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Integration of the Water Evaluation and Planning System Model with the Nash Bargaining Theory for Future Water Demand and Allocation in the Kabul River Transboundary Basin under Different Scenarios

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Abstract

This study provides a comprehensive examination of the water supply and demand dynamics within the Kabul River basin, a region of critical geopolitical importance due to transboundary water issues. This study highlights the complexity of transboundary water disputes and cooperation and proposes a novel approach to equitable water sharing among transboundary river basins between Pakistan and Afghanistan. This research examines the escalating water scarcity in the Kabul River basin using the Water Evaluation and Planning System (WEAP) model and the Nash Bargaining solution. A range of scenarios was conducted by considering several factors, including population growth and agricultural expansion, to predict future water allocation in the transboundary Kabul River basin. The results indicate that as demand increases and supply remains constant, unmet water demand will ultimately increase, such that significant water shortages are projected in the future if both countries continue to rely on agricultural expansion. Nash's Bargaining solution accomplished this demand-supply gap theory and addressed the issue of water allocation between Afghanistan and Pakistan. The theory presents a unique solution that distributes resources equally between actors, considering their demands. The findings indicate that water allocation could decrease to 49% for Afghanistan and 61% for Pakistan by 2040 under conditions of severe water scarcity.

Keywords: Transboundary water basin; water supply-demand gap; Water evaluation and planning; Nash bargaining solution; Kabul river basin.
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1. Introduction

Water scarcity, intensified by a 1% annual increase in global water usage over the past century, has become a central global concern.[1] This scarcity arises when water availability falls short of the demands of agriculture, industry, and other sectors.[2] The situation becomes complex when considering transboundary rivers such as the Nile, Indus, and Colorado Rivers, which support billions of people and are woven into the socio-economic and ecological fabrics of numerous countries. Recent studies have emphasized the potential for international disputes over these shared waters,[3],[4] even suggesting the possibility of wars centered on water conflicts.[5] As nations navigate the challenges presented by shared water resources, combined with diplomacy and historical rights, this issue emerges as an emerging challenge of the 21st century, necessitating coordinated, global solutions.

Climate change is greatly affecting water management worldwide, with the majority of the world's population at risk of water scarcity.[6] The expected changes in river flow patterns due to climate change, combined with factors such as accelerated glacier melt and recurring floods, are affecting

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water availability in many basins.[7] This change not only introduces hydrological challenges but also fosters social and economic interdependencies between nations, especially for downstream regions reliant on upstream water.[8] These regions are vulnerable to climate-induced changes in upstream runoff and consumption, which significantly impact downstream water stress.[9-11] Climate change intensifies these intricacies with a growing concern that climate change might increase political issues and complications related to sharing river resources. The climatic challenge's impact on transboundary water resources highlights the importance of both local and upstream rivers in determining water stress.[12]

The Kabul River basin serves as the primary source of water for both Afghanistan and northern Pakistan, both countries mainly dependent on agriculture.[13] The Kabul River is the major source of water in Afghanistan, contributing 12% annually to the country's flow. It contributes to 11% of Afghanistan's total agricultural water supply and meets 30% of irrigation water requirements even in the dry season.[14] The Indus River in Pakistan, at its Dakah discharge point, has an annual average flow of 19.35 billion m^3. Remarkably, 9.2% of this water was contributed by the waters from the Kabul River.[14] The Kunar River originates from Pakistan, and contributes around 15 billion cubic meters of water annually, which represents 71% of water in Kabul River (Afghanistan).[15] The Kabul River Basin relies mainly on its tributaries for its needs, and its significance is further enhanced by its role in industrialization and intensive agricultural growth.[13] The river enhances agriculture, power generation, and provides water to Peshawar. Moreover, it contributes in irrigation, industrial application, and hydropower generation, thereby fulfilling socio-economic needs.[16]

Historically, water allocation among transboundary regions, such as the Indus Treaty between Pakistan and India, has often resulted in new sets of challenges. For instance, dams constructed in India on rivers designated for Pakistan have created issues.[17] The Kabul River basin, crucial for irrigation and hydropower in Afghanistan and Pakistan, is a potential conflict point due to Afghanistan's proposed construction of 17 dams, potentially reducing Pakistan's water flow by up to 17%, according to the Pakistani National Daily Dawn.[13] The proposed Kalabagh dam in Mianwali, Pakistan, faces significant risks due to potential reductions, which could harm the river's ecosystem and disrupt existing irrigation systems.[18]

The Water Evaluation and Planning (WEAP) model is widely used to assess the supply and demand control plans of complicated water systems.[19] The WEAP model allows us to explore "what-if" scenarios and to predict water availability and requirements by comparing different climatic and socio-economic scenarios. For instance,[20] utilized the Hydro-Economic WEAP model to analyze the impact of increasing population growth, urbanization, and living standards on future water demand. Similarly,[21] employed the WEAP model to compare future and past scenarios for the maintenance of the Tarbela Dam.,[54] utilized the WEAP model and SWAT to predict future climatic behavior and water demand-supply scenarios in the Hongshi River basin.[19] used the WEAP model to formulate water demands for domestic and agricultural use in Punjab and Sindh until 2040 by considering 2015 as the base scenario.[22] The research utilized the WEAP model to address water scarcity in Jeddah, highlighting the need for additional resources and reduced consumption to meet future water demand. The research projected the transboundary Medjerda River needs from 2020 to 2050, exploring four scenarios, i.e. high population growth, extended climate sequence, the water year method and industrial development, to gauge both the present and future water supply and demand for Tunisia and Algeria.[23]

Several studies have attempted to address water distribution conflicts among riparian countries, demonstrating the importance and complexity of these issues.[24] As the application of Bankruptcy Theory, in particular, has proven beneficial for water allocation among riparian countries.[25] Its rules and principles are compatible for managing resource distribution under conditions of scarcity.[26-28] Bankruptcy theory is generally applied when there is no negotiation or bargaining power among the parties, whereas Nash bargaining theory is used when parties can negotiate and reach a mutually beneficial agreement.[29] Nash's Bargaining Theory offers a unique framework for identifying optimal solutions in complex scenarios like water distribution, providing a theoretical foundation for policy decisions. It has been successfully implemented to allocate critical gas supplies among provinces in Pakistan considering different bargaining weights.[30] The Euphrates transboundary river basin was examined using a two-stage allocation negotiation model (TSANM), an innovative two-stage water allocation model integrated with bankruptcy theory and the Nash bargaining solution. Nash Bargaining model allocated 30.00%, 22.00%, and 48.00% of the Tigris-Euphrates River's water resources to Turkey, Syria, and Iraq, respectively. After adjustments, the allocations were revised to 24.98% for Turkey, 21.30% for Syria, and 53.72% for Iraq.[31]

This study analyzes water disputes in the Kabul River basin, recommending a holistic, scientific, and policy-based approach to water management. It uses the WEAP model and Nash Bargaining theory to ensure equitable water distribution between Pakistan and Afghanistan, considering irrigation water demands.[32] The study evaluates, water demand in Pakistan's KRB using WEAP model and HEC-HMS, assessing supply-demand disparities for agricultural uses and Nash's Bargaining theory for practical water allocation in reduced availability and increased demand scenarios. This research presents a distinctive approach to water distribution, complementing previous efforts to address water distribution conflicts among riparian nations.[33-54] The data scarcity and the variability in hydrological and climatic conditions significantly affect the accuracy of the WEAP model's water simulations for demand and supply. Such variability initiates the uncertainty to the model. In KRB, obtaining accurate, comprehensive, and latest data can be challenging, affecting the model's predictive capabilities.

