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ORIGINAL ARTICLE

Assessing water demand and supply in the Upper Indus Basin using integrated hydrological modeling under varied socioeconomic scenarios

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Abstract

This study projects future water demand scenarios in the Upper Indus Basin, focusing on reference, high population growth, increased irrigation, and lower population growth scenarios. The baseline scenario indicates a significant rise in water demand from 35.74 billion cubic meters (BCMs) in 2020 to 60.28 BCM by 2035, driven by population growth and increased domestic water consumption. High population growth exacerbates this demand, reaching 62.96 BCM by 2035. This research aims to address domestic water needs under various growth scenarios, considering factors such as population growth rate and per capita consumption. The study employs integrated hydrological modeling to simulate water demand under different socioeconomic conditions. Key methods include analyzing baseline water demand, projecting future scenarios, and evaluating the impact of increased irrigation and population growth on water resources. Results reveal that without intervention, stagnant water supply management will lead to severe water shortages. Increased irrigation, influenced by a 3% growth in irrigated land, pushes agricultural water demand to 56.37 BCM by 2035. Mitigation efforts, such as a 15% reduction in domestic water consumption, could decrease overall demand to 51.23 BCM by 2035. Further reductions are explored through a 50% cut in agricultural water consumption, involving efficient irrigation techniques. The study highlights the critical role of technology and farmer awareness in achieving these reductions, despite current irrigation scheme losses of 20%. A lower population growth scenario shows a contrasting trend, with water demand decreasing to 49.11 BCM by 2035, attributed to a 1.8% population growth rate and decreased per capita consumption to 82 m^3 per day. These findings underscore the importance of proactive water management strategies, technological advancements, and demographic considerations in addressing future water demand challenges in the Upper Indus Basin. This research provides proper insight into the impact of varied socioeconomic scenarios on water resources and the necessity for strategic interventions.

Keywords Water demand · Water supply · Upper Indus Basin · Integrated hydrological modeling · WEAP (water evaluation and planning) model · Socioeconomic scenarios

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Introduction

Around 2.4 billion people, or more than one-third of the world's population, reside in water-stressed nations. By 2025, this proportion is projected to increase to two-thirds (Vörösmarty et al. 2010). A long-term water crisis is being brought on by large changes in yearly flows in rivers throughout the world, together with a decline in snowfall and an increase in glacier melt. This will have an impact on the availability of water for residential and agricultural use as well as the world's water resources (Gosling and Arnell 2016). Urbanization, economic development, and population expansion are all contributing to increased demand for freshwater supplies. In addition to population expansion and other administrative strategies, one of the most major variables impacting the availability of surface water and groundwater resources is climate change (Zohrabi et al. 2017). In addition, the Himalayan glaciers are receding more quickly as a result of climate change, which has an impact on river flows and groundwater recharge (Xu et al. 2009). The availability of fresh water per person decreases as a result of these causes worldwide, especially in emerging nations where water management has not received priority (Bakken et al. 2016).

Pakistan is confronted with significant obstacles concerning food, water, and economic stability. It is totally dependent upon the water of the Indus River and the related groundwater systems. It manages the Indus Basin Irrigation System (IBIS), the biggest continuous irrigation system in the world, which helps the country with food production, energy production, and stock, residential, and industrial supplies (Briscoe et al. 2005). Water managers confront a difficult and time-consuming task in predicting future seasonal inflows and the ensuing seasonal allocation, delivery, and distribution of surface water resources across the IBIS (Ahmad et al. 2018). Changing resource availability is one of the basin's water security concerns (Khan et al. 2020; Archer et al. 2010; Stewart and Podger 2018; Immerzeel and Bierkens 2012), an increase in rival consumers' demands and sedimentation's loss of storage capacity (Yu et al. 2013; Kirby et al. 2050; Al-Saidi and Elagib 2017; Rajbhandari et al. 2015; Kara and Schwentick 2011; Nepal and Shrestha 2015; Lutz et al. 2016; Laghari et al. 2012).

The Tarbela Dam, the largest earth-filled dam globally, is one of the two reservoirs on the Indus River managed by the Water and Power Development Authority (WAPDA). Tarbela Dam has a storage capacity of 7,400.89 million cubic meters of water and can generate 3,478 MW of power. It serves multiple purposes including flood control, hydropower production, and water storage. Consequently, water scarcity in the Tarbela Reservoir negatively impacts both hydropower generation and agricultural output. Currently, the majority of climate change research focuses on understanding its effects, managing water resources in response to climate change, and developing policies to mitigate these effects while ensuring maximum sustainability (Arnell et al. 2011; Wiltshire et al. 2013; Olmstead 2014; Zhang and Balay 2014). Ehsani (Ehsani et al. 2017) asserted that taking into account the effects of a prospective climate change will likely increase the reservoir's operational reliability. The river flow will shift seasonally due to climate change (Brekke, et al. 2009; Matonse et al. 2013).

The impact of climate change on future water resources has been the subject of several research. Some of these research also focused on some socioeconomic variables including population expansion and rising income as key drivers of future rises in water stress. Climate change is projected to have diverse geographical effects; some will likely have higher stress while others may see less stress (Vörösmarty et al. 2000; Oki and Kanae 2006; Gerten et al. 2011; Fung et al. 1934; Arnell 2004; Alcamo et al. 2007). Many international researchers have combined socioeconomic issues with various methodologies for assessing water resources. For instance, the distribution of water resources within a basin is planned using the Water Resources Management Model (WRMM) (Cutlac and Horbulyk 2011). The Spatial Agro Hydro Salinity Model (SAHYSMOD) is an integrated method for addressing physical, hydrological, and socioeconomic challenges in a basin. The method may be applied to conduct a more thorough analysis of water resources and create a long-term sustainable structure (Inam et al. 2017). The Water Evaluation and Planning (WEAP) model research predicts water demand by taking into account factors and climate change scenarios outlined by the IPCC. According to the projection of population growth the amount of water used per person, per day is expected to increase from 82.9m^3 in 2015 to 120m^3 in 2050 (Amin et al. 2018). The Modular Simulator (ModSim) is a tool that helps with both short-term and long-term planning, strategies creation, and water allocation analysis in the management of river basins (Ashraf Vaghefi et al. 2015). The Water Evaluation and Planning (WEAP) model has been widely used in basins as the most frequently utilized water allocation model, over the past few decades (Yates et al. 2009). In order to allocate water resources under various socioeconomic and climate change scenarios, WEAP has shown to be an effective technique (Mohd Firdaus Hum and Abdul Talib 2016). The water requirements for urban and environmental sectors up to 2050 were forecasted using the WEAP model developed by Rayej (2012), taking into account factors such as population growth and the effects of climate change. The study reveals that urban water demands escalated rapidly with population expansion scenarios, whereas the impact was less pronounced under regional climate change scenarios.

The Indus River, along with its tributaries (Kabul, Jhelum, Chenab, Ravi, Beas, and Sutlej), constitutes the largest irrigation system worldwide. Encompassing an area of 1,140,000 square kilometers, the Indus River system is classified as a transboundary basin (Frenken 2011). The Indus River Basin in Pakistan extends from the Himalayan Mountains in the north to the arid alluvial plains of Sindh Province in the south, where it eventually empties into the Arabian Sea (Steenbergen et al. 2015). The Indus Basin covers 520,000 km in Pakistan making up roughly 65% of the country's overall land area. The Indus Basin and its tributaries heavily depend on the melting of snow and glaciers to supply 50% of their base flow (Mukhopadhyay and Khan 2015). However, this crucial water source is being affected by the melting of glaciers (Amin et al. 2018). Water stress conditions are predicted to worsen in Pakistan as a result of hydrological and socioeconomic variables, since water demand is expected to rise by 2.5% by 2025. One of the nations in the world with the biggest water shortages is Pakistan (Akbar et al. 2021). Pakistan's water supplies are deteriorating at an alarming rate. Several studies have been conducted to assess the water quality of the aquifer, beneath the Indus River and analyze the hydrology of the Indus River Basin (Hussain, et al. 2017). The majority, 74% of the water, in the Indus River is directed toward irrigation canals making it the main source of water for agriculture in Pakistan. However, there is a shortfall of 11% in terms of water availability, for irrigation compared to the amount needed by crops (Yaqoob 2016). The most significant obstacle to increasing agricultural yields is a lack of water, while climate unpredictability has disrupted Pakistan's cropping pattern (Asif 2013). Groundwater is being over-exploited in order to fulfill water needs, which is continuously depleting groundwater in canal commands. By the end of 2025, Khan et al. (2008) predicted that groundwater levels in the Indus Basin will drastically fall from 10 to 20 m. The groundwater, in the Central Indus Basin (CIB), has been depleted because of population growth and excessive use, for livestock and agriculture (Hassan et al. 2017). The Thal Doab region faces significant pollution concerns, affecting approximately 76% of its area. High salt concentration renders some tube well water unsuitable for irrigation in the area (Shah and Ahmad 2015). The Hunza River Basin employed the runoff model to predict daily flow and examine the effects of climate change (Tahir et al. 2011). Under the strain of an ever-increasing water demand in the basin, these studies have not provided a complete analysis of the water demand and supply, in a basin (Amin et al. 2018).

To assess the future availability of water, for water management, in the Upper Indus basin (UIB), our focus was not limited to hydrological modeling alone. We also delved into examining the demand and supply conditions surrounding it. The primary objective of the study is to enhance our understanding of the water demand and supply management system for our study area. Additionally, it aims to investigate how a combination of climatic changes could impact irrigation consumption in the long run, ultimately affecting the availability of water, in the UIB region. The findings from this research will be valuable for comprehending and strategizing the country's water resources in a manner across all sectors while also considering the implications of development and climate change.

