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Resolving water security conflicts in agriculture by a cooperative Nash bargaining approach

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ABSTRACT

Water scarcity is increasingly driven by socio-economic dynamics, climate change, and population growth. Conflicts among water users, including states, complicate sustainable water management, necessitating collaborative solutions. Building on important studies in water resource management, this study integrates the Water Evaluation and Planning (WEAP) model with the Nash bargaining solution to develop a fair water allocation system, which we apply to the Lower Bari Doab area of Punjab, Pakistan. This case study area is characterized by high demands for agricultural, domestic, industrial, and environmental water. To ensure fair allocation of water resources, we analyze future water trends, anticipate demands, and address supply-demand gaps under various scenarios. Our findings demonstrate that by utilizing WEAP in conjunction with the Nash bargaining solution, we can effectively achieve a balance between water demand and supply. This approach enables us to compare various water-use strategies and ensures fair distribution among agricultural stakeholders, who often have lower priority compared to the domestic, industrial, and environmental sectors. More importantly, we demonstrate that Nash bargaining solutions can be mutually beneficial and can maximize overall coverage of water demand. This approach ensures that all agents are better off compared to a non-cooperative outcome, promoting fairness and equity by balancing the needs of all parties. This integrated approach provides a robust framework for sustainable water management and is applicable to other regions facing similar challenges.

1. Introduction

Sustainable management of freshwater ecosystem services is crucial for the well-being of current and future generations. Being central to human well-being, water is a resource that is linked to a wide range of ecosystem services. These include instream water supply, extractive water supply and the provision of cultural and supporting services related to water (Brauman et al., 2007). To achieve sustainable management of water resources, it is essential that all social and natural dimensions of the human-water system are addressed (Wagener et al., 2010; Reynard et al., 2014). With rising water demands and consumption rates, nearly one-third of the world's population will face water scarcity by 2025 (Ganguli et al., 2017; Awotwi et al., 2019).

Water scarcity and its improper and inequitable allocation is a major factor restricting sustainable development, especially in agrarian-based and under-developed countries like Pakistan (Qureshi et al., 2010). This situation is further aggravated in transboundary river basins (both intra- and international), where the predominant factors driving many toward water bankruptcy are typically identified as increasing water demand from a range of regional actors, along with the repercussions of climate change (Ngounou, 2009; Madani and Hipel, 2011; Ansink and Houba, 2015). In arid and semi-arid geographical regions, the effects of these factors on the quantity of available water are notably more pronounced. Many scholars have integrated hydrological models with socio-economic models to develop water resource management solutions (Goyal et al., 2018; Nivesh and Kumar, 2018; Skoulikaris and Zafirakou, 2019; Malik et al., 2020; Peng et al., 2020; Sharafati et al., 2020; Degife et al., 2021; Xiang et al., 2021; Salman et al., 2021; Boufala et al., 2022; Fanta et al., 2022). For example, one such approach, Water Evaluation and Planning (WEAP), has been extensively employed to predict future water demands, assess the impacts of socio-economic and environmental changes, and develop strategies to address the

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supply-demand gap in shared river basins. This involves not only estimating future water requirements under different scenarios but also evaluating the effectiveness of potential interventions, such as water conservation measures, infrastructure improvements, and policy changes, in ensuring sustainable water supply across multiple users and sectors within these basins.

These studies include Amin et al. (2018a), Asghar et al. (2019) and Hassan et al. (2019), who used the WEAP model to investigate water supply and demand in the Upper and Central Indus River system. They each assessed the impact of socio-economic factors and IPCC climate change scenarios on water demand and supply in the Indus River Basin using the WEAP model, projecting significant increases in water demand and unmet needs by 2050. Basharat and Tariq (2014) used WEAP to estimate crop water demand for the Lower Bari Doab Canal. Their study evaluated reallocating 25 % of canal water from the head to the tail of the Lower Bari Doab Canal to improve irrigation cost equity and manage groundwater stress, resulting in significant cost savings and enhanced climate adaptation. Mukhtar and Mutar (2021) used the WEAP model to evaluate optimal water allocation in Baghdad under various future scenarios, revealing unmet water demand and supply, highlighting the urgent need for sustainable water management in Iraq. Several other studies have used scenario-based modelling in conjunction with WEAP to find the best combination of scenarios that meet future water demands (Amin et al., 2018a,b; Agarwal et al., 2019; Al-shutayri, 2019; Al-juaidi and Al-shotairy, 2020; Yao et al., 2021). A major limitation of WEAP is that it only estimates the future water demands and allocates the water proportionally among the agents and does not inherently ensure fair and equitable allocation of water.

To ensure fairness and equity among the agents, several studies have focused on the development of cooperative game models for water resource allocation problems. For instance, Wang (2003) used a cooperative game theory approach to initially assign water rights based on existing systems and then reallocate water through transfers to achieve efficient use. This method aimed to balance fairness with economic efficiency in river basin management. Kucukmehmetoglu and Guldmann (2004) developed a linear programming model to allocate Euphrates and Tigris River waters among Turkey, Syria, and Iraq, maximizing net benefits for agricultural and urban uses. They applied cooperative game theory to ensure stable water allocations that encourage cooperation among the three countries. Dinar et al. (2008) further developed the approach by combining a negotiation procedure and companion modelling to address a water allocation problem in the Kat watershed in South Africa.

Several cooperative game theoretic solutions, including nucleolus, Nash-Haryansi, Shapley and the core, were applied to a groundwater allocation problem by Madani and Dinar (2011). Mahjouri and Ardestani (2011) developed cooperative and non-cooperative methodologies for large-scale water allocation in Southern Iran. They compared their economic benefits and demonstrated that cooperation enhances revenue while maintaining water quality and quantity standards. Following this, Jafarzadegan et al. (2013) developed Fuzzy Variable Least Core (FVLC) solution concept for fuzzy cooperative games and applied it to water allocation in inter-basin transfer systems. The study used an Integrated Stochastic Dynamic Programming model and FVLC-based methodology to equitably allocate water and benefits, demonstrated through a large-scale project in Iran. Safari et al. (2014a) proposed a two-level leader–follower model for resolving water conflicts, with the Iran Water Resources Management Company as the leader and various users as followers. The model, compared with the Nash bargaining solution, showed increased benefits for the leader, using Genetic Algorithm optimization to avoid local optima. Zomorodian et al. (2017) developed a cooperative game model for the optimum water allocation in the Langat River basin in Malaysia. The study introduced a coupled simulation-optimization method combining system dynamics and game theory to address complex, multi-reservoir water resource conflicts. Degefu et al. (2018) applied cooperative game theory allocation for water resources among Syria, Iraq, and Turkey. They combined bankruptcy games and Nash bargaining theory to introduce a fair negotiation framework, enabling agents' engagement and addressing conflicting interests.

While a number of studies have investigated the value of using the bankruptcy theory and Nash bargaining solution (Kaufman et al., 1997; Thomson, 2003, 2012; Sechi and Zucca, 2015) to address the supply-demand gap in shared rivers, to the best of our knowledge, there is a notable lack of studies that combine the predictive capabilities of the WEAP model with the equitable resource allocation framework of the Nash bargaining solution to address the supply-demand gap in water resources. In this study, we use the WEAP model to simulate future water demands under multiple "what if" scenarios. We then integrate this with the Nash bargaining solution to ensure fair and efficient distribution of water resources, with and without bargaining weights. This integrated approach not only enables accurate prediction of future water demands but also ensures socially and politically acceptable water allocation policies by aiding in conflict resolution and enhancing adaptation under changing conditions. By addressing this gap, the study contributes to the development of robust, fair, and efficient water resource management strategies. Here, we apply the proposed approach to the Lower Bari Doab agricultural region in Pakistan as a case study. We quantify future water shortages using WEAP under various scenarios and achieve a Nash bargaining solution to distribute the scarce available water among the agricultural agents/stakeholders equitably and efficiently. Based on this, we propose management policies to address future water shortages for the region.

