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PAKISTAN AND THE BELT & ROAD INITIATIVE

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Sustainability of Water Resources along CPEC: Assessing Current Supply and Projecting Future Demand

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Abstract

The Indus Basin Irrigation System (IBIS), encompassing the primary water storage reservoirs of Tarbela on the Indus and Mangla on the Jhelum, along with numerous barrages, headworks, and canal networks, stands as the world's largest integrated irrigation system. A substantial portion of water for these reservoirs is derived from the melting of snow and glaciers in the Himalaya-Karakoram-Hindukush (HKH) mountain ranges. At the same time, the remainder is contributed by monsoon precipitation and groundwater sources. The freshwater resources supporting these reservoirs, crucial for food security, domestic and industrial use, and power generation along the China-Pakistan Economic Corridor (CPEC), are susceptible to the impacts of climatic variability, socio-economic factors, and transboundary issues. Anticipated population growth in the country will likely elevate future water demand for irrigation and urban purposes. Although climate change scenarios indicate an increase in streamflow from all tributaries and rivers of the Upper Indus Basin (UIB), the existing storage capacity is insufficient to accommodate the projected increase in discharge water (inflow). The future poses challenges such as environmental degradation of river basins and the rapid reduction of storage capacities due to sedimentation and mismanagement of available resources. Addressing these challenges is critical, as there is also a need to augment the average volume of river flow and manage variability and seasonal changes. Failure to do so may lead to downstream flooding during high inflow periods in summer and water shortages for winter and summer crops, including wheat, gram, rapeseed, barley, and mustard. Considering these factors, it is imperative and timely to conduct an in-depth study evaluating the necessity for the construction of 2 to 3 large reservoirs or proposed dams upstream or downstream within the Indus River system.

Introduction

Pakistan is an agriculture-based country, with a significant portion of its economy reliant on available water resources in the Himalaya, Karakorum, and Hindukush (HKH) region—a hub for ten (10) major river systems of Asia. This region provides water for approximately 1.9 billion people downstream for various daily needs, including agriculture, power generation, and drinking (Molden et al., 2022).

The agricultural sector not only meets the demands of the country's growing population but also serves as a source of raw materials for industries. Water from the high-altitude freshwater resources of the Upper Indus Basin (UIB) in Pakistan is stored in Tarbela Dam, one of the country's largest water reservoirs. This dam plays a crucial role in regulating water supply through the Indus Basin Irrigation System (IBIS) for the fertile agricultural lands of Pakistan (Archer, Forsythe, Fowler, & Shah, 2010; K. Garee, Chen, Bao, Wang, & Meng, 2017b).

IBIS, recognized as the world's largest irrigation system (Archer et al., 2010), includes Tarbela and Mangla on the Indus and Jhelum rivers, respectively, along with a combination of barrages and canals (Figure 1). Most of this system originates from high-altitude snow/ice and glaciers in the HKH region. Another significant water contribution to IBIS comes from summer monsoon rainfall during the monsoon season, from June to September each year.

The dryness index of the Upper Indus River Basin varies from arid to semi-arid, with an annual precipitation of 200mm in lower elevations (less than 2500m) (Archer et al., 2010). According to Archer and Fowler (2004), the annual maximum precipitation occurs during the summer monsoon season, reaching up to 1800mm on the southern slopes of the Himalayan region.

Significant agricultural lands are in Pakistan's Punjab and Sindh provinces (K. Garee et al., 2017b; Tahir, Chevallier, Arnaud, Neppel, & Ahmad, 2011a). During the winter season, the agricultural lands in these two provinces relied on water distributed from the Tarbela and Mangla reservoirs via IBIS (Figure 1). These reservoirs also store water from summer snow and glacier melting and collect monsoon rainfall, playing a crucial role in mitigating downstream flood impacts. Pakistan's total cultivable land, approximately 23 million hectares, sees irrigation on 18 million hectares (78%) through IBIS (FAO, 2021-22). IBIS utilizes 60% of the available stored water for irrigation, as indicated by Peña-Arancibia, Yu, Stewart, Podger, and Kirby (2021), while the remaining land is irrigated through groundwater replenished by river and canal systems (A. S. Qureshi, 2020).

Any minor alterations in the existing water resources of the Upper Indus Basin (UIB) due to socio-economic factors, international regulations, or variations in climate change could significantly affect Pakistan's food security and environmental conditions. The country's water resources are currently strained in terms of per-capita water availability and withdrawals compared to runoff, as highlighted by (A. S. Qureshi, 2020). The situation is expected to worsen in the future with the projected population changes outlined by (Abel, Barakat, Kc, & Lutz, 2016).

Numerous studies, such as those conducted by (Archer et al., 2010; K. Garee et al., 2017b; Tahir, Chevallier, Arnaud, Neppel, & Ahmad, 2011b), have highlighted a significant concern: the diminishing storage capacity of water in reservoirs, particularly in Tarbela, due to substantial sedimentation. Unfortunately, no mechanisms were implemented during construction to address sedimentation removal from the reservoir. The potential consequences of reduced reservoir storage include heightened waterlogging and salinity, an increase in groundwater levels, and the necessity for reallocations to address environmental concerns in the Indus Delta or fulfill domestic demands—all of which contribute to a decrease in overall water availability for irrigation.

In the future, the demand for water in urban and agricultural sectors is anticipated to rise, reducing the likelihood of increased available water supplies from the Indus River system and its tributaries. This challenge is further compounded by potential mismanagement of water resources, degradation of river basins, encroachments, inefficient water utilization, and the adverse impacts of climate change, exacerbated by rapid development and industrialization.

The hydrology of numerous major rivers worldwide has undergone significant changes, primarily due to the escalating extraction of ground and surface water for agricultural, industrial, and urban purposes (Laghari, Vanham, & Rauch, 2012). The Indus River basin, comprising multiple river basins, faces a compelling shortage of storage capacity and is strained by the increasing daily water demand (Archer et al., 2010; Laghari et al., 2012). It is one of the most pressured basins globally, and it has been characterized by a nearly complete absence of ecological streams (environmental flows) in recent years (Sharma et al., 2013). Over the past few years, water has reached the sea during the flooding season (2010-2015) due to a lack of storage capacity. However, in the upcoming years, the Arabian Sea may not receive additional water due to the high demand for water usage. Therefore, it is imperative to conduct thorough studies and formulate policies to effectively manage and utilize the water resources of the Upper Indus Basin (UIB) and Indus Basin Irrigation System (IBIS) in response to current water demand scenarios and future climate perspectives, considering socio-economic factors, to ensure the sustainability of water resources and their efficient management.