Materials and methods

Study area

The present study includes seven districts in Khyber Pakhtunkhwa: Dera Ismail Khan, Tank, Lakki Marwat, Bannu, Karak, Hangu, and Kohat on the Indus River as shown in Fig. 1. The study area encompasses approximately 20,409 square kilometers and had a population of 8.0 million as per the 2017 census. The Upper Indus Basin encompasses the northern regions of Pakistan, particularly the province of Gilgit-Baltistan. Originating from the Tibetan Plateau, the Indus River flows through this mountainous terrain, shaping the landscape and providing essential water resources to the region. The Upper Indus Basin holds strategic importance in terms of water management, ecology, and local livelihoods. This area plays a crucial role in the hydrological dynamics of the broader Indus River system. Upper Indus Basin is roughly situated between approximately 31° to 33° N latitude and 70° to 72° E longitude. The Upper Indus Basin has a harsh climate with cold winters, featuring temperatures well below freezing and frequent snowfall in the higher elevations. Summers are relatively short and can be cool, even at higher altitudes. Precipitation is generally low, and much of it comes as snow during the winter. Glacial meltwater from the significant glaciers in the region is crucial for river flow during the warmer months. The high altitude of the basin, ranging from approximately 3,000 to 8,000 m, contributes to its challenging climate and influences the cold temperatures experienced throughout the area.

Dataset used

Detailed information on the dataset used for the WEAP model is shown in Table 1. An ArcGIS-generated distance to river map of the research region is displayed in Fig. 2. The land cover dataset archives of the MODERATE-resolution Imaging Spectroradiometer (https://earthexplorer.usgs.gov/)

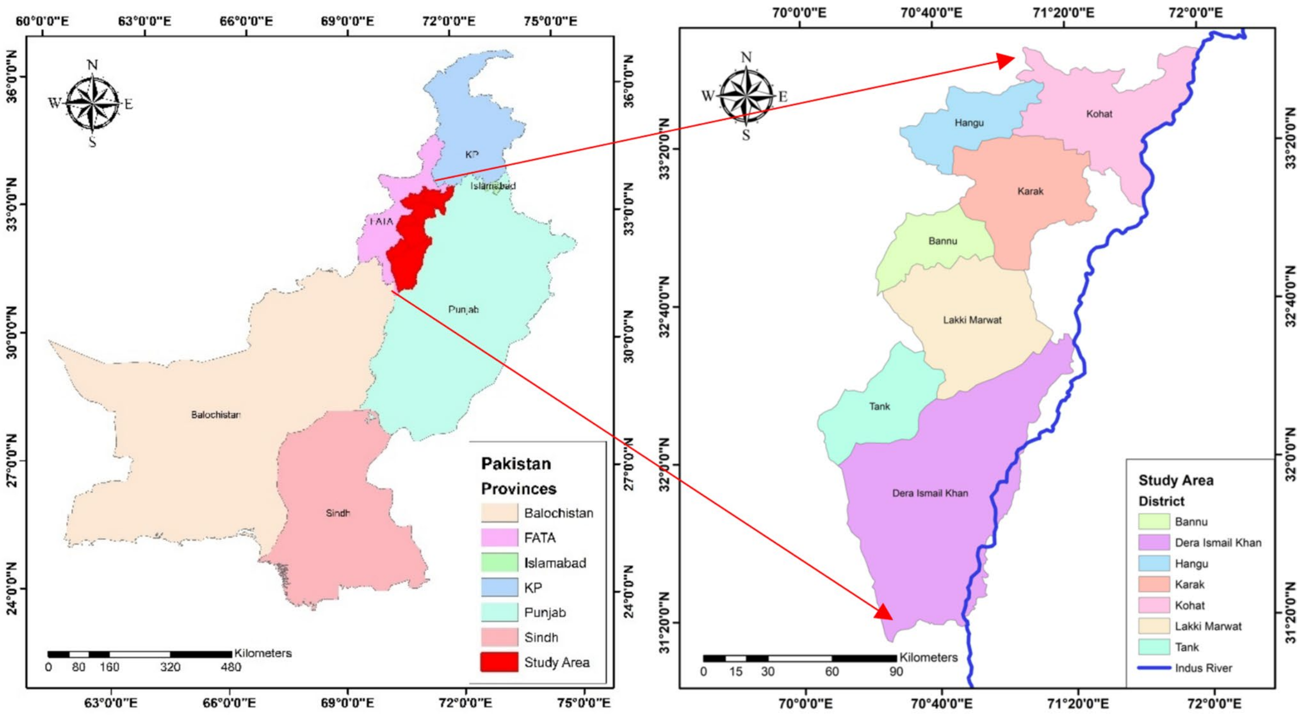


Fig. 1 The study areas geographical location display all the districts and the primary Indus River, in the Indus River region

Table 1 Datasets that the water evaluation and planning model utilizes

Data	Description	Sources
Meteorological data (1995–2020)	Precipitation, Evapotranspiration	Pakistan Meteorological Department (PMD), KPK
Hydrological data (2000–2020)	River Discharge data	Water and Power Development Authority KPK, Indus River System Authority, KPK
Land cover data (2022)	Land cover from MODIS	USGS (https://eartheplorer.usgs.gov/)
Information About Demographics (1995 – 2020)	Data related to land usage, population dynamics, growth rates, water consumption levels, and the demand, for water, in agriculture	The Pakistan Bureau of Statistics, in Islamabad has released a set of reports, on the development statistics of KPK

were used to get the land cover data. The research area's land cover classifications are depicted in Fig. 3.

WEAP modeling

A complete software program for managing and planning water resources is called WEAP (Water Evaluation and Planning System). Numerous water-related issues, such as pollution, flooding, droughts, and lack of water, are modeled and evaluated using the WEAP model (Mugatsia 2010). With the use of WEAP's scenario-based methodology, users may assess the effects of various policies and tactics in a range of potential future scenarios.

Watershed water management is an area where WEAP excels. It may be used to simulate the intricate relationships that exist between natural and man-made systems, such as the processes of rainfall and runoff, the supply and demand for water, and infrastructural functions. WEAP uses embedded algorithms to model rainfall-runoff processes in basins and sub-basins using climatic time-series data. This enables the evaluation of climate change's effects on water supplies and the creation of adaptation plans (Mangoro 2021). The schematic input data utilized for the WEAP modeling are displayed in Fig. 4.

The WEAP model offers five approaches to calibrate the model, including (1) the rainfall-runoff method, (2) a simplified approach, for irrigation demands only, (3) the soil moisture method, (4) the MABIA method which stands for 'control of irrigation needs, in agriculture,' and (5) the plant growth method. The rainfall-runoff technique was selected for this study's model calibration because

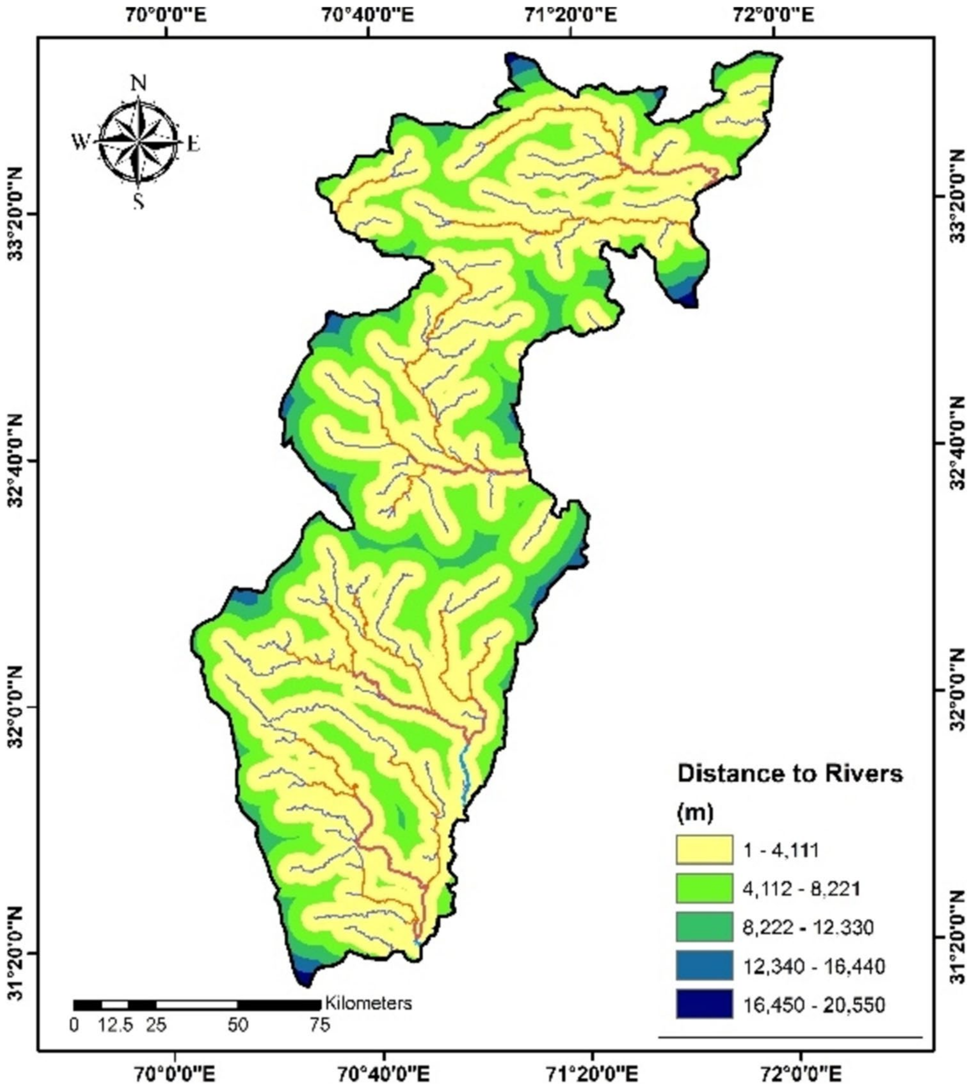


Fig. 2 Distance to river map of the study area

it assumes that demand locations have simplified evapotranspiration, rainfall, and crop growth processes. Demand sites that are not related to agriculture are also included. The starting point for WEAP modeling is the inclusion of layers that encompass all the nodes related to supply and demand. Through the use of transmission lines and nodes, the schematic view connects all spatial aspects. A schematic depiction of the lower Indus River Basin is presented in Fig. 5. The research area's demand locations for cattle, homes, and irrigation are known as point features. The demand locations are connected to the water supply by a transmission link. The districts of Bannu, Lakki Marwat, Dera Ismail Khan, Tank, Hangu, Karak, and Kohat serve as both domestic and agriculture demand sites. To address the unique requirements of each district, water demand for livestock was also taken into account across all districts. The Indus River serves as the primary source of water supply.