2. Materials and methods

In this study, the WEAP simulation model and Nash bargaining solution were employed to develop a sustainable water allocation scheme. The sequential procedure of our adopted methodology is shown in Fig. 1. In the first part, the WEAP simulation model was implemented to simulate the future water demands under various scenarios. In the second part, the results from the WEAP model were imported into MATLAB, where the Nash Bargaining Solution was applied to allocate water fairly and efficiently among the agents. After defining the objective, the fundamental principles of water sharing as stated in Eqs. (1), (2) and (3) were defined. The disagreement points as well as the amount of water available for consumption were determined. The allocation of water among the agents was done using the Nash bargaining solution. When the demand and available water changed over time, the Nash bargaining solution was reapplied to update the disagreement points and again allocate the water. A detailed description and discussion of the WEAP and Nash bargaining solution is provided later in this section.

2.1. Case study area description

Pakistan has five main rivers, namely the Indus, Jhelum, Chenab, Ravi, and Sutlej. The Ravi and Sutlej are tributaries of the Indus River and the land between them, comprising large alluvial deposits, is known as Bari Doab. Covering an area of approximately 29,000 square kilometers, this is one of the most productive agricultural regions in the South Asia sub-continent (Basharat and Tariq, 2014). Our study area, the Lower Bari Doab, lies in the center of Bari Doab in the Punjab province, with a total irrigated area of 0.8 million hectares. The area of Lower Bari Doab (Fig. 2) is divided into four divisions (zones) namely Kasur, Sahiwal, Khanewal and Okara (Pasha et al., 2021; Khanam et al., 2023).

The area under the Lower Bari Doab Chenab (LBDC) has the second largest irrigation system in Punjab having 65 distributaries under its administrative area. These are made up of 2261 kilometers of distributaries - minor and sub-minor - in addition to a total of 53.5 km of branch canals. Agriculture is the most dominant water use sector in the Lower Bari Doab area and Punjab Irrigation Department is responsible for the

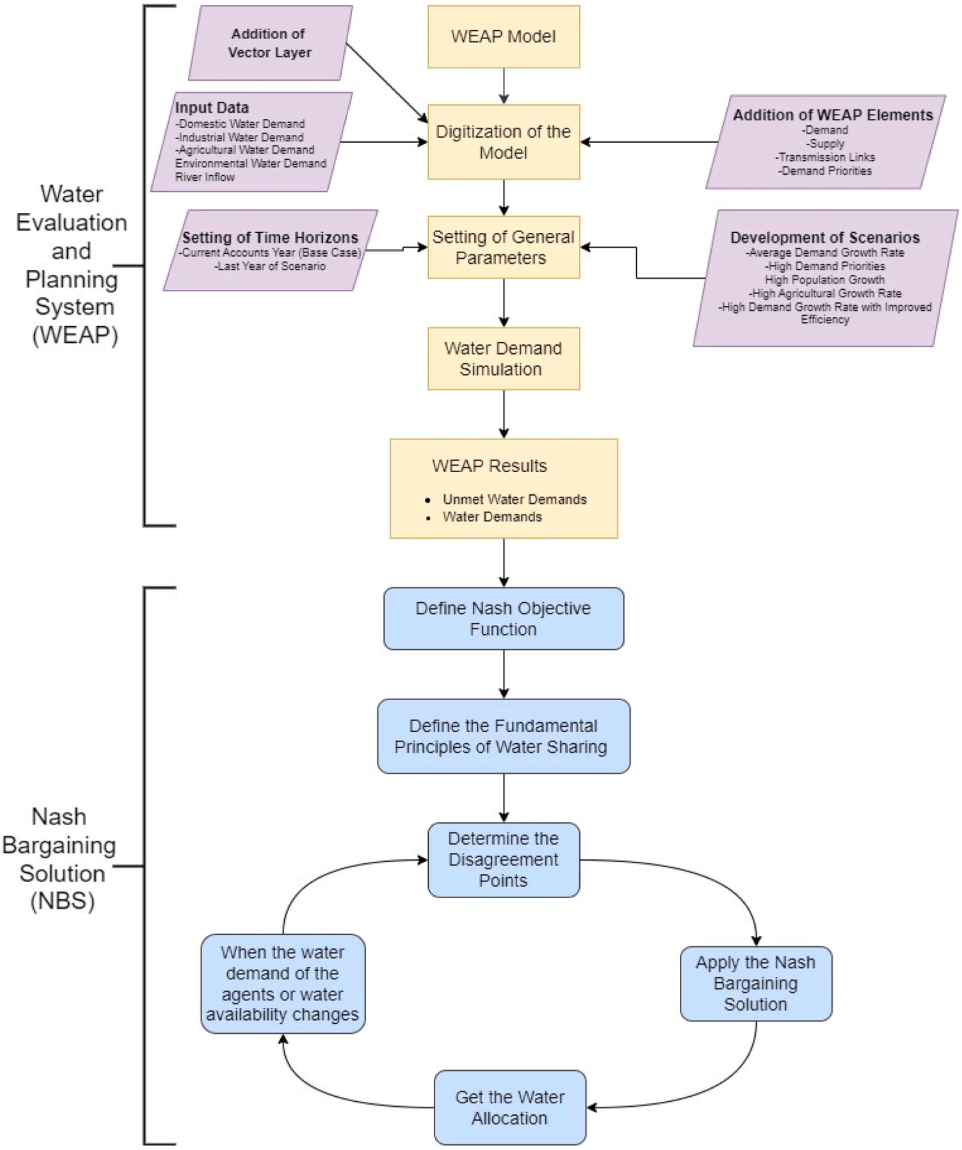

Fig. 1. Sequential procedure of adopted methodology including WEAP and its inputs and the integration with Nash bargaining solution (NBS).

water distribution to the farmers (Maqbool et al., 2021).

A significant issue associated with the current water allocation mechanisms, followed at the provincial and district level, is the establishment of fixed water allocations, resulting in a quantified entitlement (Mikosch et al., 2020; Hassan et al., 2021). This rigid water allocation mechanisms result in allocations that are deemed unacceptable for agents, particularly in the face of uncertainties, droughts, and the unpredictable nature of river flows.

2.2. Data collection

Data used in the water balance analysis in this study included streamflow, water demand (industrial, agricultural, domestic, and environmental), land cover and various population increase trends and cropping patterns (Table 1). These data were collected from the Pakistan Meteorological Department (PMD), Punjab Monitoring and Implementation Unit (PMIU), Pakistan Bureau of Statistics (PBS) and other studies (Shakir et al., 2011; Javed et al., 2020; Pasha et al., 2021; Khanam et al., 2023).

The population of the four Lower Bari Doab administrative districts and their corresponding water demands, based on the latest population census of 2015, are given in Table 1. The average annual water demand per person here is taken as 33.5 cubic meters (Ashraf et al., 2010; Khanam et al., 2023). Okara, the most populous division, has the highest domestic demand and Khanewal the lowest; Sahiwal has the highest land cover area and agricultural water demand whereas Kasur has the lowest. Annual industrial water demand in Lower Bari Doab is reportedly 149 million cubic meters (MCM), whereas the environmental water demand is 300 MCM (Nawaz et al., 2015).

In addition, there are 28,956 acres (117 km^2) of forests in the Sahiwal district, necessitating environmental flows to sustain the area's ecosystems. According to the National Water Policy (NWP), 300 MCM of water is delivered annually through the forest distributaries to restore and sustain ecological integrity (Nawaz et al., 2015). In our study, the "Environmental Water Demands", as outlines in Table-1 were designated as "Environmental Flow Requirements" for the Lower Bari Doab and were incorporated in the WEAP software.