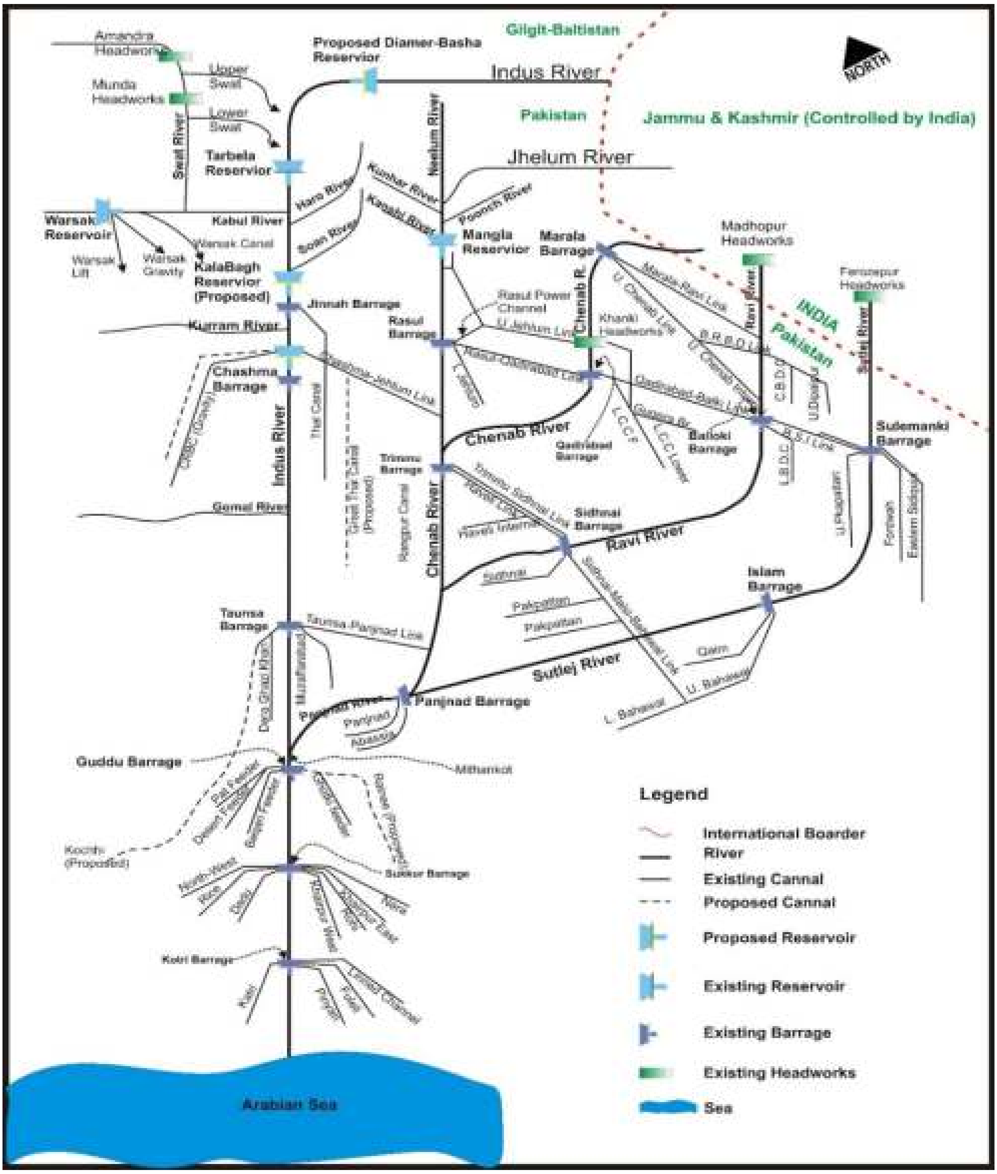

Figure 1. Indus Basin Irrigation System diagram (Source: WAPDA)

Impact of Climate Change

Climate change variability poses a significant challenge to the available water resources, particularly those sourced from snow and glaciers in the Indus River system. The SWAT model has simulated this impact for the Hunza River basin.

Increasing Gap in Water Supply and Demand

A widening disparity between water supply and demand is anticipated, driven by elevated needs for domestic and industrial purposes. Population growth (Figure 2), urbanization, and industrial expansion contribute to higher water demands, affecting food security and energy production (Abel et al., 2016; Archer et al., 2010).

Low Water Storage Capacity

The IBIS faces limited water storage capacity, constituting only 15% of the total annual river flow. This issue arises from sedimentation and unmanaged and inadequate irrigation infrastructures (Dougherty & Hall, 1995; Janjua, Hassan, Muhammad, Ahmed, & Ahmed, 2021).

Degradation of Water Resources and Unsustainable Groundwater Use

Due to groundwater scarcity for agricultural purposes, the shift from surface water to groundwater depletes groundwater resources. It increases salinization, threatening the sustainability of water resources.

Transboundary Water Issues

Challenges related to transboundary water management exist, involving the sharing of water resources between India and Pakistan since 1960 and negotiations with Afghanistan regarding the utilization of the Kabul River (Archer et al., 2010).

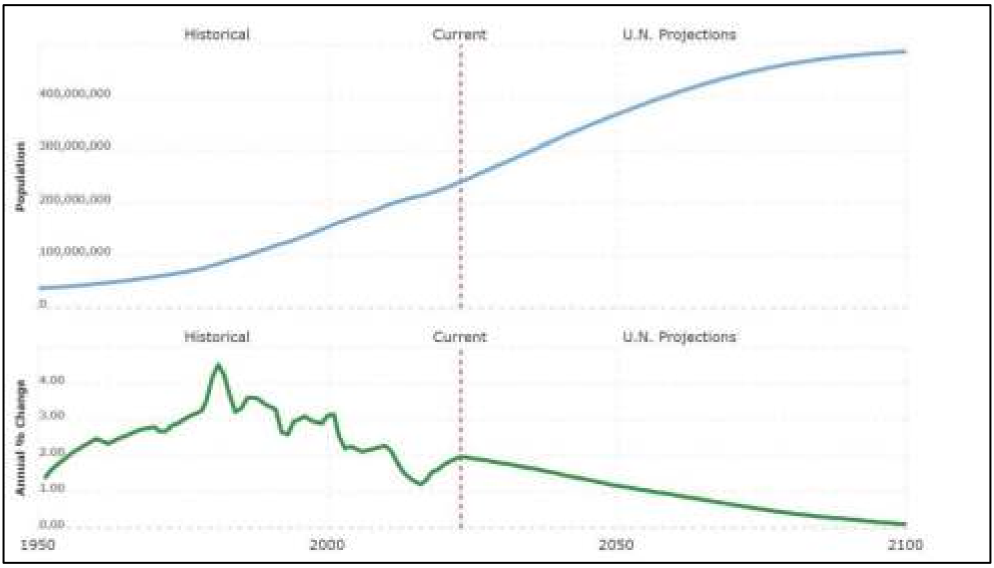

Figure 2. Population Trend with Annual % Change
Source: https://www.macrotrends.net/countries/PAK/pakistan/populatio
Original data source: United Nations - World Population Prospects.