Water requirements and demand estimation

The research area's various sectors' present and future water needs were evaluated. The disaggregated-based method in the WEAP model was used to analyze water demand across all industries. The estimation of water needs for cattle, agricultural, and residential use served as a gauge for the socioeconomic dynamics present in the region. The amount of water required by each sector was broken down into individuals, hectares, and heads, and this information was then multiplied by the sector's yearly water usage rate.

Every district had requirements for residential water that included both rural and urban regions. The district-level total water demand was determined using the 2020 population census (Table 2). Water consumption for the reference scenario was estimated using each district's rate of population increase (Table 2). Both rural and urban regions needed 60 gallons of water per person every day (Amir and Habib 2015). The crop water requirement was calculated by

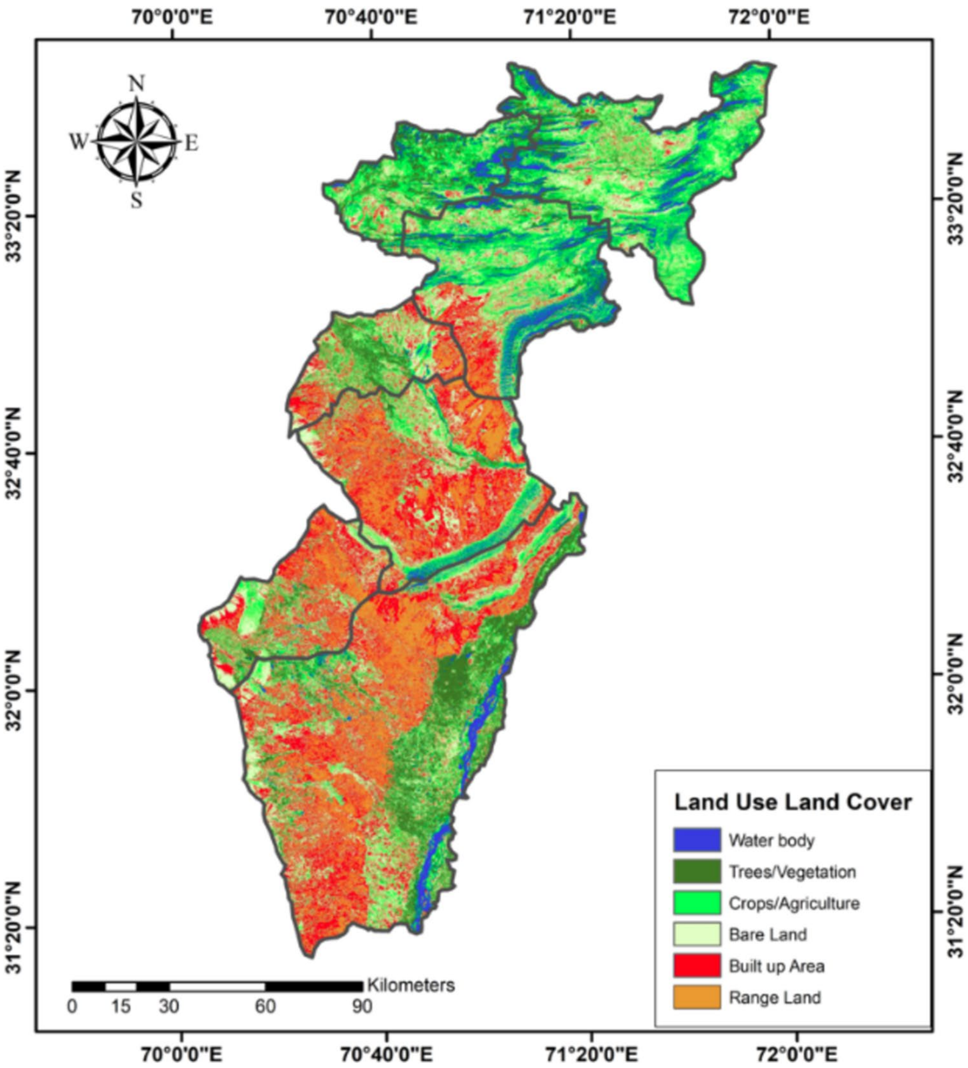


Fig. 3 Land use land cover classification of study area

utilizing the crop values obtained from Food and Agricultural Organization (FAO) statistics and relevant literature taking into account the farmland conditions (Frenken 2011). The literature and PMD were used to determine the values of evapotranspiration and effective precipitation. Next, taking into account the farmed areas and patterns in UIB, the irrigation water requirement was computed.

Future water demand and scenarios' development

Since the data from 2020 were thorough enough to create the socioeconomic and IPCC climate change scenarios, they were used as a reference year or baseline year for the overall water demand for the major sectors (agricultural, livestock, and household usage). The reference scenario pertains to the standard operating procedures that were developed based on the water demand and climate conditions for the period of 2020–2035. Every socioeconomic and meteorological scenario was created using the water demand and meteorological conditions for the years 2020–2035. The average population growth rate for each district in the reference scenario is displayed in Table 2. The most crucial aspect of WEAP modeling is the creation of all additional scenarios (Fig. 6).

Two different management scenarios were suggested to assess the impact of climate change on the future water demand situation. These scenarios focused on reducing both drinking water consumption and basic irrigation water consumption. Additionally, four exploitation scenarios were proposed, including the reference scenario, population growth and increased irrigation demand. The development of these scenarios was based on the climate forecast data, for the research region (Moss et al. 2010). The following scenarios were employed in the study:

1. Reference scenario describes the current account that made use of all real-time data. There was a little increase in the demand for water.

