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Advancing Water Security and Agricultural Productivity: A Case Study of Transboundary Cooperation Opportunities in the Kabul River Basin

Yar M. Taraky , Ed McBean, Andrew Binns and Bahram Gharabaghi *

School of Engineering, University of Guelph, Guelph, ON N1G 2W1, Canada; ytaraky@uoguelph.ca (Y.M.T.); emcbean@uoguelph.ca (E.M.); binns@uoguelph.ca (A.B.)
* Correspondence: bgharaba@uoguelph.ca; Tel.: +1-(519)-824-4120 (ext. 58451)

Abstract: The Kabul River Basin (KRB) is witnessing frequent flood and drought events that influence food production and distribution. The KRB is one of the world's poorest regions regarding food security. Food security issues in the KRB include shifts in short-term climate cycles with significant river flow variations that result in inadequate water distribution. Due to the lack of hydro-infrastructure, low irrigation efficiency, and continuing wars, the Afghanistan portion of the KRB has experienced low agricultural land expansion opportunities for food production. This research assesses the relationship between flood mitigation, flow balances, and food production and, cumulatively, assesses the social and economic well-being of the population of the KRB. SWAT modeling and climate change (CCSM4) implications are utilized to assess how these relationships impact the social and economic well-being of the population in the KRB. The intricacies of transboundary exchange and cooperation indicate that the conservation of ~38% of the water volume would nearly double the low flows in the dry season and result in the retention of ~2B m^3/y of water for agricultural developmental use. Results show that the peak flood flow routing in reservoirs on the Afghanistan side of the KRB would have a substantial positive impact on agricultural products and, therefore, food security. Water volume conservation has the potential to provide ~44% more arable land with water, allowing a ~51% increase in crop yield, provided that improved irrigation efficiency techniques are utilized.

Keywords: flood management; water security; food security; agricultural production; Kabul River Basin; Afghanistan

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1. Introduction

The Kabul River Basin (KRB) is overpopulated due to the six major cities in the basin, with populations of 50,000 people or more in each city. Kabul, the capital of Afghanistan with a population of ~5 million [1], is the largest city, followed by Peshawar in Pakistan, with a population of ~2.5 million; these cities and four others in both Afghanistan and Pakistan have been experiencing chronic food shortages in recent years.

On the other hand, there are severe water shortages during the low flow seasons that predominantly occur for three main reasons: (a) climate change results in flows with more extreme seasonality, seen as extreme peak flows and low flow events ([2,3]); (b) a lack of hydro flood routing structures such as reservoirs, barrages, and irrigation canals to store and direct the excess water; and (c) concentrations of the population in locations such as Kabul, Jalalabad, and Peshawar, where water needs exceed water availability.

Hydrologic extremes play an essential role in water shortages, where flooding is a frequent climate event in this region, and droughts have occurred in the basin approximately once per decade in the past century [4]. Water security and availability directly impact the quantity of food produced in the KRB. The low flow season between October and March in Afghanistan is the second season of cultivation in the eastern province of Nangarhar, Afghanistan, and most areas of Khyber Pakhtunkhwa (KPK) of Pakistan. Hence, the cropping seasons in the KRB represent an opportunity for water sharing and food exchange that must be seized. Environmental and climate variations often impact transboundary arrangements and water resource management. An example of water resource allocations based on an ecosystem approach via the international watershed initiative, in which multiple factors led to the formation of new institutional arrangements, is the Great Lakes Water Quality Agreement (GLWQA) [5].

Recent studies (Mayar [6]; Samaya, [7]; and Taraky [8]) have reported on the frequent flooding and drought in the KRB, and the impacts of these events on people and infrastructure have been quantified. Other studies have focused their emphasis on the evaluation of flooding events that have already occurred in the KRB; these studies include Sayama [7], Khattak [9], Mayar [6], Farooq [10] Mehmood [11], and Khan & Nafees [12]. While these studies have provided important pathways for quantifying the hydrologic trends, considerable research is still required to connect the relationships between the flow regimes and food production within the basin. The current seasonal flow regimes in these agricultural lands entail higher-than-usual flows from April through September and significantly lower flows between October and March. The crop seasons in the downstream parts of the KRB are extending into the winter months.

Considering these opportunities, several international agencies have studied the possibilities of regional connectivity initiatives, including water resource development in the KRB. In this respect, the World Bank, in 2010, developed a comprehensive document focused on enhancing the potential for agricultural production in the Afghanistan portion of the KRB [13]. The report proposed the construction of several large and small dams on the Kabul River and its tributaries to help meet the increasing water demands for agriculture. This strategic scoping document of the World Bank concluded that water retention infrastructure will facilitate meeting the potential for increased agricultural land utilization, increasing food production in Afghanistan, and encouraging transboundary cooperation [2,13]. The Food and Agricultural Organization of the United Nations (FAO) 2024 report on the state of food security and nutrition emphasizes the need for increased food production to meet the rapidly razing demand [14].

The KRB has experienced land use changes and increases in cropland, grassland, and water bodies, while forest and snow/ice cover are declining [15]. In contrast, the agricultural land use changes were less than ~10%. Land use change is important in hydrologic processes, including hydrologic extremes [16]. Land use is changing rapidly on Pakistan's side of the KRB due to population growth along the various streams. The GDP share of agriculture in Pakistan is ~20%, and over ~50% of Pakistan's labor force is engaged in the agricultural sector [17]. There have been increases of ~47% in agricultural land expansion in the Khyber Pakhtunkhwa (KPK) Province of Pakistan during the past 30 years due to water retention and population growth within the province. The issues of self-sustained food production and sufficiency have proven to be essential survival mechanisms that are closely related to water security and irrigation efficiency [18–20])

Since there are numerous studies focused on the hydrologic assessment of the KRB, this research uses the results of the quantitative study of the KRB in terms of flood frequencies under various GreenHouse Gas (GHG) emission scenarios and the construction of reservoirs by donor agencies to address the social and economic impacts of the changing factors related to water resource sharing in the KRB.

This study investigates the following objectives:

(1) The analysis of the modeling results of hydrologic studies and the comparison of the baseline flow regime and the future climate change-impacted flow regimes with the baseline agricultural productivity in KRB;
(2) The analysis of the application of the baseline flow regime and the flow under future climate scenarios, as well as the future demands for agricultural products, to determine the future agricultural production and transboundary exchange with regard to future water availability;

(3) The investigation of agricultural land expansion and food production trends in the Afghanistan and Pakistan portions of the KRB.

2. Materials and Methods

2.1. Study Area

The KRB, with an area of 101,000 km^2, is a shared basin between Afghanistan and Pakistan. The KRB's land use is primarily made of mixed grassland and vegetated barren land, and the remaining ~30% of the land area is covered by mountains, forestry, and glaciers [21]. Soils in the KRB predominantly have a high permeability structure and, thus, enable high vertical infiltration during intense precipitation in the KRB; however, the soils are covered with terrestrial lacustrine sediments [22], followed by loess underlain by sand and gravel aquifer layers [9]. Over 80% of the irrigation (on both sides of the KRB) uses surface water resources [23]. Figure 1 depicts the location of the transboundary Kabul River Basin.