Current Water Status and their Demand for Power Generation and Agriculture

The Pakistani economy relies heavily on agriculture, with 90% of this sector depending on the water supply from the Indus River System. Tarbela Dam, depicted in Figure 1, prioritizes water supply for agriculture, with 95% of its water used to irrigate 60-80% of cultivable land in the downstream areas of Punjab and Sindh. The remaining 5% serves domestic and industrial purposes. Since the construction of Tarbela and Mangla Dams, there has been a notable increase in irrigated cultivable land, ranging from 15-20%, leading to a significant boost in crop production (Archer et al., 2010; Tahir et al., 2011b). Additionally, the dams facilitate water from the summer (Kharif season) to the spring (Rabi season). Wheat, a staple food for a portion of the population, is the main crop during the Rabi season. The total net irrigation demand in 2010 was 113 billion m3. Tarbela Dam caters to a substantial portion (60-70%) of this demand, with the remainder met by other water sources and groundwater extraction (Edwards & Prosser, 1999; Hussain, 2004; K. A. Khan, 2022). However, the capacity of Tarbela Dam is diminishing due to sedimentation, with reports suggesting a decline of up to 30% (11,600 Mm^3) in its initial capacity (Tahir et al., 2011b).

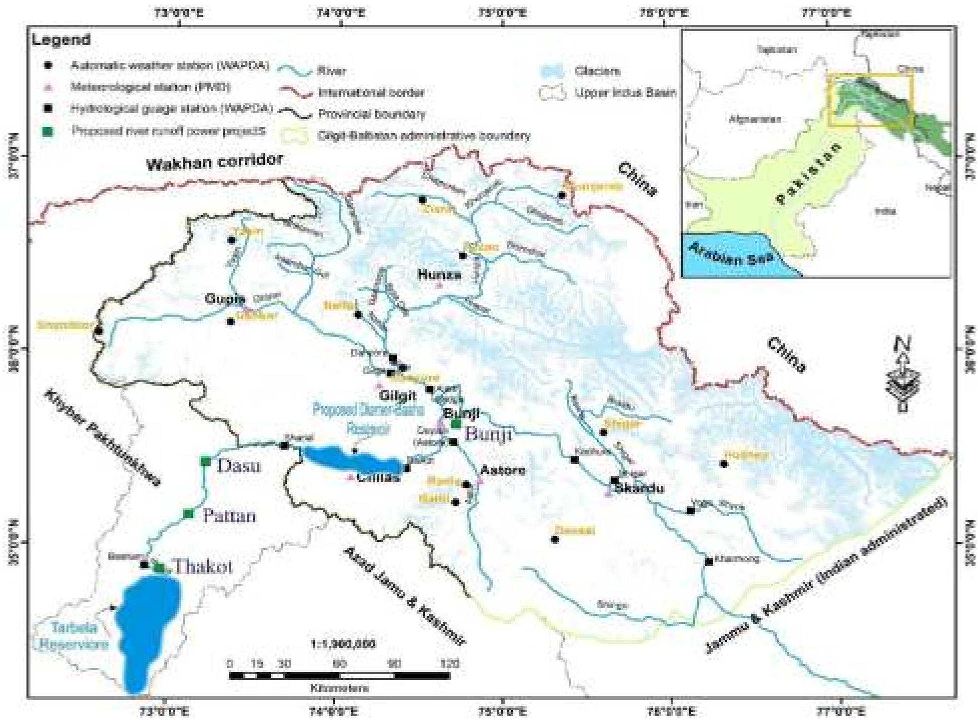

Figure 2. Location Map Gilgit-Baltistan with Basha-Diamer (under construction) and Tarbela DAM on the Indus River (Khan Garee, 2017a)

The rivers of the Upper Indus Basin and their tributaries carry a significant amount of sediment, with an annual suspended sediment load reaching 200 million tons (Ul Hussan, Khurram Shahzad, Seidel, Costa, & Nestmann, 2020). Researchers such as (K. A. Khan, 2022; N. M. Khan & Tingsanchali, 2009; Ul Hussan et al., 2020) have highlighted the adverse impact of sedimentation, leading to a reduction in the reservoir's initial capacity by 30% (11,600 Mm^3), as depicted in Figure 6 and mean monthly inflow at Besham Qila for the period 2008–2020 Figure 5 (Munir et al., 2022). Considering the future water demand and food security challenges posed by the growing population and the declining reservoir capacity due to sedimentation, there is a pressing need for new water storage infrastructure in the Upper Basin region of Pakistan. Diamer-Basha Dam received approval in 2006 following a detailed feasibility study of the site selection (Figure 1), It is situated on the Indus River in Diamer, District of Gilgit-Baltistan.

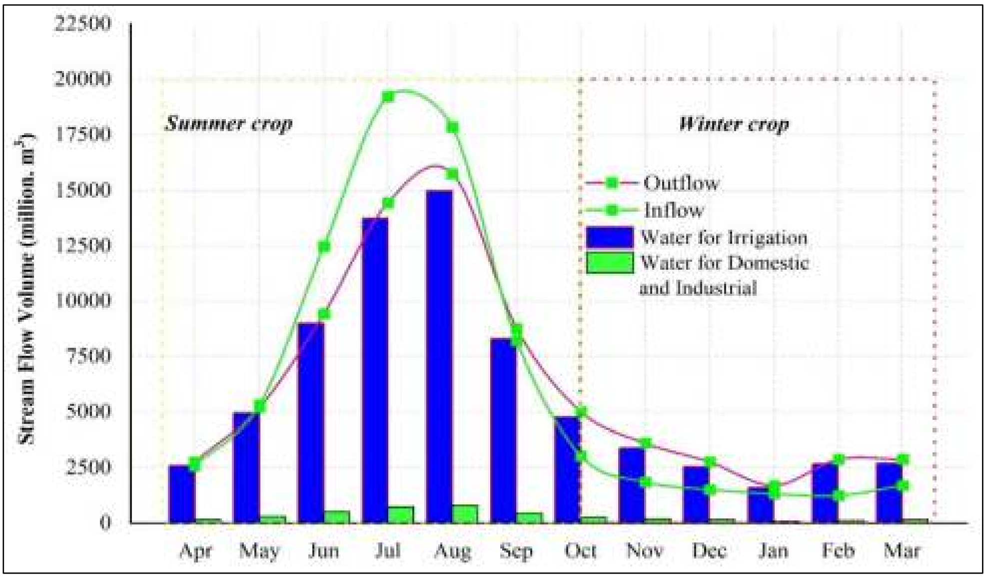

Figure 3. Average monthly flow on Diamer-Basha and inflow into Tarbela DAMs and average water released for Seasonal crops (Data source: WAPDA).