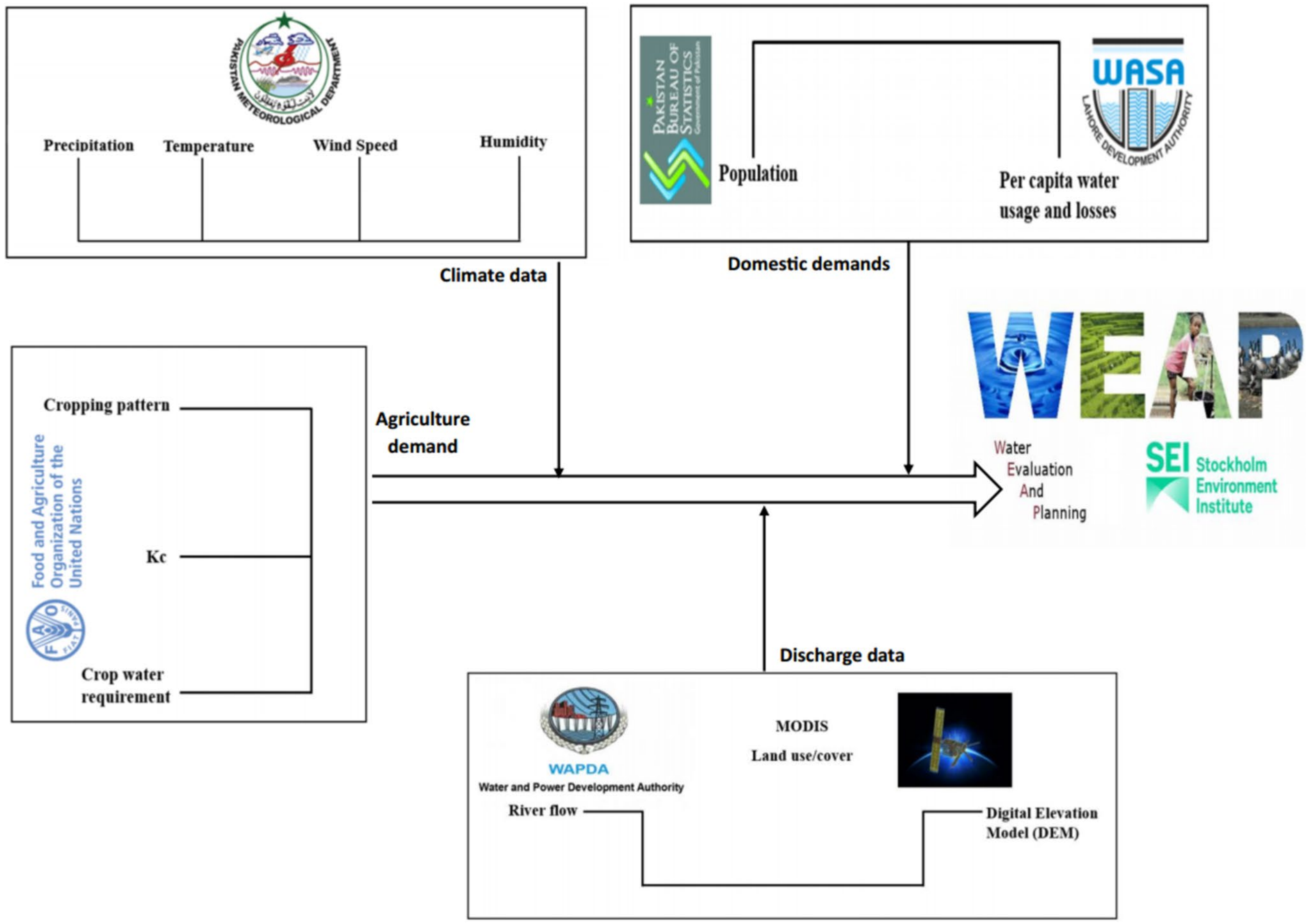


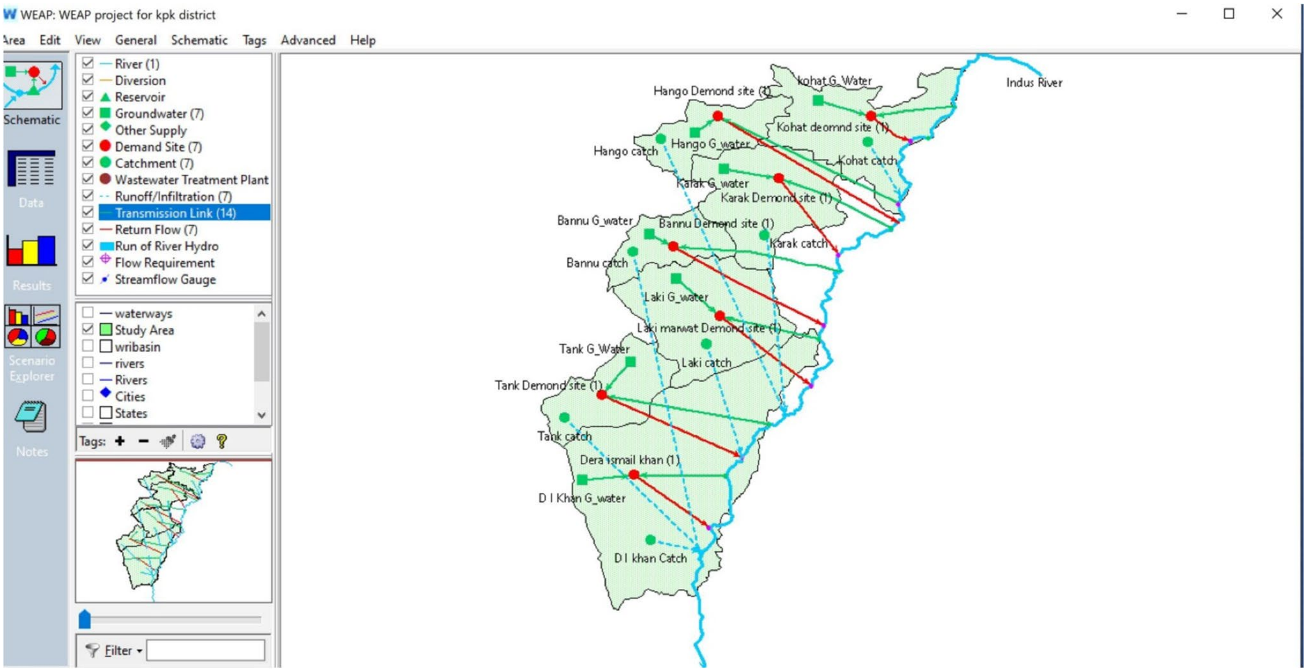
Fig. 4 Schematic input data used for the WEAP modeling (Asghar et al. 2019)

2. In the scenario of population growth, all the other factors were kept the same, as in the reference scenario. With a 3.5% rise, in the current rates of growth.
3. The irrigation requirements have risen; all other factors are derived from the baseline scenario, where there has been a 3% expansion in the area under irrigation.
4. Management scenarios: This scenario was suggested to be applied to domestic and agricultural water demand and supply. These include three sub-scenarios focused on the household and agricultural sectors:
5. All other metrics were based on the reference scenario, with a 15% drop in basic water use.

    I. As a reference scenario, all other parameters were kept the same, but the amount of water used for agriculture and irrigation was reduced by 5%.
    II. The current growth rates were reduced by 1.8%, and all other factors were applied in the same way as in the reference scenario.

Calibration process of the WEAP model

First, historical data from 1995 to 2008 (Monthly data) were used to calibrate the WEAP model. Next, data from 2008 to 2020 were used for validation. Five approaches were considered for the calibration phase, and the rainfall-runoff approach and the irrigation needs only simplified coefficient method, the soil moisture method, the MABIA method, and the plant development method were the ones selected. In order to accomplish model calibration, parameters were then found, and their adjustable ranges were ascertained. The availability of data that satisfied the requirements of the rainfall-runoff technique was the primary factor in the decision to use it for model calibration.



☑ River (1)
☑ Diversion
☑ Reservoir
☑ Groundwater (7)
☑ Other Supply
☑ Demand Site (7)
☑ Catchment (7)
☑ Wastewater Treatment Plant
☑ Runoff/Infiltration (7)
☑ Transmission Link (14)
☑ Return Flow (7)
☑ Run of River Hydro
☑ Flow Requirement
☑ Streamflow Gauge

☐ waterways
☑ Study Area
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☐ rivers
☐ Rivers
☐ Cities
☐ States

Fig. 5 Water evaluation and planning model schematics

Table 2 The district-wise population and growth rate

District	Population	Growth rate (%)
Bannu District	1,357,890	1.94
Lakki Marwat District	1,040,856	2.42
Dera Ismail Khan District	1,829,811	1.30
Tank District	470,293	1.63
Hangu District	528,902	0.32
Karak District	815,878	2.46
Kohat District	1,234,661	1.78

Results

Model calibration and validation

During this investigation, we found that the crop coefficient was the parameter that had an impact on fine tuning the model. To evaluate how well the model performed during both calibration and validation periods, we relied on two indices: the coefficient of determination (R^2) and the Nash Sutcliffe efficiency index (NSE). These indices provided us with insights, into the models performance (Gupta and Kling 2011). During the calibration and validation period, the Nash Sutcliffe efficiency index and coefficient of determination achieved values are shown in Table 3:

The findings demonstrated that the streamflow in the research region had been accurately predicted by the WEAP model, and comparable findings were published byKhan et al. (2017). Excellent agreement was seen between the calibration result and the model's validation result (Fig. 7).

Reference scenario

The reference scenario's water demand simulation and analysis are displayed in Fig. 8. This simulation served as the basis for the computation of all additional possibilities, such as increased irrigation and population expansion. The total findings indicated that the water demand will rise to 60.28 billion cubic meters (BCM) by 2035 from the 2020 water demand of 35.74 billion BCM.

Higher population scenario

Figure 9 illustrates the contrast, in water demand, between reference and high population growth scenarios. Water demand under the reference scenario was 35.74 BCM in 2020 and is expected to reach 60.28 BCM in 2035. In contrast, by 2035, the water demand in the scenario with the highest rate of population growth had climbed to 62.96 BCM. The very high population growth rate (3.5%) and the projected rise in daily water usage from 100 m3 per capita by 2020 to 120 m3 per capita by 2035 serve as justifications for the increase in household water for UIB. Due to the study area's steady population expansion, the population growth

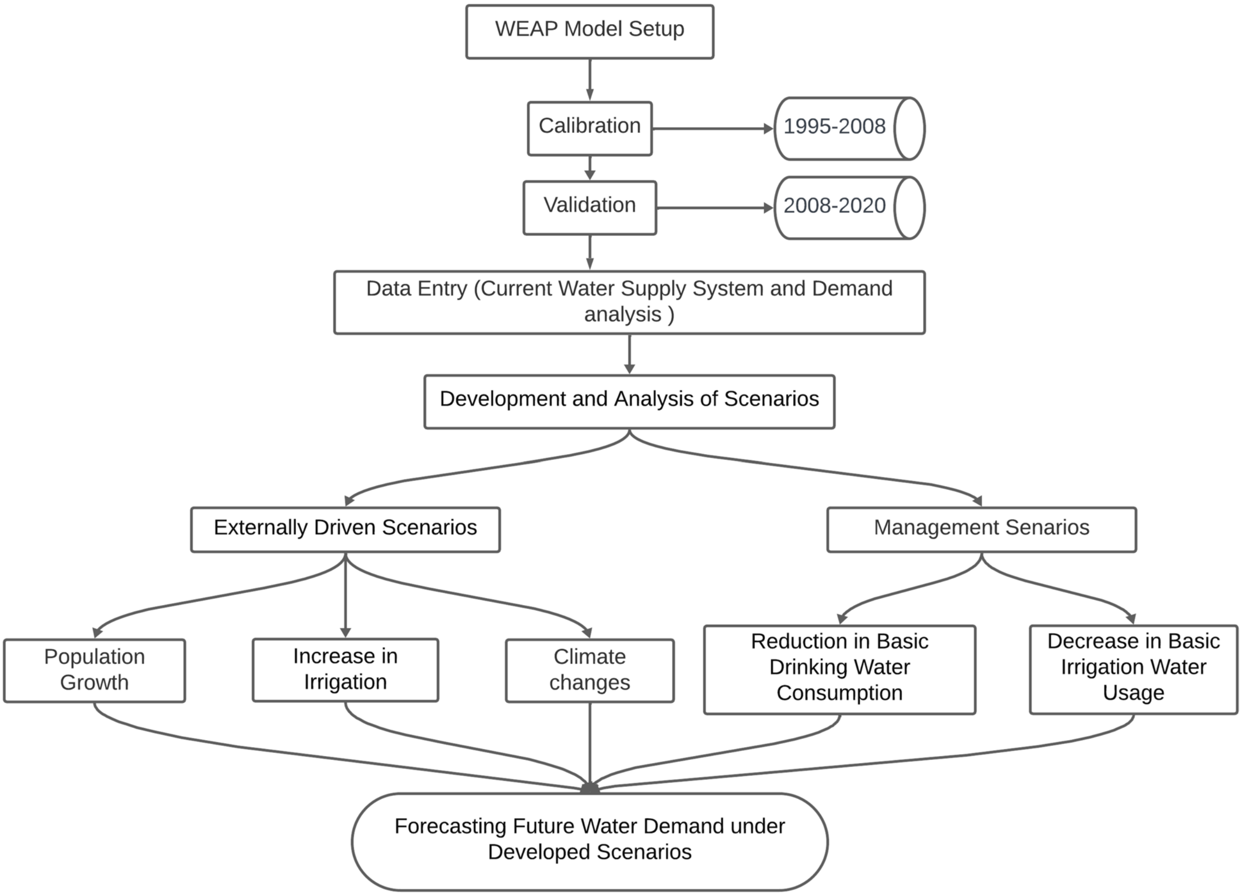


Fig. 6 The creation of scenarios, within the Water Evaluation and Planning model

Table 3 Performance statistics for calibration and validation results

	Statistics	
	NSB	R^2
Stream flow calibration (1995–2008)	0.85	0.86
Stream flow validation (2008–2020)	0.83	0.85

scenario's residential water consumption is expected to be greater than reference scenarios in the future. In the scenario where population growth's high, no assessments were made regarding any modifications, to the water delivery system. The future projections suggested that if nothing changed in water supply management, there would be serious water scarcity concerns.

Increased irrigation demand scenarios

The water requirement for agriculture will rise from 42.88 BCM in 2020 to 56.37 BCM in 2035 if the growth rate of irrigated land increases by 3%. Figure 10 depicts the progressive increase in water consumption in the agriculture sector, based on projections for the period 2020–2035. Increased need for irrigation is a result of population expansion as well.

