population, the requirements of the province are expected to increase, which will put an additional burden on water resources. The total domestic water requirements in the province, to be met from surface water sources in 2025, 2030, and 2050 and estimated assuming no change in per capita demand values, are presented in Table 10. Division-wise current and future population and water demands are provided in Annexure B.

Table 80: Past and Future Domestic Water Demands in Sindh

Administrative Units	Annual Demand 2017 (MAF)	Annual Demand 2025 (MAF)	Annual Demand 2030 (MAF)	Annual Demand 2050 (MAF)
SINDH	**1.19**	**1.45**	**1.64**	**2.66**
RURAL	0.31	0.37	0.42	0.67
URBAN	0.88	1.08	1.22	1.99

3.7 Industrial Water Requirement

Industrial activity is mostly practiced in urban cities such as Karachi and Hyderabad. Some small-scale industries are situated in rural areas all over the Province (Azad et al., 2003). Sindh Industrial Trading Estate (SITE) in Karachi has the most extensive industrial setup in the province with maximum water demand among other industrial estates. Total water supplied to the Karachi city includes industrial water share as well.

The industrial water demand of Pakistan was found in many reports (UNDP, 2017; Parry et al., 2015), but comprehensive data specifically for the Sindh province were not readily available. A summary of their findings is presented in Annexure C along with the industrial network of Sindh and daily demands of the industrial estates wherever these details were available.

Around 1% of the net annual withdrawal of the Indus River after adjusting the double-counting error is suggested as industry use (Young et al., 2019). The same 1% of total Sindh water share is assumed for the Sindh province as well, which will make the Sindh industrial water use to be 0.45 MAF. Reliable projections regarding industrial water use are not available (Azad et al., 2003), and therefore, the future need could not be precisely estimated.

3.8 Environment

A substantial quantity of water is required to ensure environmental protection—sustainability of wetlands and mangrove forests, reducing seawater intrusion, and increasing irrigated forestry (Planning Commission, 2012.). Not meeting this requirement will also impact river ecology by disturbing the lifecycle of many fish species that much rely on natural variability in the river flows (Amir & Habib, 2015). In this regard, the quantity and quality of below Kotri Barrage flows are of critical importance.

The Indus River Accord 1991 recommended at least 10 MAF freshwater environmental flows for the downstream deltaic ecosystem. The 10 MAF value was suggested by WAPDA only for average and wet flow conditions, and 5 MAF for below average, 2 MAF for poor, and no flow for the worst conditions (NWRDP, 1994). IWMI also approved 10.0 MAF (which is 7% of the average system inflow) as the volume of water to be discharged on average and wet years below the Kotri Barrage to check seawater intrusion (Khan, 1999). However, this amount is not adequate, as reported by the International Union for Conservation of Nature (IUCN), to maintain the effective functioning of the wetlands' ecosystem in the Indus delta (IUCN, 2004). The IUCN has recommended releases of 27 MAF below Kotri Barrage for the continued sustenance of the deltaic ecosystem. Much lesser flows (3.6 to 5 MAF) were recommended in some recent studies, but these also called for assured flows (Gonzalez et al., 2005).

In this regard, it should be noted that there are specific periods when water does not reach the sea, and there are no flows down Kotri barrage, especially in winter seasons, which are detrimental for the deltaic ecosystem. Based on 21-year flow records (1998-1999 to 2018-2019), the mean annual flows downstream Kotri Barrage were highly variable with mean = 13.8 MAF and standard deviation =13.58 MAF. The availability of annual flows short of 10 MAF (accord allocated flow), 5 MAF, 3.6 MAF, and 2 MAF were observed in 11, 6, 5, and 4 years, respectively, out of total 21 years of flow record. The lowest mean annual flow at the Kotri Barrage is only 0.28 MAF (2004-2005). All these shortages occurred during the average or the below-average flow years (except one in 2014-2015). With increasing dry years due to changing climate, there is a need to reevaluate the requirement of downstream Kotri flows for the sustainability of the coastal resources

On the one hand, the flows in the river have decreased due to diversions of irrigation water for irrigation and other uses; on the other hand, the saline drainage water is being added into the River, increasing its salinity. This is the reason that although substantial flows are present during wet seasons with only slightly higher salinity at Kotri than upstream reaches, salinity at Kotri often reaches critical levels during dry seasons with insufficient flows to the Arabian Sea required to meet ecological and sanitary requirements (Azad et al., 2003). The active Indus delta has been significantly reduced to its original size by seawater intrusion caused by increasing zero-flow periods during the winter season.

A recognizable change in the hydrological behavior of the river at the Lower Indus Basin is also noticed during the past several decades. The decrease in the average annual inflows has caused low water and land productivity in the irrigated areas of the province (Khero et al., 2013). During 1976-2016, an annual average of over 30 MAF water escaped below Kotri, varying from 0.3 MAF to 92 MAF. However, shortfalls from 10 MAF flows were observed in 10 out of 40 years (Fig 11).

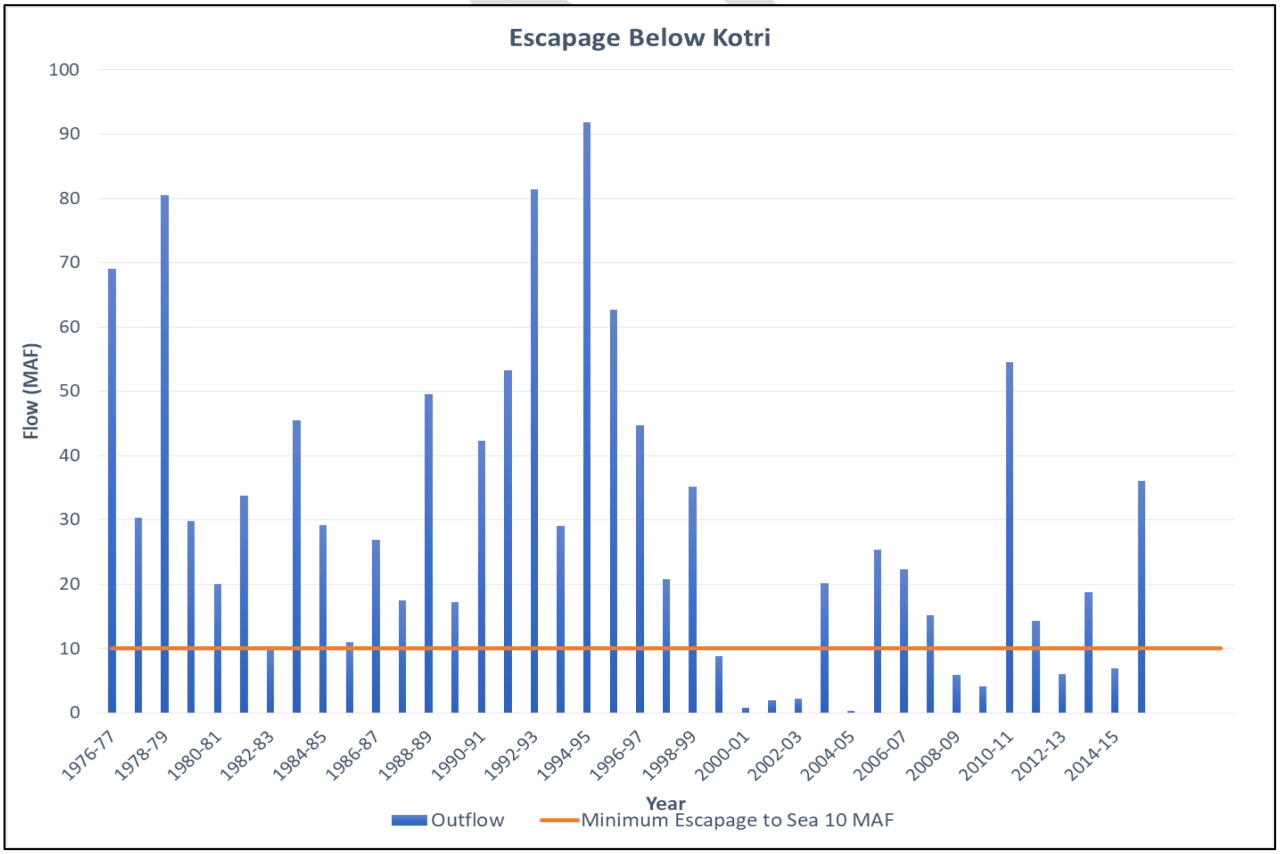

Figure 11: Historical Escapes below Kotri Barrage (Data courtesy: Sindh Irrigation Department)

Besides river diversions, river losses also contribute to reducing the river flows (Table 11). These losses are offset with the gains in the Guddu - Sukkur reach on a long-term basis. However, in the Sukkur – Kotri reach, the average losses (8 MAF in *Kharif*) are much higher than the gains (1.5 MAF in *Rabi*) on a long-term basis, causing an average net loss of 6.5 MAF (Azad et al., 2003). The high loss in Sukkur-Kotri reach reduces water availability below Kotri Barrage, which needs to be investigated and managed.

Ecosystem management in the Indus basin was also not given due consideration except declaring a limited number of protected areas. Indus delta region is vulnerable to induced environmental and social disasters. The inefficient system for irrigation supplies with drainage problem is imposing costs of environmental externalities such as waterlogging and salinity. Drainage issues were also considered as ‘environmental’ issues in the World Bank’s National Drainage Plan. Although the plan focused on the environmental aspect of the drainage projects—Left and Right Banks Outfall Drains (LBOD and RBOD), no detailed ex-post assessment of environmental impacts of the completed water projects were conducted (Wescoat et al., 2000). Both drains are also said to be destroying many wetlands in Sindh (Dawn, 2008). The design failure of LBOD has also increased the risk of sea intrusion in the coastal belt of Sindh, especially the deltaic regions.

Table 9: Flow Variability to the Arabian Sea (Below Kotri Barrage), Pre - and Post - Tarbela Periods

Percentile Flow	**Flow Downstream Kotri Barrage (MAF)**					
(%)	**Pre - Tarbela Period**			**Post - Tarbela Period**		
	(1940 - 1975)*			**(1976 - 2016)**		
	Kharif	***Rabi***	**Annual**	***Kharif***	***Rabi***	**Annual**
Minimum	8.11	0.00	8.11	0.20	0.00	0.28
10%	25.38	0.24	25.62	4.00	0.04	5.87
25%	49.70	2.19	50.51	10.93	0.11	14.26
50%	65.34	5.76	77.34	25.19	0.62	26.90
75%	80.50	10.54	91.21	40.60	2.71	44.79
90%	93.88	16.46	106.04	64.05	4.98	69.03
Maximum	**108.47**	**20.67**	**128.90**	**88.18**	**12.26**	**91.79**
*source: Randhawa, 2002						

3.9 Water Quality

Besides declining per capita water quantity, the quality of freshwater resources has also been deteriorated, further reducing the availability of usable water. At agricultural lands, the use of poor-quality groundwater for irrigation may affect crop growth. Pakistan is said to have the worst salinity problem in the world where secondary salinization, due to the use of saline groundwater, is threatening the sustainability of agriculture produce (Qureshi, 2011).

Another threat to the quality of freshwater is wastewater. Municipal sewage from leaky pipes is being mixed with water supply lines, and drainage effluent and untreated industrial wastewater are being released directly into the freshwater bodies containing pollutants such as heavy metals, pathogens, and other dangerous chemicals (Bhutto et al. 2019; Khan et al., 2018). With increasing, population and development of the industrial sector, not only the water demand will increase, but if current practices prevail, water pollution will continue to stress available water supplies. Bhutto et al. (2019) have compiled available literature to identify water quality in different districts of Sindh, which is showing a severe violation of the World Health Organization (WHO) standards (Annexure F). The most polluted drinking waters are found in Karachi, Hyderabad, and Shaheed Benazirabad.

Like other provinces of Pakistan, the quality of water in Sindh province is unfit for drinking purposes (Kalhoro, 2017). The inquiry commission of the Supreme Court of Pakistan reported that "*78.1% of all water samples tested were found unsafe for drinking*". The major contaminants found in water are pathogens, chemicals, and toxic materials (69% bacteria, 24% arsenic, 14% nitrate and 5% fluoride) (Bhutto et al., 2019).

3.10 Sustainable Water Balance

A sustainable water balance as defined by the International Water Stewardship Standard (AWS, 2014) is *"the state when the amount and timing of water use, including whether the volumes withdrawn, consumed, diverted, and returned at the site and in the watershed, are sustainable relative to renewable water supplies and are maintaining environmental flow regimes and renewable aquifer levels."*

For sustainable water balance, not only the volume of flow matters but the timings are also important—ensuring the right amount of water at the right time and place is essential in this regard. Water availability and demand change both in time and space—during the *Kharif* season, water availability is sufficient to fulfill the demand of all users, whereas, the *Rabi* is a water deficit season. The down Kotri water availability has not been sufficient in the past—many times, even in the *Kharif* seasons, the environmental flows were inadequate. This shows that water in Sindh is not being managed well, which is causing substantial wastages. The ability of IBIS to meet the long-term water needs of all users including the natural ecosystem in the backdrop of climate change (and shift), will make this system sustainable.