Future Water Demand for Drinking, Power Generation, and Agriculture (Perspectives of Diamer-Basha Dam)

Agriculture is Pakistan's economic backbone. Pakistan has a population of over 193 million. Due to the loss of reservoir storage capacity, the country is already facing serious water scarcity in terms of food security. If the trend continues, Pakistan will become one of the food deficit countries. Therefore, new storage needs to be constructed for expanding agriculture production (Data source: WAPDA).

The Diamer-Basha Dam is a significant hydroelectric and water storage project located in Gilgit-Baltistan, Pakistan. The government of Pakistan made the decision to construct this dam in 2006, aiming to address various water-related challenges in the region. The project involves the construction of a multipurpose gravity dam on the Indus River.

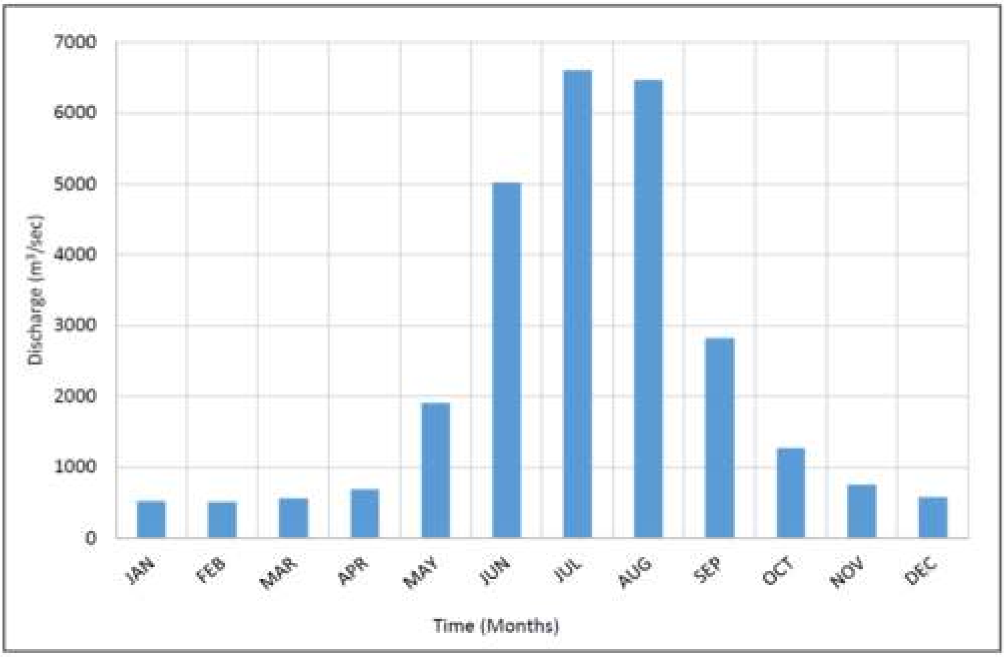

Figure 5. Mean Monthly runoff at Besham Qila from 2008 to 2020 (Munir et al., 2022)

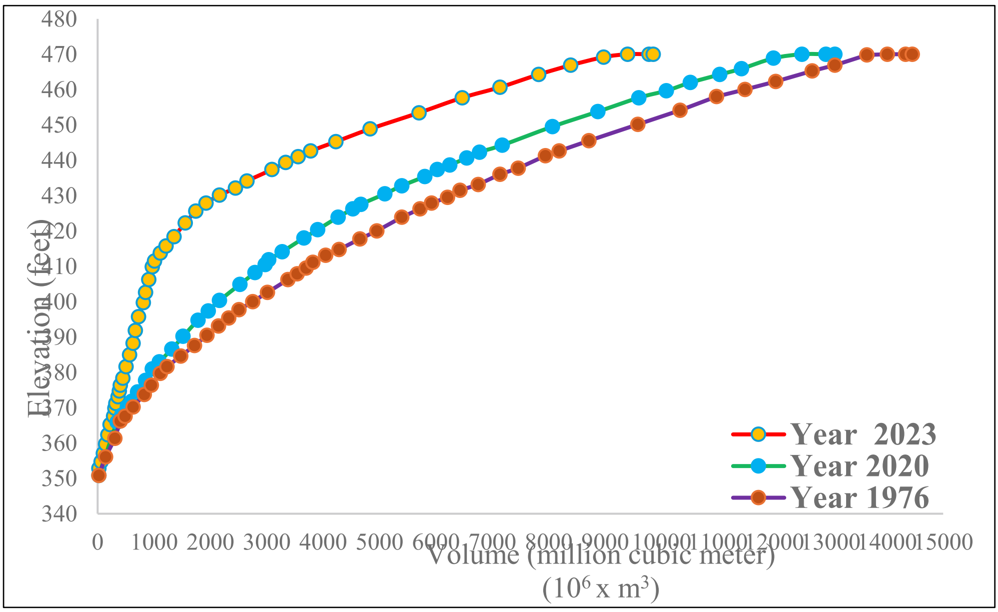

Figure 6. The capacity curve of the Tarbela reservoir in the years 1976, 2020, and 2023 (Data source: WAPDA

The government of Pakistan decided in 2006 to construct five multipurpose reservoirs within the country over 10-12 years, and the Diamer-Basha Dam was part of this initiative. The process of dam construction is divided into phases. The first phase was completed in 2016, but the project experienced a three-year delay. Final completion was expected in 2019. However, due to the political situation in Pakistan, the project was continuously delayed, and it will be completed in 2029. The Diamer-Basha Dam serves various purposes, including storing summer inflow, controlling sediment in the Indus River system, meeting the winter water shortage requirements of the Indus Irrigation, enhancing power generation capacity, controlling floods, and providing water for domestic and industrial use. The dam is situated in Gilgit-Baltistan, 165 km downstream of Gilgit city and 315 km upstream of Tarbela Dam. The dam structure has a maximum height of 270 meters above sea level (ASL) and covers an area of 75,000-acre feet (9.25x10^9 m^3). The storage volume of the dam exceeds 7.89×10^9 m^3 (6,400,000-acre feet). The project site covers an area of 110 km2 and extends 100 km upstream to the Raikot bridge on the Karakoram Highway (KKH) at the dam site (Data source: WAPDA).

The Diamer-Basha Dam is a crucial infrastructure project that aims to address water scarcity, provide hydroelectric power, and support various water-related needs in the region, and its capacity curve is represented in Figure 7. The dam's completion is expected to significantly impact water resource management and energy generation in Pakistan (Data source: WAPDA).