The comprehensive assessment of climate variability and Land Use and Land Cover (LULC) changes within the Kabul River Basin (KRB) has been analyzed by Ref. [42,14], Further, Ref. [32] and similar studies by Ref. [55] and [56] addressed water shortages and climatic impacts on LULC within the KRB region. However, these studies did not focus on the entire KRB region to evaluate its water scarcity and propose water distribution solutions among the riparian states. This study introduced a comprehensive solution to the challenges of transboundary water management considering the dynamic agricultural demands of riparian states. Moreover, the Kabul river is a major tributary of the Indus Basin and any change in its flow will affect the major proposed Kalabagh Dam project of Pakistan.

The practical significance of this study is ensuring that water sharing aligns with current and growing needs. The proposed solution has the potential to prevent future disputes between states such as India and Pakistan. Furthermore, by adopting this method, significant positive impacts on international relations and sustainable water sharing practices can be anticipated. The key novelty and contribution of this paper lie in its unique approach to transboundary water management. As both countries are agricultural dependent countries, this study covers the entire KRB region, offering a distinctive solution that considers the varied agricultural water demands of the basin's riparian states. This comprehensive analysis and proposed solution stand to make a significant contribution to the fields of environmental science and international relations, marking a critical step forward in the equitable and sustainable management of shared water resources.

2. Study area and dataset

2.1 Study area

The Kabul River originates from the northwest Hindukush Mountains of the Sanglakh mountain ranges in Afghanistan and flows through the Kabul to Khyber Pakhtunkhwa of Pakistan, finally joining the Indus River at the Khairabad Kund in District Attock (Fig. 1). The region lies between longitude 67.67° to 71.7° East and latitude 33.55° to 36° North and its total length is 700 Km.[34] The Kabul River basin is transboundary, comprising 76908 Km^2 of area in Afghanistan and 14000 Km^2 of area in Pakistan. Fig. 1a shows the black Durand Line as the boundary between Pakistan (green) and Afghanistan (blue) with the study area highlighted with red (Fig. 1b). Fig. 1c illustrates the elevation of the Kabul River basin ranges from 300 m at the lower outlet (blue) to 7000 m at the mountain ranges in Afghanistan (brown).[14] Major glacial masses and snow masses are found above 5000 m in elevation and below these elevations, the Hindukush Mountains are engulfed with rocks and bare stones. Furthermore, the KRB is distinguished by significant geographic variance in mean annual temperature and precipitation. Fig. 1d displays the Kabul River Basin's tributary system with the high mountain region lying in the northern region of the basin. It receives up to 1600 mm of annual maximum precipitation, with peak rainfall occurring during spring (March-May).[35] In the Kabul River Basin, topography significantly influences precipitation. Afghanistan's eastern mountains in the KRB experience more spring precipitation due to westerly winds, while its western and southwestern areas are drier.[36] In Pakistan, Gilgit in the north receives less rain due to its rain-shadow location relative to the Himalayas. However, the Himalayan foothills receive more rain from the monsoon. Further south, towards Sindh, precipitation drops as the climate becomes arid.[37]

In Pakistan, the major contributor to the Kabul River basin is the Swat River, while the Bara, Jindi, and Kalpani Rivers contribute 10% to 12% of the Indus River.[38] Snow and glacier melt generate more than 73% of the river flow in the KRB. The contribution from the upper parts of the Kabul River basin is only 2.6% mainly due to the relatively low snow-melt and precipitation in the region.[39] However, the Panjsher River in downstream adds approximately 15% of the annual flow to the Kabul River basin supplemented by the Kunhar, Chitral, and Bara Rivers. Seven major cities of Jalalabad, Charikar, Jabal Saraj, Mehtarlam, and Pule-Alam, are in Afghanistan, whereas six main cities in Pakistan are dependent on the flow in the Kabul River basin.[39] The river flows toward Pakistan from Afghanistan through the Kabul River and irrigates 11% of the area in Afghanistan.[15]

This schematic map (Fig. 2) outlines the Durand Line in red, identifying the Afghanistan-Pakistan border, with the Kabul River and its tributaries highlighted with blue colors. The green nodes indicate agricultural demand sites while red dots for water outlets. It illustrates the water distribution and management within the Kabul River basin. The Kabul River covers 12% of the region of Afghanistan and accounts for 26% of the total of Afghanistan's annual river flow.[40] Furthermore, agriculture generates more than 50% of GDP growth. Over 10% of the land in KPK is not irrigated, whereas 44% of the cropland is irrigated through the Kabul River. The Kabul River, a vital shared resource between Afghanistan and Pakistan, supports over 10% of land uncultivated, 44% of cropland uses water for irrigation, and supplies drinking water to cities like Peshawar. It also supports fisheries and local livelihoods, highlighting the need for cooperation.

2.2 Data

Our research data comes from various trusted sources. Much of our information, especially about flow data and agriculture, comes from.[14] We also used data from other authors, such as Mehmood and Saifullah. Table 1 below lists all the main data sources we used.

3. Methods

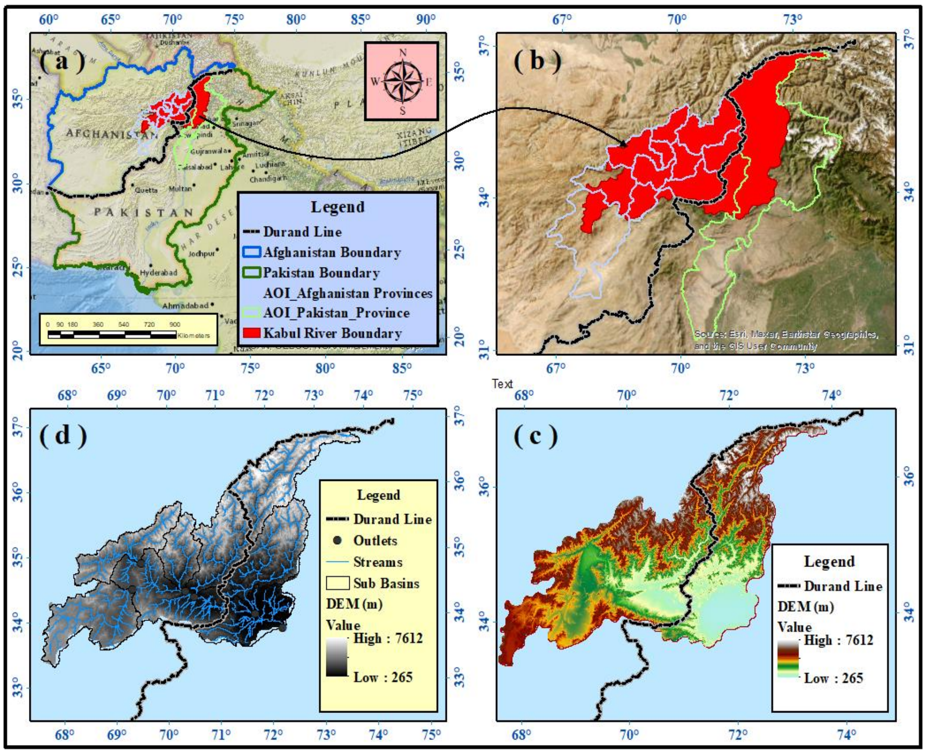

Fig. 1 Geographical location of the transboundary Kabul River Basin.
source: https://www.arcgis.com/home/webmap/viewer.html?layers=c61ad8ab017d49e1a82f580ee1298931.