3.11 Limitations of the Study

A recent World Bank report (Young et al., 2019) on Pakistan's waters indicated the following issues regarding secondary data availability.

1. Actual water consumption is not directly measured, and therefore, difficult to assess. However, some complex indirect measurements are done on a limited scale.
2. Complete and consistent national resource estimates are not available in published form.
3. Only approximate resource estimates are available (no accounting), especially in the case of groundwater.

The values of the parameters used for water balance, not only change spatially but temporally as well. For precise estimates, extended historical data are needed. Information on consumptive crop water use was not readily available from secondary sources and was derived from satellite data. Area covered by the crops was not available at the canal command levels, and therefore, crop-specific consumptive water volumes cannot be calculated for the study period. The time available for this study allowed estimating crop evapotranspiration (ET) only for two *Rabi* and one *Kharif* seasons (2017-2019).

A water balance study has temporal and spatial boundaries, and therefore, accurate evaluation of inflows, outflows, and change in storage are challenging on a single year basis. Other studies on water balance were consulted that may have the following common mistakes as identified by the Food and Agriculture Organization (Azad et al., 2003).

1. Physical and temporal (time) boundaries of evaluation are not defined.
2. Evaluating a limited number of years incapable of catering to the temporal change in water balance values.
3. Water double counting.
4. Counting all pumped water as water inflows.
5. Recoverable seepage and deep percolation losses are over-estimated.
6. Beneficial and non-beneficial uses are incorrectly assigned.

Inconsistencies and gaps in data might have resulted in either double-counting, overestimating, or underestimating water balance parameters. Although factual data available through bona fide agencies were used, gaps in the acquired data cannot be disregarded. However, valid approaches to handle missing data were applied to minimize the influence of this limitation.

3.12 Strengths, Weaknesses, Opportunities, and Threats—SWOT Analysis

Table 12 present strengths, weaknesses, opportunities, and threats related to this study. This analysis is focused on converting weaknesses into strengths and threats to opportunities. The evaluation of SWOT elements will give insight to the decision-makers and water managers to select appropriate strategies and propose a policy for integrated water resources management in the Sindh Province.

Table 12: SWOT Analysis

WEAKNESSES - Systems losses in irrigation network and water distribution system - Unfair irrigation water distribution and water thefts. - Reservoir operations based on personnel's judgments increasing risks. - *Warabandi* (fixing turns) water distribution system - Inadequate water quality and quantity monitoring data for all water users. - Insufficient groundwater data. - Inefficient irrigation practices. - Water-intensive cropping pattern and industrial processes. - Low crop water productivity. - Inadequate industrial waste water treatment (dumping of industrial waste in surface waterbodies). - Water quality issues of drinking water. - Insufficient water supply network to cater the need of the entire population. - Coordination among water sector institutions is missing. - Ineffective policies, lack of regulation, and laws.	**THREATS** - Floods and droughts. - Urbanization and population growth are causing a decline in per capita water availability. - Climate change-imposed water stress. - Seawater intrusion. - Poor water quality - Wastewater impairing the fresh waterbodies - Inequity in water distribution
STRENGTHS - Largest contiguous irrigation system of the world. - Presence of several water sector departments and institutions (Sindh Irrigation department and Sindh Irrigation and Drainage Authority-SID/SIDA, WSIP, Indus River System Authority-IRSA, Water And Sanitation Agency-WASA, Environmental Protection Agency- EPA, Public Health Departments, Karachi Water and Sewerage Board-KWSB, Federation of Pakistan Chambers of Commerce & Industry-FPCCI, etc.). - Increasing food demand with economic incentives has made agriculture a profitable sector, which is attracting progressive and commercial farmers, and, as a result, high-value crops are displacing food grains. - To compete in the international market, mill owners are required to comply with various regulatory compliances and get certification.	**OPPORTUNITIES** - Floodwater can be stored for later use, reducing water shortage risks. - Water shortages will demand for adoption of water conservation through water-efficient practices and optimization of water distribution by renovating/reconstruction/retrofitting of faulty irrigation and water supply systems to reduce system losses. This may also lead to adoption of water metering and pricing and introduction of economic incentives to water conservation and water trading among users. - The enormous potential of an improved economy through increased water productivity, which will create additional jobs in the agriculture and industrial sectors. - Water conserving culture in industries is becoming popular due to economic incentives—clean production technology is an effective tool to attract the attention of the industrialists by giving an incentive of a direct financial return.

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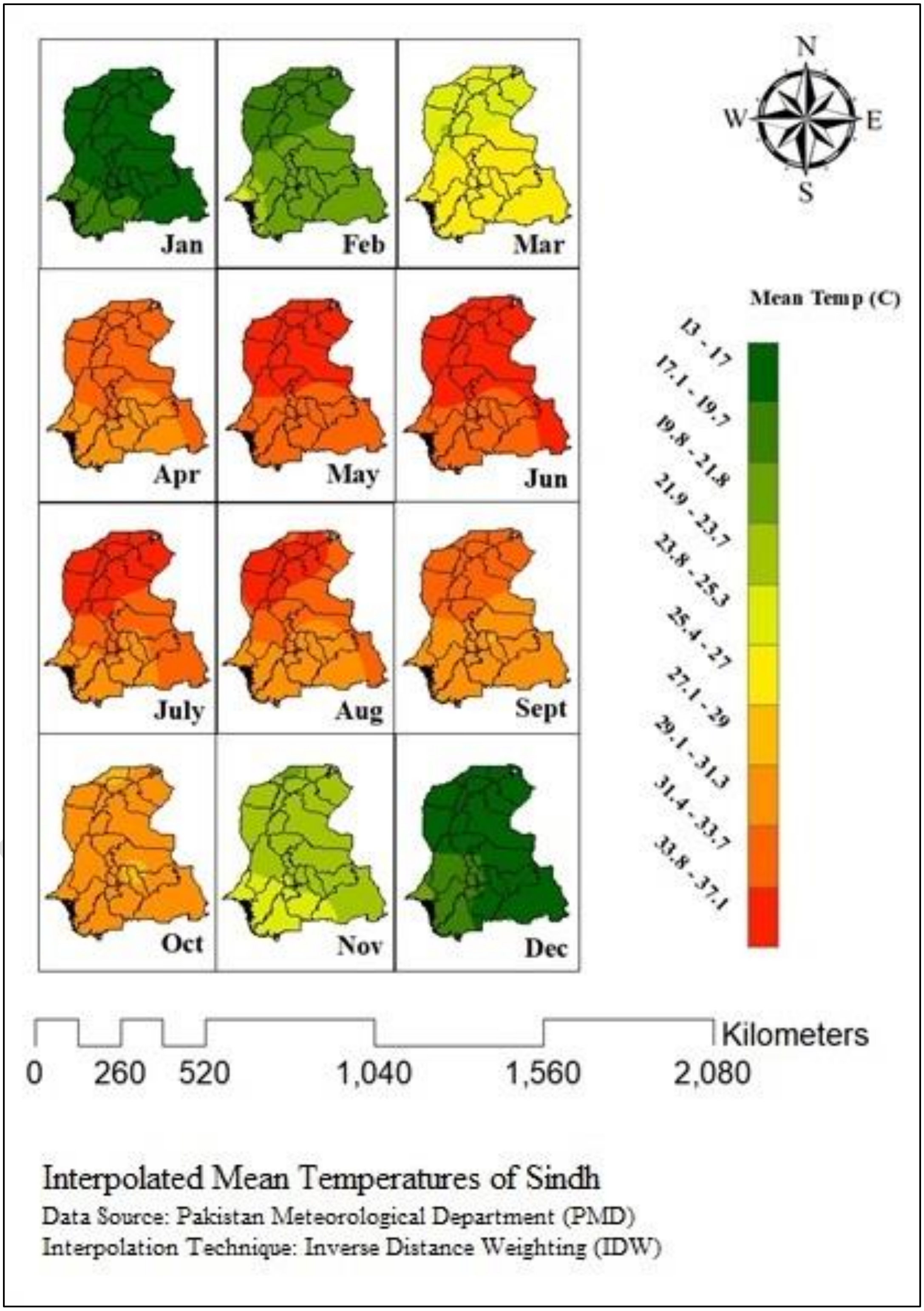
ANNEXURE A

SINDH—WEATHER AND CLIMATE DATA



Interpolated Mean Temperatures of Sindh

Data Source: Pakistan Meteorological Department (PMD)

Interpolation Technique: Inverse Distance Weighting (IDW)

Figure A-1: Mean Temperature in Sindh (2018)

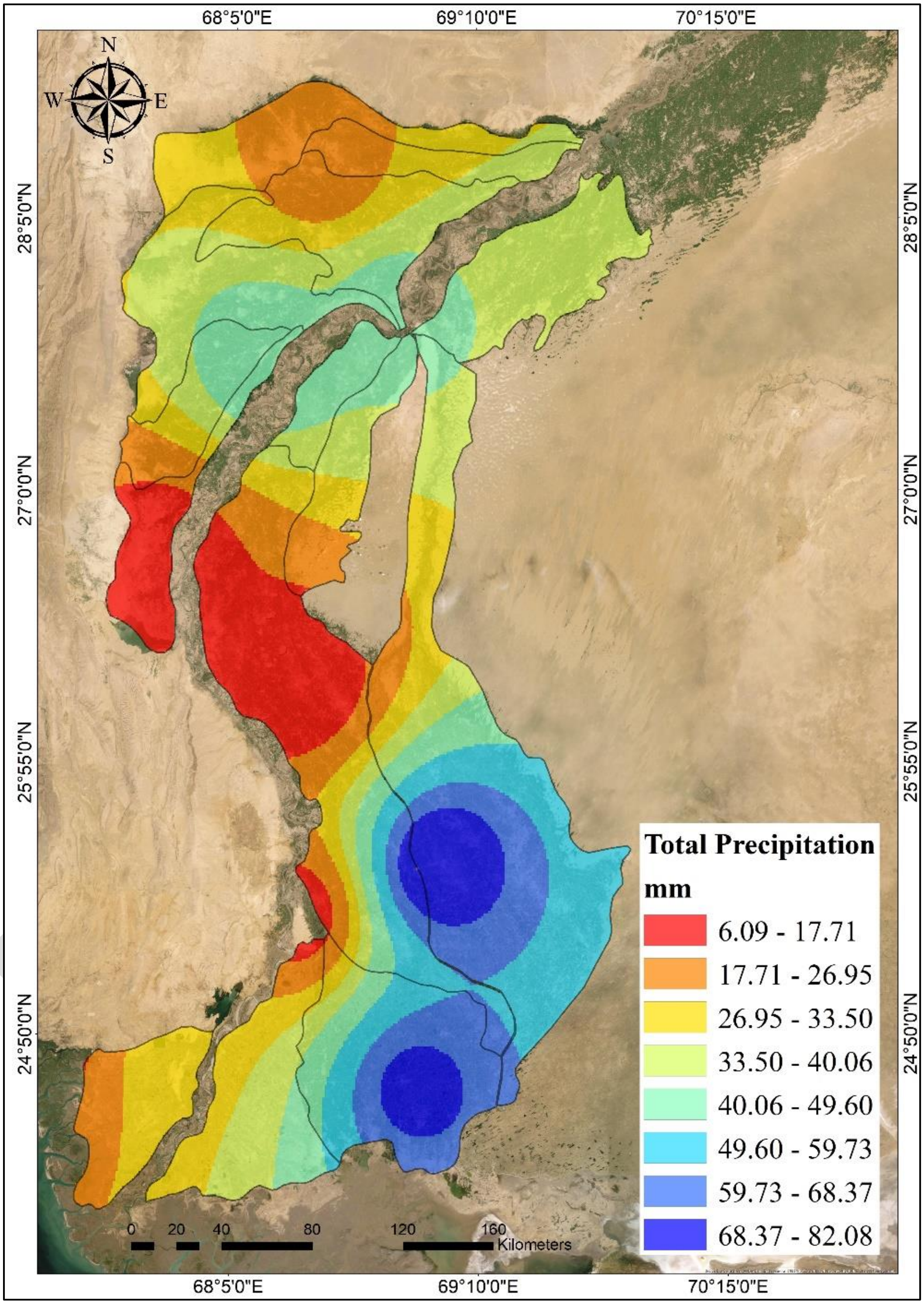


Figure A-2: Total Precipitation in Sindh CCA (2018)

Agro-Ecological Zones of Sindh

Sindh province has been categorized into following agro-ecological zones, two of which are divided into sub-zones, as presented in Table 2.1.