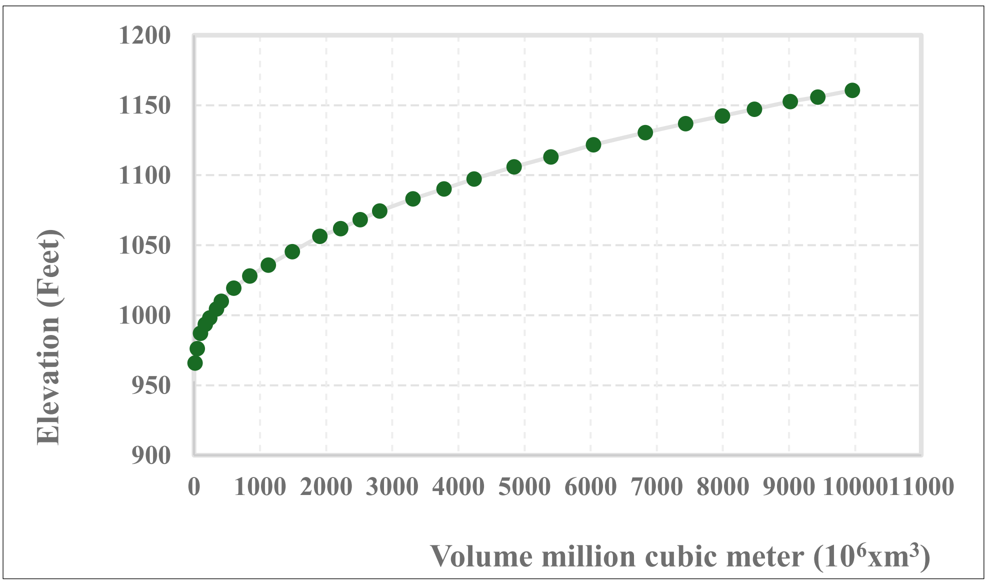

Figure 7. Capacity cure of proposed Diamer-Basha Dam (Data source WAPDA)

Distribution of Water for Domestic and Irrigation Use from the Proposed Diamer-Basha Dam (DBD)

The distribution of water for domestic and irrigation purposes from the proposed Diamer-Basha dam is illustrated in Figure 7. Given the country's escalating demand for water supply, particularly for irrigation and food security, attributed to a continuous increase in population with a fertility rate of 3.65 in 2016 (Chellaney, 2011), the allocation of water from the planned Diamer-Basha reservoir is recommended. This recommendation is based on analyzing available data on maximum, minimum, and average stream flows and flood routing through Dimer Basha DAM, as depicted in Table 1. The irrigation water supplied by Diamer-Basha, when integrated into IBIS, is intended to address future water needs and bridge the shortfall during summer and winter crop seasons, as per information from WAPDA.

Table 1: Maximum, minimum, and average stream flows estimated from the discharge data of the proposed dam site (source: WAPDA).

Period	**Max ($x10^9$ m^3)**	**Min ($x10^9$ m^3)**	**Average ($x10^9$ m^3)**
October-March	9.3 (1990-91)	6.9 (1984-85)	8.1 (1963-2010)
April-September	75.4 (1972-73)	38.5 (1964-65)	53.7 (1963-2010)
Annual	83.0 (1972-73)	47.8 (1964-65)	61.8 (1963-2010)

Table 2. Summary of Flood Routings Through Diamer Basha Dam Reservoir (Tarar, 2011).

Flood Event	**Peak Inflow**	**Starting Reservoir Level**	**14 Spillway Gates (11.5 × 17.5 m) Operative**		**One Spillway Gate Inoperative**		**14 Spillway Gates along with 5 RFOs & 2 LLOs Operative**	
			Peak Outflow	**Maximum Reservoir Level**	**Peak Outflow**	**Maximum Reservoir Level**	**Peak Outflow**	**Maximum Reservoir Level**
	(m^3/s)	(m asl)	(m^3/s)	(m asl)	(m^3/s)	(m asl)	(m^3/s)	(m asl)
Basic Design Flood-1 (1 in 10,000 years)	20,170	1160.00	18,859.56	1160.36 970.73 *	18,412.19	1160.85 970.40 *	-	-
Basic Design Flood-2	23,710	1160.00	19,957.62	1160.90 971.43 *	19,144.59	1161.23 970.92 *	-	-

(SHYOK GLOF)								
Safety Check Flood-1 (SHYOK GLOF + 1 in 100 years)	32,690	1160.00	25,293.6 0	1163.37 974.60 *	24,640.7 9	1163.94 974.20 *	29590. 8	1160.55 976.90 *
Safety Check Flood-3 (BIAFO GLOF / PMF)	49,410	1160.00	35,689.6 1	1167.71 979.80 *	34,920.6 4	1168.49 979.50 *	37710. 4	1164.23 980.80 *

According to Briscoe, Qamar, Contijoch, Amir, and Blackmore (2007), ,water demand for domestic and industrial purposes is anticipated to increase by 4% to 15% in the next 20 years. The future escalation in water demand is attributed to the projected population growth in downstream areas/basins, with a concurrent increase in industrialization and urbanization, and an improvement in people's living standards. Consequently, the water allocation from the Diamer-Basha dam for domestic and industrial use is set at 10%. Figure 8 April -September and October- March from the average expected inflow and outflow for the period of April -September and October- March from the Diamer-Basha reservoir in 2025.

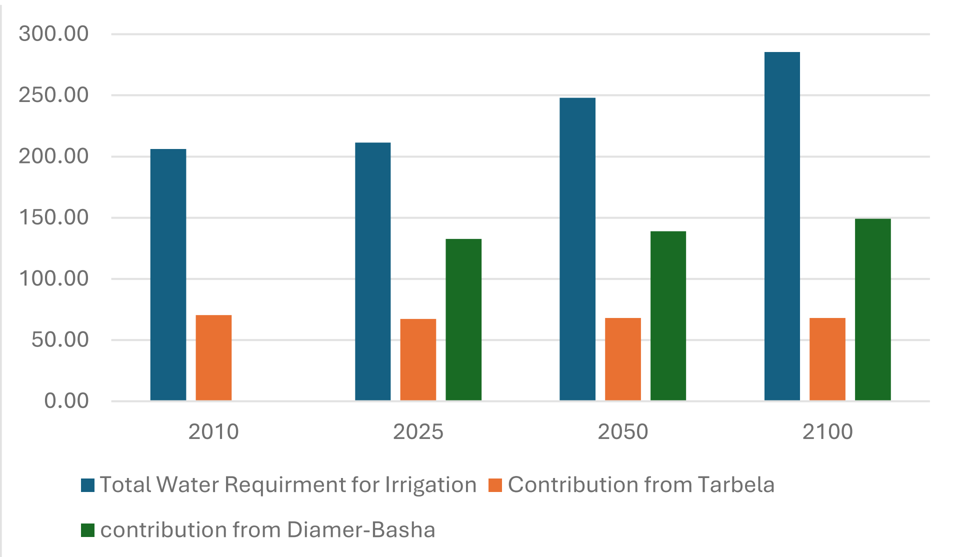

Figure 8. Average expected inflow to Diamer-Basha reservoir in 2025 and average water release for April-September and October-March (Khan Garee, 2017a)

The Diamer-Basha Dam (BDD) plays a crucial role in managing sedimentation. It is a large-scale dam project located on the Indus River in Pakistan. The dam is designed to be situated near Chilas in the Diamer District of Gilgit-Baltistan. Once completed, it is expected to be one of the highest dams in the world, with a height of around 272 meters.