2.3. The WEAP software and model setup

WEAP was initially designed by the Stockholm Environment Institute (SEI) in 1988 for the purpose of integrated water management and

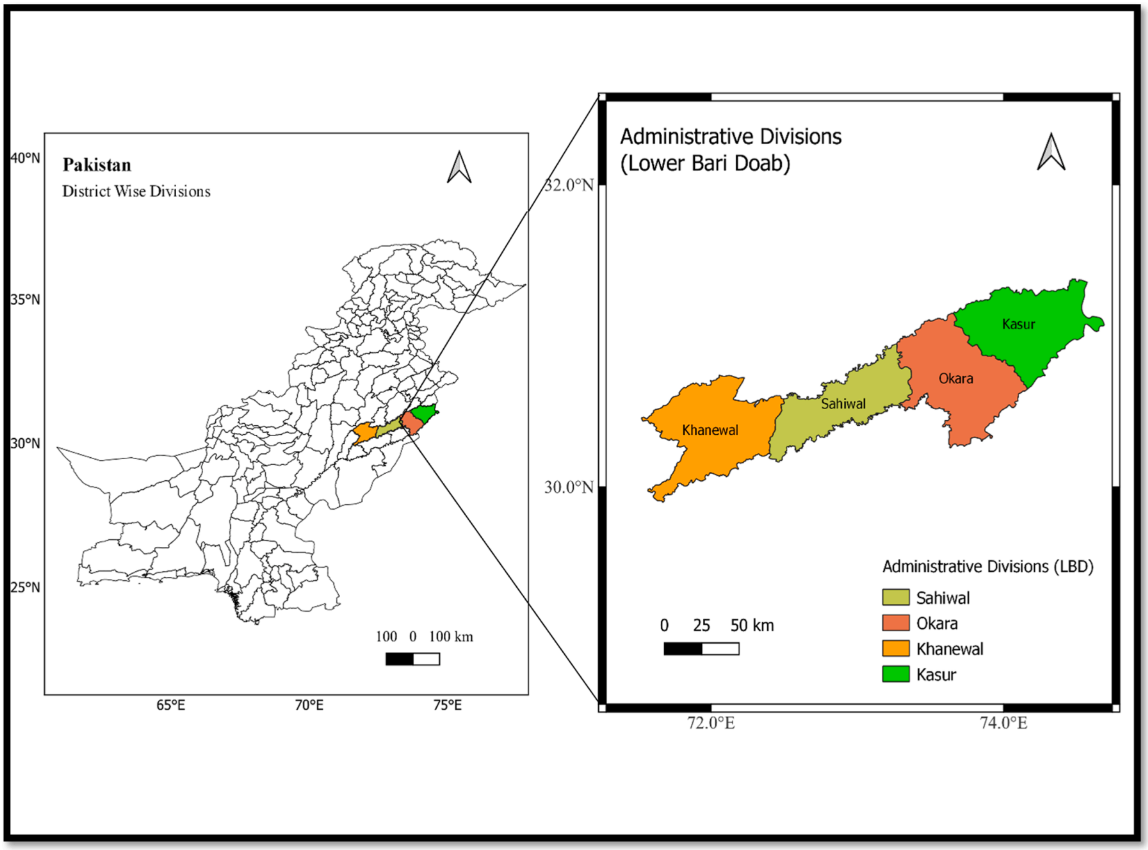

Fig. 2. Lower Bari Doab (Administrative Divisions).

Table 1
Domestic, agricultural, industrial and environmental water demands of Lower Bari Doab Divisions (MCM is 10^6 m^3).

Division	Population	Domestic water demand (MCM)	Agricultural water demand (MCM)	Industrial water demand (MCM)	Environmental water demand (MCM)
Okara	2915,324	102	530	149	300
Sahiwal	2414,994	81	1713		
Khanewal	730,928	24	445		
Kasur	792,045	31	238		

Note: The industrial and environmental water demands correspond to the entire region of LBD.
Source: Khanam et al. (2023) and Pakistan Bureau of Statistics.

planning (Amin et al., 2018b; Yao et al., 2021). It is primarily based on the water balance and requires inputs such as supply sources, land cover, water quality and water demand or withdrawals for industrial, domestic, environmental, agricultural and other water requirements. The modelling scenario in the WEAP model comprises three stages: (i) the current year or base year; (ii) a reference scenario based on the current accounts, which projects the development in the system with or without intrusion; and (iii) various future developments based on 'what-if' scenarios.

In order to easily locate the canal command area and the demand sites, GIS vector and raster layers were added in the schematic view of the WEAP. The demand nodes for the agricultural, industrial, domestic and environmental water demands were drawn. The year 2015 was taken as the base-case scenario which signifies the condition of the area for the initial year, that is, 2015. The future water demands of the area will be predicted using this scenario as a base case. Various other scenarios (Table 2) were developed after consultation with experts and a review of studies.

In our study, the WEAP model was run for the Lower Bari Doab area and included the main river supply, the demand nodes (agricultural, industrial and domestic), instream (environmental flows) and transmission links. In the SETUP portion of the WEAP model, the analysis parameters and the components of the water resource system of the study were defined for three primary system components: (1) river supply; (2) demand sites (agricultural, domestic, industrial and environmental); and (3) nodes or transmission links. The water system was then configured, and the demand sites were linked with the river supply. Water was transmitted over the system links to the demand sites on a yearly basis to satisfy demands (Dimova et al., 2014; Negasa Jaleta et al., 2019). In this study, we took the year 2015 as the current account year or base year; estimates for future projections were based on the base year and other external driving factors as discussed in Table 2. Water was then allocated under various scenarios informed by the river basin's response to a number of future policies, demographic changes, changes in cropping patterns, and other management scenarios, also described in Table 2.

2.4. The Nash bargaining solution

Disputes and conflicts arise among the water users when the existing

Table 2

Description of water demand simulation scenarios.

Scenario	Scenario name	Description of the scenario
Base case	-	The year 2015 was selected as the base case scenario representing the current year. It shows the current state of the system, including the demand zone and water supply, keeping in view the existing water distribution and existing irrigation systems. Future water demand was predicted for various other scenarios (given below) using this scenario as a base case.
Scenario 1	Average demand growth rate	We assumed that the demand for each sector increased with the annual average growth rate. Therefore, the demand growth rates of industrial, agricultural, and domestic sectors in this scenario were expected to increase by 1 %, 2.77 %, and 1.8 % per annum, respectively. Demand priorities for the domestic and industrial agents were set to 1, whereas the demand priorities for the agricultural agents were set to 2. The environmental water demand was kept the same as that in the base case.
Scenario 2	High demand priorities	Everything was kept the same as Scenario 1 except for the demand priorities. All the sectors in this scenario were given a demand priority of 1.
Scenario 3	High population growth rate	A high population growth rate of 2.2 % was assumed for the domestic sector, while growth rates for other sectors were kept the same as those in Scenario 1.
Scenario 4	High agriculture growth rate	Keeping in view the increasing agricultural water demands in the country, it was assumed that demand for agricultural water will increase at a rate of 4.4 %.
Scenario 5	High demand growth rate with improved irrigation efficiency	High growth rates were assumed for all the sectors. The demand growth rates of industrial, agricultural and domestic sectors were increased by 3.6 %, 4.4 % and 2.2 % per annum, respectively. This scenario represents the current rehabilitation and upgrading works undertaking by the Asian Development Bank on the one-hundred-year-old Balloki Barrage and LBDC System to support economic growth and improvement in the sustainability of water and land resources in the LBDC command area. Once completed and operational in 2025, it is expected that the irrigation efficiency will be increased, and the canal water supplies would increase by 40 percent.

water distribution mechanisms fail, and this generally happens when demand exceeds the total available water supply. Optimization techniques can be helpful during such water scarcity situations. These techniques can be used to prevent the collapse of a water supply system and buffer the conflicts.

Allocation of water among competing stakeholders (agents) is identical to the bankruptcy problem when demand exceeds the total available resources (Kalai, 1977; Nehra and Caplan, 2022; Chessa et al., 2023). The bankruptcy problem can be formulated here as a collection$(N, E, \mathbf{c}, \overline{\mathbf{x}})$. In this, $N = \{1, 2, \ldots, n\}$ represents a finite set of agents. In the water bankruptcy problem, these agents can be administrative units, cities or even riparian countries who are competing for a limited resource, which in our case is 'water'. 'E' represents the available water resources, which are not sufficient to satisfy the demands of all the competing agents. $\mathbf{c} = \{c_i, i \in N\}$ is the amount of water claimed by the agents or riparian users. The amount of water allocated to each stakeholder is denoted by $\overline{x}_i(\overline{\mathbf{x}} = \{\overline{x}_i, i \in N\})$. If we assume that the water amount available to the stakeholder i is a_i, the total available water resources in the entire study area will be $E = \sum_{i=1}^{n} a_i$.

If we assume that $\overline{x}_i$is the total water allocated to the agent i, the following three conditions of bankruptcy, detailed by Eqs. (1), (2) and (3), should be met:

$$\sum_{i=1}^{n} x_i = E \tag{1}$$

Eq. (1) above ensures that the total value of the available resource should be exactly distributed among the agents who are competing for the limited resource.

$$\overline{x}_i \leq c_i \tag{2}$$

Eq. (2) helps to prevent resource misuse or overuse leading to 'tragedy of the commons' situations (Hawkshaw et al., 2012; Ling et al., 2014; Yang et al., 2022).

$$\overline{x}_i \geq 0 \tag{3}$$

Eq. (3) ensures that none of the riparian system is allocated a negative value. In other words, it ensures non-negativity.