Table A-1: Agro-Ecological Zones of Sindh

Zone-A - Sub-zone A1 - Sub-zone A2	Rice/Wheat zone of the Right Bank of River Indus (upper Sindh). Main area Piedmont soil region
Zone-B - Sub-zone B1 - Sub-zone B2	Cotton/Wheat zone of the left bank of River Indus. Guddu Barrage command area Sukkur Barrage command area
Zone-C	Rice/Wheat/Sugarcane zone of lower Sindh.
Zone-D	Desert area in the east of Sindh
Zone- E	Western hilly zone

Source: Azad, Rasheed, & Memon, 2003.

ANNEXURE B

DOMESTIC WATER DEMAND

Table B-1: Division Wise Current and Future Water Demand in Sindh

Administrative Units	1998-2017 Average Annual Growth Rate	Population				Annual Demand (MAF)			
		2017 (Census)	2025 (Projected)	2030 (Projected)	2050 (Projected)	2017	2025	2030	2050
Division									
LARKANA	2.05	6,192,380	7,295,951	8,083,456	12,180,295	0.13	0.15	0.17	0.26
SUKKUR	2.52	5,538,555	6,775,639	7,685,486	12,722,011	0.12	0.14	0.16	0.26
HYDERABAD	2.33	10,592,635	12763,110	14,340,088	22,852,464	0.23	0.28	0.31	0.51
KARACHI	2.60	16,051,521	19,762,844	22,506,488	37,856,535	0.54	0.67	0.76	1.28
MIRPUR KHAS	2.62	4,228,683	5,214,747	5,944,644	10,039,131	0.07	0.09	0.10	0.17
SHAHEED BENAZIRABAD	2.17	5,282,277	6,283,689	7,003,831	10,809,845	0.10	0.12	0.14	0.21
Total		**47886,051**	**58,095,979**	**65,563,992**	**106,460,281**	**1.19**	**1.45**	**1.64**	**2.70**

ANNEXURE C

INDUSTRIAL WATER ESTIMATES

Table C-1: Industrial Network of Sindh

Industrial Network	Cities	No. Industrial Units
SITE Limited	SITE Karachi	2600
	SITE Superhighway Phase I	368
	SITE Superhighway Phase II	50
	SITE Nooriabad	68
	SITE Kotri	145
	SITE Hyderabad	439
	SITE Tando-Adam	44
	SITE Nawabshah	1
	SITE Sukkur	76
	SITE Larkana	nil
Bin Qasim Industrial Park	Karachi	20
LATI (Landhi Association of trade and Industry)	Karachi	46
Industrial Estate Thatta	Thatta	30
Export Processing Zone (EPZ)	Karachi	
Port Qasim Industrial Area	Karachi	
Source: Kalhoro, 2017		

Table C-2: Industry Water Recharge and Discharge

Industry	Water Recharge MGD	Water Discharge MGD	Water Requirement MGD
SITE (Karachi)	3-4	92 of industrial effluent	35 – 40
Landhi Association of Trade and Industry	35		100
SITE Hyderabad		25	1.2
SITE Kotri		1.8 – 2	
SITE Larkana		20	
SITE Sukkur		11	
Bin Qasim	0.04		
Port Qasim	7		
Karachi Port Trust	0.1 from KW&SB* 0.2 through private contractor		2.5
Source: Kalhoro, 2017 *Karachi Water and Sewerage Board.			

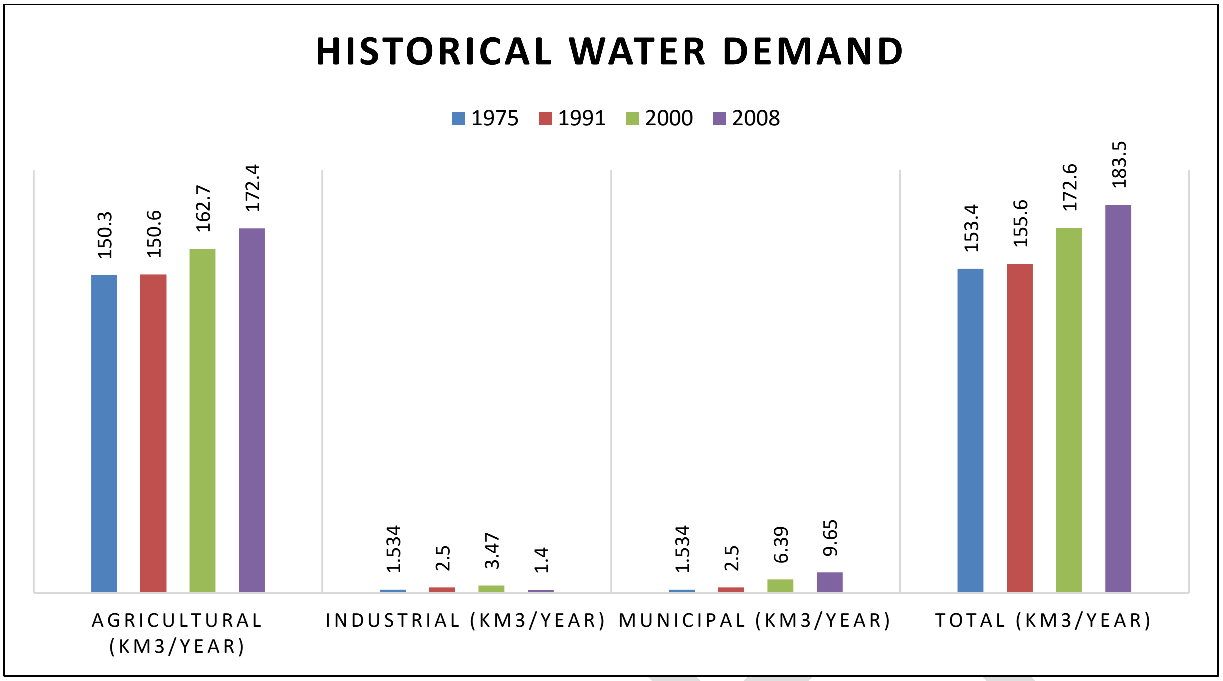


Figure C-1: Historical Water Demand of Pakistan (Parry, Osman, Terton, Asad, & Ahmed, 2015)

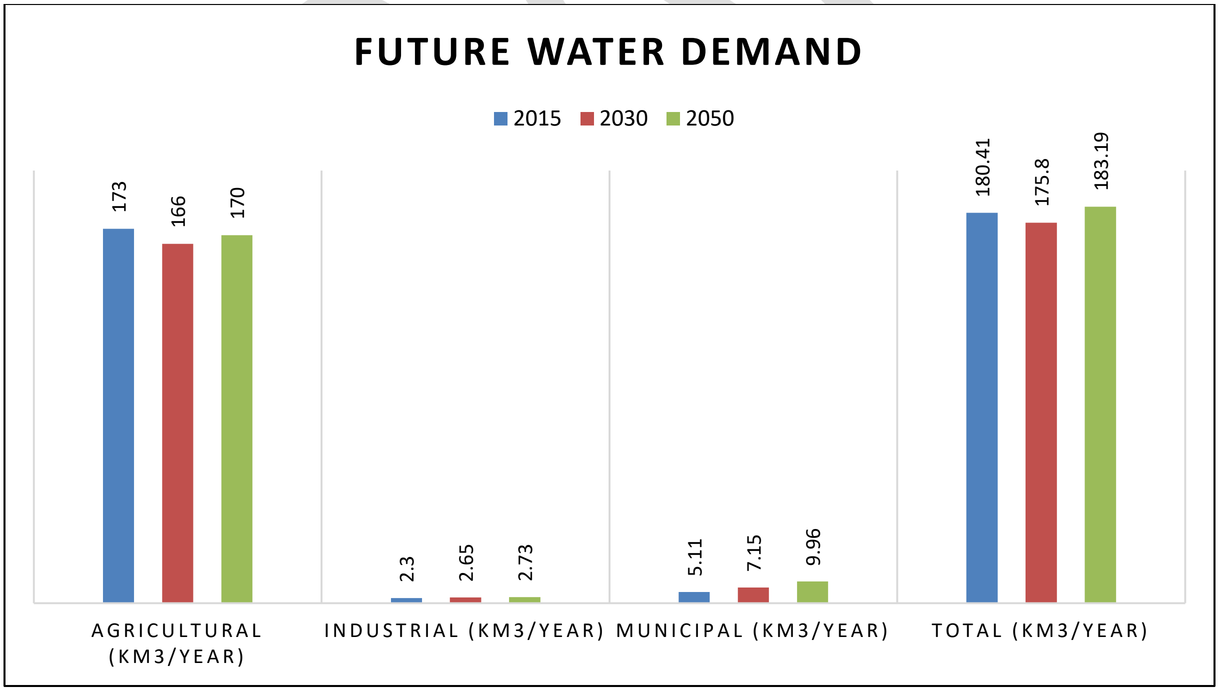


Figure C-2: Future Water Demands of Pakistan (Parry, Osman, Terton, Asad, & Ahmed, 2015)