The primary purposes of the Diamer-Basha Dam include water storage, flood control, and hydroelectric power generation. The dam is strategically positioned to harness the water resources from the Himalayan and Karakoram Mountain ranges, particularly the snow/ice and glaciers in the HKH (Hindu Kush Himalaya) region. The dam's storage capacity is crucial for mitigating water scarcity issues and managing the flow of the Indus River.

One of the notable features of the Diamer-Basha Dam is its contribution to sedimentation control, particularly about the Tarbela Dam. By impeding the flow of sediment-laden water, the Diamer-Basha Dam is expected to extend the lifespan and enhance the storage efficiency of the Tarbela Dam, a significant reservoir downstream of the Indus River.

The construction of the Diamer-Basha Dam is a significant infrastructure project for Pakistan, with the potential to address water management challenges, provide flood protection, and contribute to the country's energy needs through hydroelectric power generation. The project is expected to have far-reaching impacts on the region's water resources and energy sustainability once it is completed.

The anticipated completion of the proposed Diamer-Basha Dam (expected post-2029) is poised to alleviate sedimentation in the Tarbela Dam by impeding the flow of sediment-laden water. According to the findings presented in Table 3, the Diamer-Basha Dam contributes to an increased lifespan and enhanced storage efficiency of the Tarbela Dam. By effectively controlling sedimentation upstream of the Tarbela Dam, the Diamer-Basha Dam is forecasted to extend its lifespan by 36% until 2070, as illustrated in the projected results in Table 3 (source WAPDA).

Table 3. Storage capacity of Tarbela (pre and post-Diamer-Basha) and Diamer-Basha dam in 2020 and 2070

Reservoir	**Operation Scenario**	**Storage Volume (Million.m^3)**			
		Initial (2020)		**After 50 Years (2070)**	
		Gross	**Live**	**Gross**	**Live**
Tarbela	Alone	8548.155	8326.125	2269.64	2269.64
	In Conjunction With Diamer-Basha	8548.155	8326.125	6389.53	6278.515
Diamer-Basha	In Conjunction with Tarbela	9991.35	7882.065	3688.165	3564.815

Power Generation Capacity (DBD) and its Impact on the Economy of the Country

Historically, Pakistan has been an energy-deficient country in the world. The persistent energy crisis has consistently impeded economic progress in Pakistan. This challenge primarily stems from inadequate management, policy shortcomings, and a lack of emphasis on non-conventional energy sources. The country's existing energy generation capacity is around 14,000–16,000 MW, encompassing hydro, thermal, and nuclear sources. However, the demand for energy ranges between 20,000–22,000 MW, creating a substantial deficit of 4,000–6,000 MW (Ali, Mahar, & Sheerazi, 2019; Durrani, Khan, & Ahmad, 2021). Projections indicate that this shortfall is expected to worsen with the rising demand for power supply.

Pakistan is fortunate to possess abundant freshwater resources, presenting numerous opportunities for power generation. Figure 9 represents that the current hydropower contribution to the national grid is only 11% of the total power generation of Pakistan (F. Qureshi & Akintug, 2014). It is estimated that Pakistan has a hydropower potential of about 60,000 MW , but only 11% of it is utilized to produce electricity , with a significant portion, around 99%, situated in the Upper Indus Basin (UIB) (Rasheed & Ahmad, 2023). The proposed Diamer Basha Dam (DBD) is among the identified hydropower potential projects, boasting a proposed capacity of 4,500 MW to be added to the national grid in the future (http://www.diamerbhasha.com). This, in turn, is expected to alleviate the energy shortfall in the country substantially.

The Diamer-Basha Dam is envisioned as a large structure on the Indus River in Pakistan, intended primarily for water storage to support irrigation, flood control, and hydroelectric power generation. Upon completion, the dam is expected to progress significantly impact the country's economy, after the completion of a few new under-progressed projects (Table 4).

One of the primary benefits of the Diamer-Basha Dam is its potential to generate a substantial amount of hydroelectric power (Figure 9), recognized as a clean and renewable energy source that could significantly contribute to Pakistan's energy mix. With the increase in power generation capacity, the country may witness a reduction in load shedding, thereby establishing a more stable and reliable electricity supply. This improvement can positively affect various sectors of the economy, including industry and commerce.

A reliable and increased power supply has the potential to stimulate economic development by attracting investments, fostering industrial growth, and creating job opportunities. Industries that rely on a consistent and ample power supply, such as manufacturing, could benefit significantly from the dam's contribution to the energy sector.

The dam's water storage capacity is critical for irrigation, ensuring a more dependable water supply for agriculture. Improved irrigation has the potential to increase agricultural productivity and contributing to food security.

Additionally, the dam's capacity for flood control can mitigate the impact of floods (Table 2) in downstream areas, protecting lives and property (Figure 9). This, in turn, can have indirect economic benefits by preventing losses due to flooding. It's important to note that large infrastructure projects like dams often involve complex environmental, social, and geopolitical considerations. Environmental impact assessments, resettlement plans, and community engagement require careful attention throughout the planning and implementation phases.

Table 4. Development of hydropower projects downstream of DBD after its completion (Source: WPDA).