2.5. *Asymmetric Nash bargaining solution*

In economics, the Nash bargaining solution and bankruptcy rules are used when the available assets are not enough to satisfy the claims of stakeholders. When available resources are less than the aggregated demand, the claim of each agent needs to be reduced by an amount to address the supply-demand gap. This gap can be addressed via a Nash bargaining solution, which represents a set of cooperative game theory solutions. The main challenge is to develop a scheme that can fairly allocate available resources among the beneficiaries, who all have different demand (claim) levels. As stated above, WEAP distributes the deficit proportionally among the agents and does not consider other factors such as different levels of adaptive capacity and exposure to risks associated with the water shortage. Water sharing rules based on Nash bargaining solutions can take these additional factors into account, thereby achieving more "reasonable and equitable utilization" (Safari et al., 2014b; Degefu et al., 2017; Zeng et al., 2019).

In this study, the concept of bankruptcy is combined with asymmetric Nash bargaining theory and applied to the Lower Bari Doab region to facilitate the fair and equitable allocation of water among the administrative units under the condition of a supply-demand gap. Building on recent works (Sgobbi, 2011; Houba, 2013; Safari et al., 2014a; Degefu and He, 2016; Qin et al., 2019), this study proposes a Nash bargaining solution concept for the fair and equitable allocation of water among the four administrative divisions of Lower Bari Doab.

To ensure self-enforceability and equity in a closed and bounded space, the bargaining weights $\{w_i, i \in N\}$and the disagreement allocations $\{m_i, i \in N\}$are also considered. Such an optimization solution not only satisfies a set of desirable properties, but also recommends a unique solution by maximizing the area between the pareto-optimal frontier ($\overline{x}_i$) and the disagreement allocations (m_i). These are the minimum allocations that the riparian agents are willing to accept (Ashraf et al. 2010; Shakir et al. 2011; Dimova et al. 2014; Negasa Jaleta et al. 2019; Khanam et al. 2023).

For each agent (i.e., riparian user), the disagreement point formula is defined by Eq. (4):

$$d_i = U_i(m_i), \tag{4}$$

where $d_i, i \in N$ are the Nash disagreement points and U_i the utility functions.

The problem of minimal water allocation to each agent can be solved by the theory of bankruptcy when the total available water is less than the total water demand. Therefore, the minimal water allocation to each riparian user is given by,

$$m_i = \max\left(0, E - \sum_{k \neq i} c_i\right) \tag{5}$$

where $\sum_{k \neq i} c_i$is the summation of the claims of other agents except the stakeholder i. Eq. (5) is subject to the constraint, $E < C$, where E is the total available water and C is the sum of claims.

The minimum water allocation to each riparian user may become zero if we use the above equation of bankruptcy. This may be especially true for riparian users that have very small claims. Practically, each riparian user will demand a minimum amount of water λ_i in the process of water resource allocation. Using the above theory of bankruptcy, the minimum water allocation may be less than the minimum water requirement of each riparian user λ_i, which the riparian user may not accept. To avoid this, we propose Eq. (6), which addresses this issue and determines the minimum water allocation to each riparian user considering their minimum requirements.

$$I_i = \max\left(\lambda_i, E - \sum_{k \neq i} c_i\right) \tag{6}$$

where λ_i is the minimum water requirement of each riparian user or claimant. In this study, this is taken to be twenty-five percent of the stakeholder's claims.

After defining the minimal water requirements, the Asymmetric Nash bargaining theory (Nash, 1950; Houba, 2013; Madani et al., 2014; Safari et al., 2014a,b; Fu et al., 2018) is combined with the concept of bankruptcy for the fair and equitable allocation of water among the administrative units under the condition of a supply-demand gap. For the optimization problem, the respective water claims of the riparian users serve as the upper bounds and Eq. 6 defines the lower core bounds. The optimization problem for water allocation under the water bankruptcy scenario can be written as the following (Harsanyi, 1982; Safari et al., 2014b; Fu et al., 2018)

$$\text{MaximiseN}^{w} = \prod_{i=1}^{n} (\overline{x}_i - I_i)^{w_i} \tag{7}$$

This model is constrained by feasibility and individual rationality. The claims and the disagreement points serve as the upper and the lower bounds, respectively. Therefore, the river sharing optimization problem for the agricultural divisions of Lower Bari Doab can be formulated as stated in Eq. 8:

$$\begin{aligned}\text{MaximiseN}^{w}_{\text{LBDC}} = {} & (\overline{x}_{\text{Sah}} - I_{\text{Sah}})^{w_{\text{Sah}}} * (\overline{x}_{\text{Kha}} - I_{\text{Kha}})^{w_{\text{Kha}}} * (\overline{x}_{\text{Kas}} - I_{\text{Kas}})^{w_{\text{Kas}}} \\ & * (\overline{x}_{\text{Oka}} - I_{\text{Oka}})^{w_{\text{Oka}}}\end{aligned} \tag{8}$$

where,

$$w_{\text{Sah}} + w_{\text{Kha}} + w_{\text{Kas}} + w_{\text{Oka}} = 1$$

and,

$\overline{x}_{sah}$ is the optimized agricultural water allocation for Sahiwal.

I_{Sah} is the lower core bound for Sahiwal (agricultural).

w_{Sah} is the bargaining weight for Sahiwal.

$\overline{x}_{kha}$ is the optimized agricultural water allocation for Khanewal.

I_{Kha} is the lower core bound for Khanewal (Agricultural).

w_{Kha} is the bargaining weight for Khanewal.

$\overline{x}_{Kas}$ is the optimized water allocation for Kasur.

I_{Kas} is the lower core bound for Kasur (agricultural).

w_{Kas} is the bargaining weight for Kasur.

$\overline{x}_{Oka}$ is the optimized water allocation for Okara.

I_{Oka} is the lower core bound for Okara (agricultural).

w_{Oka} is the bargaining weight for Okara.

The following constraints are set for this allocation model. The water allocation to each district should be more than its lower core bound and less than its claim, given by:

$$I_i \leq \overline{x}_i \leq c_i. \tag{9}$$

The claims provided by each district are based on their demand patterns, as identified in the literature (see data collection section above). We note, however, that estimating evapotranspiration could be another useful approach to assess water demand and validate the district-level claims.

The total water allocation for all the districts should be equal to or less than the total available water,

$$\sum_{i=1}^{n} \overline{x}_i \leq E. \tag{10}$$

2.6. Determination of bargaining weights

The optimization model, stated in Eq. 8, is applied to reallocate the water among the four administrative units of Lower Bari Doab. Two cases of the Nash bargaining solution have been applied in this study. In the first case, the bargaining weights of all four administrative units were assumed equal (homogeneous). In the second case, different bargaining weights were given to the administrative units as all the riparian users (water sharing agents) are different in terms of their environmental and socio-economic status. In our case, the bargaining weights of the agents were selected based on the mean annual rainfall they received from 1990 to 2020 (Table 3). The bargaining weights applied were inversely proportional to the mean annual rainfall received over this period; that is, the greater the amount of rainfall received, the less the bargaining weight of the province.

3. Results

3.1. Water evaluation and planning (WEAP) modelling

As expected among these scenarios, Fig. 3 indicates that the aggregate unmet water demand of the LBDC is more sensitive to the agricultural water demand which typically has a lower demand priority than those of the domestic, environmental, and industrial sectors. The specific water demands of all the scenarios are discussed below.

3.1.1. Scenario 1 – average growth rates

This scenario assumed that the water demand for each sector increases at the current annual average rate of increase (i.e., 1 %, 2.77 %, and 1.8 %, respectively, for the industrial, agricultural, and domestic sectors) with the exception of environmental water demand, which was kept the same as that of the base case. By setting the demand priorities for the domestic, environmental and industrial agents to 1, but those for the agricultural agents to 2, the aggregate unmet water demand for the Lower Bari Doab increased from 1213 MCM in 2015–2792 MCM in 2030 (Fig. 3; Table 4). This increase is driven by the increasing unmet water demands in agriculture toward 2030 of all the provinces (Table 4) due to the lower priority of water for the agricultural sector. In this case,

Table 3

Mean annual rainfall (1990–2020) and corresponding bargaining weights of four regions in the Lower Bari Doab, Pakistan.