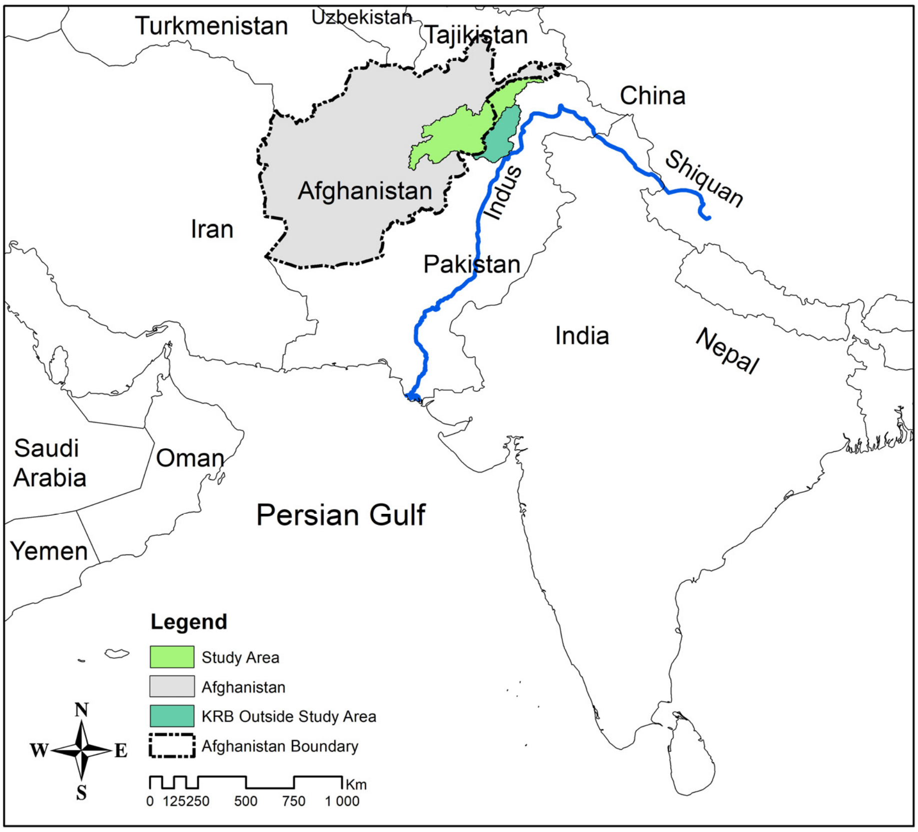
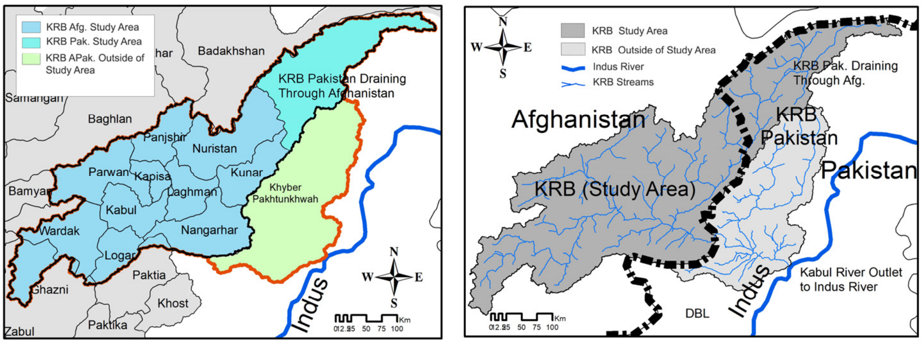


Figure 1. Location of the Kabul River Basin.

The KRB is made up of 11 provinces in Afghanistan and 1 province in Pakistan. However, the population density on Pakistan's portion (~35 million) is significantly higher than on the Afghanistan side of the KRB, with ~11 million people. A portion of the Pakistan side includes a watershed that flows into Afghanistan from the Chitral region of the Kunar River, which joins the Kabul River near Jalalabad Afghanistan, just before the entire river re-enters Pakistan at Dakah, in the Laalpur district of Afghanistan (see Figure 2).



(**a**) (**b**)

Figure 2. (**a**) The KRB's administrative and economic regions; (**b**) the study area and the flow direction.

Over 20 million people live along the banks of the Kabul River Basin [24]. The Kabul River is ~700 km long and has over a dozen small and large tributaries (see Figure 3). Several rivers, such as the Logar, Panjshir, Alengaar, and Konar join the Kabul River in Afghanistan territory. Other rivers, such as the Bara, Swat, Kalpani, and Jindi Rivers join the Kabul River in Khyber Pakhtunkhwa (KPK) as schematically depicted in Figure 3.

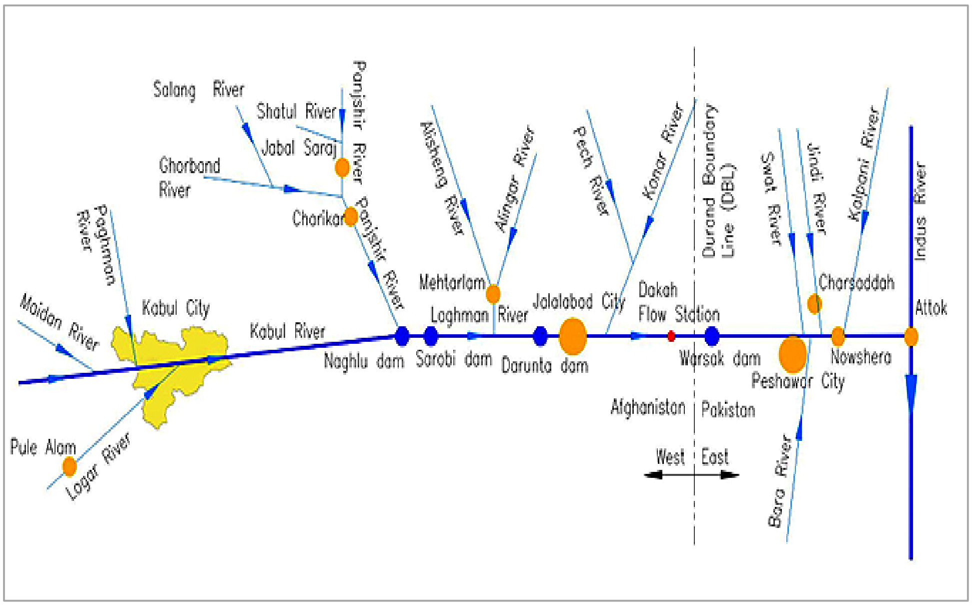


Figure 3. The Kabul River's schematic direction and its tributaries.

The land cover is changing gradually, with glaciers retreating, grazing land and agricultural land turning into urban land, and new agricultural land emerging on the outskirts of the urban centers. The KRB climate and aridity maps indicate that the KRB land area is ~48% semi-arid land, ~32% moist–sub-humid land, ~8% dry–sub-humid land, and ~12% humid land. Cropland on the Afghanistan side of the KRB is ~9%, with only ~2% expansion over the past 25 years [25]. With an annual average precipitation rate of ~459 mm [16,26], an annual average temperature of ~8 °C, and an increasing meltwater supply from the continuing glacier retreat, the KRB is expected to have adequate water resources for the coming decades.

2.2. Data Availability

This study builds from the hydrologic modeling results on flooding and drought events as forecast under the future (GHG) emission scenarios of Representative Concentration Pathways (RCP 8.5 and RCP 4.5) in the KRB. Afghanistan has built more than 70 weather stations since the mid-1930s, although the quality of the obtained data is poor due to prolonged wars. The simulated weather data, such as temperature, precipitation, wind speed, solar radiation, and relative humidity, from 1979 to 2014 were obtained from the National Centres for Environmental Prediction (NCEP).