Management scenarios

The scenario of reduced water usage, in households

A 15% decrease in each district's home water usage was projected in this scenario. The decline may be the consequence of public education campaigns and information exchange on water conservation. It is also anticipated that other technological methods to lessen losses would be developed. For instance, whether in an urban or rural area, the water supply must match the demand node. Since the demand for water in rural areas is always lower than that in urban areas, the distribution of water in rural areas must differ from that in urban areas. The results indicate that even though water usage decreased by 15% the demand for water in all seven districts also decreased. In 2035, the total amount of water

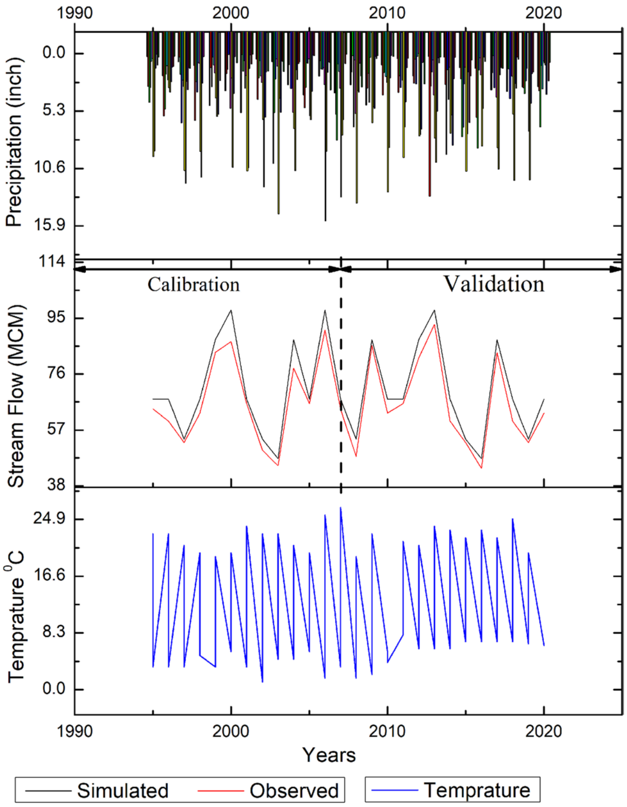


Fig. 7 Observed versus simulated streamflow (monthly) with precipitation and temperature of the Central Indus Basin during calibration and validation processes

demanded was 51.23 MCM (million cubic meter), compared to over 9.5 MCM, in the reference scenario (Fig. 11).

The decrease in irrigation/agriculture water consumption scenario

Agriculture water demands may be decreased by 50% by implementing various water saving measures. This scenario was created in response to the low irrigation efficiency in the research region. The existing irrigation schemes are said to have a 20% loss (Shaikh et al. 2015). Farmers have the potential to decrease water consumption by applying their expertise in adopting irrigation methods like pivot, drip and sprinkler systems and embracing precision agriculture practices. The introduction of modern irrigation schemes and the management of leaks and losses through canal lining will lower the demand for water. Figure 12 illustrates the variation in water demand between the reference scenario and the scenario with lower basic irrigation water usage.

`Lower population scenario

Figure 13 illustrates the contrast, in water consumption between scenarios, with reference population growth and reduced population growth. The reference scenario predicts that the water consumption would rise from 36.89 MCM in 2021 to 60.28 MCM in 2035. In contrast, by 2035, the water demand in the scenario with slower population increase had dropped to 49.11 MCM. The

Fig. 8 Water use per year (BCM) for the household, agricultural, and animal sectors under normal circumstances (2020–2035)

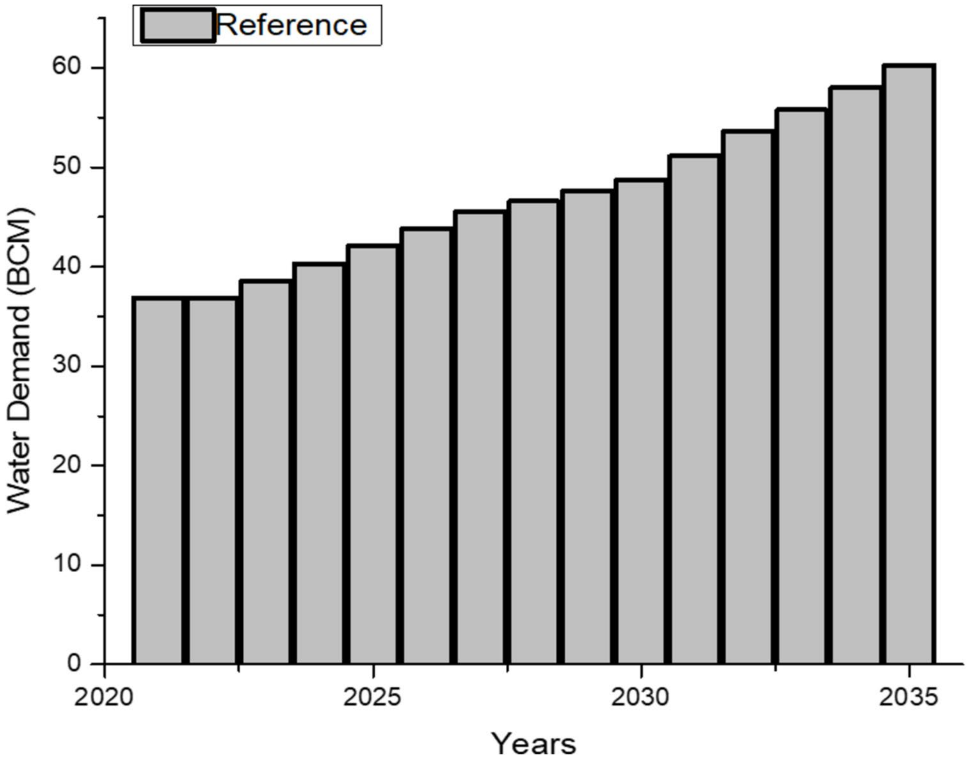


Fig. 9 Water consumption per year for the household sector in scenarios with substantial population increase (2020–2035) and reference data

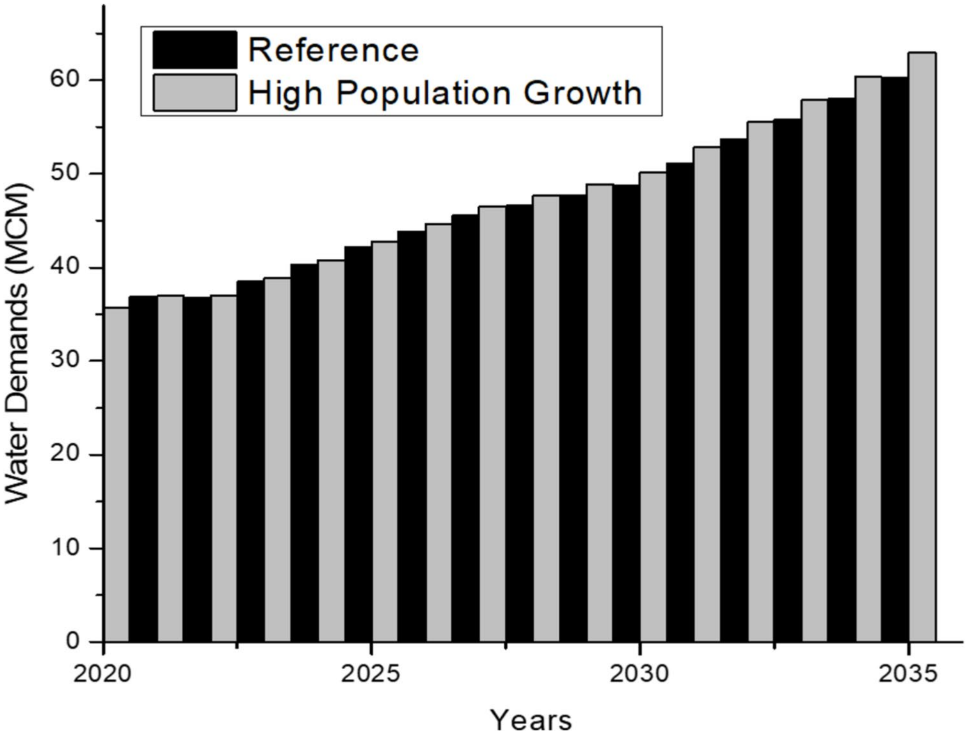
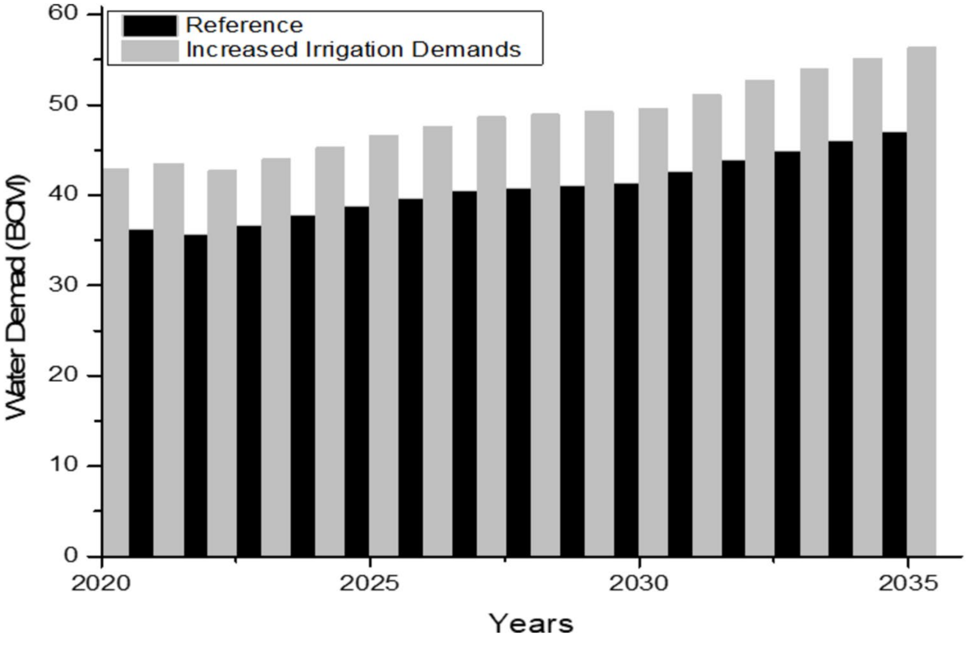


Fig. 10 The irrigation sector's future projections and rising irrigation demand scenarios (2020–2035)



comparatively slower rate of population increase (1.8%) and the reduction in daily water usage from 100 m3 per capita by 2020 to 82 m3 per capita by 2035 serve as justifications for the domestic water reduction for UIB. Due to the decrease in population within the research area, the amount of water needed by households in the future is lower in scenarios where population growth is slower than in reference scenarios.