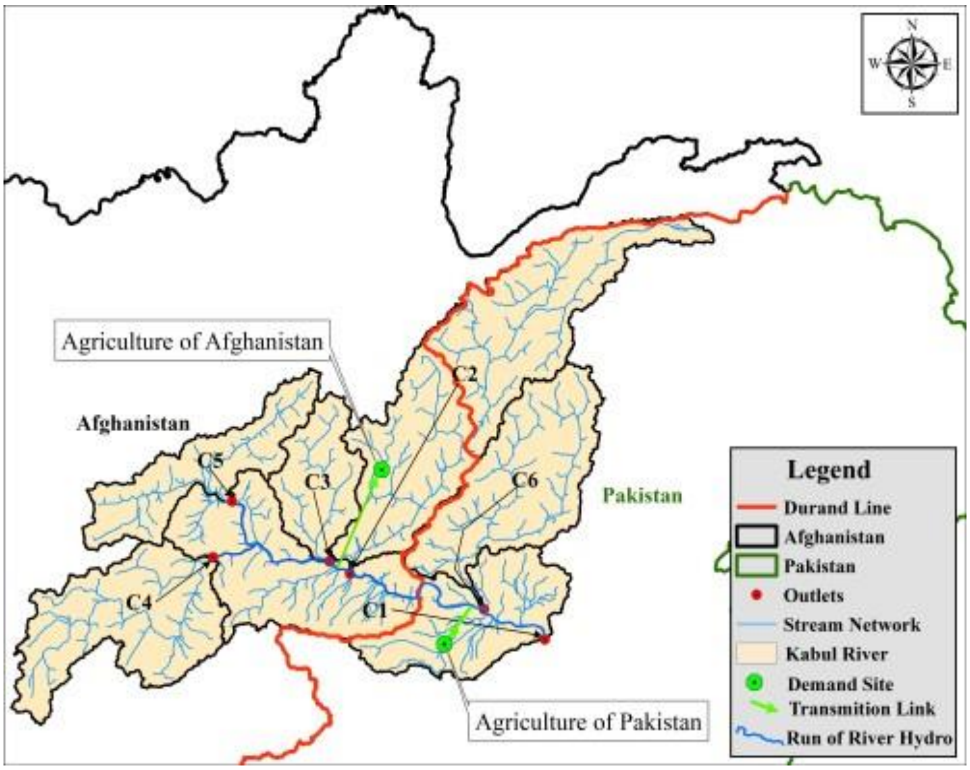

Fig. 2 Schematic view of Kabul River basin.
source: https://www.arcgis.com/home/webmap/viewer.html?layers=c61ad8ab017d49e1a82f580ee1298931

This study aims to develop and utilize the WEAP model in conjunction with the Nash Bargaining theory to determine the equivalent water resource distribution between Pakistan and Afghanistan. The proposed methodology involves four integral components: [1] delineation of the study area and extraction of the river networks in the Kabul River Basin, (ii) establishment of the current and future water supply and demand management via the WEAP model, (iii) assessment of

Table 1. List of data sources used for this study.

S. No.	Author	Data type	Citation
1	Yar M. Taraky, Yongbo Liu, Ed McBean, Prasad Daggupati and Bahram Gharabaghi	Field data	[14]
2	Yar M. Taraky, Edward McBean, Yongbo Liu, Prasad Daggupati, Narayan Kumar Shrestha, Albert Jiang and Bahram Gharabaghi	Field data	[34]
3	Asif Mehmood, Shaofeng Jia, Aifeng Lv, Wenbin Zhu, Rashid Mahmood, Muhammad Saifullah and Rana Muhammad Adnan	Field data	[32]
4	Muhammad Saifullah, Muhammad Adnan, Muhammad Zaman, Andrzej Wał˛ega, Shiyin Liu, Muhammad Imran Khan, Alexandre S. Gagnon and Sher Muhammad	Field data	[41]
5	Omaid Najmuddin, Xiangzheng Deng and Ruchira Bhattacharya	Field data	[42]
6	Sami Ullah, Muhammad Farooq, Muhammad Shafique, Muhammad Arfa Siyab, Fazli Kareem, Matthias Dees	Field data	[43]
7	Suliman Yousaf	Field data	[15]

water shortages under different scenarios and projections through 2040, and (iv) water resource allocation in both countries based on their claims and needs by using Nash Bargaining theory. The detailed methodology is outlined in the flowchart (Fig. 3).

3.1 Water Evaluation and Planning Model (WEAP)

WEAP is a user-friendly integrated software tool for planning and management, which uses a scenario-based approach to assess current and future water demand under various conditions.[44] It is a pragmatic semi-hypothetical and

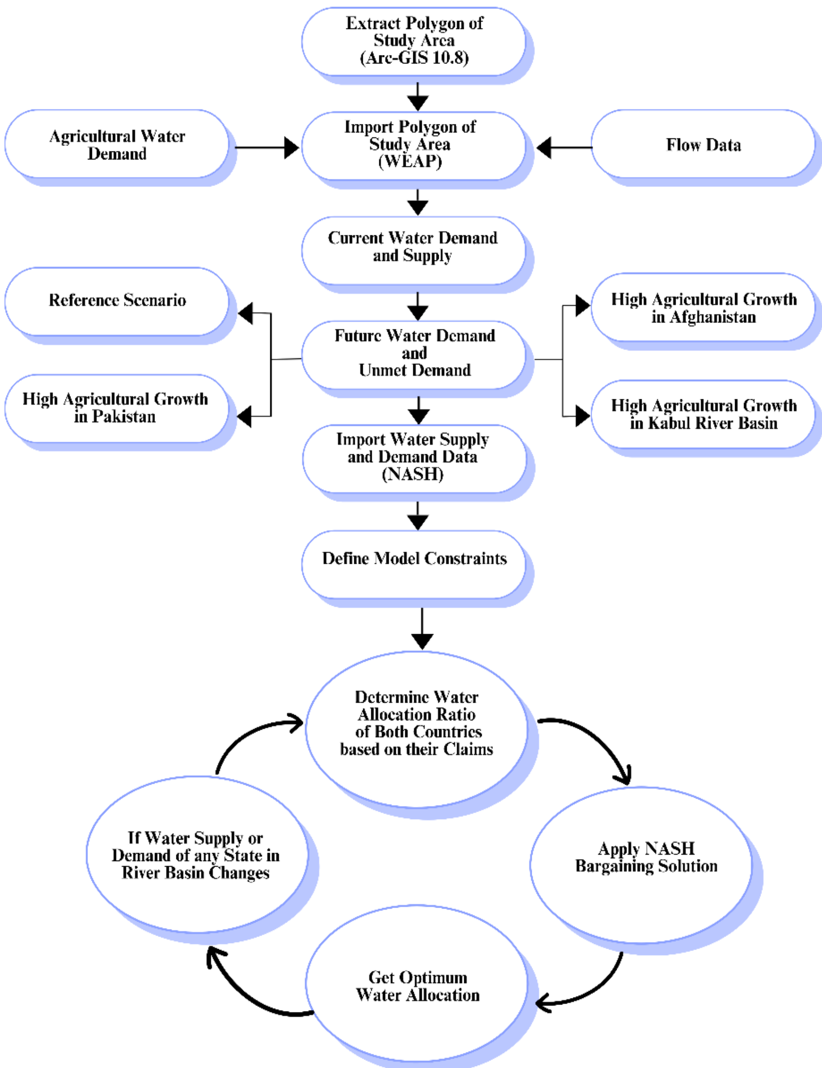

Fig. 3 Flowchart of methodology.