Climate Forecast System Reanalysis (CFSR) data were used for SWAT modeling in the KRB. CFSR is a global data collection mission that started in 1979, involving the collection of global, high-resolution climate data from coupled atmosphere–ocean–land, surface–sea, and ice systems. CFSR is considered one of the most accurate data sets, providing the best estimate of the state of the climate, in a high resolution, over a large scale and a prolonged period [27].

CFSR is designed to provide state-of-the-art coupled domains over a specified period. The CFSR global atmosphere resolution is ~38 km (T382), with 64 levels. The global modeling is 0.25° at the equator, extending to a global 0.5° beyond the tropics, with 40 levels. The CFSR variable parameters enable the analysis of climate changes due to multiple factors (https://climatedataguide.ucar.edu/), accessed from 1 January 2020 to 30 June 2020. The scattered, measured data from ten flow stations in the KRB were obtained from the Ministry of Energy and Water of Afghanistan. Due to data divergences, only the data from 2007 to 2015 from the ten flow stations were used. These were organized for calibration purposes, along with the global weather data over the same period.

The regression analysis findings from the simulated and measured data showed satisfactory results, indicating that the average coefficient of determination was 0.71 for precipitation and 0.76 for the temperature at the ten climate stations [14]. Geospatial data such as a 30 m resolution DEM, soil data, land use data, and the GIS data of the stream network, basin boundary, climate change, hydrometric stations, and existing and potential dam sites were obtained during the research process. The existing and future water demands for irrigation and other uses were determined based on various data from the Ministry of Energy and Water (MoEW) and the Ministry of Agriculture Irrigation and Livestock (MAIL) of Afghanistan. In contrast, the proposed reservoirs' hydraulic features were determined based on the MoEW of Afghanistan and the World Bank's (2010) data.

The productivity data were obtained from the World Food Organization (FAO) and the Ministry of Agriculture Irrigation and Livestock of Afghanistan (MAIL). The FAO studied irrigation and food production in 2013 and identified several areas of food growth in the KRB [28]. This study connects the results of the FAO food price index with the findings using the Soil–Water Assessment Tool (SWAT) modeling results that quantified the flow under different (GHG) emission scenarios under existing and future conditions with and without proposed reservoirs.

2.3. Methods

For the purposes of this study, two sets of data were considered:

(1) Hydrologic data simulation under different GHG emission scenarios for the KRB and considering various routing reservoir scenarios.

(2) Food production data and practices in the KRB that were obtained from the Ministry of Agriculture Irrigation and Livestock (MAIL) of Afghanistan and the analysis of the water conservation with the food production scenarios under these circumstances.

The Soil–Water Assessment Tool (SWAT) hydrologic mapping of the KRB was conducted under 30 case scenarios, the three remaining quarter centuries until 2099, and the cases of existing historical flow conditions and proposed routing reservoirs, as proposed in Table 1. The study used the SWAT modeling tool, ArcGIS, and different statistical tools [16]. SWAT modeling also considered the existing irrigation water use on the Afghanistan side of the KRB and future water consumption due to irrigation water use under future scenarios with no reservoirs.

Table 1. Peak flows for the current and future emission scenarios and reservoir scenarios.

RCP GHG	Return Period (Year)	Peak Flow 1 (m^3/s) Historical 1990–2014	Peak Flow 2 (m^3/s) CCSM4 2025–2099	Peak Flow 3 (m^3/s) CCSM4 2025–2099
4.5	2	2078	2506	1875
	5	2726	3799	2560
	10	3217	4777	3077
	25	3707	5750	3562
	50	4355	7049	4280
	100	4846	8027	4798
8.5	2	2078	2795	1842
	5	2726	4199	2691
	10	3217	5261	3333
	25	3707	6664	4181
	50	4355	7726	4823
	100	4846	8788	5465

Daily rainfall and temperature data for the baseline and future periods of the KRB were accessed for six high-resolution (0.25°) Global Circulation Models (GCMs) from the 5th Coupled Model Inter-Comparison Project (CMIP5), the Regional Integrated Multi-Hazard Early Warning System's (RIMES) portal (RIMES 2019). After the careful analysis of the expected changes in seasonal temperatures over each quarter century from 2025 onwards compared to the 1990–2014 baseline data for the six GCMs in the KRB, the climate data from the CCSM-4 GSM for the KRB were used to study the climate change impact of flow regimes in the basin. Global Circulation Models (GCMs) of high spatial and temporal resolutions were employed to develop climate change scenarios. This involved the use of daily rainfall and temperature data for the baseline and the future periods of the KRB for six high-spatial-resolution (0.25°) GCMs from the 5th Coupled Model Inter-Comparison Project (CMIP5), the Regional Integrated Multi-Hazard Early Warning System's (RIMES) portal (RIMES, 2019).

The simulated weather data (precipitation, temperature, solar radiation, wind speed, and relative air moisture) were generated from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR). CFSR was started as a global data collection mission in 1979, collecting global, high-resolution climate data from coupled atmosphere–ocean–land, surface–sea, and ice systems. The CFSR global atmosphere resolution is ~38 km with 64 levels. With these variable parameters, the modeling strategy described herein provides a unique assessment strategy, by which to estimate the impacts of changes in the Earth's climate; it has been applied to a highly controversial area which has long suffered huge obstacles to the resolution of the long-standing issues in this complicated area of the world.

The SWAT model was set up based on the available geospatial data of the Digital Elevation Model (DEM) of the KRB, the 30 m projected NED DEM, the National Land Cover Database (NLCD), land cover data (land use), and soil data (soil use). Only the KRB portion within Afghanistan and the Konar River (located in Pakistan), with their joint outlet located near Dakah (Laalpur, Nangarhar Province), were used in this study to delineate the main river channels in the KRB. The delineation resulted in 301 sub-basins. A total of 1949 HRUs were created for the KRB SWAT model, with an average HRU area of 39.5 km^2. Five elevation bands were made in each sub-basin, based on the DEM, to account for the vertical variation of the climate in the mountains.

The SWAT model is a widely used model for simulating water management scenarios in agricultural watersheds. It also assists in predicting the environmental effects of differences in inland use, land management practices, and climate change. In this research, the SWAT model was developed for the KRB using geospatial data, including the 30 m projected NED DEM, the National Land Cover Database for land use, and soil data specific to the KRB. This research focused on the KRB region in Afghanistan and a part of the Konar region in Pakistan, to identify the primary river channels in the KRB. As a result, a total of 301 sub-basins were delineated. To address the vertical climate variations in the mountains, five elevation bands were created for each sub-basin, based on the DEM.

For the purpose of calibration, the 1990–2014 historical data were used, with the future periods being 2025–2049; 2050–2074; and 2075–2099. The datasets employed the daily time-series historical data of six GCMs for 1990–2014 and the future periods of 2025–2049; 2050–2074; and 2075–2099. The analyses included the change of precipitation rates and temperatures on both an annual and a seasonal basis. The changes in the average annual precipitation and temperature for 2025–2049, 2050–2074, and 2075–2099, compared to the 1990–2014 baseline data, for the six GCMs in the KRB are summarized in Table 1.

The demand for current and future agricultural products was analyzed, based on the flow data from the SWAT model. The methodology in this study includes the co-examination of the relationships between the increased and balanced flow with agricultural productivity. The historical and future flow data were then analyzed with current and future agriculture and food data under existing and future population scenarios.