	Kasur	Khanewal	Okara	Sahiwal
Mean annual rainfall (millimeters)	432	637	221	374
Bargaining weights	0.21	0.14	0.41	0.24

Note: These bargaining weights have been used in the 'Nash bargaining model under bargaining weights'.

Source: Pasha et al. (2021).

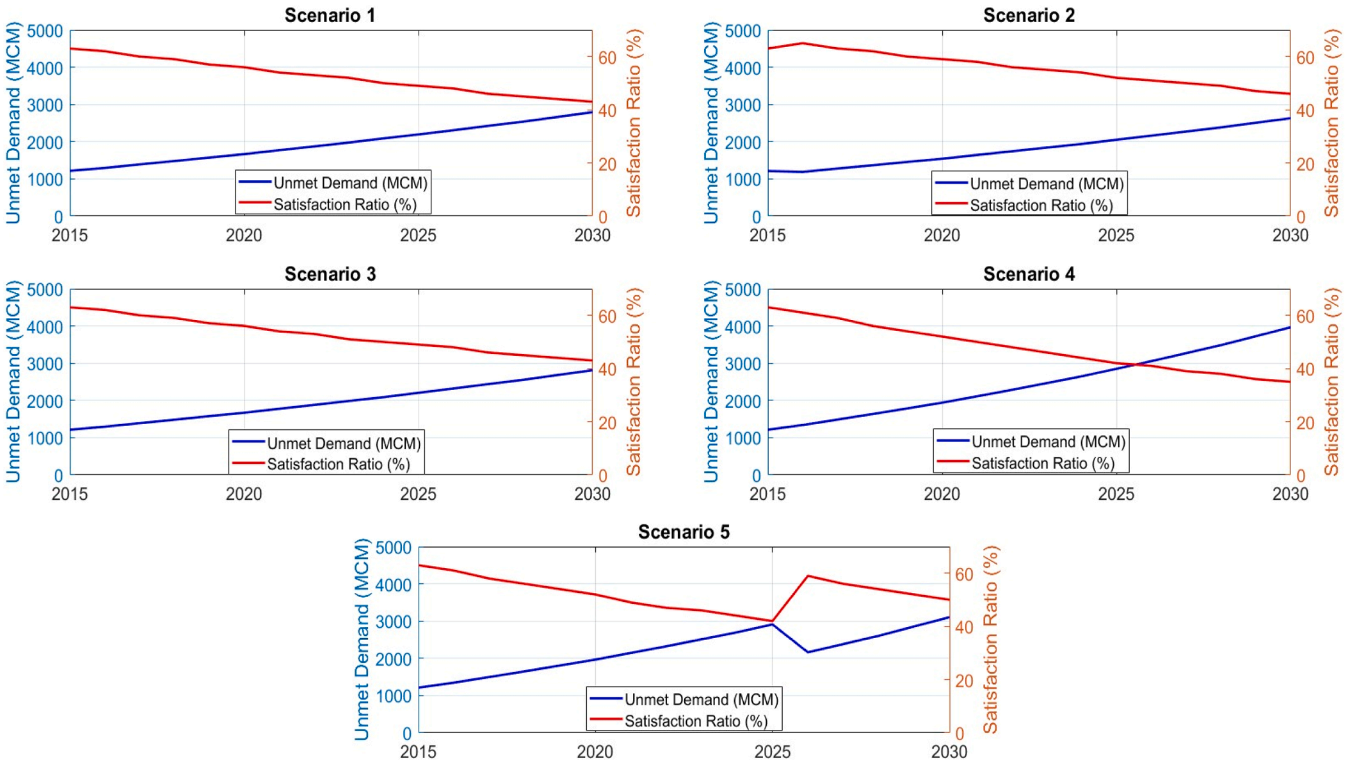

Fig. 3. Scenario-Based analysis of unmet water demands and satisfaction ratios in MCM and Percentage. Scenario 1 has average growth rates, Scenario 2 has equally high demand priorities for all sectors, Scenario 3 has a high population growth rate, Scenario 4 a high agriculture growth rate, Scenario 5 has high demand growth rates for all sectors (see Table 2 for more details regarding each scenario).

Table 4
Unmet water demands for different water use sectors (in million cubic meters, MCM) and percentage of water requirements met in the Lower Bari Doab, Pakistan, under Scenario 1. The percentages of requirements met (demand coverage) for each site and sector are given in parentheses.

Demand Site (Sector)	2015	2016	2020	2025	2030
Kasur (Agricultural)	98 (59 %)	105 (57 %)	135 (50 %)	178 (43 %)	226 (37 %)
Kasur (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Khanewal (Agricultural)	184 (59 %)	197 (57 %)	253 (50 %)	334 (43 %)	425 (37 %)
Khanewal (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Okara (Agricultural)	220 (59 %)	234 (57 %)	302 (50 %)	398 (43 %)	506 (37 %)
Okara (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Sahiwal (Agricultural)	710 (59 %)	758 (57 %)	975 (50 %)	1285 (43 %)	1635 (37 %)
Sahiwal (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
(Industrial)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Agricultural Deficit	**1212 (59 %)**	**1294 (57 %)**	**1665 (50 %)**	**2194 (43 %)**	**2792 (37 %)**
Total Deficit	**1212 (63 %)**	**1294 (62 %)**	**1665 (56 %)**	**2194 (49 %)**	**2792 (43 %)**

agricultural agents each receive 43 % of their future annual water demand, while the water demands for domestic and industrial sectors are all met until 2030 across the provinces (Table 4).

3.1.2. Scenario 2 – high demand priorities

All agents in this scenario were given a demand priority of 1 while the growth rates were kept the same as those in Scenario 1. Fig. 3 shows the change in aggregate unmet water demand over the considered time horizon (2015–2030) for the entire Lower Bari Doab, which for this scenario is similar to that for Scenario 1. Sector-wise unmet water demands for the individual administrative sites, however, showed increasing water deficits in future domestic use (Table 5) due to the competition from agricultural water demand, which was at equally high priority. When all the sectors were given equal demand priorities, the

Table 5
Unmet water demands for different water use sectors (in million cubic meters, MCM) and percentage of water requirements met in the Lower Bari Doab, Pakistan, under Scenario 2. The percentages of requirements met (demand coverage) for each site and sector are given in parentheses.

Demand site (Sector)	2015	2016	2020	2025	2030
Kasur (Agricultural)	98 (59 %)	85 (65 %)	111 (59 %)	148 (52 %)	192 (46 %)
Kasur (Domestic)	0 (100 %)	11 (65 %)	14 (59 %)	17 (52 %)	22 (46 %)
Khanewal (Agricultural)	185 (59 %)	160 (65 %)	209 (59 %)	280 (52 %)	361 (46 %)
Khanewal (Domestic)	0 (100 %)	9 (65 %)	11 (59 %)	14 (52 %)	17 (46 %)
Okara (Agricultural)	220 (59 %)	190 (65 %)	249 (59 %)	333 (52 %)	430 (46 %)
Okara (Domestic)	0 (100 %)	36 (65 %)	45 (59 %)	58 (52 %)	71 (46 %)
Sahiwal (Agricultural)	710 (59 %)	616 (65 %)	803 (59 %)	1075 (52 %)	1388 (46 %)
Sahiwal (Domestic)	0 (100 %)	28 (65 %)	36 (59 %)	46 (52 %)	56 (46 %)
(Industrial)	0 (100 %)	52 (65 %)	64 (59 %)	78 (52 %)	93 (46 %)
Agricultural Deficit	**1213 (59 %)**	**1051 (65 %)**	**1372 (59 %)**	**1836 (52 %)**	**2371 (46 %)**
Total Deficit	**1213 (63 %)**	**1189 (65 %)**	**1542 (59 %)**	**2051 (52 %)**	**2631 (46 %)**

deficits were shared proportionally between all the agents. As a result, the percentages of requirements met for each sector indicate the demand coverage for all the sectors were equal by the year 2030, when all the agents received 46 % of their total water demands.