ANNEXURE D

AVERAGE ACTUAL EVAPOTRANSPIRATION IN CANAL COMMAND AREAS

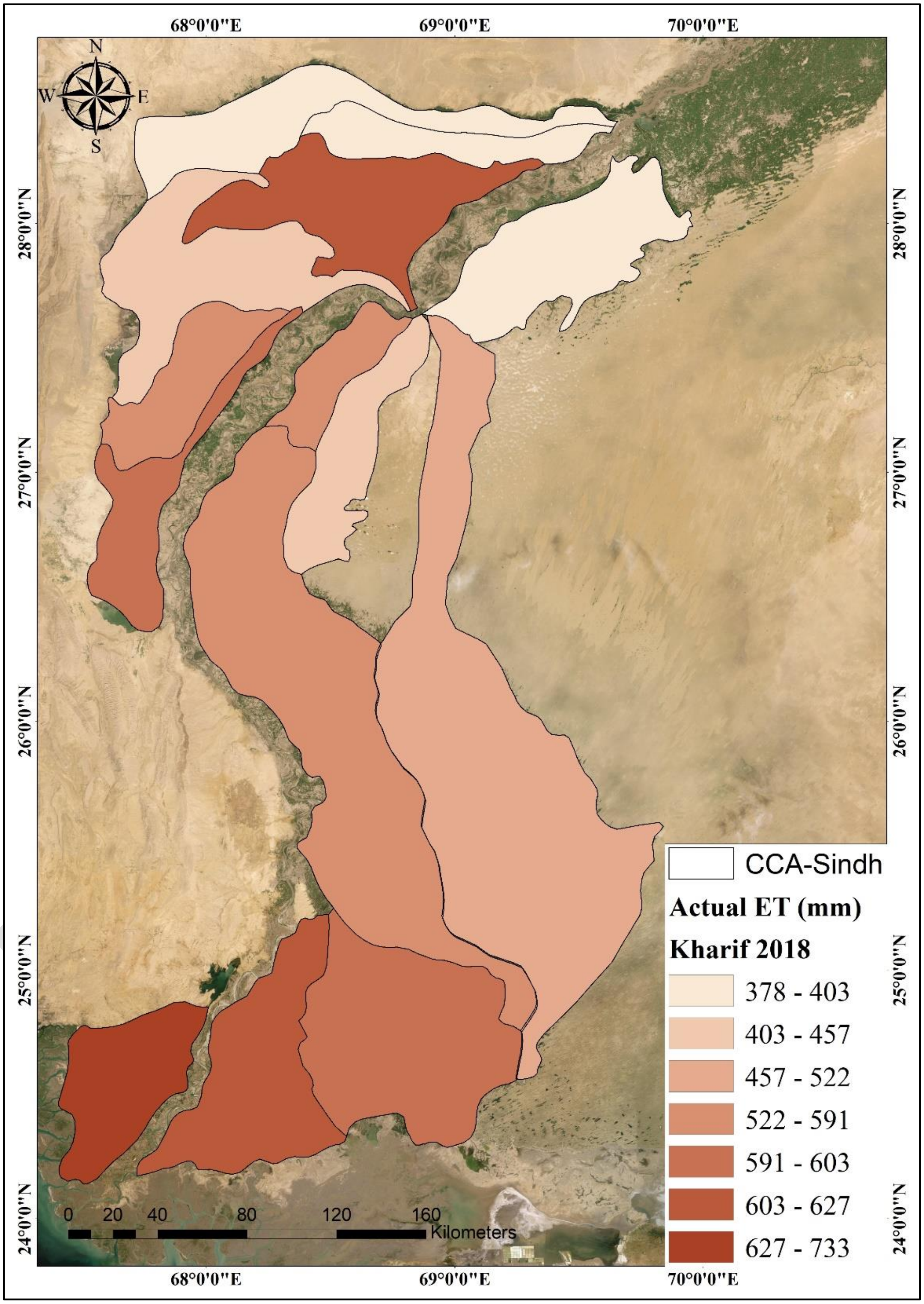


Figure D-1: Average Actual ET in Sindh CCA during *Kharif* 2018

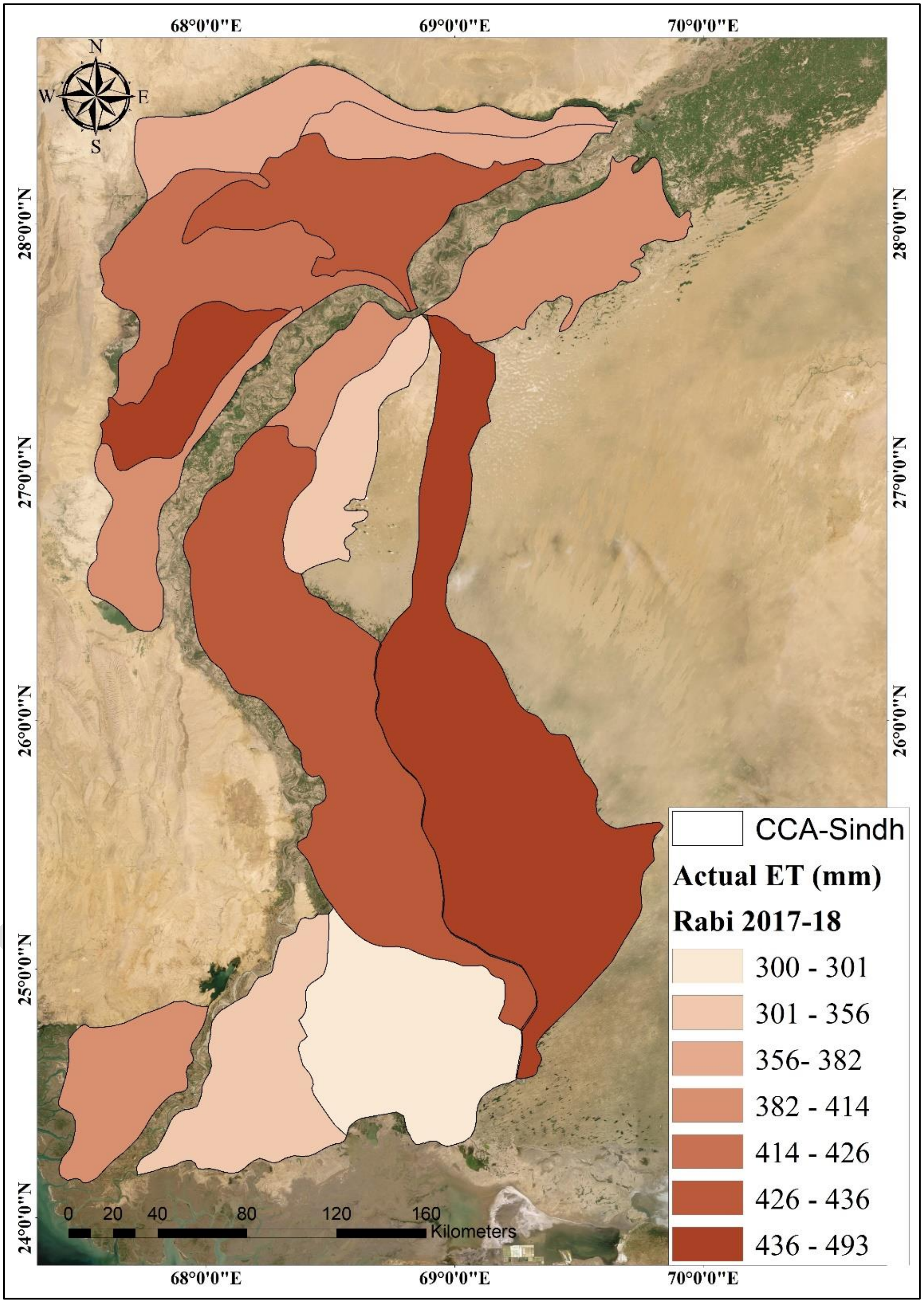


Figure D-2: Average Actual ET in Sindh CCA during *Rabi* 2017-2018

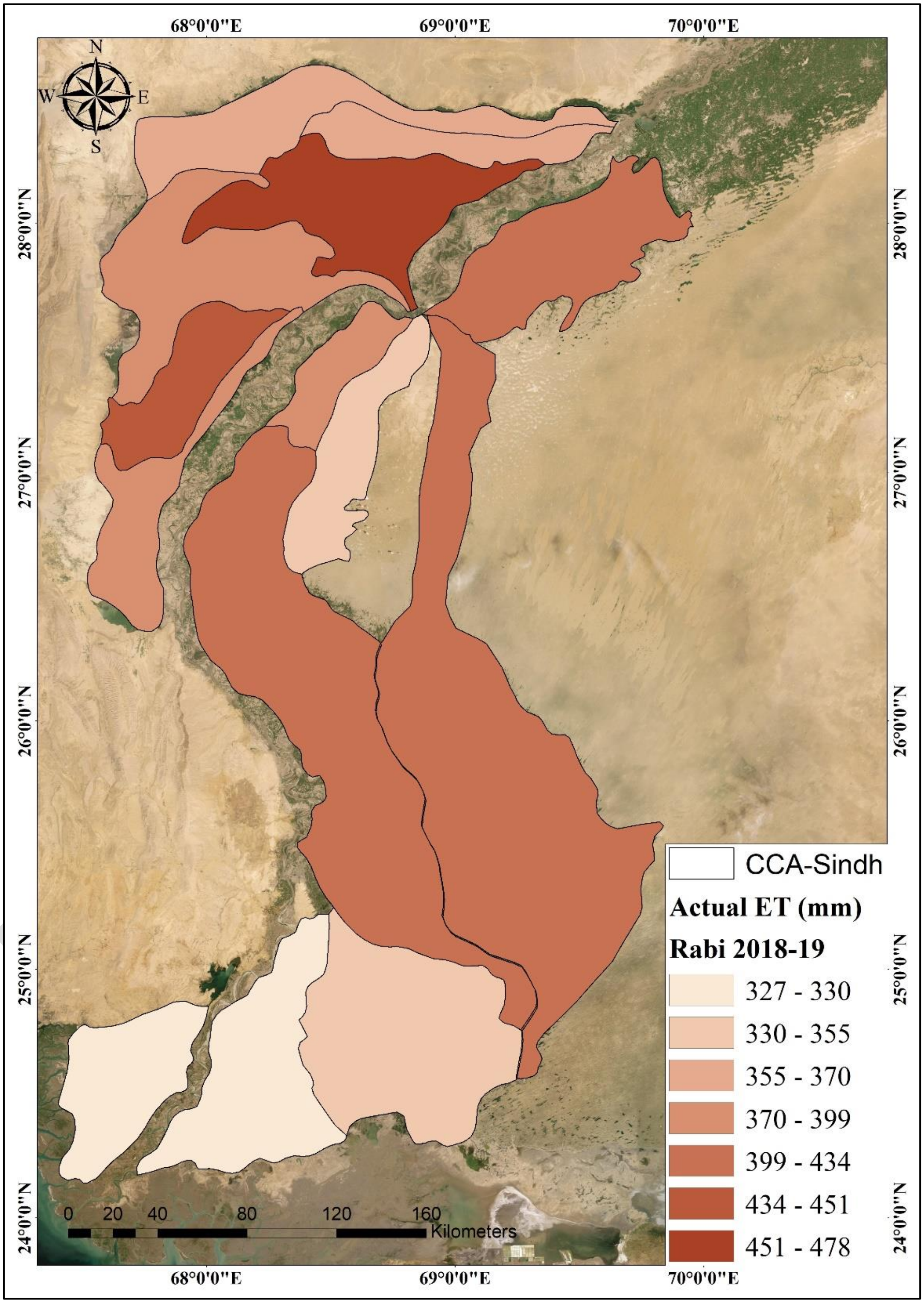


Figure D-3: Average Actual ET in Sindh CCA during *Rabi* 2018-2019

ANNEXURE E

CROP SPECIFIC WATER ESTIMATES

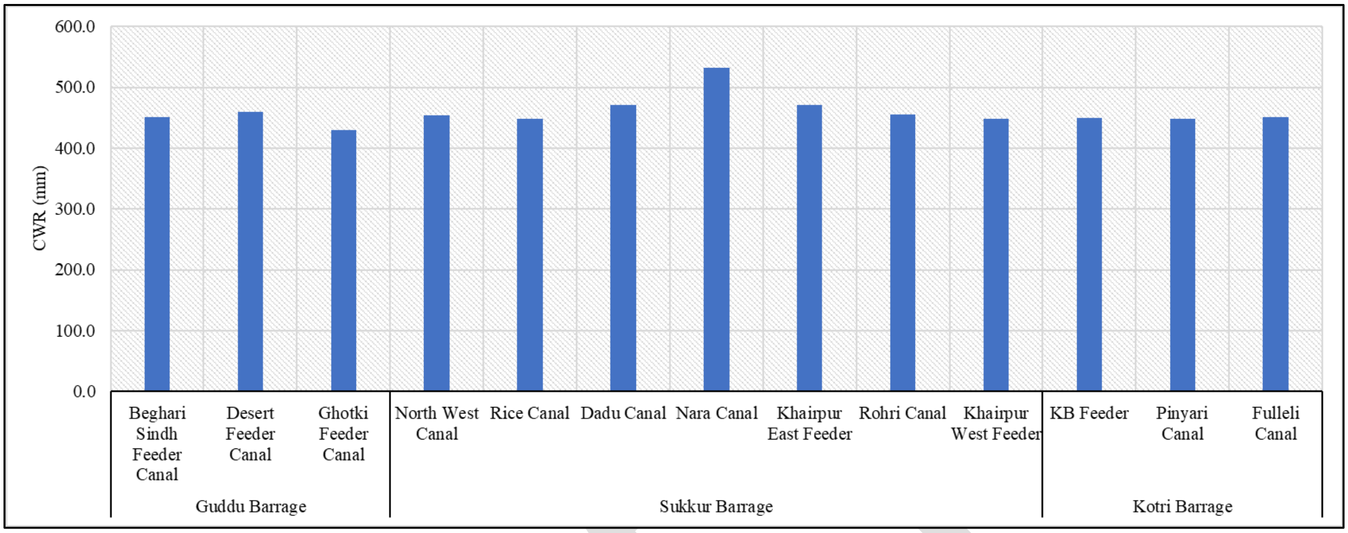


Figure E-1: Crop Water Requirement of Wheat in Sindh

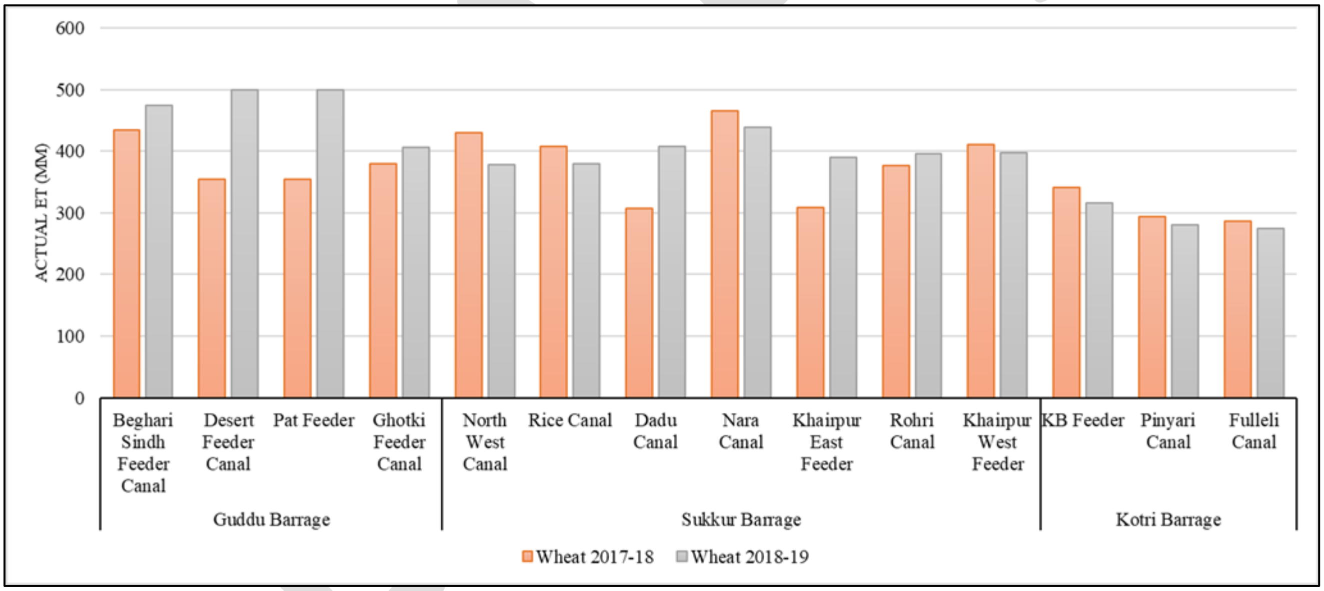


Figure E-2: Average Actual ET of Wheat in Sindh Canals during *Rabi* 2017-2018 and 2018-2019