Major international donors and governments have also studied the socio-economic perspective of the KRB (WB 2010). Food security, while an attribute of the people's entitlement as per the Sen's theory [29], is directly linked with water availability and distribution. The intricacies of water conservation and distribution directly impact economic development and agricultural productivity. The relationship between water conservation and food production is direct, but the magnitude of the relationship for different regions shows how future water conservation can respond to more food production. For example, water diplomacy has been a point of contention between Turkey, Iraq, and Syria, although food exchange and socio-political dominance overshadowed water diplomacy due to the over-withdrawal of water by Turkey without an international reaction [30]. The relationship between the amount of water conserved in the reservoirs and efficient irrigation measures may not have a linear impact on the food quantity produced in the same region.

The SWAT model's results, the agricultural data analysis for the KRB, and the results of the current and future irrigation water demand and land expansion provide a quantifiable account of the relationships between the water availability and food production perspectives. This research also considers food exchange scenarios that may impact the well-being of the population in the basin. The results will provide recommendations on the informed and equitable utilization of water resources in the KRB.

3. Results

The modeling results in the KRB under most climate and reservoir scenarios show steady-to-increased flow due to glacier melt (+17.5% by the end of the century) and precipitation [8,31–33]. The provision/construction of water retention structures, such as reservoirs and barrages, will improve the flow balancing throughout the year.

The effects of climate change and the proposed dams on peak flood flows are presented in Table 1. The three peak flow scenarios presented in Table 1 include the Peak Flow 1 scenario that includes the historical flows with the existing dams; Peak Flow 2, with the existing reservoirs as well as the future flows and the future water demands (the Community Climate System Model version 4—CCSM4 climate data); and the Peak Flow 3 scenario, with both the existing and proposed reservoirs and the future flows and the future water demands (CCSM4 climate data), under RCP 4.5 and RCP 8.5.

With the total discharge of ~38 B m^3/y to the Indus River at Attock [34], the KRB's flow will remain steady or increase under various (GHG) emission scenarios. On the other hand, the flood seasons generate excessive amounts of water, as shown in the Peak Flow 2 scenario. A graphical presentation of the peak flow and the potential for volumes that can be conserved is highlighted in Figure 4.

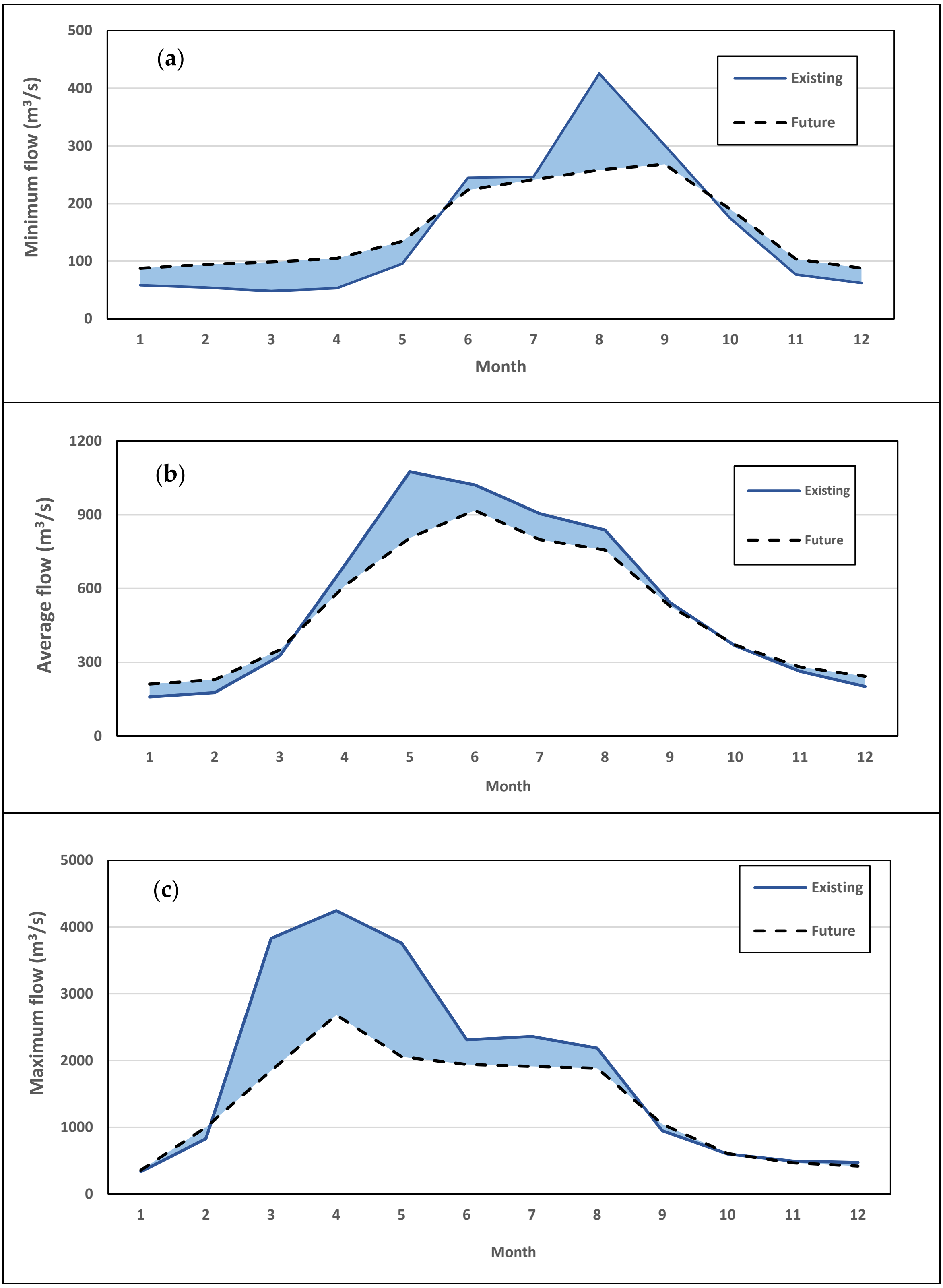


Figure 4. Flow volume conservation potentials under (**a**) minimum, (**b**) average, and (**c**) maximum flow conditions at Dakah Station. The volume of water that can be conserved under future conditions is shaded in blue.

The frequencies and the duration of flood flows and low flows, as well as their relationship with crop yields, are important economic and social indicators and constitute parts of the equitable water resource management principles for the KRB. As calculated by Maletta [35], future expansions of crops in Afghanistan will depend on larger planted areas, increasing yields per hectare, and/or both. In this case, both indicators depend on the amount of water available during the agricultural seasons.

In Table 1, with the 25-year return period with no storage provided, there is likely to be a ~35% increase in the Kabul River's discharge from Dakah station. Under the same return period, considering the CCSM4 climate data and the proposed reservoirs, ~38% of the excess water volume could be stored. This will constitute the conservation of ~3500 Mm^3/y of water, which is sufficient for the irrigation of over 350,000 ha of land over the next 25 years.

The results indicate that 38% of the peak flow waters may be stored in the reservoirs under RCP4.5 and will serve to increase the low flows between ~40% and 118% during the dry periods under most of the climate and emissions scenarios. The KRB's glacier depletion under RCP 4.5 and RCP 8.5 by the end of the 21st century will allow the meltwater to be used for irrigation to offset the current and future needs for food production in the KRB.

The results in Table 2 indicate that future flows with existing reservoirs (Peak Flow 2) will demonstrate an increase in flow volumes under all of the emission scenarios and return period scenarios. With the introduction of reservoirs that will retain ~2000 Mm^3/y, the flow rates will stabilize to the current historical flow rates under most of the emission scenarios.