Exploitation of unmet water demand and various management scenarios

The findings of the exploitation scenarios indicate a sharp rise in the demand for water. Consequently, the water supply and demand analysis of the UIB was compared using the various management scenarios that were established. The reference scenario and possible management scenarios

Fig. 11 Projections of annual water demand for basic home water usage scenarios (2020–2035) as a point of reference ad reduction

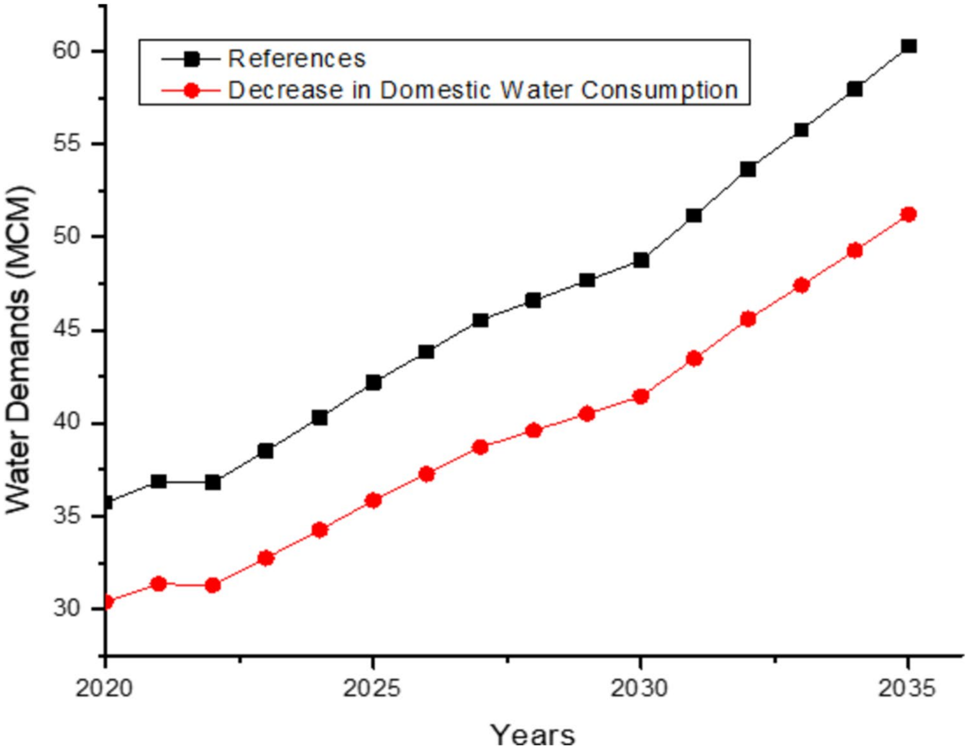
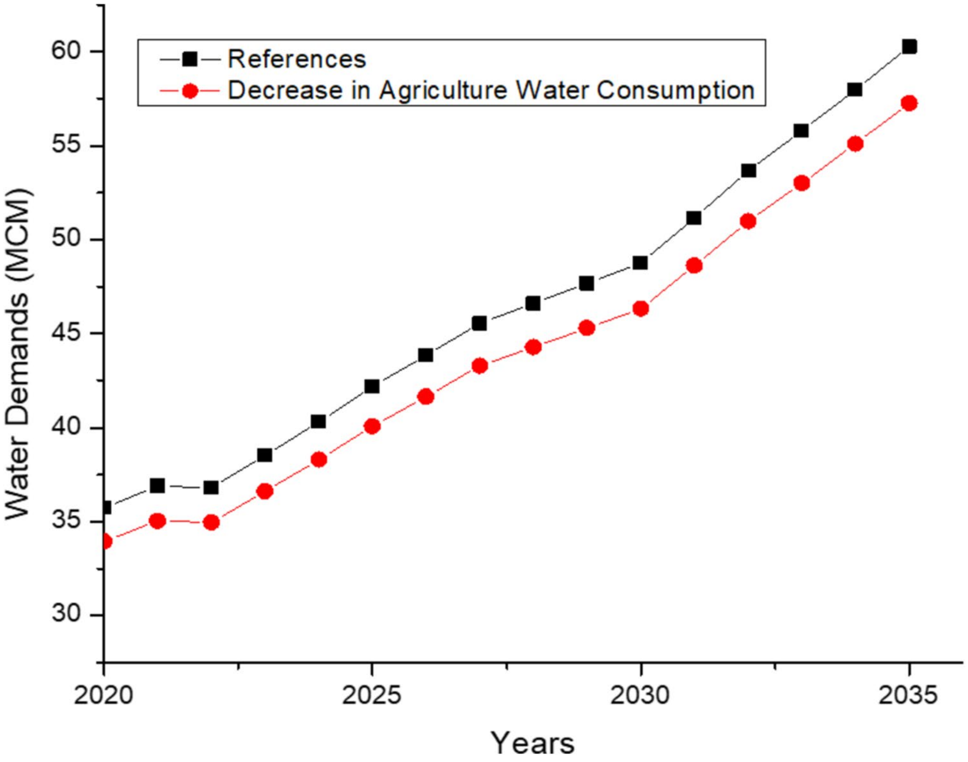


Fig. 12 Annual water needs under consideration, as well as reductions in irrigation water use scenarios (2020–2035)



(lower home water consumption, lower irrigation water consumption, and lower population scenarios) are depicted in Fig. 14, along with the unfulfilled water demand in the extraction (rapid population expansion, increasing need for irrigation). There is a rise in water demand even in management situations when consumption rates are dropping. This is due to the relatively rapid expansion of the population and the increasing amount of irrigated land in the study area.

Fig. 13 Comparing the water consumption, between reference and reduced population growth scenarios from 2020, to 2035

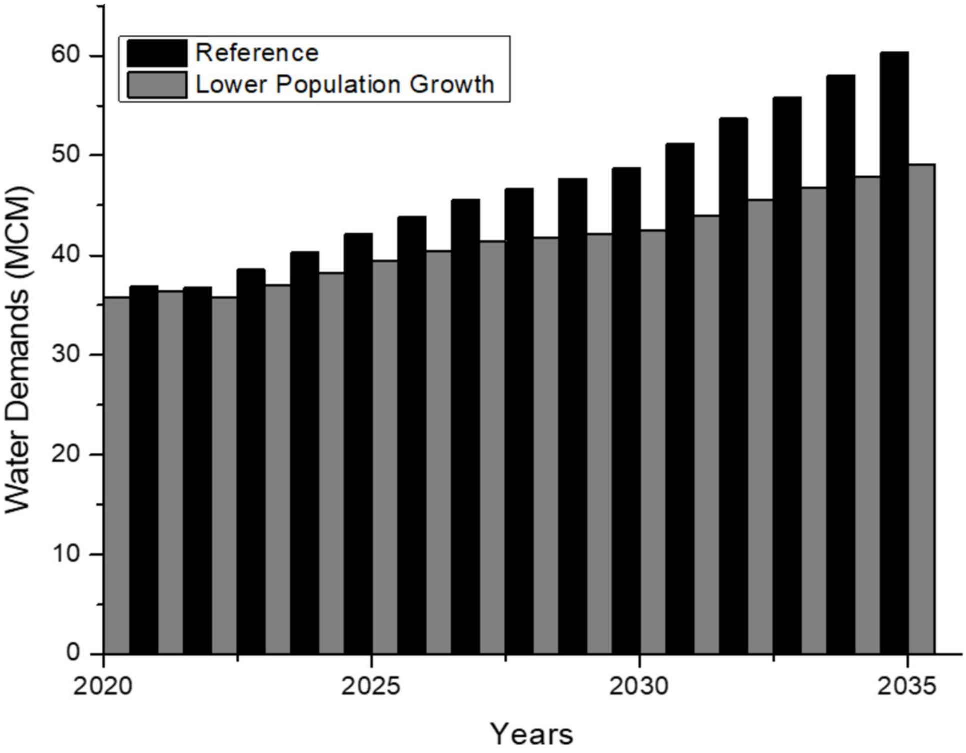
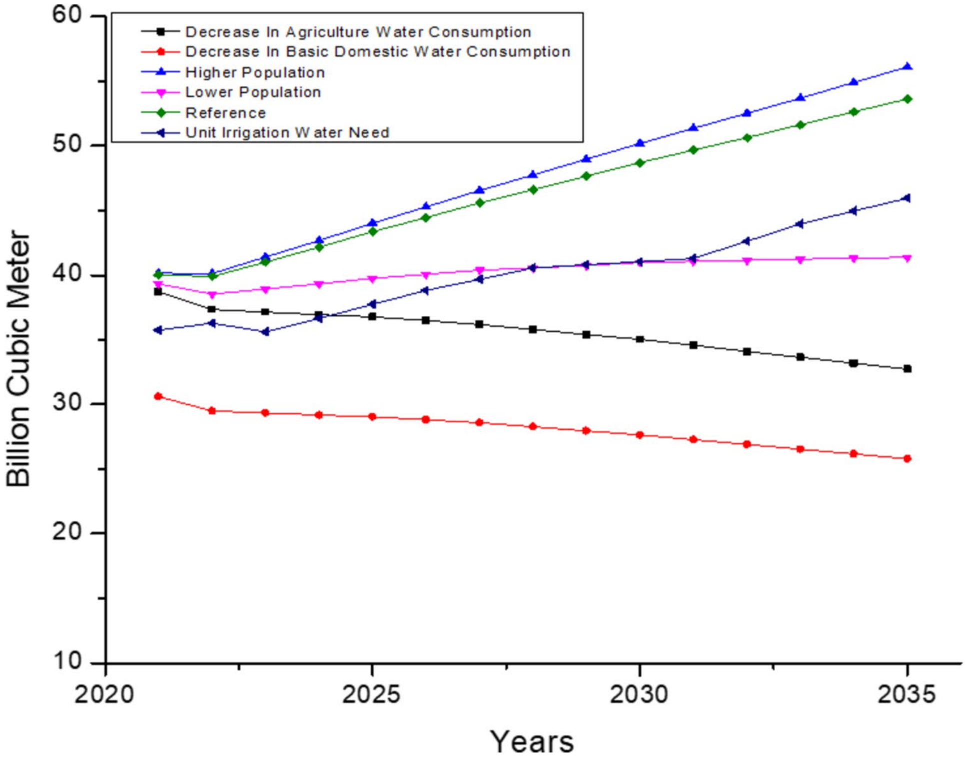