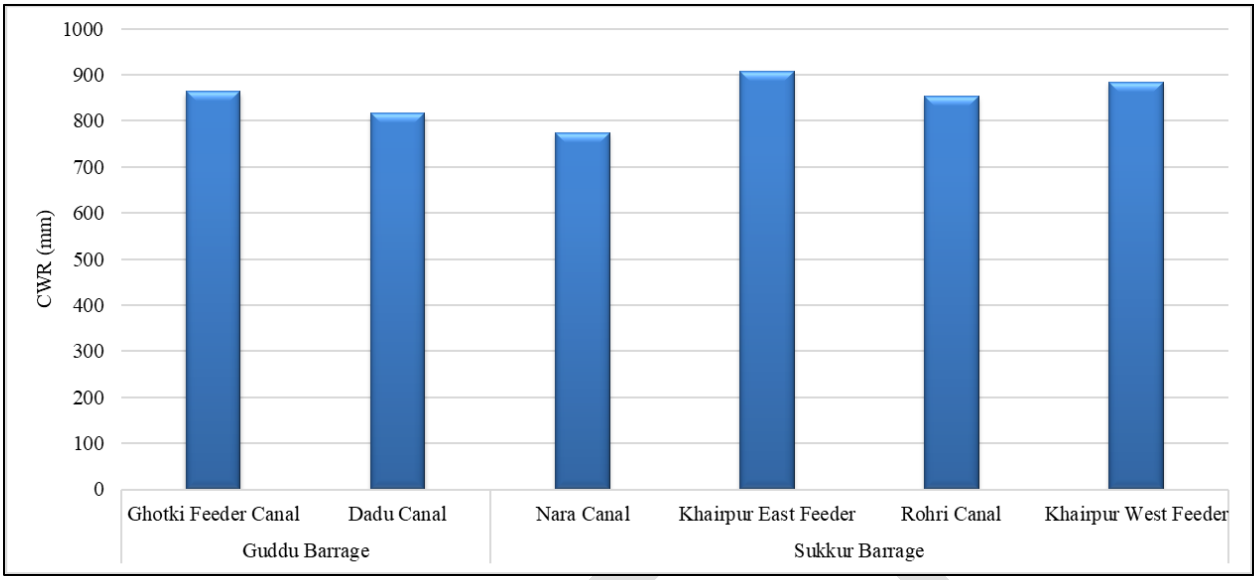


Figure E-3: Crop Water Requirement of Cotton in Sindh during *Kharif* 2018

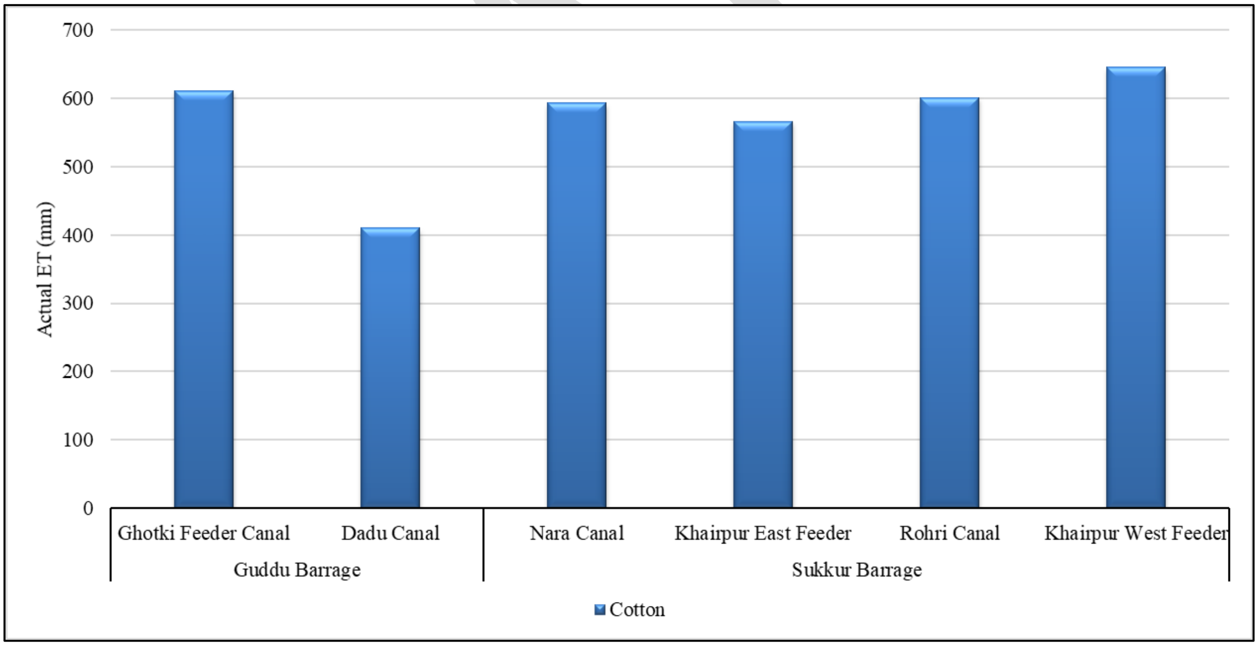


Figure E-4: Average Actual ET of Cotton in Sindh during *Kharif* 2018

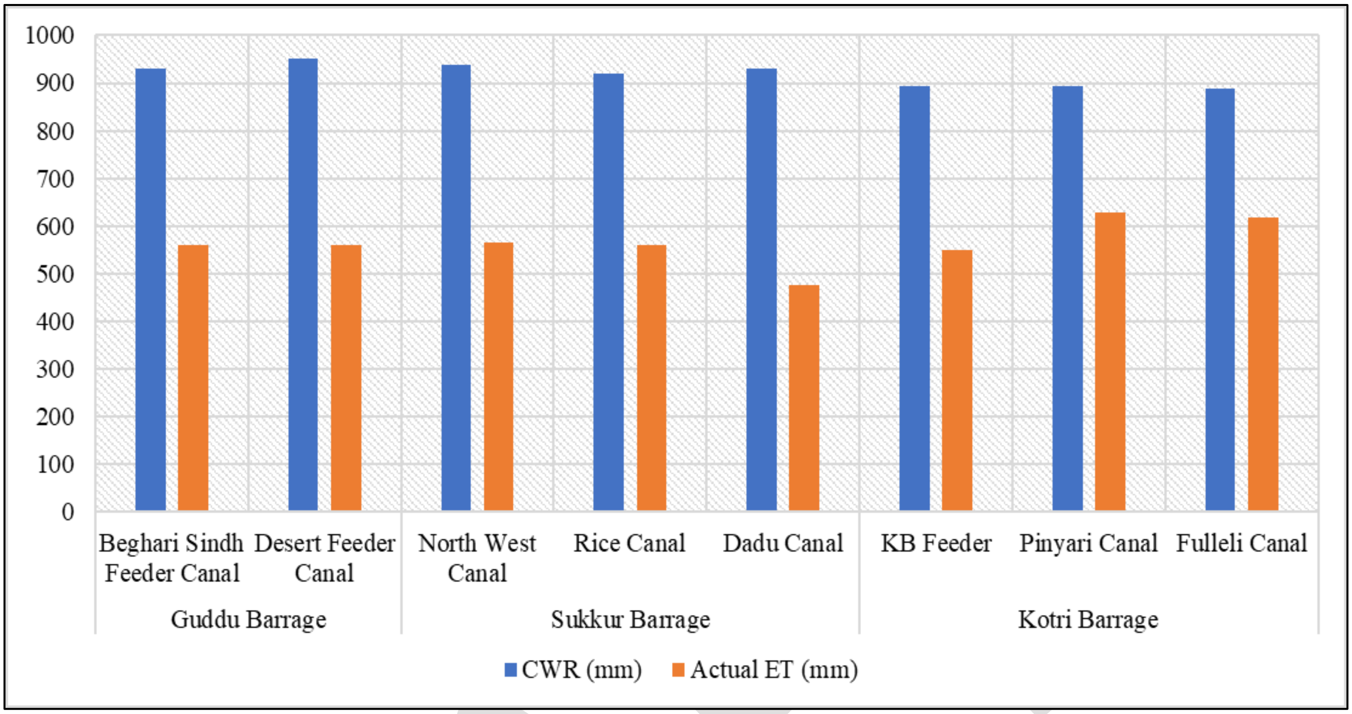


Figure E-5: Average Actual ET and CWR of Rice in Sindh CCA during Kharif 2018

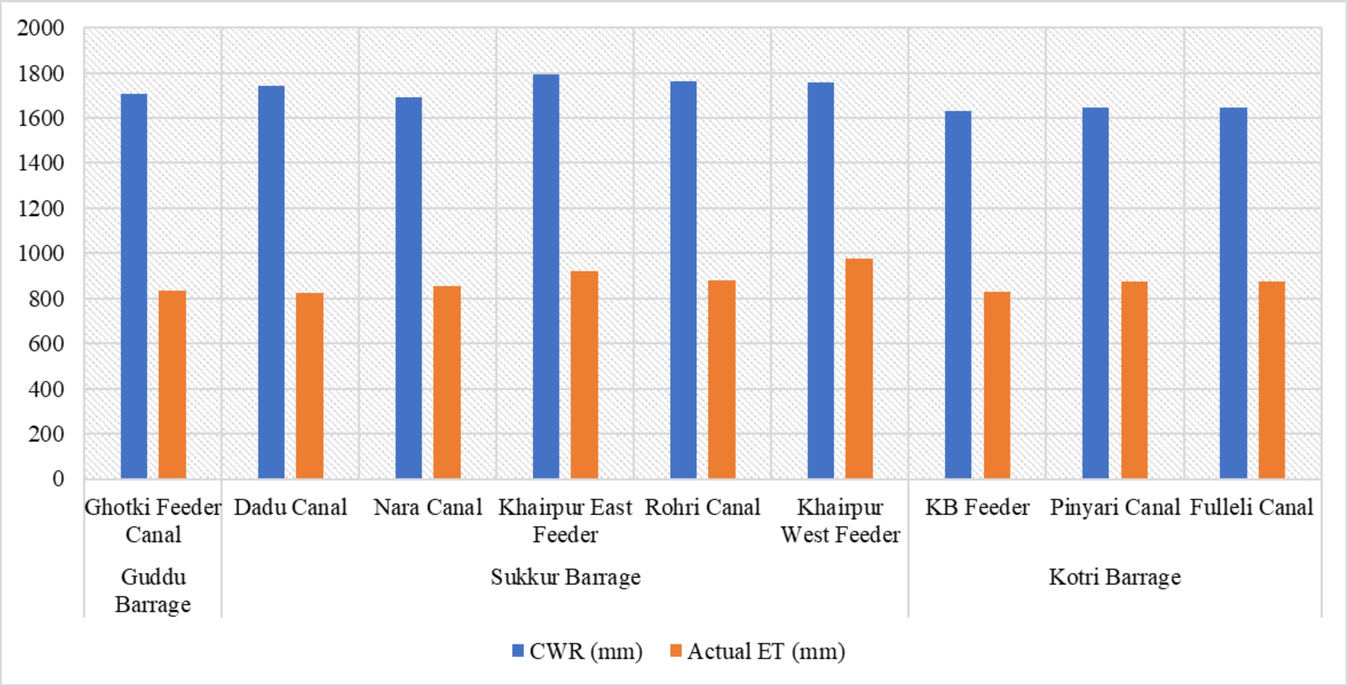


Figure E-6: Average Actual ET and CWR of Sugarcane in Sindh CCA during Kharif 2018