3.1.3. Scenario 3 – high population growth rate

In this scenario, a high population growth rate (2.2 %) was assumed for all the domestic sectors. The demand priorities for the domestic, environmental and industrial sectors/agents were set to 1, whereas the demand priorities for the agricultural agents were set to 2. It can be seen in Fig. 3 that, due to the increase in domestic water demand, total unmet water demand for the Lower Bari Doab under this scenario also increased, from 1213 MCM in 2015–2811 MCM in 2030 (Table 6), which is greater than that of the average growth rate scenario (Scenario 1). As the domestic, industrial and environmental sectors were given a demand priority of 1, the water deficit was shared only by the agricultural agents (Table 6) as in Scenario 1. Low demand priority was thus a determinant of water deficit in this instance.

3.1.4. Scenario 4 – high agricultural growth rate

This scenario accounts for the increasing agriculture water demands in the country. It assumed a rate of increase in agriculture water demand from the year 2016–2030 of 4.4 % per annum. The demand priorities for the domestic, environmental, and industrial sectors/agents were set to 1, whereas the demand priorities for the agricultural agents were set to 2. Fig. 3 shows an increase in aggregate unmet water demands for the Lower Bari Doab, from 1213 MCM in 2015–3966 MCM in 2030 under this scenario. As in Scenarios 1 and 3, the water deficit was only shared by the agricultural agents due to the low demand priority assigned to this sector. (Table 7)

3.1.5. Scenario 5 – high demand growth rate with improved irrigation efficiency

Under this scenario, high demand growth rates were assumed for all the sectors. The demand growth rates of industrial, agricultural and domestic sectors were expected to increase by 3.6 %, 4.4 % and 2.2 % per annum, respectively. Under this scenario, aggregate unmet water demands for Lower Bari Doab increased from the year 2015–2699 MCM in 2024 (Fig. 3e), but then decreased to 1953 MCM in 2025 as the new canal system becomes operational in 2025. However, due to the continuous increase in population and agricultural water demands, the unmet water demands then continued to increase to reach 3105 MCM by the year 2030. Due to the low demand priority assigned, the water deficit was only shared by the agricultural agents (Table 8).

Table 6
Unmet water demands for different water use sectors (in million cubic meters, MCM) and percentage of water requirements met in the Lower Bari Doab, Pakistan, under Scenario 3. The percentages of requirements met (demand coverage) for each site and sector are given in parentheses.

Demand Site (Sector)	2015	2016	2020	2025	2030
Kasur (Agricultural)	98 (59 %)	105 (57 %)	135 (50 %)	179 (43 %)	228 (36 %)
Kasur (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Khanewal (Agricultural)	185 (59 %)	197 (57 %)	254 (50 %)	336 (43 %)	428 (36 %)
Khanewal (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Okara (Agricultural)	220 (59 %)	235 (57 %)	303 (50 %)	400 (43 %)	509 (36 %)
Okara (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Sahiwal (Agricultural)	710 (59 %)	758 (57 %)	978 (50 %)	1291 (43 %)	1646 (36 %)
Sahiwal (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
(Industrial)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Agricultural Deficit	**1213 (59 %)**	**1295 (57 %)**	**1670 (50 %)**	**2205 (43 %)**	**2811 (36 %)**
Total Deficit	**1213 (63 %)**	**1295 (62 %)**	**1670 (56 %)**	**2205 (49 %)**	**2811 (43 %)**

Table 7
Unmet water demands for different water use sectors (in million cubic meters, MCM) and percentage of water requirements met in the Lower Bari Doab, Pakistan, under Scenario 4. The percentages of requirements met (demand coverage) for each site and sector are given in parentheses.

Demand Site (Sector)	2015	2016	2020	2025	2030
Kasur (Agricultural)	98 (59 %)	109 (56 %)	157 (47 %)	231 (37 %)	322 (29 %)
Kasur (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Khanewal (Agricultural)	185 (59 %)	204 (56 %)	295 (47 %)	434 (37 %)	603 (29 %)
Khanewal (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Okara (Agricultural)	220 (59 %)	243 (56 %)	351 (47 %)	516 (37 %)	719 (29 %)
Okara (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Sahiwal (Agricultural)	710 (59 %)	786 (56 %)	1136 (47 %)	1668 (37 %)	2322 (29 %)
Sahiwal (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
(Industrial)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Agricultural Deficit	**1213 (59 %)**	**1341 (56 %)**	**1940 (47 %)**	**2849 (37 %)**	**3966 (29 %)**
Total Deficit	**1213 (63 %)**	**1341 (61 %)**	**1940 (52 %)**	**2849 (42 %)**	**3966 (35 %)**

3.2. Agricultural water allocation results under WEAP and Nash bargaining solution

In four out of the five scenarios investigated above, we assigned a demand priority of 2 for agricultural agents, while other sectors were assigned a higher priority of 1. As a result, the demand coverage (water satisfaction indicates the % of water requirement met) for the domestic, industrial and environmental sectors was always 100 percent, leaving the water deficit to be shared among the agricultural agents only. In

Table 8
Unmet water demands for different water use sectors (in million cubic meters, MCM) and percentage of water requirements met in the Lower Bari Doab, Pakistan, under Scenario 5. The percentages of requirements met (demand coverage) for each site and sector are given in parentheses.

Demand Site	2015	2016	2020	2025	2030
Kasur (Agricultural)	98 (59 %)	109 (56 %)	159 (46 %)	158 (57 %)	252 (44 %)
Kasur (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Khanewal (Agricultural)	185 (59 %)	205 (56 %)	299 (46 %)	297 (57 %)	473 (44 %)
Khanewal (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Okara (Agricultural)	220 (59 %)	244 (56 %)	356 (46 %)	354 (57 %)	563 (44 %)
Okara (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Sahiwal (Agricultural)	710 (59 %)	788 (56 %)	1151 (46 %)	1143 (57 %)	1820 (44 %)
Sahiwal (Domestic)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Industrial	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)	0 (100 %)
Agricultural Deficit	**1213 (59 %)**	**1346 (56 %)**	**1966 (46 %)**	**2908 (57 %)**	**3105 (44 %)**
Total Deficit	**1213 (63 %)**	**1346 (61 %)**	**1966 (52 %)**	**2908 (42 %)**	**3105 (50 %)**

order to then equitably share water amongst the agricultural agents, the Nash bargaining solution was then applied, considering both homogeneous and heterogeneous weights. Heterogeneous bargaining weights of the agents were based on the average annual rainfall they received from 2001 to 2020, with more rainfall reflected in lower bargaining weights (Table 3).

Agricultural water allocations and resulting agricultural water satisfaction under the Nash bargaining solutions change annually based on the agricultural agents' claims and average recorded rainfall amounts, while WEAP consistently allocated the deficits equally among the agricultural agents (Fig. 4 and 5). For example, under Scenario 4, WEAP, the water satisfaction in 2025 is equal among the agricultural agents, each receiving 37 % of their water demands. Under the same scenario in 2025, the Nash bargaining solution under equal weights allocates 71 %, 47 %, 43 % and 27 % of the water demand to Kasur, Khanewal, Okara and Sahiwal, respectively, while under bargaining weights allocations are 63 %, 35 %, 58 % and 27 %, of district water demands, respectively. Similarly, under Scenario 5 for 2030 (Fig. 5), all the agents were allocated 44 % of their water demands using WEAP, while the Nash bargaining solution under equal weights (and under bargaining weights) allocates 95 % (83 %), 60 % (42 %), 54 % (75 %) and 30 % (30 %) of district water demands, respectively. As shown in Table 3, Khanewal receives the highest amount of rainfall among the four agents; as a result, its allocation under the heterogeneous (bargaining) weights is reduced under all scenarios for all years (Fig. 4 and 5).

More water was allocated among the agricultural agents resulting in better agricultural water satisfaction in Scenario 2 because agricultural water was set to have the same priority as those of domestic, environmental and industrial demands. The water deficit was thus shared among all the sectors, meaning more water for agriculture in this particular scenario. Scenarios 1 (average growth rate) and 3 (high population growth rate) have similar levels of agricultural water satisfaction in all three allocation schemes by WEAP, Nash bargaining solution under equal weights, and Nash bargaining solution under bargaining weights. Scenario 4 (high agricultural growth rate) results in the lowest water allocations (satisfactions) among the agricultural agents. This demonstrates that the development rate in lower demand priority sectors such as agriculture in LBDC will put a higher pressure on water shortage in agriculture (drought risk) and need to be carefully planned.