Table 2. Agricultural expansion due to water availability in the KRB (Afghanistan).

Period	Irrigation		Urban		Total		Agriculture Expansion (Afghanistan)	
	Option 1 (Mm^3/y)	Option 2 (Mm^3/y)	Option 1 (Mm^3/y)	Option 2 (Mm^3/y)	Option 1 (Mm^3/y)	Option 2 (Mm^3/y)	Option 1 (ha)	Option 2 (ha)
Increase in water demand compared to the existing demand (Mm^3/y)							Increase in ag. land (ha)	
2025–2049	109	217	53	162	162	379	11,937	23,765
2050–2074	206	542	132	320	338	862	22,561	59,358
2075–2099	315	1084	241	538	556	1622	34,498	118,716
Increase in water demand compared to the existing demand (%)							Increase in ag. land (%)	
2025–2049	4.1	8.1	94.6	289	5.9	13.9	4	8
2050–2074	7.7	20.3	236	571	12.4	31.6	7	19
2075–2099	11.8	40.6	430	961	20.4	59.5	11	34

Water conservation is partly able to attain high volumes of water during the peak flows that occur on a bi-annual basis. The results show that under the existing and proposed dams with the future water demand scenarios, using the CCSM4 climate model data, all of the reservoir construction scenarios will result in flood reductions (Table 2, see Peak Flow 3).

As an example, the 25-year return period under RCP 4.5 shows 3707 m^3/s flow in the historical period between 1990 and 2014. The 25-year period between 2025 and 2099, with no added reservoirs, shows 5750 m^3/s. This represents a 2043 m^3/s flow increase from historical flows but with no added reservoirs. When water is retained for agricultural and urban use during the same future period, the flow is estimated to be 3562 m^3/s, which is 145 m^3/s less than the historical flows.

The same conclusion can be assumed for all of the pre- and post-reservoir cases under all of the emission scenarios. In the case of "no action" in the future, the comparisons indicate a 61.9% increase in flooding in a 50-year return period (RCP4.5) and a 56.4% increase in flooding in a 50-year return period (RCP8.5) under existing reservoirs and future flow scenarios, and, hence, flooding will increase under the current water retention situation, assuming future climate change according to RCP 4.5. This is the volume of water that can be stored for agricultural use (see Table 1).

The reduction in the peak flow volumes of ~2000 Mm^3/y shows the effect of flood routing, which will increase the water availability for existing and future agricultural lands.

These analyses predict that water conservation and the equitable redistribution of water resources will lead to up to 165,000 ha of additional agricultural land receiving irrigation water within the KRB, producing a crop yield of ~560,000 tonnes/y of wheat equivalent. This represents a potential ~41% increase in agricultural land. The current population of the Pakistan portion of the KRB is over three times that of the population of the KRB on the Afghanistan side. According to Pakistan's Census Centre, the population of the KPK between 1998 and 2017 increased by 78%, to 38 million people [17]. Studies by Iqbal [32] predict that the agricultural land in the KPK will increase by ~25% in the next two decades. The pace of population increase on the Afghanistan side of the KRB is ~2.9% annually [36]. The KRB in Afghanistan is also impacted by the inflow of refugees, which makes this region densely populated. In contrast, the agricultural land expansion on the Afghanistan side of the KRB is lagging for multiple reasons due to the continuing civil war, the lack of investment in infrastructure, and poor governance. Crop production in Pakistan has increased by ~34% between 1961 and 2011 due to water availability and better irrigation techniques [37]. The crop production on the Afghanistan side of the KRB stagnated between 1992 and 2002 due to poor food production results and low agricultural land expansion (~10%).

Under mid–high-efficiency irrigation, a 1 ha area of land will require ~9133 m^3 of water per year [36] (WB 2010). However, in some instances, high-efficiency irrigation will require less water, as predicted by Amini (5372 m^3/h) [38]. Over 80% of this water comes from surface intake. With a predictable increase of ~25% in agricultural land area in Pakistan (Iqbal 2018), and assuming modernization and efficient agricultural business practices, the future water demands for all of the existing and future agricultural lands in the KRB in Afghanistan and Pakistan will be ~5200 Mm^3/y, which shows a ~23% increase from the current water available for irrigation. This will require the availability of an additional ~1.5 Bm^3/y of water for irrigation due to new agricultural land expansion. However, this volume of water will only be available if water security measures are implemented, which would be possible if the peak flow volumes are reduced and stored in reservoirs for further redistribution throughout the year.

Flow volume by itself is not an economic indicator. A higher flow volume at the same time as a lower irrigation water demand is wasted water. The flow volume at the Attock junction to the Indus River shows that any given flow of 2000 m^3/s and higher causes flooding and, hence, ~40% of the water volume to be wasted. Considering the minimum and maximum flows at the Attock station under future emission scenarios with no future reservoirs, the water conservation potentials for the peak flow months are shown in Figure 4, showing higher volumes of water during peak flows in the high flow seasons that have the potential to be retained. The ends of the graphs show that the lowest flows under the future reservoir scenarios can increase between 40% and 118%.

4. Discussion

4.1. Water Stress Impact on Food Security

A report from the United Nations Food and Agriculture Organization (FAO) acknowledged the water stress worldwide [39]. The same report indicates that the South Asia region (where the KRB is located) will experience a higher level of water stress in agriculture than the worldwide water stress of 18.5% of total water availability, as predicted by the FAO. The study results show an annual water wastage of ~42% in the KRB due to floods and seasonal peak flows, indicating that water stress can be addressed by adopting an array of measures, including water conservation in the reservoirs, improving irrigation methods, redistributing water resources within the basin, and avoiding water-intensive crops such as cotton.

The purpose behind introducing the reservoirs is to (a) re-route the floodwater for later irrigation use, (b) conserve higher-volume waters that otherwise would flow out from the basin, and (c) produce the necessary electricity for the population and industries in the basin. The difference between the low flow and the high flow adequately corresponds to the volume of water stored in the reservoirs. The minimum flow during the low flow season is less than 50 m^3/s, while the maximum flow during the high flow season is more than 2000 m^3/s [8]. While hydropower plants are generally developed to cater to local and domestic energy needs, some plants can have transboundary dimensions when they harness potential sites along transboundary waters [40]. Another aspect is the introduction of joint water retention initiatives such as the friendship dams and hydropower generation sites that have been practiced around the world [41].

Considering the debate about Afghanistan's rights to use its water resources, several international agencies such as the World Bank Group, Toosab, RECS International Inc., Yachiyo Engineering Co., Ltd., CTI Engineering International Co., Ltd. and Sanyu Consultants Inc. joined forces and worked with the government of Afghanistan to conserve around 5000 Mm^3 of water in 14 reservoirs and barrages. Since Afghanistan's geography is best suited for establishing small and large dams due to the natural mountainous terrain, some studies have proposed the locations for the proposed reservoirs and barrages in their feasibility studies. The list and storage capacity of the proposed reservoirs are shown in Table 3.

Table 3. Proposed reservoirs and their storage capacity in the KRB (Afghanistan).