deterministic water resource arranging tool that integrates water supplies and calculates the requirement on the demand side. The WEAP model simulates the supply and demand of water under scenarios such as climate change, population growth, and agricultural growth for the required period.[45] The model requires the complete actual data of water availability with the demand of the current year, noted as the current account. This current account is taken as a baseline scenario with which other scenarios are compared.[46] The demand sites, dams, storage places, and canals off points are shown with nodes that further connect with the main structure through transmission links.

The study uses a WEAP model to analyze the water supply and demand in Afghanistan and Pakistan. The model considers agricultural land growth rates in 2020 and 2040, with Pakistan experiencing the highest growth rate of 4.3% in scenario-1. The model assumes that agricultural land expansion in Pakistan has increased, with Afghanistan showing maximum growth. In scenario-2, the growth rate is normal, with only Afghanistan experiencing maximum expansion by 2.3 %. The model reflects unmet water demand until 2040, highlighting the challenges in managing water supply and demand in the Kabul River basin. In scenario-3, we considered that both countries experienced maximum growth in agricultural lands. With the expansion of agricultural land, the water demand increased in the entire basin. Thus, the WEAP model reflects the unmet water demand until 2040.

3.2 Nash bargaining and calculation of weights

Nash proposed a theory to allocate resources among stakeholders or units with a strong base in the economy. Many researchers have used linear programming, Nash Bargaining theory and Bankruptcy theory for equivalent resource distribution.[47-49] Nash Bargaining theory is primarily used when limited resources are available rather than when demand is available. The supply is not enough to assure the claims and each agent gets a lower share to reduce the supply-demand gap. Therefore, this theory develops a scheme that equally distributes resources between agents regarding their claims.

The Nash bargaining equation *(4)* for water allocation is represented by parameters *N, E, c,* and *x*. *N* is the finite number of agents who claim the resource within the concerned area. *E* is the total available water resource for sharing between the states. Moreover, *c* is water claimed by each state and *x* is the water that is allocated to the state after applying Nash Bargaining theory. While applying the Nash Bargaining theory, we use disagreement points ($d_1, d_2, \ldots di, \ldots, d_n$) and Bargaining weights ($wi = w1, w2, w3, \ldots, wn$) to the riparian countries for equivalent sharing of water among countries are calculated. To resolve the conflict of resource sharing, a unique optimization solution for their needs is presented by Nash theory. The minimum water allocated to each agent is represented by ($I_1, I_2, \ldots, I_n$), which denotes the minimum benefits that any state can accept.[30] It is important to set minimum and maximum standards for water allocation that represents the significance of individual requirements. It is defined by the following equation:

$$d_i = u_i(m_i) \tag{1}$$

The Nash Bargaining Solution in distribution water resources would be to maximize the product of the differences between the allocated and claimed water for each riparian. The minimum water equation formula is given by

$$m_i = max(0, E - \textstyle\sum_{k \neq i} c_i) \tag{2}$$

Based on: $E < C$

The minimum water distribution to any of the states, mainly for those with fewer claims than others, may reach zero, if we apply the Nash Bargaining theory. In such a case, the specific riparian state will receive no share of resources. Therefore, the minimum share for each riparian is λ_i in water resource allocation. By employing the Nash Bargaining solution for water allocation, the methodology seeks an allocation that considers the claims and needs of each riparian in a manner that maximizes the collective benefit or welfare of the group, given the constraints of the available water resources.[50] This approach offers a theoretical way to distribute limited water resources among competing states fairly and efficiently:

$$I_i = max(\lambda_i, E - \textstyle\sum_{k \neq i} c_i) \tag{3}$$

The minimum need for water (λ_i) for each riparian is considered to be half of the claim of any of the riparian states. For optimization purposes, the claim of riparian states is considered as the upper core.[30] The optimization problem for water sharing under the Nash Bargaining equation is as follows:

$$Maximize\ N^w = \left(x_1^- - \left(E - \textstyle\sum_{i\in N/[1]} c_i\right)\right)^{w_1} \left(x_2^- - \left(E - \textstyle\sum_{i\in N/[2]} c_i\right)\right)^{w_2} \left(x_3^- - \left(E - \textstyle\sum_{i\in N/[3]} c_i\right)\right)^{w_3} \ldots \left(x_n^- - \left(E - \textstyle\sum_{i\in N/[n]} c_i\right)\right)^{w_n} \tag{4}$$

The above model is restricted by feasibility and independent rationality. The disagreement points and claims of riparian zones are considered as lower and upper bounds, respectively. Hence, the water-sharing optimization problem in the Kabul River basin between the two countries can be formulated as follows:

$$Maximize\ N^w = \left(x_A^- - \left(E - \textstyle\sum_{i\in N/[A]} c_i\right)\right)^{w_A} \left(x_P^- - \left(E - \textstyle\sum_{i\in N/[P]} c_i\right)\right)^{w_P} \tag{5}$$

Here, $\sum_{i=1}^{n} w_i = 1$ in equation *(5)*, and we focus on the optimization of water allocation between Afghanistan and Pakistan. Specifically, x_A^- denotes the optimized water allocation for Afghanistan, with the IP representing its lower core bound. Moreover, x_P^- illustrates the optimized water allocation for Pakistan, where I_s serves as its lower core bound. The equation's primary objective is to maximize the weighted Nash objective function, denoted as N^w.

The following constraints are considered when applying the Nash Bargaining theory.[30]

1. The water allocation to each country should be more than or equal to its lower core bound.

$$x_i^- \leq I_i, i = 1,2,\ldots,n \quad (6)$$

2. The allocation of water to each country should be less than or equal to its and more than or equal to its lower core bound.

$$I_i \leq x_i^- \leq c_i \quad (7)$$

3. The total water resources distributed between both countries should be equal to or less than the available supply of water.

$$\sum_{i=1}^{n} x_i^- \leq E \quad (8)$$

This paper used equation *(5)* to optimize water allocation between Pakistan and Afghanistan in the transboundary Kabul River basin. Equivalent water allocation is essential because of the increasing water demand. Earlier studies have emphasized equity and sustainability in water allocation,[51,52] a sentiment echoed in this research through the utilization of an optimization. The optimization model is utilized for determining the water distribution in the Kabul River between Afghanistan and Pakistan.