Fig. 14 Exploitation of unmet water demand and various management scenarios (2020–2035)



Birhanu et al.(Birhanu et al. 2019) utilized the WEAP model's high (4.6%), medium (3.8%), and low (2.8%) population growth rates to simulate Addis Ababa's water demand projections. According to their analysis, no water management system could guarantee 100% coverage of water demand by 2025. Figure 15 demonstrates how the study region might benefit from various possible management scenarios as an adaptation. The unmet water demands in the reference scenario were anticipated to reach 53.64 BCM in 2035 if no adaptation measures were implemented. According to the exploitation scenarios, by 2035, the unmet water demand will rise to 56.11, 31.58 BCM. No mitigation strategy was used in the scenarios of rapid population expansion and rising irrigation demand. There is no way that adjustments to socioeconomic and climatic change scenarios may lead to a serious scarcity of water in the Thal Doab. The unmet water needs are projected to drop to a significantly lower level under the possible management scenarios. In order to effectively plan water resources and ensure food security, the what-if scenarios technique may be used to assess the current and forecast water demand/supply situation in various basins throughout the world.

Discussion

Water shortage impacts 120 million individuals, in Pakistan during times of the year. It is noteworthy that 85% of these individuals reside in the Indus Basin illustrating the seriousness of this issue (Mekonnen and Hoekstra 2016). Pakistan is among the dry nations with a meager 15% yearly river flow capability for water storage (Janjua et al. 2021). By 2010, Pakistan's per capita water availability has dropped from 5,260 m3 in 1951 to 1,050 m3 (Bhatti and Nasu 2010). By 2025, there will be an estimated 32% water deficit, which would result in a 70 million tons food scarcity (Marsily and Abarca-del-Rio 2016). An important part of Pakistan's agricultural economy is the groundwater sector. It was projected that climate change will have extremely negative economic repercussions on Khyber Pakhtunkhwa (KPK) province agriculture. The Indus Basin Irrigation System (IBIS) is expected to experience increased scarcity due to the effects of climate change on river flow, especially in the downstream regions where river flows are decreased during the dry season. The rising temperatures and decreasing rainfall in the area will have an impact on farming practices. The Pakistan Agricultural Research Council has recognized that improving agricultural efficiency in Pakistan faces several challenges, with water management being one of the top priorities for reforms among six identified areas (Aslam 2016). Pakistan, a lower riparian nation, would have less access to water as a result of India's construction of various water storage facilities on transboundary rivers. Water security will be the focus, in the coming years. The Pakistan Water and Power Development Authority (WAPDA) has proposed upgrading the waterways throughout IBIS with the goal of reducing water losses by 5 million acre-feet (MAF)(Ahmed et al. 2007). After considering scenarios of climatic changes, we conducted an analysis to suggest practical water management practices and policies, for both current and future water supply needs.

A comprehensive study on water demand was conducted to ensure sustainable water supply in the future, utilizing various management and exploitation scenarios. Initially, the study determined the water demands of each sector in the research region. Subsequently, it identified the potential impacts of exploiting factors such as rapid population growth, increasing irrigated land, and the effects of climate change. The study then formulated multiple management plans aimed at mitigating these impacts, including strategies to reduce water usage across industries.

In one scenario with a 3.5% high population growth rate, the estimated water demand in the UIB was found to be 56.11 BCM. This highlights how external factors such as population growth and climate change are influencing the future water demand in the region. Rapid population expansion, coupled with rising irrigation needs and the effects of climate change, has led to a consistent increase in water demand. The study underscores the urgency of implementing effective water management strategies. One proposed approach involves integrating water resource modeling to inform policies, including both exploitation scenarios and future management plans. To determine the optimal management strategy for the research region, a comprehensive analysis was conducted, comparing various scenarios (refer to Fig. 13). This thorough examination enables the identification of the most suitable approach to address the region's water management needs. Toure et al. (Ahmed et al. 2007) conducted this study, while Saraswat et al. (Saraswat et al. 2010) utilized the WEAP model to estimate water demand in the Klela Basin, situated in Mali. The researchers considered socioeconomic and climate change scenarios. Projected that water consumption would increase from 76 million cubic meters (MCM) under the reference scenario to 224 MCM by the year 2050 (Saraswat et al. 2017) observed similar findings in a research done in Kathmandu Valley. The research focused on integrated urban water management under various circumstances. They discovered that a 6% rise in population will raise water consumption from 135 to 150 L per capita per day.

Conclusion

In conclusion, the simulation and analysis of water demand indicates a significant increase from 35.74 BCM in 2020 to 60.28 BCM in 2035 under the reference scenario. The high population growth scenario further amplifies this demand, reaching 62.96 BCM by 2035, particularly driven by increased domestic water needs. The study underscores potential water shortages if no changes are made to the water supply system. Implementing a 15% reduction in domestic water consumption, through education and technology, proves effective in mitigating demand, reducing it to 51.23 BCM by 2035. For agriculture, a 3% growth in irrigated land leads to increased water demand, reaching 56.37 BCM by 2035. However, by adopting water conservation strategies and improving irrigation efficiency, a 50% reduction in agricultural consumption is achievable, showcasing the impact of technological advancements and farmer awareness. The comparison with a lower population growth scenario reveals a contrasting trend, with a decrease in water demand to 49.11 BCM by 2035. This reduction is attributed to a lower population growth rate and decreased per capita water consumption, emphasizing the importance of demographic factors in water demand projections. In summary, the findings thus emphasize the critical role of population growth, water conservation strategies, and technological interventions in shaping future water demand scenarios. Consideration of these factors is crucial for sustainable water management and averting potential shortages.

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Data availability The datasets generated and/or analyzed during the current study are not publicly available due to privacy reasons but are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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Consent to participate Not applicable.

Consent for publication Not applicable.

References

Ahmad M, Stewart JP, Podger GM (2018) Modelling the surface water allocations and deliveries in the world's largest continuous irrigation system, Indus Basin Pakistan. Geophys Res Abstr 20:2018–1633

Ahmed A, Iftikhar H, Chaudhry GM (2007) Water resources and conservation strategy of Pakistan. Pak Dev Rev 46(4):997–1009. https://doi.org/10.30541/v46i4iipp.997-1009

Akbar M, Khan SA, Dilawar S, Hassan MT (2021) Water crisis in Pakistan: prospects and implications. PalArch's J Archaeol Egypt/egyptology 18(1):4884–4892

Alcamo J, Flörke M, Märker M (2007) Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrol Sci J 52(2):247–275. https://doi.org/10.1623/hysj.52.2.247

Al-Saidi M, Elagib NA (2017) Towards understanding the integrative approach of the water, energy and food nexus. Sci Total Environ 574:1131–1139. https://doi.org/10.1016/j.scitotenv.2016.09.046

Amin A, Iqbal J, Asghar A, Ribbe L (2018) Analysis of current and futurewater demands in the Upper Indus Basin under IPCC climate and socio-economic scenarios using a hydro-economic WEAP Model. Water (Switzerland), 10(5). https://doi.org/10.3390/w10050537.

Amir P, Habib Z (2015) Estimating the impacts of climate change on sectoral water demand in Pakistan. https://www.Cyphynets.Lums.Edu.Pk/, November, p 107

Archer DR, Forsythe N, Fowler HJ, Shah SM (2010) Sustainability of water resources management in the Indus Basin under changing climatic and socio economic conditions. Hydrol Earth Syst Sci 14(8):1669–1680. https://doi.org/10.5194/hess-14-1669-2010

Arnell NW (2004) Climate change and global water resources: SRES emissions and socio-economic scenarios. Glob Environ Chang 14(1):31–52. https://doi.org/10.1016/j.gloenvcha.2003.10.006

Arnell NW, van Vuuren DP, Isaac M (2011) The implications of climate policy for the impacts of climate change on global water resources. Glob Environ Chang 21(2):592–603. https://doi.org/10.1016/j.gloenvcha.2011.01.015

Asghar A, Iqbal J, Amin A, Ribbe L (2019) Integrated hydrological modeling for assessment of water demand and supply under socio-economic and IPCC climate change scenarios using WEAP in Central Indus Basin. J Water Supply Res Technol AQUA 68(2):136–148. https://doi.org/10.2166/aqua.2019.106

Ashraf Vaghefi S, Mousavi SJ, Abbaspour KC, Srinivasan R, Arnold JR (2015) Integration of hydrologic and water allocation models in basin-scale water resources management considering crop pattern and climate change: Karkheh River Basin in Iran. Reg Environ Chang 15(3): 475–484. https://doi.org/10.1007/s10113-013-0573-9

Asif M (2013) Climatic change, irrigation water crisis and food security in Pakistan

Aslam M (2016) Agricultural productivity current scenario, constraints and future prospects in Pakistan. Sarhad J Agric 32(4):289–303

Bakken TH, Almestad C, Rugelbak JM, Escobar M, Micko S, Alfredsen K (2016) Climate change and increased irrigation demands: What is left for hydropower generation? Results from two semi-arid basins. Energies 9(3). https://doi.org/10.3390/en9030191

Bhatti AM, Nasu S (2010) Domestic water demand forecasting and management under changing socio-economic scenario. Soc Manag Syst

Birhanu BZ, Traoré K, Gumma MK, Badolo F, Tabo R, Whitbread AM (2019) A watershed approach to managing rainfed agriculture in the semiarid region of southern Mali: integrated research on water and land use. Environ Dev Sustain 21(5):2459–2485. https://doi.org/10.1007/s10668-018-0144-9

Brekke LD et al., (2009) Assessing reservoir operations risk under climate change. Water Resour Res, vol 45(4). https://doi.org/10.1029/2008WR006941