No.	Proposed Dam	Irrigation Major Purpose	Installed Storage Capacity (Mm^3)
1	Barak	Irrigation/Hydropower	390
2	Panjshir 1	Irrigation/Hydropower	1130
3	Konar_A	Irrigation/Hydropower	1010
4	Totumdara	Irrigation/Hydropower	340
5	Baghdara	Irrigation/Hydropower	330
6	Konar_B	Hydropower	48
7	Laghman_A	Irrigation/Hydropower	288
8	Sarobi -II	Hydropower	128
9	Kama	Hydropower	48
10	Haijan	Irrigation/Hydropower	200
11	Gat	Irrigation/Hydropower	440
12	Tangi_Wardag	Irrigation/Hydropower	300
13	Shatoot	Kabul	225
14	Kajab	Irrigation/Hydropower	365
	Total Planned Water Conservation in The Basin		5242

The contributions of agriculture to Afghanistan's gross domestic product (GDP) are between 23% and 25%, while the labor force engaged in this sector is around 61.6% of Afghanistan's total labor force [42]. The current and future trends in agricultural land expansion in both portions of the KRB are shown in Figure 5.

In small watersheds, water security is assessed using various methods, such as Water Security Status Indicators (WSSIs) [43]; however, in large river basins, water security can be linked to food security and, therefore, to the economics of food and water in the basins.

The KRB, as the most populated basin in Afghanistan and the second-most populated region in Pakistan, is marked by food security issues. According to the FAO, more than half (54.5%) of Afghanistan's people live below the poverty line, and 53.2% of the country's total population is food insecure, and 35% (or more than 11 million people) are at risk of acute food insecurity [44,45]. The food and nutrition situation in Afghanistan has shown a decline since 2012 and has reached a critical benchmark following the takeover of power by the Taliban in 2021.

On the other hand, food prices accelerated from 2006 onward [19]. According to the FAO Food Price Index (FPI), food prices are also increasing across the globe (see Figure 4). Food prices have accelerated due to the COVID-19 outbreak and supply chain disruption in 2020 and 2021. The year 2022 was marked by higher inflation due to regional conflicts and disruption continuing in grain transportation. According to the FAO, food prices have nearly doubled from 2016 (the food prices in 2016 are taken as a 100), as shown in Figure 6.

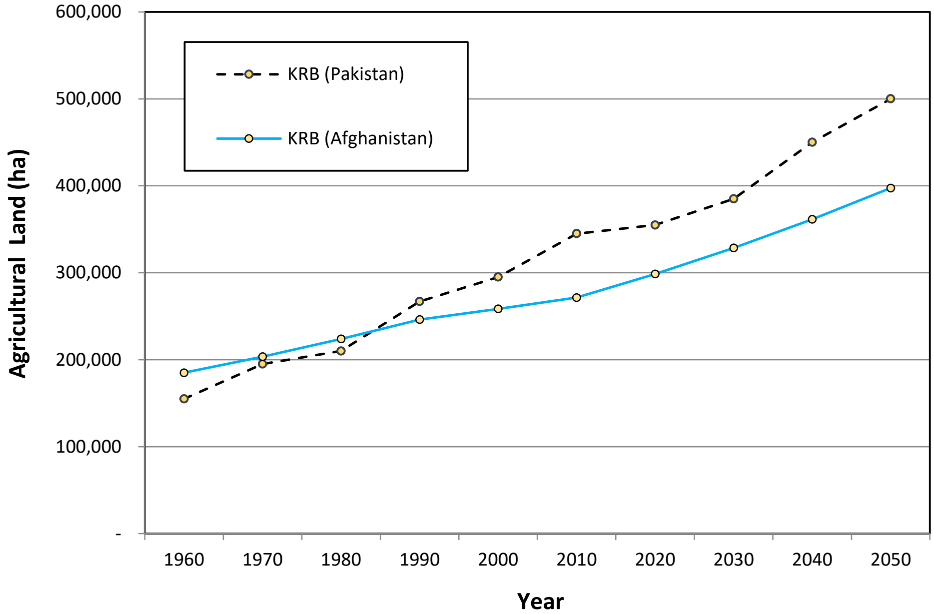


Figure 5. The KRB's estimated agricultural land increase (ha) (1960–2050).

A cooperative environment in water resource redistribution by itself may not necessarily amount to better food exchange. Transboundary crop exchange and cooperation are the other requirements for the KRB's food security. As a Best Management Practice (BMP), it is important to study the river basin from an issue and theme perspective, rather than from a river basin and boundaries perspective [46]. This study's results from 30 climate and reservoir scenarios indicate that water conservation would allow water needs to be met for the expansion of agricultural lands by ~1.2 Bm^3/y and represent an increase of ~34% more than the current water needed for irrigation. This volume of water is sufficient to irrigate up to 160,000 ha of land on both sides of the KRB. However, it is noted that a substantial increase in the land available for irrigation does not necessarily mean the same percentage increase in agricultural productivity due to low irrigation efficiency, poor water conservation infrastructure, and challenges in food transportation and exchange. Additionally, agricultural productivity may be increased exponentially by adopting improved technology and innovative methods [47] for food harvesting and, most importantly, adopting a basin approach to a transboundary environment [46].

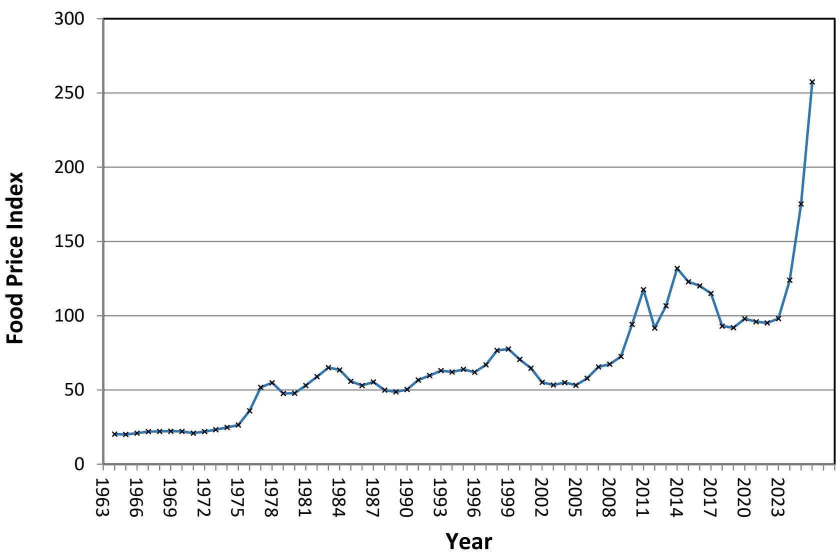


Figure 6. FAO food price index [14].

Many scholars predict that with more agricultural land expansion, water availability from groundwater sources, and the construction of new, small- and medium-sized reservoirs, Pakistan will meet the demand for food by 2050 [37]. This optimistic statement is based on Pakistan's food production trend between 1960 and 2010. The current consensus is that Pakistan should utilize groundwater resources to meet the growing demand. With the new realities of lower growth, inflation, and flooding in 2022 in Afghanistan and Pakistan, it is highly unlikely that both countries will have their food baskets filled in the next decade. Utilizing groundwater resources will require time and financial resources that neither country possesses. The population growth trends in Afghanistan and Pakistan are not slowing down. With the average population growth of ~2%/year in both Afghanistan and Pakistan and the inflow of migrants from rural areas to the cities, food production estimates may not meet the needs of the population by 2050.

The issue of crop selection, including the use of low-water-demand crops, is something both countries could successfully implement to reduce water usage. Adopting better and more efficient irrigation practices, along with less-water-intensive crops (namely, removing cotton from the agenda), can positively impact water utilization.