The study uses bargaining weights to allocate water resources between Afghanistan and Pakistan, focusing on agricultural land distribution in the Kabul River basin. It suggests prioritizing countries with higher land expansion in water allocation decisions. The analysis recommends advanced irrigation systems to conserve water resources. Currently, 34% of agricultural land in Afghanistan and 66% of agricultural land in Pakistan are cultivated, with irrigation needs of 2672Mm³/year and 1383Mm³/year, respectively.

4. Result

4.1 Assessment of water supply and demand under different scenarios

The agricultural growth of any basin continuously increases with time to meet the needs of the growing population, which results in limited available water resources. This study examines the impact of agricultural growth on water resources in the transboundary Kabul River basin. It analyzes different scenarios, considering the normal rate of expansion, to estimate future water shortages. Comparative analysis shows varying water demands in Pakistan and Afghanistan under different scenarios.

The reference scenario anticipates that the water demand will increase from 4.05 MAF in 2020 to 5.91 MAF by 2040, as shown in Fig. 4. The agricultural land of the whole basin will expand to 647,290 MAF by 2040. Based on the expansion of agricultural land, the water demand will increase from 4.05 BCM to 5.91 BCM in 2040, and the water demand will increase linearly. The results in Fig. 4 show that additional irrigation water will support increasing agricultural activities in the basin. Therefore, the unmet water demand has been growing consistently since 2020. Scenario-1 focuses on the unmet water demand in the Pakistani basin has been increasing since 2020, despite high agricultural growth in Pakistan. The water demand is expected to reach 3.21 BCM by 2040.

Table 2 provides data on water demand in relation to the growth of agricultural land for both Pakistan and Afghanistan over 2040. From 2021 to 2040, the baseline water demand will increase by approximately 43%. When factoring in high agricultural growth in Pakistan, there is an estimated 61% increase in demand. For Afghanistan, the increase is around 60%. However, when both countries experience high agricultural expansion, the combined demand surges by about 78%, highlighting the substantial water implications of agricultural practices in the region. The overall trend suggests a growing water demand in both countries, with the steepest increase observed when both Afghanistan and Pakistan experience high agricultural land growth simultaneously.

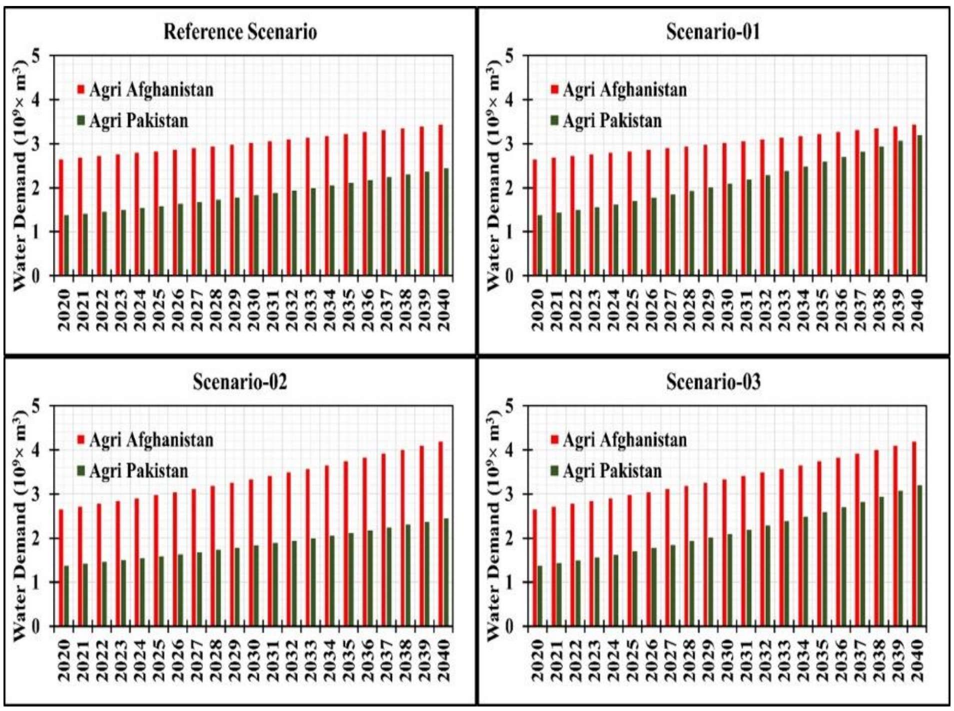

Fig. 4 Water demand of Afghanistan and Pakistan under different scenarios.

Table 2. Future water demand for irrigation in the KRB.

Year	Reference ($10^6 \times m^3$)	High agricultural land growth rate in Pakistan ($10^6 \times m^3$)	High agricultural land growth rate in Afghanistan ($10^6 \times m^3$)	High agricultural land growth both in Pakistan and Afghanistan ($10^6 \times m^3$)
2021	4130	4149	4157	4176
2025	4446	4557	4589	4701
2030	4881	5147	5195	5461
2035	5367	5844	5882	6359
2040	5909	6669	6660	7421

Table 3 shows the water requirements in Pakistan and Afghanistan under the different agricultural growth scenarios. By 2040, the reference water requirement will increase to 1844 million m³. However, with high agricultural growth in Pakistan, this area has grown to 2604 million m³, and in Afghanistan, it has reached 2595 million m³. Remarkably, if both nations simultaneously experience high agricultural growth, the demand will reach 3355 million m³. This highlights an escalating demand in the face of intensified agriculture, emphasizing the critical need for water resource management in the region.

In contrast to scenario-1, scenario-2 assumes that the agricultural land in Afghanistan is increasing by 2.3%, where agricultural growth is stable. In this scenario, the growth rate of irrigation land expansion remained unchanged. Additional agricultural land requires more water for cultivation, which results in a water shortage, and the water demand in Afghanistan will increases to 4.21 BCM by 2040. Furthermore, scenario-3 considers high agricultural growth rates both in Pakistan and Afghanistan, where the agricultural growth rates in Pakistan and Afghanistan are 4.3% and 2.3%, respectively. As both countries exhibited maximum land expansion for irrigation, the water demand in the Kabul River basin rose to 7.42 BCM. As both nations heavily rely on river water for irrigation, this scenario predicts an increase in unmet water demand. The equilibrium indicates that, at the starting point, there is no water stress, and all agricultural activities have their water needs adequately addressed. As time progresses, even though the water supply remains constant, there is a growing gap between supply and demand due to an increase in demand points. In the reference scenario, this leads to an unmet water demand reaching 2.84 BCM. This shift from a zero unmet demand in 2020 to 2.84 BCM underscores the growing strain on the water resources of the basin. This situation is exacerbated in the fourth scenario, which is highlighted in Fig. 5. Here, the unmet water demand peaks at 3.35 BCM. This pronounced increase signifies severe water scarcity, with demands far outstripping the available supplies.

Table 3. Future unmet water demands in the KRB.