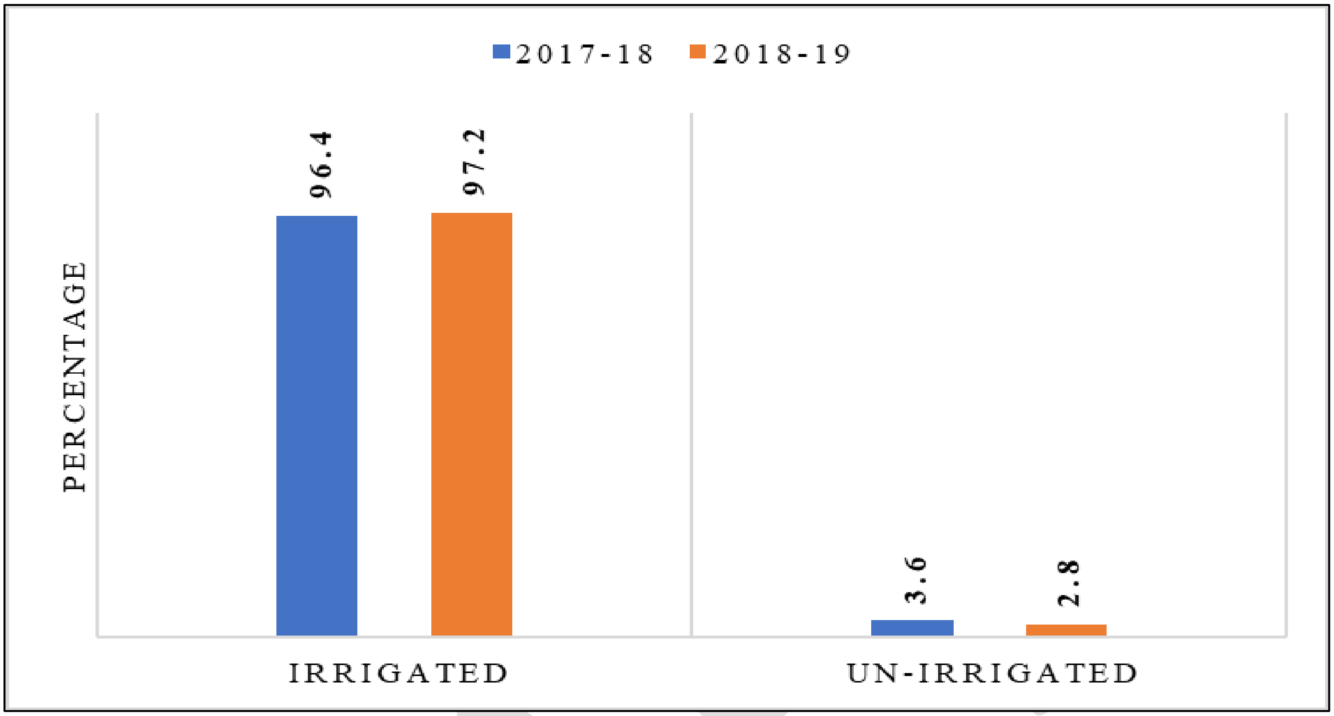


Figure E-7: Wheat Crop Percent Irrigated and Un-irrigated Areas in Sindh from 2017 to 2019