Another aspect of water conservation is irrigation efficiency, which can be identified as a counterargument to the routing reservoirs. Irrigation efficiency means reducing water wastage and increasing agricultural productivity. Studies show that up to 66% of the water dedicated to irrigation can be saved with the use of proper irrigation efficiency techniques. The efficiency techniques proposed by the MAIL include Bubbler irrigation, Terrance irrigation, and Drip irrigation. The KRB, with its steep terrain and mountainous landscape, is well suited to all of these methods, including the Terrance irrigation. However, considering the cost of irrigation efficiency techniques and the country's economic situation, these methods may not be possible to implement by the local farmers.

Irrigation canals with watertight floors and sides can be a cheaper and more doable option for Afghanistan's agriculture. Afghanistan's main construction material is stone, which can provide a good medium for irrigation canals. Watertight, narrow irrigation canals can provide water conservation. With the average annual temperature of about 8 °C, the KRB evaporation index is lower compared to other basins in Afghanistan. Improving irrigation efficiency using watertight canals can provide additional water resources but may not compete with the volume of water conserved in the routing reservoirs.

4.2. The Dynamics of Transboundary Water and Food Security

The Afghanistan portion of the KRB uses ~2.74 B m^3/y of water for agricultural use. With ~80% of this volume coming from surface water resources, the surface water portion of agricultural water needs is ~2.2 Bm^3/y. The food output from this volume of water and current agricultural practices is ~627,900 tonnes/y of wheat-equivalent food in the Afghanistan half of the KRB. The wheat-equivalent food production calculation is sufficient for ~4 million people; while food imports are filling the food shortage gap for the time being, it is anticipated that the combination of the economic downturn, the long hauling costs, and population increases will likely deteriorate the access to basic food in the next two decades. Most international agencies predict that population growth will surpass the food production trends in the next 25 years if no intervention is made in the current water-sharing and agricultural production practices.

Another aspect of water and food security is the relationship between the volume of water provided for irrigation and the volume of crops harvested from the land. In many studies, this relationship is not linear. Factors such as crop water requirements and crop harvesting schedules impact water consumption. A study [48] shows the crop production and water footprint in Iran and that Iran recorded 175% crop harvest for a 122% increase in water volumes from 1980 to 210. This is a ~30% increase in crop harvesting. The crop water requirement for the first crop season in the KRB is from November to May [39]. The Kabul River high flows occur from April to August. This is the second crop season in most of the arid and semi-arid areas of the KRB. Second-season crops start in the lower plains of the KRB, predominantly based on rice and maize.

With better irrigation efficiency, the water requirements for existing and future irrigated lands will be reduced by ~30% [49]. Additionally, the subject irrigated land will be able to produce the crop based on the land productivity index per crop. An increase in agricultural land, along with the adoption of less-water-intensive crops, will reduce the water requirements for the most popular crops. Finally, fertilizers and pesticides have a role in the complex relationship between irrigation and agricultural productivity, but that is beyond the scope of this study.

The KRB's climate and aridity maps show that with balanced water distribution, agricultural lands in the semi-arid and humid regions of the KRB can be harvested for a second time in the same year. The Ministry of Agriculture Irrigation and Livestock of Afghanistan (MAIL) has reported that major KRB landmasses (Laghman, Shamali, and, partially, Logar) are not harvested for the second time in the same year due to water shortages and the lack of best agricultural practices (BAP). The relationship between crop yield, the water demand per crop, and the land efficiency index in the KRB is shown in Table 4.

Table 4. Crop yield, water demand per crop, and land efficiency index in KRB.

Culture	Harvest tonnes/ha	Water Required (m^3/y)		Harvesting Duration	Land Productivity Index
		Low Efficiency	High Efficiency		
Rice	4.5	7000	5110	5	2.4
Wheat	1.9	6500	4745	6	2.0
Maize	6.3	8000	5840	6	2.0
Beans	3.4	5000	3650	3	4.0
Soybean	12.4	7000	5110	5	2.4
Onion	21.8	5500	4015	6	2.0
Cotton	2.0	13,000	9490	7	1.8
Barley	2.0	6000	4380	5	2.4
Potato	43.0	7000	5110	4	3.0

The land productivity index is a number that indicates the multiple harvest potentials in the case of water conservation and allocation. The KRB aridity map (Figure 7), taken from the temperature distribution across the KRB, shows that ~43% of the land is predominantly semi-arid in the KRB; ~38% of the land in the KRB is moist sub-humid, and the remaining ~19% of the land is dry sub-humid and humid. The annual precipitation in the sub-humid and the moist sub-humid regions of the KRB is >500 mm, while the annual precipitation in the semi-arid areas ranges from 300–350 mm. The proposed agricultural lands will have dual cropping seasons from the outset. The study findings in this research indicate that increased water availability in low flow seasons, coupled with improved irrigation efficiency, will impact food production during secondary cropping seasons and maximize the land's output to offset future demands for food.

A balanced and basin-wide approach is necessary to adequately develop the agricultural lands and food to meet the demands of the rapidly growing population, including crop selection, irrigation efficiency, coordinated water resource utilization, flood routing, and water conservation. Water security must be an integrated approach that combines water conservation measures, the risks involved, and informed decisions to ensure safe water transfer [18,50,51]. A remedy will be required that will meet the following criteria: (a) to allow for transboundary free food transport (to both sides) through the Durand Boundary Line (DBL), (b) to adopt smart and technologically advanced irrigation systems that will produce more food and waste less water, and (c) to maintain water security equitably and responsibly.

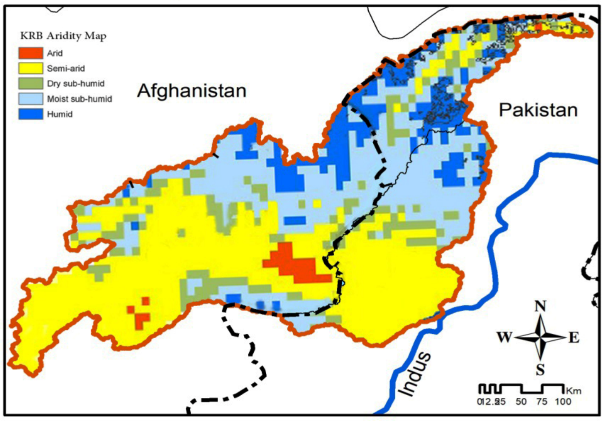


Figure 7. KRB aridity map with all of the semi-arid and dry sub-humid areas that have a land productivity rating of >2; all of the other areas have a land productivity rating of <2.

Improved food exchange between Afghanistan and Pakistan will reduce food shortages on both sides of the DBL. The chart below shows the ideal seasonal food exchange scheme, provided that both Pakistan and Afghanistan drop their hegemonic attitudes towards each other and meet the needs of the Basin's population. The seasonal fruits, vegetables, and spices exchanged between Afghanistan and Pakistan are listed in Table 5.

Table 5. KRB seasonal agricultural product exchange scenarios.