Year	Reference ($10^6 \times m^3$)	High agricultural land growth rate in Pakistan ($10^6 \times m^3$)	High agricultural land growth rate in Afghanistan ($10^6 \times m^3$)	High agricultural land growth both in Pakistan and Afghanistan ($10^6 \times m^3$)
2021	75	95	102	121
2025	391	503	535	646
2030	826	1093	1140	1407
2035	1312	1789	1827	2304
2040	1844	2604	2595	3355

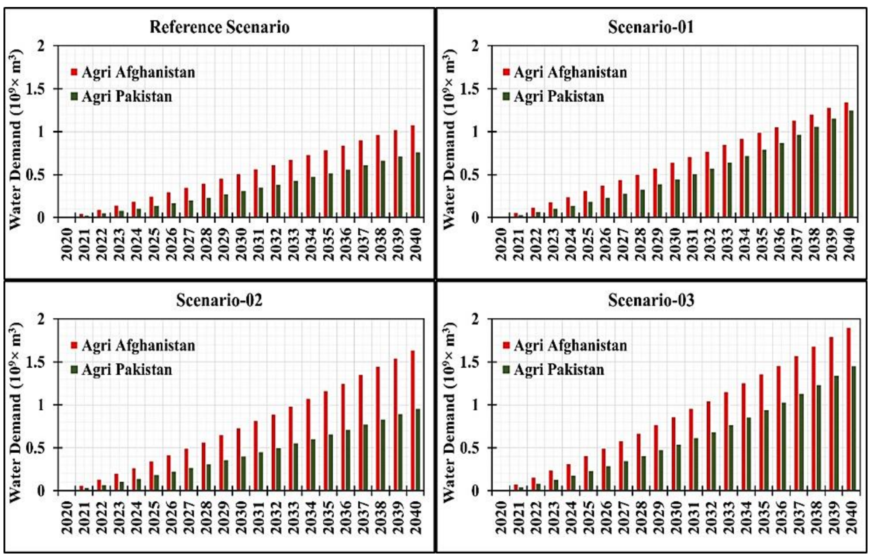

Fig. 5 Unmet water demand of Afghanistan and Pakistan in all scenarios.

4.2 Comparison of water supply and demand in all the scenarios

This research focuses on demand-side management in its exploration of various scenarios, given the planned expansion of demand points in the future. This expansion is anticipated to result in water shortages on the demand side, which in turn resulted in water shortages in the Kabul River basin. Irrigation in this basin relies on the availability of surface water/river flow and thus is under severe pressure due to extensive agricultural development under climate change. The increase in cultivated land available to meet the food security needs of the growing population eventually demands additional water, which results in an increase in water demand.

In the reference scenario, the agricultural water demand increases to 5.91 BCM from 4.055 BCM. The growth rate of agricultural land in Pakistan was 2.9%, while it was 1.3% in Afghanistan under the reference scenario. However, the results (Fig. 6) indicate that the water demand in the KRB increased to 6.67 BCM due to agricultural expansion in Pakistan. The water demand in scenario-2 further increased to 6.66 BCM. The water demand in these two scenarios will nearly become equal by 2040 due to changes in the growth rate of the regions. A high-water shortage occurs in the last scenario when both regions exhibit maximum agricultural land growth. The most critical water shortage is anticipated in the fourth scenario, which forecasts maximal agricultural land growth in both regions. Here, the water demand soars to 7.42 BCM (Fig. 6), revealing a potential severe water shortage in the future. This illustrates that the water demand will increase by 1.26% compared to that in the reference scenario in 2040. This WEAP model precisely evaluated the future availability of fresh water flow as well as the increasing demand for water resources with time in future scenarios.

All future scenarios depict increasing water shortages, emphasizing the need for strategic planning and sustainable water resource management. However, as demand escalates and supply remains static, the unmet water demand increases. In the reference scenario, the unmet demand reaches 1.84 BCM due to the continuously increasing water demand for irrigation. This shortage increases from 0.92 BCM to 2.6 BCM in the second and third scenarios, respectively. The fourth scenario indicates the most severe water scarcity, with the unmet demand escalating to 3.35 BCM. Fig. 7 depicts the comparison among abovementioned scenarios to determine severe water scarcity issues. This outcome forecasts a significant future water shortage if both countries continue their focus on agricultural expansion. In the Kabul River Basin, water scarcity may become a pressing issue in the future, particularly if agricultural activities continue to expand without corresponding increases in water supply or improvements in water use efficiency. The scenarios presented underscore the urgency and potential severity of this issue in the coming years.

4.3 Nash bargaining

The Nash Bargaining theory is applied in this study under the conditions of both equal and heterogeneous weights. Notably, surface water is the main source of irrigation water in the Kabul River basin; therefore, the bargaining weights are determined based on the agricultural land proportion in both countries. Agricultural land growth varies with time, which influences the water distribution in the Kabul River basin. The bargaining weights are determined according to the changing demands of a specific region, either by increasing or decreasing with time. As situations evolve, the bargaining weights can be adjusted, ensuring that water distribution remains relevant and equitable and maximizing overall welfare while considering the unique needs and powers of each state. The limited water resources are distributed to both countries in accordance with their needs because the supply of accessible fresh water remains constant.

Table 4 outlines water distribution projections between Afghanistan and Pakistan for 2030 and 2040 under various scenarios, using equal and bargaining weights. For 2030, Afghanistan's allocation ranges from 52.5% to 86.5%, while Pakistan's allocation spans 77.3% to 100%, depending on

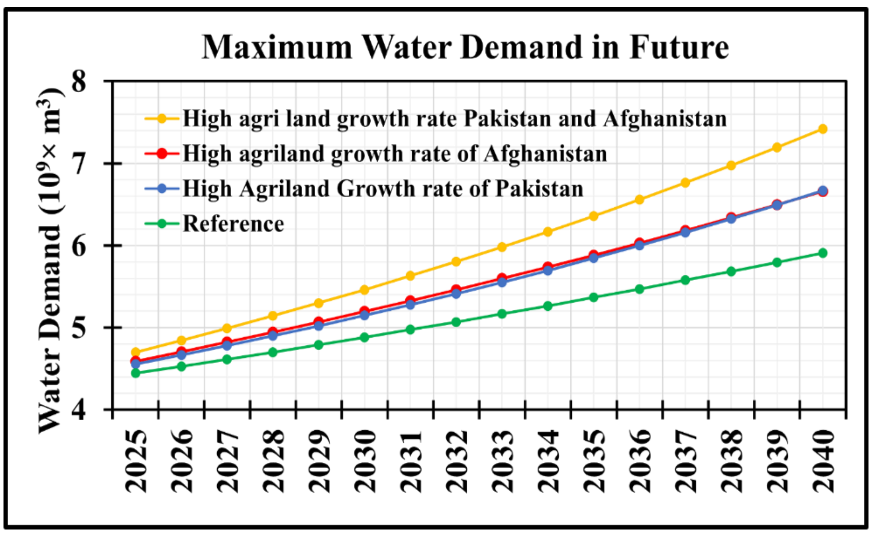

Fig. 6 Scenario comparison for maximum water demand in the future.