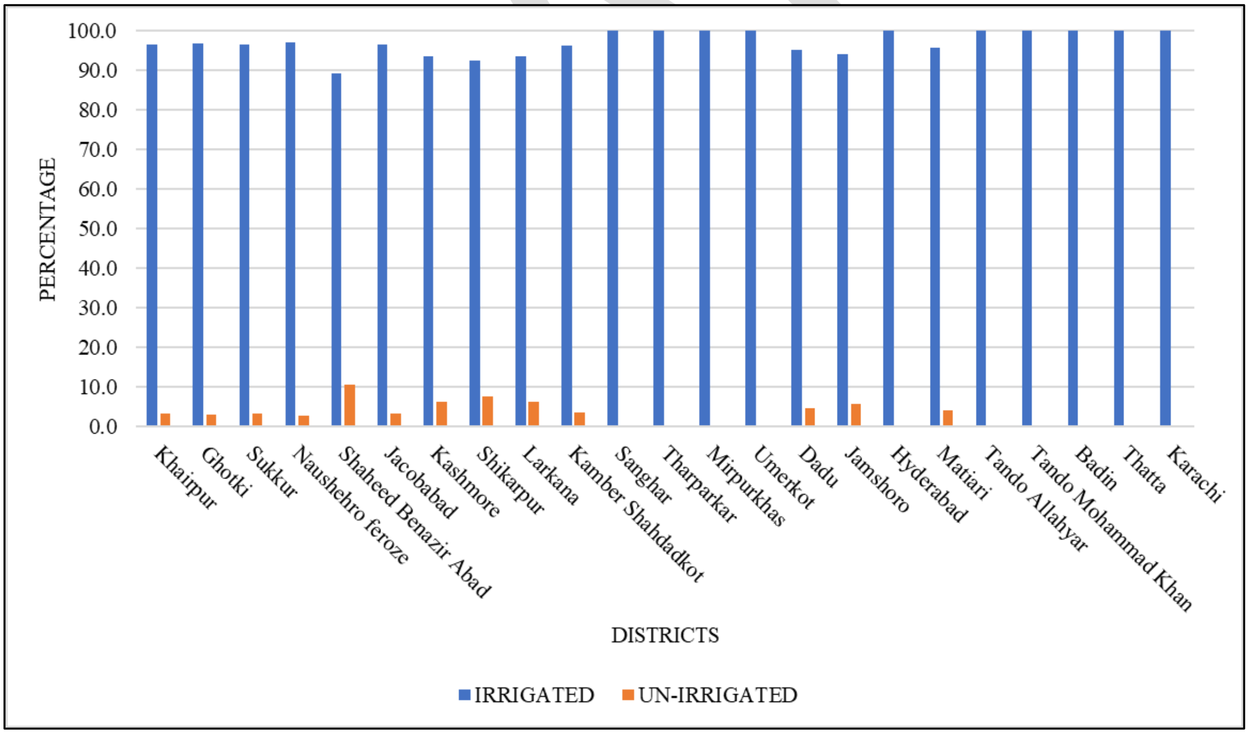


Figure E-8: Wheat Crop in Sindh Districts in *Rabi* 2017-18

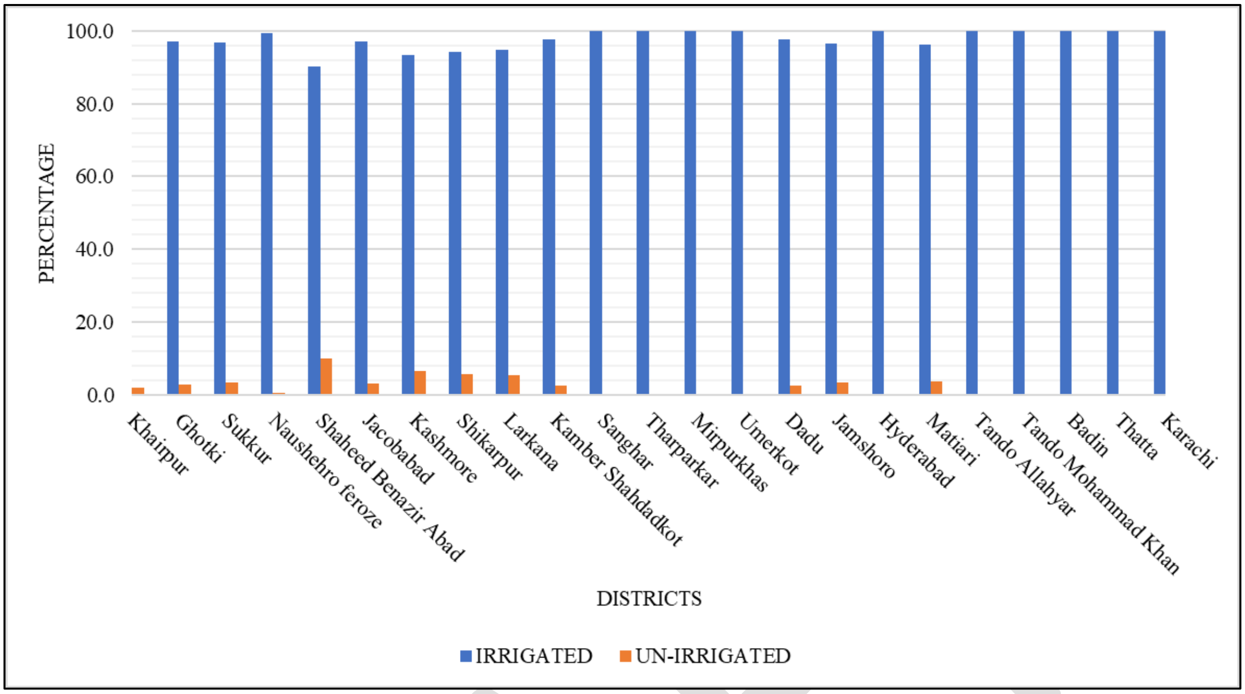


Figure E-9: Wheat Crop in Sindh Districts in *Rabi* 2018-19

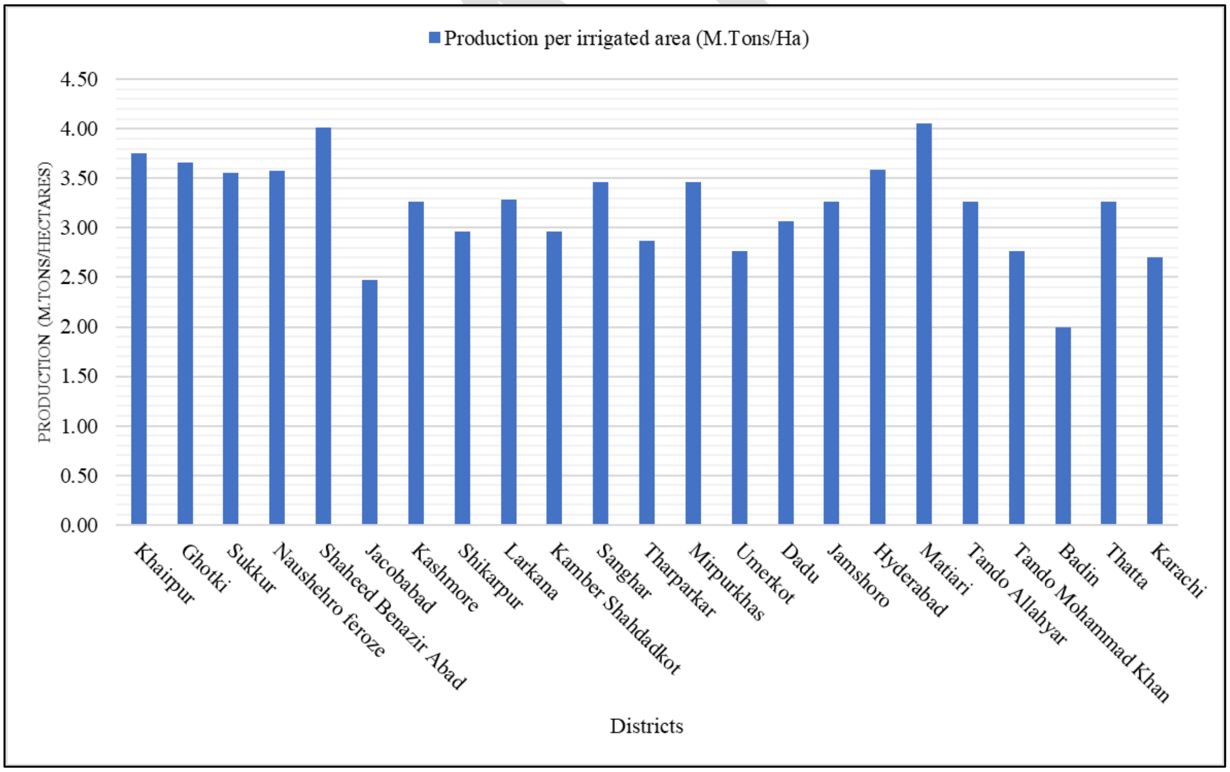


Figure E-10: Wheat Production per Irrigated Area in Sindh in *Rabi* 2017-18

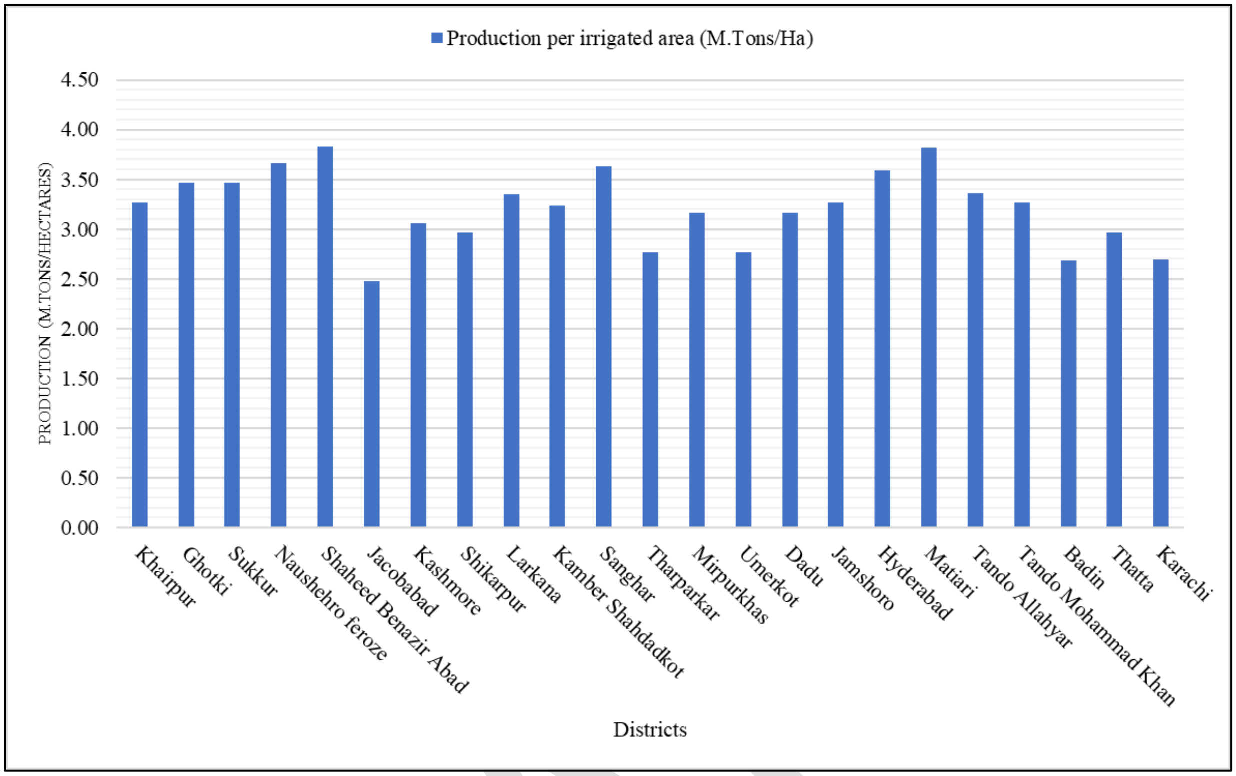


Figure E-11: Wheat Production per Irrigated Area in Sindh in *Rabi* 2018-19

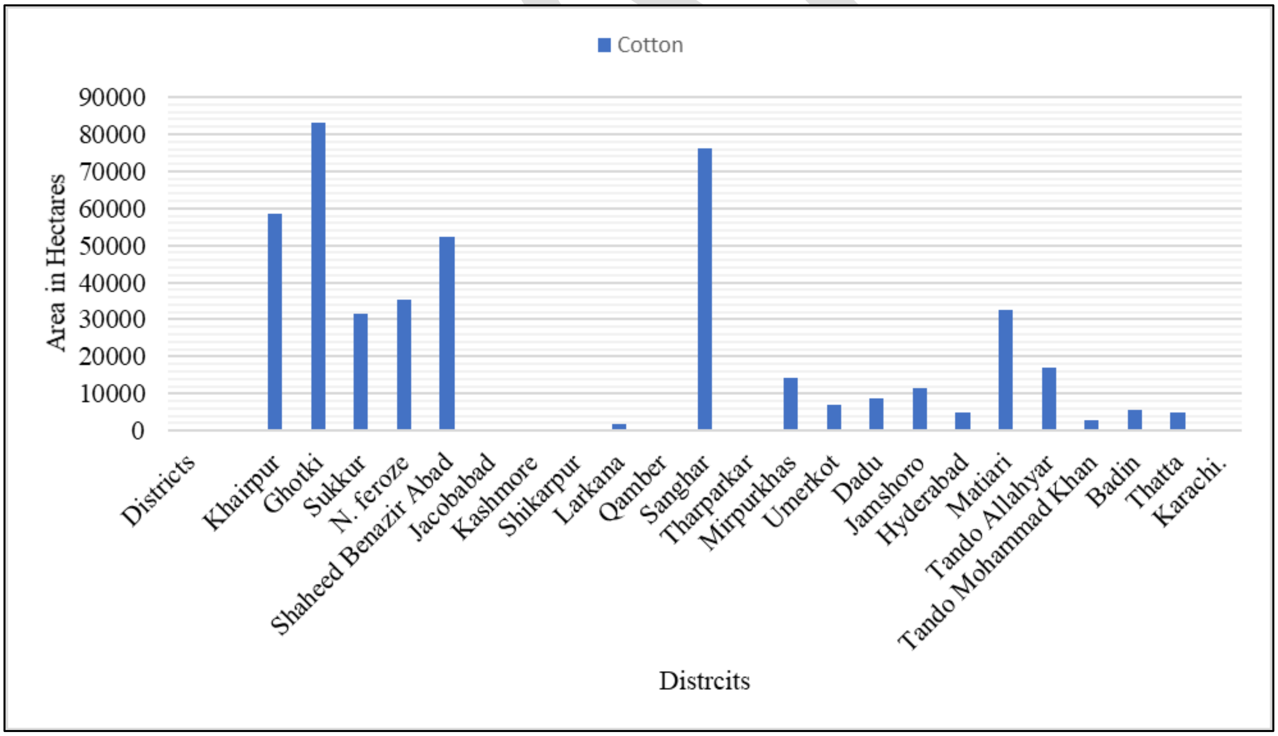


Figure E-12: Cotton Crop in Sindh Districts in *Kharif* 2018

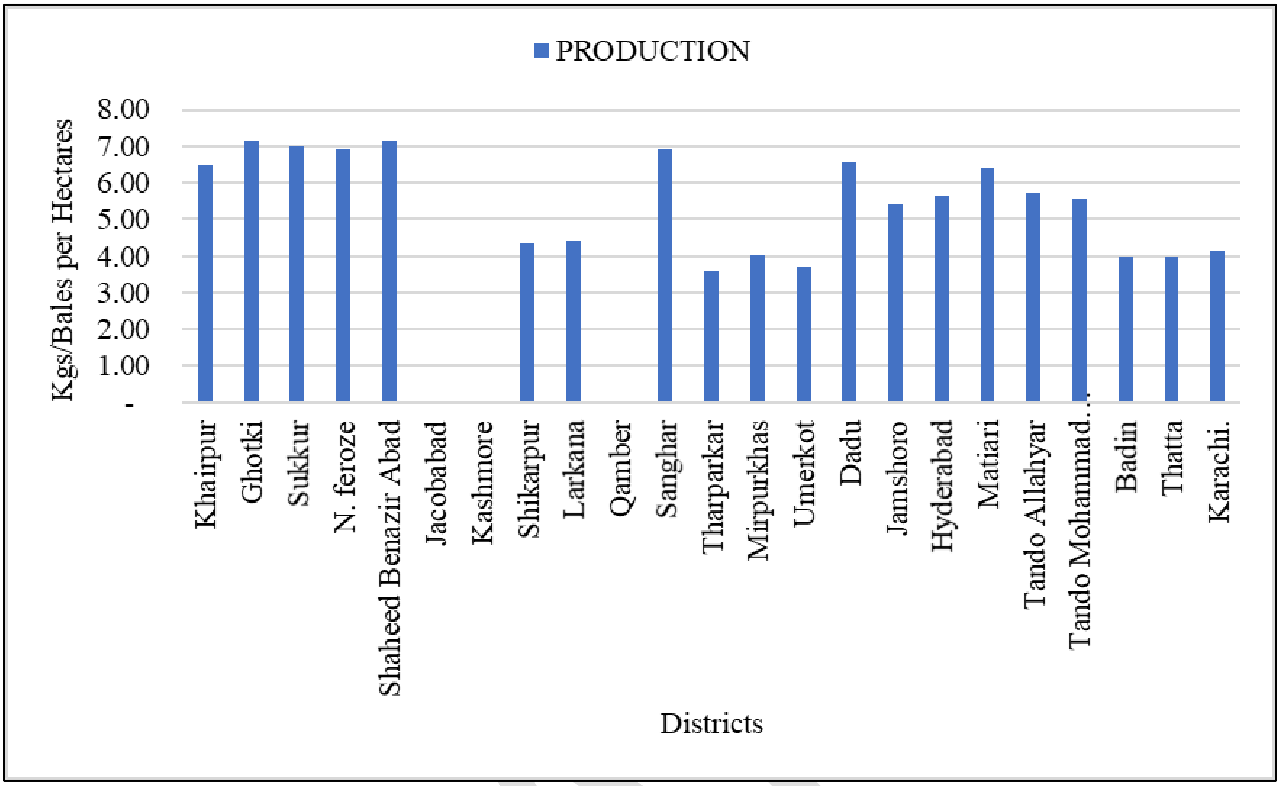


Figure E-13: Cotton Crop Production per hectares in Sindh Districts in *Kharif* 2018