Ag. Products	Season of Crop Yield	Season	From/To → To/From ←	
			Afghanistan	**Pakistan**
Grains	Wheat, Maize, Beans, Chickpeas, Poppy seed	Fall	→	←
Rice		Summer		←
Fruit (semi-arid)	Grapes, Honey Dew, Pomegranate, Apples, Apricot, Figs, Watermelon	Winter	→	←
Fruit (tropical)	Tangerine, Grapefruit, Mandarin, Lemon, Lime	Fall	→	←
Dry Fruit	Almonds, Nuts, Pistachios, Berries, Apricots, Raisins	Winter and Spring	→	
Vegetables	Onion, Tomato, Green Beans	Spring and Summer	→	←
Spices	Black Pepper, Cardamom, Saffron, Cumin, Turmeric, Ing	Fall and Winter	→	

An important component of food exchange is the seasonality of the transboundary crop yields in Afghanistan and Pakistan. There is a ~15 °C difference in temperature over a 200–300 km stretch of land from Kabul, which impacts the agricultural work season and food distribution. With heavy snow in Kabul, the cities of Jalalabad, Peshawar, and the surrounding areas enjoy a temperature difference of ±15–20 °C, with a busy agricultural season. Fruits and vegetables are harvested in January and February in Peshawar and can be transported to Kabul and beyond in large volumes. The opposite routes of transportation can be organized in the summer, when Kabul and Logar have a temperature of ±20–25 °C, while Peshawar experiences a temperature of ±40–45 °C. Grapes, melons, and Afghan honeydews can be transported to Jalalabad and Peshawar and onward to Punjab, Pakistan, and India without hesitation.

Afghanistan, as an upstream country, however, is not the strongest player in the region to dictate its rules, as described by Harmon's Doctrine on the appropriation of water in the vicinity of its territory [52]. Afghanistan is providing water resources to its neighbors but is not able to benefit from its own resources due to multiple challenges, including a lack of security, lower technical capacities, and a shortage of funding.

Afghanistan was not invited to be a part of the Interstate Commission of the Water Coordination of Central Asia (ICWCCA), where Afghanistan holds around 40% of the rights to the Amu Darya River's water contribution to the basin. This situation complicates the application of Harmon's Doctrine, the Doctrine of Prior Appropriation, and other doctrines that are applicable to several basins where the upstream state is dictating the rules [53–55]. Following the processes for equitable water resource utilization set out under the 1997 UN General Assembly Convention and the precedents set in major conflict-torn basins can be the only way for Afghanistan to engage its neighbor [56,57]. The KRB, as an important basin through which Afghanistan is providing on average 21 Mm^3/y of water to Pakistan, represents a strong case for the country to claim its rights. However, in the current environment of hydro hegemony and water-based conflicts, the country may have strong arguments for any type of negotiations.

Global water-related challenges are numerous and multifaceted, with climate change emerging as the most pressing issue that can trigger significant socio-economic and environmental disruptions, affecting not only the availability of clean water but also agricultural productivity, biodiversity, and human health [58]. As climate patterns shift, there will likely be an increase in the frequency and the intensity of extreme weather events, such as droughts and floods. In addition to the impacts of climate change, the rapid growth of the global population poses a substantial threat to the availability of natural resources, particularly freshwater. This escalating demand can result in the over-extraction and mismanagement of water resources, further endangering ecosystems and the communities that rely on them for their livelihoods and well-being. These changes exacerbate existing tensions and conflicts over water resources, making it imperative for nations to collaborate in addressing these urgent challenges [58–60].

While in hydrological terms it is possible to quantify and distribute the water resources, it is a more complex task to govern the resources in a basin with competing interests. To effectively navigate these complex challenges, essential principles such as "equitable and reasonable utilization", "no harm", "prior notification", and "consultation" can serve as guiding frameworks for negotiations between nations that share water resources. These principles, which are rooted in established International Water Law, ensure that all parties consider the rights and needs of others while striving for the sustainable management of shared water systems. By fostering a sense of equity and shared interest, these principles encourage collaborative approaches to water governance that can benefit all of the stakeholders involved. This includes incorporating adaptive governance strategies that can respond effectively to the uncertainties brought about by climate change [56–58]. Considering Afghanistan's weaker economic and political influence, equitable water resource management can help the country to attract good will from its thirsty neighbors.

Moreover, many water-related challenges stem from deficiencies in governance and policymaking, underscoring the urgent need to enhance public and governmental awareness about the conflicts and tensions surrounding water supplies. Effective communication and education initiatives can illuminate the importance of responsible water stewardship and the consequences of inaction. Raising awareness among decision makers and the public is vital for developing a culture of sustainability and encouraging proactive measures to protect water resources. Addressing transboundary water issues requires a multidisciplinary approach that brings experts from various fields together to develop strategies to depoliticize water governance. We can create more inclusive and effective water management solutions by involving local communities and various interest groups in the decision-making processes. This participatory approach enhances the legitimacy of water governance and ensures that the diverse needs and perspectives of all stakeholders are considered [61–63].

5. Conclusions

This research has identified a connection between integrated water security and food security in the KRB. The findings indicate that the volume of water conservation and the food produced as a result of water utilization is not a linear relationship (Table 2). The conservation of ~2 Bm^3/y water will irrigate up to ~16,0000 ha of land. This area will likely produce ~560,000 tonnes/y of wheat-equivalent food. This research proposes to conserve water gradually and in consultation with the neighboring countries and to reach the 5 Bm^3/y, as proposed by various studies, including the WB Scoping report, by 2050. Since agricultural land expansion is not the only answer to the growing demand for food, it is important to increase land productivity over the years. The current wheat-equivalent food production is at a rate of ~2 tonnes/year and 9131 m^3/y of water for irrigation. An 18% reduction in water usage and a 10% increase in productivity can be ensured by adopting smart irrigation systems and less-water-intensive crop selection.

Food exchange is probably the most critical factor in food security in the KRB region. Both sides of the DBL are seasonal in terms of agricultural production scheduling. There is a ±15 °C difference in temperature over a ~250 km distance within the KRB. A harsh winter in Kabul coincides with blooming greenery in Jalalabad, Afghanistan, and Peshawar (KPK—Pakistan). While the ground is covered in snow in Kabul and Konar, vegetation, fruits, and vegetables are ready for harvest in Jalalabad and Nowshera (KPK). The tropical fruits and vegetables are sufficient for the entire KRB during the winter periods, especially when there is snow on the ground in the Afghanistan portion of the KRB. By contrast, the summer fruit and vegetable harvest from the Afghanistan side of the KRB can be exported to Pakistan and India when they experience the highest temperatures. During summer and early fall, the Afghan markets have excess fruits and vegetables. Currently, up to 35% of seasonal fruits and vegetables go unused [63], due to incorrect transboundary policies and limitations imposed either for hegemonic or financial purposes. With improved transboundary trade and food exchange policies and agreements, food shortages will be decreased by ~31%.

Water security is an important factor in food security. Water security can be ensured if an integrated approach is adopted, which entails water conservation, risk assessment and management, and informed governance considering equitable access to water and food resources. The eastern provinces of Afghanistan and Khyber Pakhtunkhwa should agree on water and food exchange. With a transboundary agreement, parties can conserve up to ~2 Bm^3/y of water or ~40% of peak flow, to be retained in reservoirs for further use during the low flow season. While both parties need to limit agricultural land, an essential factor in transboundary dynamics is safe and seasonal food passage through the DBL.

Based on the historical floods, the construction of reservoirs can be an economically justifiable decision.

This research identified close relationships between water, agricultural land productivity, and food availability in the KRB. These three components make up the prerequisites for more food on the population's tables and the nutritious living of future generations in the KRB. Ultimately, a collaborative and holistic approach to water governance will be key to addressing the pressing challenges within the KRB concerning water scarcity and ensuring a sustainable future for both nations. By fostering innovation, enhancing governance, and promoting equitable resource management, neighboring states can work together to safeguard this vital resource for generations to come.

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Data Availability Statement: Some or all of the data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request due to privacy.

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