While there is a decreasing trend of agricultural water satisfaction toward 2030 in Scenarios 1–4, the hydrological infrastructure development in Scenario 5 allows allocating more water to agriculture after 2025 (Fig. 5) and thus agricultural development in the LBDC of Pakistan. However, under Scenario 5 toward 2030, there is still a decreasing trend of agricultural water satisfaction by the WEAP while Nash bargaining solutions provide more nuanced water satisfactions as they distribute the resource (water here) more fairly by considering the bargaining powers and utilities of the agents involved, leading to cooperation among the agents.

Sahiwal is less sensitive to changing bargaining weights than the other agents as it has the highest demand and thus less fluctuation is seen compared to other agents. Sahiwal, Kasur and Khanewal have the lower bargaining weights, whereas Okara has the highest bargaining

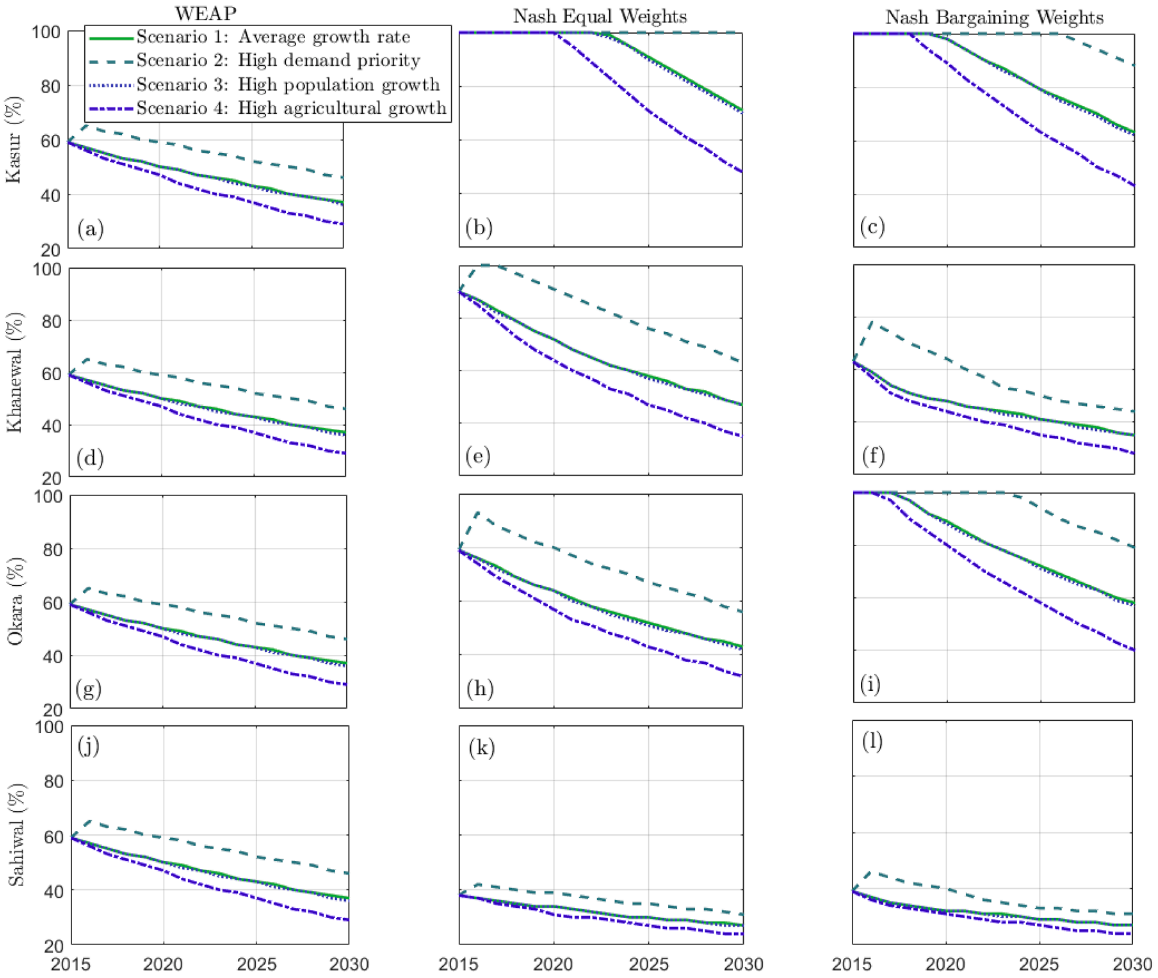

Fig. 4. Agricultural water satisfaction under WEAP and Nash (equal/homogeneous and bargain/heterogeneous) bargaining weights by district in the Lower Bari Doab, Pakistan, as a percentage of water demand met (demand coverage), for Scenarios 1–4 (2015–2030).

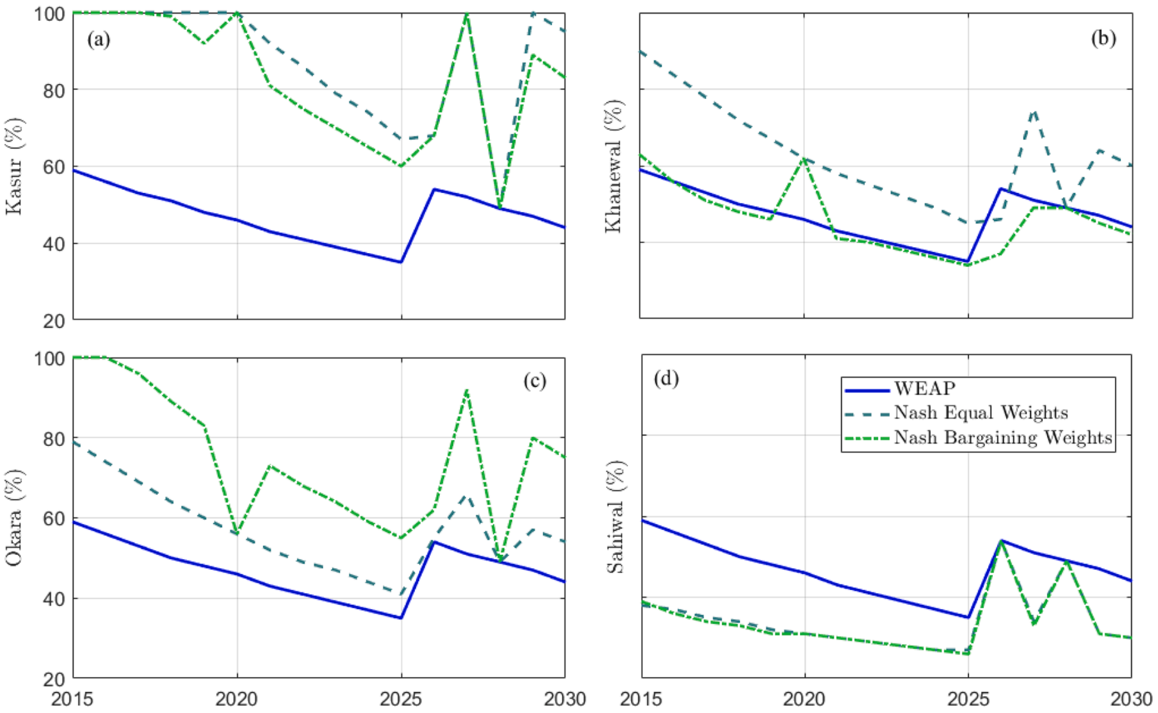

Fig. 5. Agricultural water satisfaction as a percentage of water demand met (demand coverage) for the Scenario 5 (Year 2015–2030).

weight as reflected in Table 3. When the Nash bargaining solution is applied under the bargaining weights, the Okara receives the highest improvements in water satisfaction owing to its highest bargaining weight. In contrast, Khanewal has the most significant reduction in agricultural water satisfaction due to the lowest bargaining weight. Agricultural water satisfactions for Kasur and Sahiwal are also reduced, though to a much lesser extent.