S.No	Project	Installing Capacity (MW)	Remarks
1	**DBD Project**	4,500	Multi-purpose Storage
2	**Downstream Projects**		
	Dasu	4,320	Basically, Run-off River Projects to Be Firmed up Through Storage releases from DBD
	Patan	2,800	
	Thakot	2,800	
	Sub Total (2)	**9,920**	
3	**Total (1+2)**	**14,420**	

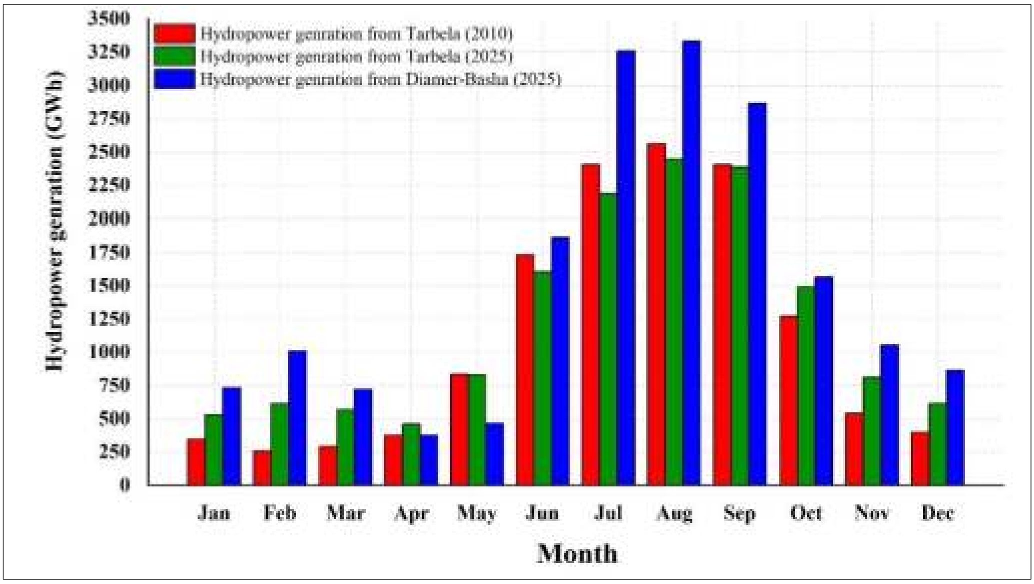

Figure 9. Mean monthly power generation at Tarbela (pre and post DB) and DBD (Khan Garee, 2017a)

Water Availability in the Indus River System: Present and Future Climate Changes

The Indus River System is a vital water source for Pakistan and parts of India. It primarily relies on snowmelt from the Himalayan glaciers and precipitation in the upper reaches. Water availability in the system is crucial for agriculture, hydropower generation, and overall socio-economic development in the region.

Climate change poses several challenges to water availability in the Indus River System. Key factors include Glacier melting, Shifts in Precipitation patterns, Increased evaporation, Extreme weather events and Future projections.

The Himalayan glaciers contribute significantly to the river's flow and are sensitive to temperature changes. Rising temperatures can accelerate glacial melting, potentially leading to increased water availability in the short term due to the release of stored water. However, this effect is not sustainable in the long run as glaciers shrink. On the other hand, climate change can alter precipitation patterns, affecting the timing and amount of rainfall. Similarly, changes in monsoon patterns may impact the river's water inflow, leading to variability in water availability. Higher temperatures can increase evaporation rates from rivers, reservoirs, and agricultural fields, reducing overall water availability. Moreover, climate change is associated with increased frequency and intensity of extreme weather events, such as floods and droughts. These events can disrupt water availability and infrastructure. According to many recent research and studies, there has been an attempt to project future water availability in the Indus River System, but predictions vary. Some models suggest increased water availability due to accelerated glacier melting, while others anticipate a decline as glaciers recede. It's crucial to note that the complex interactions between climate, hydrology, and human activities make precise predictions challenging. Moreover, socioeconomic factors, water management practices, and policies play a significant role in determining the overall impact on water availability.

Impacts of Environmental Changes on the Diamer-Basha Dam

The potential challenges to water storage capacity, particularly for the proposed Diamer-Basha Dam (DBD) and Tarbela Dam (TD), are influenced by global climate change, including variations in temperature and precipitation, a growing population, and an increasing sedimentation load in reservoirs. Projections from the SWAT model indicate a challenging future for water storage capacities in the country. The Raikot and Besham Qila stream flow gauge stations are key sources for measuring inflow water to DBD and TD, respectively (Figure 3).

Considering rising mean temperatures and expanded snow cover areas, the simulation results reveal an increasing trend in stream inflow at Raikot and Besham Qila gauge stations, nearly doubling by 2100 (Figures 10 & 11). This upward trend in water discharge and glacier melting carries a substantial sediment load, potentially reducing the capacity of these UIB storage reservoirs.

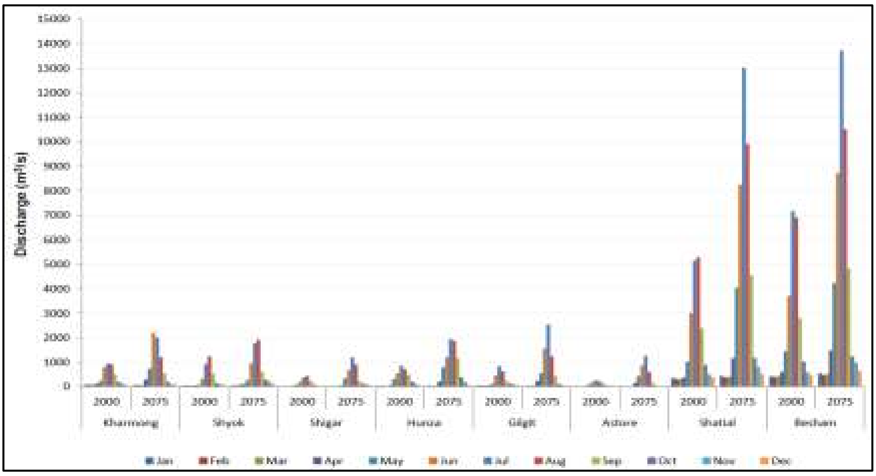

Figure 10. Present and future simulated discharge in the Upper Indus River and its tributaries (Khan Garee, 2017a)

An additional concern is the country's alarming rate of population increase putting pressure on existing and proposed reservoirs to meet food security and domestic and power demand requirements. Following the completion of the DBD project, IBIS's water demand is anticipated to rise by almost 50% in 2025 based on available UIB River water for irrigation (Figure 12). Despite an expected constant or reduced availability of water from these reservoirs (DBD and TD) in the future, there is a projected increase in discharge from UIB Rivers by the end of the century.

However, the projected increased volume of water during summers may not be effectively stored due to the challenges as mentioned above or deficiencies in storage capacity, potentially resulting in severe floods in low-lying areas of the Indus River system, similar to the events in 2010 (Mustafa & Wrathall, 2011).

Both present and past studies on future water demand and supply under various climatic conditions in the region recommend the construction of new water reservoirs and increasing storage capacities to meet future needs. Freshwater resources in the UIB region are gradually decreasing, particularly in spring. The construction of new and larger reservoirs along the river Indus is deemed necessary to address this issue. Siltation in rivers and reservoirs may also limit the current ability to generate hydroelectric power to meet the growing demand for domestic and industrial energy. In the future, the proposed DBD is expected to play a significant role in satisfying a substantial portion of irrigation and electricity demand.