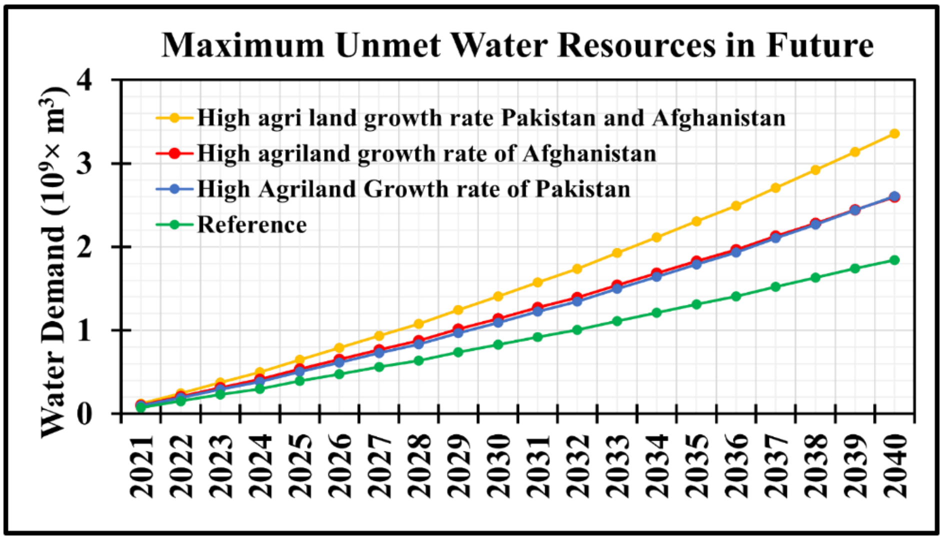

Fig. 7 Scenario comparison for maximum unmet water resources in the future.

the scenario and weight. By 2040, Afghanistan's expected share varies between 43.9% and 68.9%, and Pakistan's expected share will vary between 60.4% and 100%. The allocations fluctuate based on the chosen scenario and weighting method, highlighting potential complexities in water sharing negotiations between the two countries.

Figures 8 and 9 demonstrate that the water allocation varies under homogenous weights and after bargaining weights. Afghanistan receives less water under the condition of bargaining weights than under the scenario in which equal weights are used. The main reason is the greater agricultural land growth proportion in Pakistan; hence, more water resources are allocated to Pakistan. In countries or areas with limited agricultural land growth, the water allocation fraction is lower. The study observes variable growth rates across scenarios, with Afghanistan receiving 86.5% of its claimed share in one instance and 66% in another. Consequently, water resource allocation is not solely determined by the claims of each country but also by the rate of agricultural land growth.[53] applied this analysis and allocated water across six districts of Karachi under population growth.

The Nash Bargaining solution revealed the presence of water scarcity as allocation percentages decreased across the different scenarios. An extreme water deficiency; however, ensures that each country receives a portion of water sufficient to meet its needs. This study presents graphs of all scenarios up to 2040 and proposes a similar approach for projecting future water conditions. In conclusion, this study provides a basis for discussing and implementing future water allocation strategies between Afghanistan and Pakistan while considering the dynamic changes in agricultural land growth and water availability.

Table 4. Water allocation under equal and bargaining weights.

Year	Scenarios	Regions	Water Distribution in (using equal weights) in (10^6 × m^3)	Water distribution (using bargaining weights) in (10^6 × m^3)	Distribution in % according to claim (using equal weights)	Distribution in % according to claim (using bargaining weights)
2030	Reference Scenario	Afghanistan	2.215	2.631	72.90%	86.5%
		Pakistan	1.84	1.423	100%	77.3%
	Scenario-1	Afghanistan	1.945	2.02	63.9%	66.4%
		Pakistan	2.11	2.03	100%	96%
	Scenario-2	Afghanistan	2.21	2.22	52.5%	66%
		Pakistan	1.84	1.83	100%	99%
	Scenario-3	Afghanistan	1.944	2.08	58%	62.05%
		Pakistan	2.11	1.96	100%	92.8%
2040	Reference Scenario	Afghanistan	1.605	2.38	46.4%	68.9%
		Pakistan	2.45	1.67	100%	68.2%
	Scenario-1	Afghanistan	1.52	2.01	43.9%	58%
		Pakistan	2.53	2.04	78.8%	63.6%
	Scenario-2	Afghanistan	2.11	2.17	52.5%	66%
		Pakistan	1.94	1.88	100%	99%
	Scenario-3	Afghanistan	2.1	2.1	49.8%	49%
		Pakistan	1.94	1.95	60.4%	61%

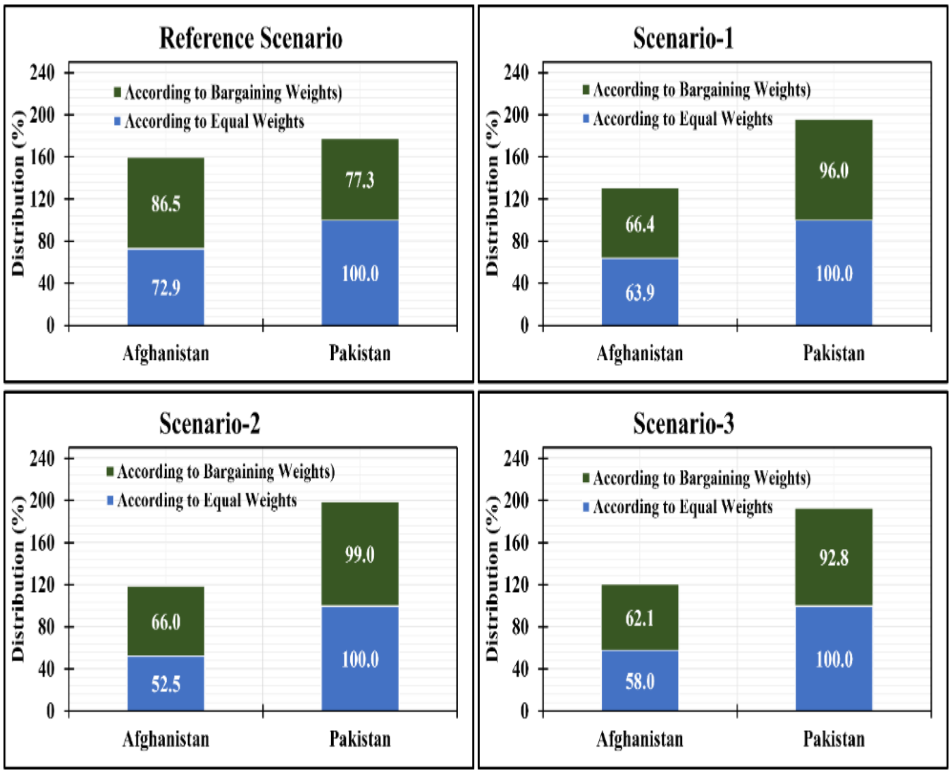

Fig. 8 Water distribution under equal and bargaining weights (NASH Bargaining results for 2030).