Briscoe WJ, Qamar U, Contijoch M, Amir P, Blackmore D (2005) 7._Briscoe_-_Qamar-_Pakistans_Water_Economy-Running_Dry-_Oxford_Univ_Press_2007. DC World Bank Publ., no. October, Washington

Cutlac I-M, Horbulyk TM (2011) Optimal water allocation under short-run water scarcity in the South Saskatchewan River Basin. J Water Resour Plan Manag 137(1):92–100. https://doi.org/10.1061/(asce)wr.1943-5452.0000092

Ehsani N, Vörösmarty CJ, Fekete BM, Stakhiv EZ (2017) Reservoir operations under climate change: Storage capacity options to mitigate risk. J Hydrol 555:435–446. https://doi.org/10.1016/j.jhydrol.2017.09.008

Frenken K (2012) Irrigation in Southern and Eastern Asia in figures. AQUASTAT survey—2011

Fung F, Lopez A, New M (2011) Water availability in +2°C and +4°C worlds. Philos Trans R Soc A Math Phys Eng Sci 369(1934):99–116. https://doi.org/10.1098/rsta.2010.0293

Gerten D, Heinke J, Hoff H, Biemans H, Fader M, Waha K (2011) Global water availability and requirements for future food production. J Hydrometeorol 12(5):885–899. https://doi.org/10.1175/2011JHM1328.1

Gosling SN, Arnell NW (2016) A global assessment of the impact of climate change on water scarcity. Clim Change 134(3):371–385. https://doi.org/10.1007/s10584-013-0853-x

Gupta HV, Kling H (2011) On typical range, sensitivity, and normalization of Mean Squared Error and Nash-Sutcliffe Efficiency type metrics. Water Resour Res 47(10):2–4. https://doi.org/10.1029/2011WR010962

Hassan D, Bano R, Burian SJ, Ansari K (2017) Modeling Water Demand and Supply for Future Water Resources Management. Int J Sci Eng Res 8(5):1745–1750

Hussain Y et al. (2017) Modelling the vulnerability of groundwater to contamination in an unconfined alluvial aquifer in Pakistan. Environ Earth Sci 76(2). https://doi.org/10.1007/s12665-017-6391-5

Immerzeel WW, Bierkens MFP (2012) Asia's water balance. Nat Geosci 5(12):841–842. https://doi.org/10.1038/ngeo1643

Inam A, Adamowski J, Prasher S, Halbe J, Malard J, Albano R (2017) Coupling of a distributed stakeholder-built system dynamics socio-economic model with SAHYSMOD for sustainable soil salinity management—part 1: model development, vol 551. Elsevier B.V. https://doi.org/10.1016/j.jhydrol.2017.03.039.

Janjua S, Hassan I, Muhammad S, Ahmed S, Ahmed A (2021) Water management in Pakistan's Indus Basin: challenges and opportunities. Water Policy 23(6):1329–1343. https://doi.org/10.2166/wp.2021.068

Kara A, Schwentick T (2011) Expressiveness of hybrid temporal logic on data words. Electron Notes Theor Comput Sci 278(1):115–128. https://doi.org/10.1016/j.entcs.2011.10.010

Khan S, Rana T, Gabriel HF, Ullah MK (2008) Hydrogeologic assessment of escalating groundwater exploitation in the Indus Basin, Pakistan. Hydrogeol J 16(8):1635–1654. https://doi.org/10.1007/s10040-008-0336-8

Khan F, Pilz J, Ali S (2017) Improved hydrological projections and reservoir management in the Upper Indus Basin under the changing climate. Water Environ J 31(2):235–244. https://doi.org/10.1111/wej.12237

Khan AJ, Koch M, Tahir AA (2020) Impacts of climate change on thewater availability, seasonality and extremes in the Upper Indus Basin (UIB). Sustain 12(4). https://doi.org/10.3390/su12041283

Kirby M, Ahmad MD, Mainuddin M, Khaliq T, Cheema MJM (2017) Agricultural production, water use and food availability in Pakistan: Historical trends, and projections to 2050. Agric Water Manag, 179:34–46. https://doi.org/10.1016/j.agwat.2016.06.001

Laghari AN, Vanham D, Rauch W (2012) The Indus basin in the framework of current and future water resources management. Hydrol Earth Syst Sci 16(4):1063–1083. https://doi.org/10.5194/hess-16-1063-2012

Lutz AF, Immerzeel WW, Kraaijenbrink PDA, Shrestha AB, Bierkens MFP (2016) Climate change impacts on the upper indus hydrology: Sources, shifts and extremes. PLoS ONE 11(11):1–33. https://doi.org/10.1371/journal.pone.0165630

Mangoro DS (2021) Assessment of the Rangitata River basin's food-energy-water nexus under a changing climate using WEAP: a thesis submitted in partial fulfilment of the requirements for the Degree of Master of Water Resource Management at Lincoln University. Lincoln University

De Marsily G, Abarca-del-Rio R (2016) Water and food in the twenty-first century. Remote Sens water Resour, pp 313–337

Matonse AH et al (2013) Investigating the impact of climate change on New York City's primary water supply. Clim Change 116(3–4):437–456. https://doi.org/10.1007/s10584-012-0515-4

Mekonnen MM, Hoekstra AY (2016) Sustainability: four billion people facing severe water scarcity. Sci Adv 2(2):1–7. https://doi.org/10.1126/sciadv.1500323

Moss RH et al (2010) The next generation of scenarios for climate change research and assessment. Nature 463(7282):747–756. https://doi.org/10.1038/nature08823

Mugatsia EA (2010) Simulation and scenario analysis of water resources management in Perkerra catchment using WEAP model. Masters Thesis, Dep. Civ. Struct. Eng. Sch. Eng. Moi Univ. Kenya, December 2010

Mukhopadhyay B, Khan A (2015) A reevaluation of the snowmelt and glacial melt in river flows within Upper Indus Basin and its significance in a changing climate. J Hydrol 527:119–132

Mohd Firdaus Hum NN, Abdul Talib S (2016) Jurnal Teknologi Modeling water supply and demand for effective water management 5:15–20

Nepal S, Shrestha AB (2015) Impact of climate change on the hydrological regime of the Indus, Ganges and Brahmaputra river basins: a review of the literature. Int J Water Resour Dev 31(2):201–218. https://doi.org/10.1080/07900627.2015.1030494

Oki T, Kanae S (2006) Global hydrological cycles and freshwater resources. Science 313(5790):1068–1073

Olmstead SM (2014) Climate change adaptation and water resource management: a review of the literature. Energy Econ 46:500–509. https://doi.org/10.1016/j.eneco.2013.09.005

Rajbhandari R, Shrestha AB, Kulkarni A, Patwardhan SK, Bajracharya SR (2015) Projected changes in climate over the Indus river basin using a high resolution regional climate model (PRECIS). Clim Dyn 44(1–2):339–357. https://doi.org/10.1007/s00382-014-2183-8

Rayej M (2012) California Future Water Demand Projections (WEAP Model): Implications on energy demand

Saraswat L, Bhattacharya S, Maheshwari A, Bhattacharya S (2010) Maternal and perinatal outcome in women with threatened miscarriage in the first trimester: a systematic review. BJOG an Int J Obstet Gynaecol 117(3):245–257

Saraswat C, Mishra BK, Kumar P (2017) Integrated urban water management scenario modeling for sustainable water governance in Kathmandu Valley, Nepal. Sustain Sci 12(6):1037–1053. https://doi.org/10.1007/s11625-017-0471-z

Shah ZUH, Ahmad Z (2015) Hydrochemical mapping of the Upper Thal Doab (Pakistan) using the geographic information system. Environ Earth Sci 74(3):2757–2773. https://doi.org/10.1007/s12665-015-4463-y

Shaikh IA, Wayayok A, Bin Abdullah AF, Soomro AM, Mangrio M (2015) Assessment of water application losses through irrigation surveys: a case study of Mirpurkhas Subdivision, Jamrao Irrigation Scheme, Sindh, Pakistan. Indian J Sci Tech 8(11):1–15

Van Steenbergen F, Basharat M, Lashari BK (2015) Key challenges and opportunities for conjunctive management of surface and groundwater in mega-irrigation systems: Lower Indus, Pakistan. Resources 4(4):831–856. https://doi.org/10.3390/resources4040831

Stewart J, Podger GM (2018) Indus river system model (IRSM)—a planning tool to explore water management options in Pakistan

Tahir AA, Chevallier P, Arnaud Y, Neppel L, Ahmad B (2011) Modeling snowmelt-runoff under climate scenarios in the Hunza River basin, Karakoram Range, Northern Pakistan. J Hydrol 409(1–2):104–117. https://doi.org/10.1016/j.jhydrol.2011.08.035

Vörösmarty CJ et al (2010) Global threats to human water security and river biodiversity. Nature 467(7315):555–561. https://doi.org/10.1038/nature09440

Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global water resources : vulnerability from climate change and population growth contemporary population relaglobal water resources : vulnerability from climate change and population growth contemporary population relative to demand per dischargetive to D. Sci 289(5477):284–288

Wiltshire A et al (2013) The importance of population, climate change and CO2 plant physiological forcing in determining future global water stress. Glob Environ Chang 23(5):1083–1097. https://doi.org/10.1016/j.gloenvcha.2013.06.005

Xu B et al (2009) Black soot and the survival of Tibetan glaciers. Proc Natl Acad Sci U S A 106(52):22114–22118. https://doi.org/10.1073/pnas.0910444106

Yaqoob A (2016) Climate change and institutional capacity in the Indus Basin. Spotlight Reg. Aff., 10(10)

Yates D et al (2009) of the Sacramento Basin, California. J Water Resour Plan Manag 135(October):303–313

Yu C et al (2013) “The way forward”, Routledge Libr. Ed Linguist Mini-Set A Gen Linguist 1–11:180–200

Zhang Z, Balay JW (2014) How Much is Too Much?: Challenges to Water Withdrawal and Consumptive Use Management. J Water Resour Plan Manag 140(6):1–3. https://doi.org/10.1061/(asce)wr.1943-5452.0000446

Zohrabi N, Nassaj BN, Shahbazi A (2017) Evaluating the impacts of improving irrigation efficiency on water resources system reliability. In: The 85th annual meeting, ICOLD