The reliance on alternative water sources (such as groundwater) for Rabi (spring) crops may lead to a rapid decline in groundwater tables, making tube well usage impractical (Archer et al., 2010). Therefore, a comprehensive study of the UIB hydrological regimes is essential, along with examining the potential construction of 3-4 new reservoirs in the up and downstream areas of the Indus River system, considering all social and environmental impacts.

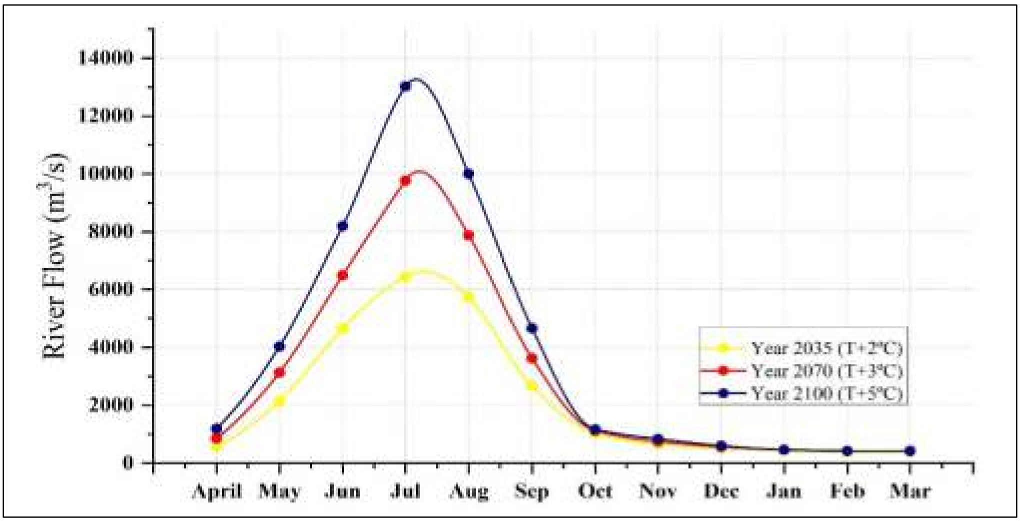

Figure 11. Simulated discharge in the Indus River at Raikot bridge under projected climate change scenarios for years 2035, 2070 and 2100

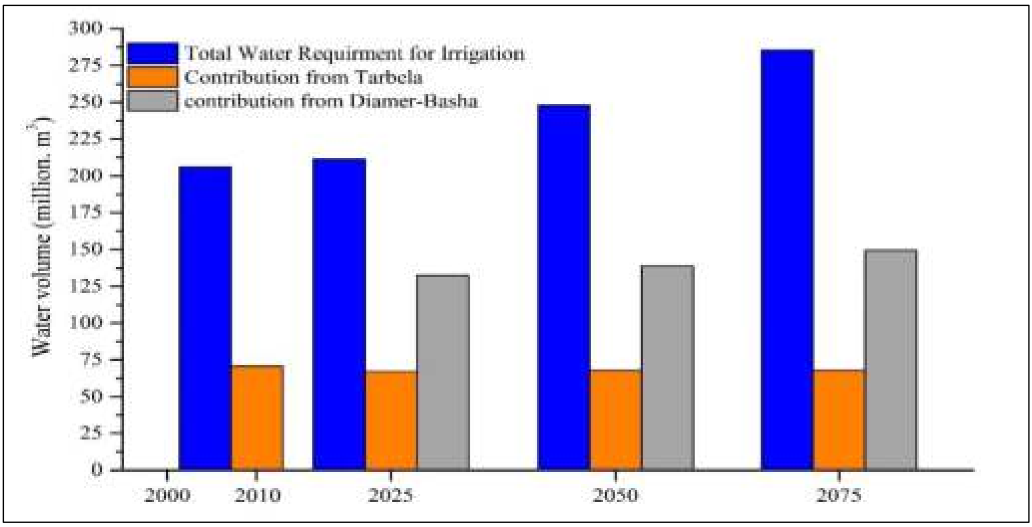

Figure 42. Total present and future irrigation water requirement in Pakistan and the water available from Tarbela and Diamer-Basha reservoirs to satisfy this demand (Khan Garee, 2007).

Conclusion

The Indus Basin Irrigation System (IBIS), which encompasses the vast Tarbela and Mangla reservoirs, is a testament to human engineering on a grand scale, representing the world's largest integrated irrigation network. Originating primarily from the formidable Hindu Kush Himalaya (HKH) mountain ranges, the system's reliance on climate-sensitive water sources underscores its water resources' vulnerability, significantly impacting regional food security and diverse water-related applications. As global climate variations intensify, the Indus Basin faces increasing challenges in sustaining its irrigation system. The delicate balance of water availability is continually disrupted, necessitating a comprehensive strategy to address emerging issues. One of the pivotal challenges is the escalating demand for water, propelled by a burgeoning population. This demand stresses the IBIS more, amplifying issues such as insufficient storage capacity, sedimentation concerns, and mismanagement of vital resources. To fortify the resilience of the Indus Basin Irrigation System, there is an urgent need to explore solutions beyond the existing infrastructure. The proposition of new reservoirs emerges as a critical consideration in adapting to the heightened variability in water availability. Among the proposed projects, the Diamer-Basha and Kalabagh Dams hold particular significance. However, their implementation necessitates thorough environmental assessments and due consideration of local factors to mitigate potential ecological and societal impacts. In pursuing sustainable water resource management, it becomes imperative to adopt a proactive approach that involves regularly monitoring glaciated areas. This entails leveraging advanced technologies and establishing comprehensive data-sharing mechanisms to enhance scientific understanding and facilitate informed decision-making. The dissemination of knowledge about the changing dynamics of the glaciated regions contributes to a more robust understanding of the Indus Basin's hydrological complexities. Even though a substantial portion, 74% to be precise of the river flows is dedicated to irrigation, the existing canal system operates with notable inefficiencies, leading to significant water losses. Addressing this inefficiency becomes a crucial aspect of any strategy to optimize water use within the IBIS. Decision-makers must prioritize establishing a long-term water management plan that incorporates modern techniques such as the Water Evaluation and Planning (WEAP) system. Proven effective globally, WEAP offers a sophisticated modeling approach that can enhance decision-making processes specific to the Upper Indus River Basin.

In conclusion, the Indus Basin Irrigation System, a engineering marvel, faces multifaceted challenges that demand a holistic and forward-thinking approach.

As population growth and climate variations continue to strain water resources, it is imperative to explore innovative solutions, including the construction of new reservoirs, thorough environmental assessments, and the adoption of modern water management techniques like WEAP, proven effective globally and beneficial for the Upper Indus River Basin. Only through a determined effort can the Indus Basin adapt and thrive in the face of evolving climatic and demographic pressures.

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