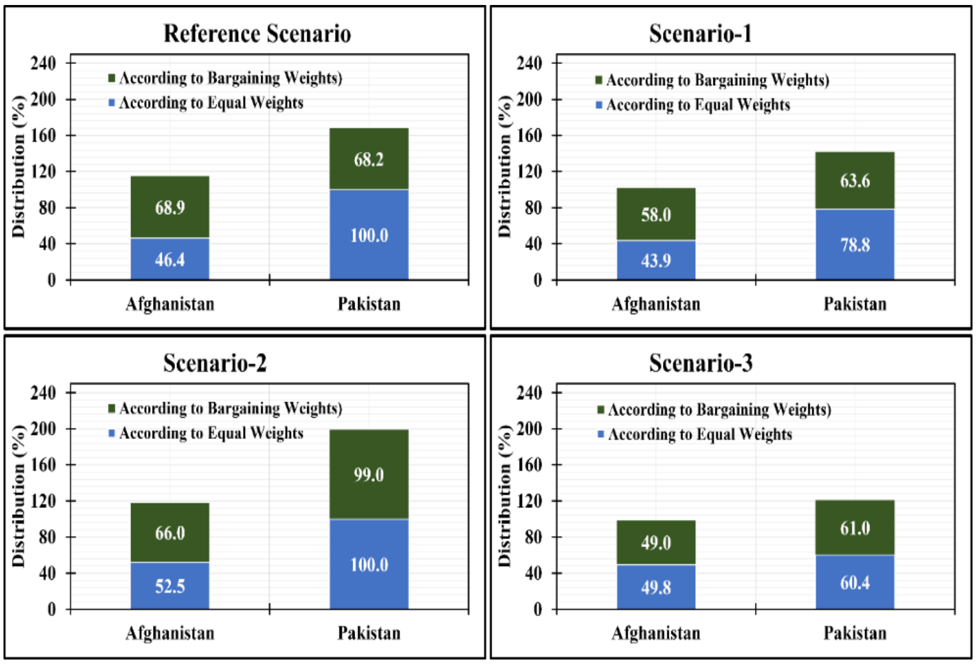

Fig. 9 Water distribution under equal and bargaining weights (NASH Bargaining Results for 2040).

5.Discussion

This research delves into the complex challenges of transboundary water disputes, with a pointed focus on the Kabul River Basin. By incorporating the WEAP model and the Nash Bargaining theory, it presents a novel methodology for navigating equitable water allocation in such contentious areas. HEC-RAS and SWAT models were applied to observe flood risks in the KRB recently.[14] This approach is particularly relevant to the global increase in water scarcity issues, situation intensified by climate change and population growth.[57,58] This study proposed the Nash Bargaining solution for water distribution among Afghanistan and Pakistan addressing the water shortage identified by WEAP, while Ref. [28] utilized similar bargaining technique employed to allocate water resources in Karachi focusing on population dynamics, this study shifts the emphasis towards agricultural growth. This pivot not only ensures a more balanced allocation but also fosters an environment of cooperation and sustainable water management.

Highlighting this research's unique contribution,[32] limited their scope to population growth and land cover variations in the KRB,[56] studied the LULC in Kabul region, Afghanistan, our study represents a step further. This research tackles an untouched terrain—evaluating water demands in the Kabul River basin, specifically catering to the often-overlooked irrigation sector. The findings of this research regarding the behavior of the Kabul River across the two states of concern underscore the escalating water demands, primarily for irrigation. These demands, relevant with the scenarios presented by Ref. [23], for the Madjerda River Basin, not only validate these study projections but also draw attention to the pronounced gap between water supply and demand. A case in point is the alarming rise in water demand, which is projected to increase from 4.15 BCM to a staggering 7.42 BCM by 2040, chiefly due to enhanced agricultural activities in the KRB. It demonstrates if the agricultural growth rate increase in the KRB, the water demand become nearly double by 2040.

Nash Bargaining theory presents a water distribution solution focusing on the claims, needs and development plans of both states. By 2030, Afghanistan will be able to meet approximately 62% of its water demand. However, this percentage is expected to drop to 49% by 2040 due to the growth of agricultural areas in the Kabul River Basin. For Pakistan, the situation starts off better, with nearly 93% of its water needs being met by 2030. But, as time goes on, this figure will decrease to 61% with increase in agricultural land. This approach aims to balance water distribution based on the changing demands and agricultural expansion of both countries.[59] This strategy is associated with that of Ref. [49], who proposed an asymmetric bargaining model for the Euphrates River Basin. The allocation strategy was predominantly based on negotiation, military power, and economic independence while this research prioritizes irrigation demands. It underscores the novelty and relevance of this research approach, which gives primacy to practical needs over geopolitical dynamics

This study uses the WEAP model and NASH bargaining theory to evaluate agricultural water demand and allocation in the Kabul River Basin, for Afghanistan and Pakistan. This study prioritizes agricultural growth while neglecting extreme weather and environmental impacts. It promotes for incorporating socio-economic, environmental, domestic, industrial and climatic factors in future studies to execute more accurate water distribution in transboundary rivers. It focuses the effectiveness of combining WEAP and Nash Bargaining for developing adaptive and inclusive water management strategies. Moreover, it recognizes that the effectiveness of Nash Bargaining can be affected by the socio-political dynamics between the two countries.[60] It encourages a more comprehensive strategy that resolves both technical and socio-political challenges in water resource management.

6. Conclusion

This research paper introduce an innovative approach for addressing anticipated water demand and challenges in the Kabul River basin by integrating the WEAP and Nash Bargaining model. The study projects potential water shortages by developing multiple scenarios to assess maximum water demand for irrigation purpose in future. It indicates the complexities of transboundary disputes. Moreover, it highlights the urgent need for a strategic approach of water sharing among Pakistan and Afghanistan, which are among the most water-stressed Asian countries. The analysis reveals an increasing demand has been observed under continuous agricultural growth. It concludes that future residents in the Kabul Basin will experience water scarcity conditions. The major key findings are summarized below.

- The water demand increase is approximately 46% from the baseline year (2020) to 2040.
- For high agricultural growth scenarios in Pakistan and Afghanistan individually, the demand increases are estimated at 61% and 60% respectively.
- Both countries when experience high agricultural expansion simultaneously, the combined demand surges by about 78%. Unmet water demand rises to 3.35 BCM by 2040, indicating severe future water scarcity.
- Highlights potential conflict between Pakistan and Afghanistan due to lack of formal water-sharing treaty.
- Applies Nash Bargaining theory to equitably distribute water resources based on demand and agricultural land proportion and allocates water based on agricultural land proportion in both countries, using both equal and heterogeneous bargaining weights to adjust shares dynamically.
- Using bargaining weights, Afghanistan's share decreases from 62.5% to 49% from 2030 to 2040. While Pakistan water share reduces from 92.8% to 61% by 2040, which indicates the water scarcity conditions in future.
- The study highlights the increasing water demand by 2040 in the Kabul River Basin, presenting equitable water distribution solution between Pakistan and Afghanistan.
- It proposes strategic water allocation model specifically for irrigation to reduce water scarcity and mitigate potential conflicts.
- It encourages to employ comprehensive models that encompass political, social, and economic factors to improve transboundary water management in future works.
- It recommends the integration of socio-economic, environmental, and climatic factors in future research to execute a more precise and effective water distribution in transboundary river systems.

In conclusion, this study significantly contribute in resolving transboundary water conflicts in KRB through strategic and equitable water distribution solutions. It sets a foundation for future research by recommending the comprehensive and cooperative strategies that include other influencing factors. By focusing on sustainable management and cooperation, it provides an effective way towards addressing one of Asia's crucial water vulnerability issues. It is adaptable for water allocation challenges across different regions, promoting enhanced sustainable management and cooperation.

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Conflict of Interest
There is no conflict of interest.

Supporting Information
Not applicable.

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