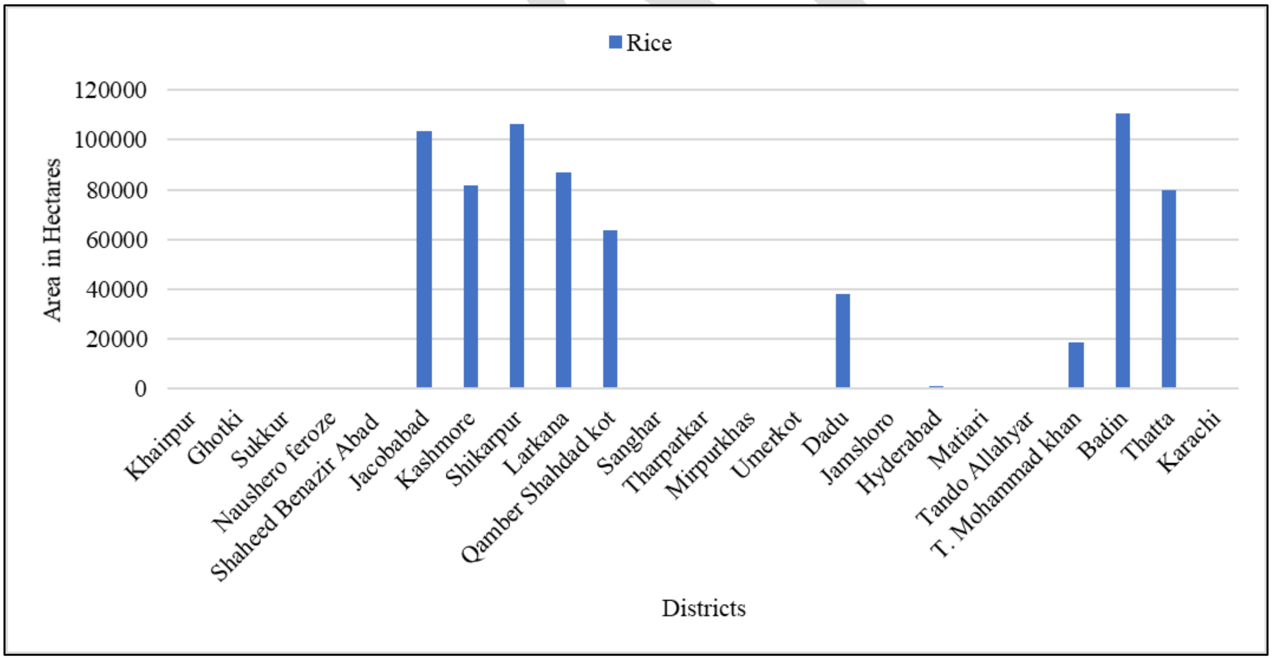


Figure E-14: Rice Crop in Sindh Districts in *Kharif* 2018

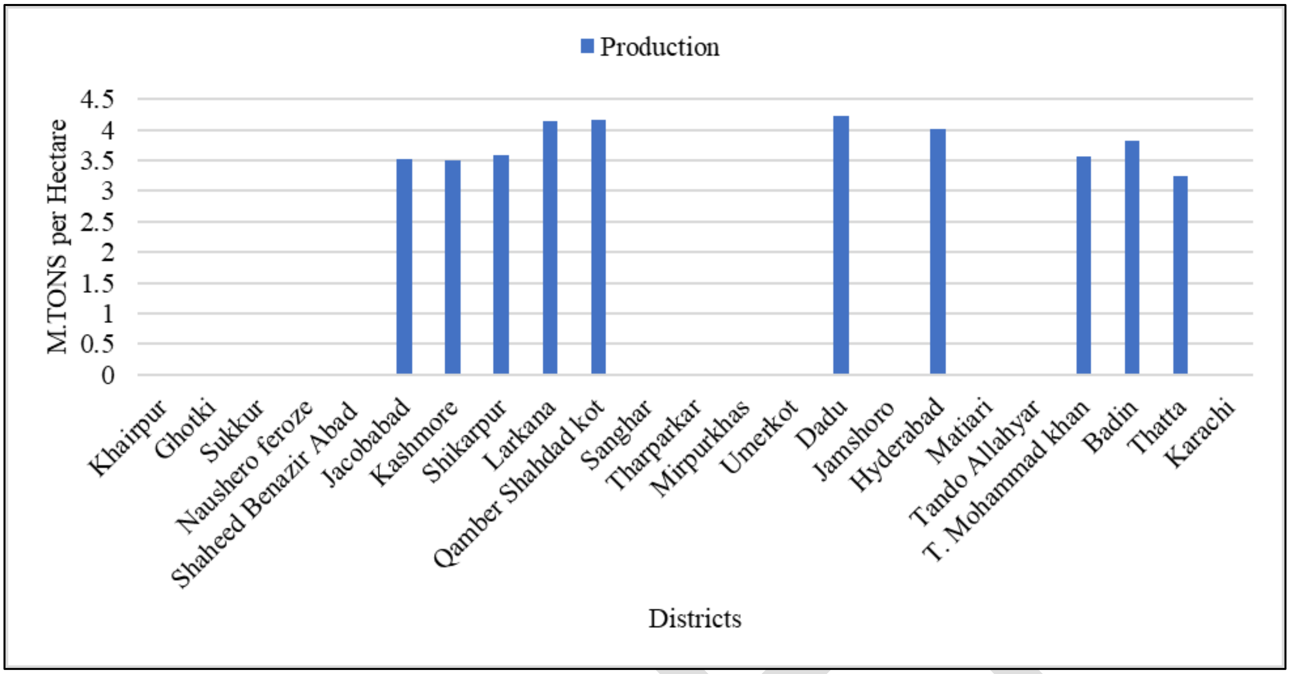


Figure E-15: Production per hectare of Rice in Sindh Districts in *Kharif* 2018

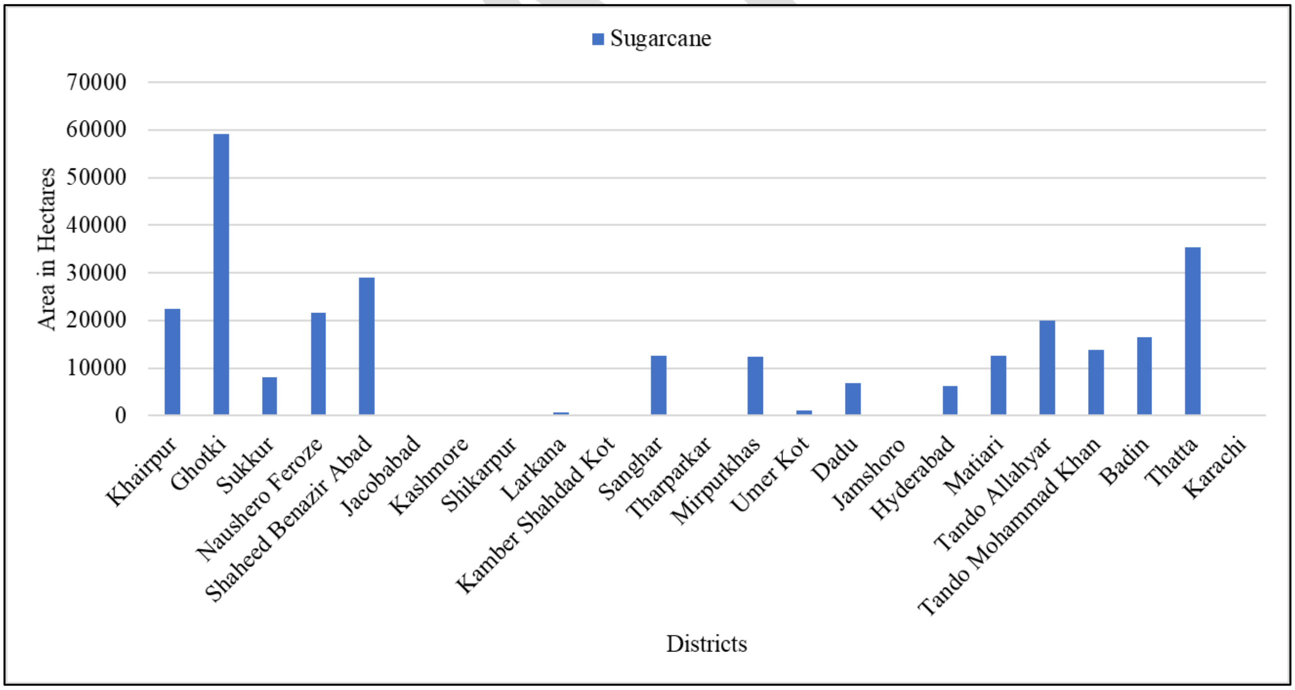


Figure E-16: Sugarcane in Sindh Districts in *Kharif* 2018

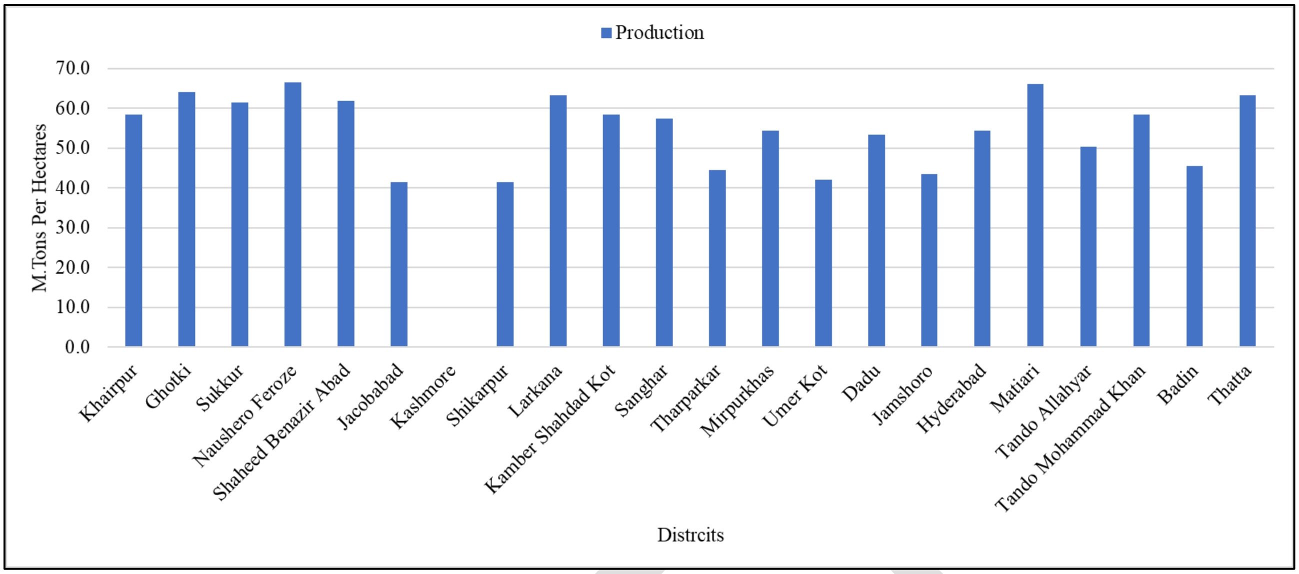
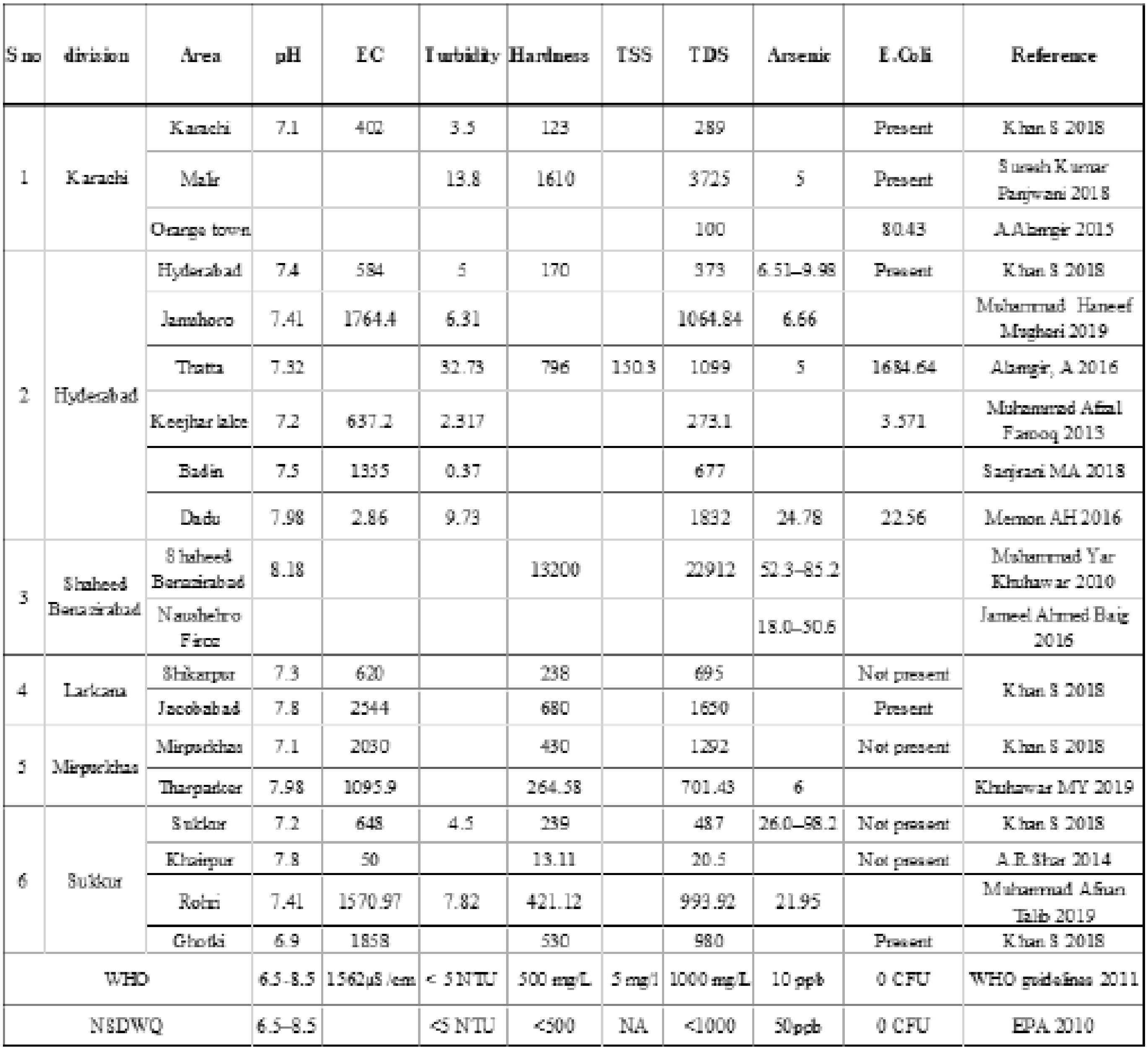


Figure E-17: Production per hectare of Sugarcane in Sindh Districts in *Kharif* 2018

ANNEXURE F

WATER QUALITY

Table F-1: Water Quality in Different Districts of Sindh (Bhutto et al. 2019)



S no	division	Area	pH	EC	Turbidity	Hardness	TSS	TDS	Arsenic	E.Coli	Reference
1	Karachi	Karachi	7.1	402	3.5	123		289		Present	Khan S 2018
		Malir			13.8	1610		3725	5	Present	Suresh Kumar Panjwani 2018
		Orange town						100		80.43	A.Alamgir 2015
2	Hyderabad	Hyderabad	7.4	584	5	170		373	6.51–9.98	Present	Khan S 2018
		Jamshoro	7.41	1764.4	6.31			1064.84	6.66		Muhammad Haneef Mughari 2019
		Thatta	7.32		32.73	796	150.3	1099	5	1684.64	Alamgir, A 2016
		Keejhar lake	7.2	637.2	2.317			273.1		3.571	Muhammad Afzal Farooq 2013
		Badin	7.5	1355	0.37			677			Sanjrani MA 2018
		Dadu	7.98	2.86	9.73			1832	24.78	22.56	Memon AH 2016
3	Shaheed Benazirabad	Shaheed Benazirabad	8.18			13200		22912	52.3–85.2		Muhammad Yar Khuhawar 2010
		Naushehro Feroz							18.0–50.6		Jameel Ahmed Baig 2016
4	Larkana	Shikarpur	7.3	620		238		695		Not present	Khan S 2018
		Jacobabad	7.8	2544		680		1650		Present	
5	Mirpurkhas	Mirpurkhas	7.1	2030		430		1292		Not present	Khan S 2018
		Tharparkar	7.98	1095.9		264.58		701.43	6		Khuhawar MY 2019
6	Sukkur	Sukkur	7.2	648	4.5	239		48.7	26.0–98.2	Not present	Khan S 2018
		Khairpur	7.8	50		13.11		20.5		Not present	A.R.Shar 2014
		Rohri	7.41	1570.97	7.82	421.12		993.92	21.95		Muhammad Afnan Talib 2019
		Ghotki	6.9	1858		530		980		Present	Khan S 2018
WHO			6.5-8.5	1562µS /cm	< 5 NTU	500 mg/L	5 mg/l	1000 mg/L	10 ppb	0 CFU	WHO guidelines 2011
NSDWQ			6.5–8.5		<5 NTU	<500	NA	<1000	50ppb	0 CFU	EPA 2010