4. Discussions

The analysis of various scenarios for the Lower Bari Doab area reveals critical insights into the complex dynamics of water distribution. All the scenarios demonstrate that allocation prioritization considerably affects the unmet water demands of all the sectors, with the agricultural sector bearing the largest impact due to its lower priority settings (according to policy). High agricultural and population growth rate aggravates unmet demands, particularly for the agricultural sector. Comparison of agricultural water satisfaction results between the Nash bargaining solution and WEAP highlights the benefit of using context-sensitive and adaptive water allocation methods, which can lead to more acceptable and equitable outcomes.

In our study, we initially created a base case scenario and estimated the current unmet demands in the Lower Bari Doab to be 1213 MCM. The highest unmet demands were reported in 2030, under Scenario 4, where the unmet demands reached 3966 MCM. Amin et al., (2018a),b conducted a similar study for the Upper Indus Basin and reported that the future unmet water demand is likely to reach 134 MCM by the year 2050. Asghar et al. (2019) applied the WEAP model for the prediction of future water demand and supply in the Indus River Basin. They considered socio-economic factors and IPCC climate scenarios (RCP4.5 and RCP8.5) from 2015–2050. Results indicate significant increases in water demand by 2050. In another study conducted by Khalil et al. (2018) in the Mae Klong Basin of Thailand, it was reported that the unmet water demand in that basin would reach 62 MCM in the future. Saraswat et al. (2017) conducted a similar study using the WEAP model for the Kathmandu Valley, Nepal. They showed that future water demand is likely to reach 765 million liters per day (MLD) by the year 2030 from the estimated current demand of 388.1 MLD. The findings of these studies suggest that even after the completion of the proposed dams and improvements in irrigation efficiency, the gap between water supply and demand is likely to widen. In this study, in addition to exploring water management options and predicting future water demands using WEAP, the Nash bargaining solution is also proposed as a method to fairly address the supply-demand mismatch among various water use agents by considering factors of the agents which are reflected in their bargaining powers.

In our study, WEAP allocated the water deficit equally among the agricultural agents because other factors such as water use efficiency, groundwater usage, the amount of rainfall received, or disagreement points were not considered. The water allocation using WEAP is thus not likely to be acceptable to all agents; therefore, Nash bargaining solution was used to allocate the water fairly. Nash bargaining solutions increase water satisfaction in three agricultural agents excepting the Sahiwal agent. Despite relatively low rainfall and high weighting, Sahiwal has low satisfaction rate as the Nash bargaining solution actually results in a lower allocation than the WEAP. This is due to the fact that Nash bargaining solutions can lead to less satisfaction for the agent which has high demands as it seeks to maximize the overall satisfaction, balance the utilities and ensure equitable allocation of water. Nash bargaining solutions are designed to be mutually beneficial and maximize overall utility. This approach ensures all agents are better off compared to a non-cooperative outcome, promoting fairness and equity by balancing the needs of all parties. The agent with the higher claim (Sahiwal here) understands that a cooperative, stable agreement is more advantageous than risking conflict or inefficiency by insisting on a larger share. Additionally, even with a lower percentage, the agent still gains a significant more amount of water than other agents, making the agreement worthwhile (Table 9).

The Nash bargaining solution is widely used in water allocation problems to achieve a fair and efficient distribution of resources among stakeholders (Kilgour and Dinar, 2001; Madani and Hipel, 2011; Madani et al., 2014; Batabyal and Beladi, 2021; Naghdi et al., 2021; Hosseini et al., 2023). Bargaining weights represent the relative power, preferences, or influence of the parties involved in the water allocation

Table 9

Allocated volume (MCM) of available agricultural water to the four agents using Nash bargaining solution with heterogeneous weights under Scenario 5. The efficiency enhancement owing to the rehabilitation and upgrading works in Scenario 5 results in an increase in canal water supplies. Thus, the water supply, which was 1714 MCM in 2015, is projected to rise to 2477 MCM by 2030, representing an approximate 40 % increase.

Agent	Allocated water volume (MCM)			
	2015	2020	2025	2030
Kasur	238	293	218	377
Khanewal	278	344	234	360
Okara	530	366	447	760
Sahiwal	668	659	693	980
Total available water	**1714**	**1663**	**1592**	**2477**

negotiation, significantly impacting the final allocation where a party with higher bargaining weight is more likely to receive a larger share of the water (Madani, 2010). As expected, the Nash bargaining solution under bargaining weights in the present work better accounts for the rainfall differences among the agricultural agents than the Nash bargaining solution under equal weights i.e., there are considerably more reductions in water satisfaction in the Khanewal and Kasur. The reduction in satisfaction level for Sahiwal is very less while it increases for Okara which has relatively less average recorded rainfall. Bargaining weights, however, might be transient reflecting the contextual dynamics between the agents. This dynamic can lead to strategic behaviour, where agents might seek to increase their perceived or actual bargaining power (Ringler, 2001). Average recorded rainfall of agricultural agents might not reflect the actual rainfall they receive in the coming cropping season or in future long-term agricultural development given the changing climate. Future application research of Nash bargaining solution in water management should better account for rainfall uncertainty being reflected in bargaining weights by considering seasonal climate forecasts (An-Vo et al., 2019a, b; An-Vo et al., 2021), drought monitors (Gacenga et al., 2024), and climate change projection (An-Vo et al., 2024).

The findings from this study suggest several management and policy implications. Firstly, demand prioritization is crucial to ensuring that important sectors like domestic water supply are not compromised. However, rigid prioritization can also lead to serious deficits in lower priority (but still important) sectors, necessitating a more balanced approach. Secondly, the implementation of context-sensitive and adaptive water allocation methods, such as the Nash bargaining solution, can lead to more equitable water distribution outcomes that are more acceptable to all stakeholders. Thirdly, an integrated approach which considers various sectoral demands, population growth, regional disparities and fair allocation is essential for a sustainable water resource management in water stressed regions such as the Lower Bari Doab Region. Lastly, infrastructure improvements and efficiency gains must also be a part of a broader strategy addressing regional water demand growth across all sectors.

5. Conclusions

We applied the WEAP-Nash bargaining solution approach to address water allocation challenges in Lower Bari Doab, Punjab, Pakistan. Employing the WEAP model, we estimated future water demands under different scenarios. Our results show that water demand exceeded available resources in all scenarios, posing significant challenges for future water management, therefore, requiring policymakers to develop strategies to mitigate supply-demand gaps equitably and efficiently.

We found that using the WEAP modelling approach alone failed to ensure the fair and equitable allocation of water resources among the four agricultural divisions of Lower Bari Doab. This failure could result in escalating conflicts among different divisions. However, when combined with the Nash bargaining solution approach, we showed that integrating these two methods can improve the management of limited water supplies, generating significant benefits in all sectors.

Given that an agent's preference is a key problem in allocating water to meet demand, the Nash bargaining solution in the final allocation resulted in a greater level of acceptance by agents and reduced conflict. Therefore, the basin authority and the diverse range of stakeholders will be more likely to accept the policy that delivers these outputs. We envisage such a policy will be more sustainable and meet optimum criteria compared to the current fixed water allocation approach.

Our study has a number of limitations including the absence of groundwater extraction data and environmental and socio-economic data for the individual divisions, along with a focus on demand variability and not supply. The results of the proposed model can be improved by addressing these limitations (e.g., by incorporating groundwater extraction data), thereby allowing for a more accurate representation of actual water use. Also, inclusion of environmental and socio-economic data can enhance the solution's fairness by considering broader impacts on ecosystems and communities. Fourthly, the aspect of water treatment and water quality should also be incorporated into the analysis, which would provide a more holistic water management approach by addressing not only the water quantity but also its sustainability for various uses. The inclusion of this aspect would ensure a comprehensive understanding of the region's water needs and will improve long-term sustainability. Lastly, focusing on both demand and supply variability will ensure a more comprehensive and balanced approach, promoting sustainable and equitable water resource management.

Our approach offers a potential method that government authorities and policymakers could utilize to facilitate negotiations for managing conflicts and disputes over the allocation of water resources, not only in Pakistan but also in similar situations in other countries. This approach could also provide additional options for water-sharing entities when negotiations become difficult.

CRediT authorship contribution statement

Shahmir Janjua: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Duc-Anh An-Vo:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis. **Kathryn Reardon-Smith:** Writing – review & editing, Validation, Supervision, Conceptualization. **Shahbaz Mushtaq:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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