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A Three-stage Cooperative Game Model for Water Resource Allocation Under Scarcity Using Bankruptcy Rules, Nash Bargaining Solution and TOPSIS

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Abstract
The global water security situation is deteriorating due to unequal distribution of water resources and changing climate, leading to increased conflicts in many regions. This article proposes and develops a three-stage collaborative water resource allocation model and applies this to the Indus River basin in Pakistan, where water resources are shared by four provinces (agents): Punjab, Sindh, Balochistan, and Khyber Pakhtunkhwa (KPK). The model uses bankruptcy rules, Nash bargaining theory, and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) to allocate water resources. The model considers various factors, such as water risk and water satisfaction to achieve the best possible (most equitable and acceptable) outcome. Water allocation was conducted under three scenarios of 'median', 'maximum' and 'low' river flows. In the first stage of water allocation, the positive and negative ideal solutions were defined for all agents (in this case, provinces). These initial ideal solutions provided a baseline for the negotiation process. In the second stage, water allocation ratios of the four provinces Punjab, Sindh, Balochistan and KPK, using the Nash bargaining solution, under the median flows were 57.61%, 29.91%, 6.24% and 6.24%. In the third stage, water allocation ratios demonstrated the reduction in the allocation for those provinces facing high risks and having high satisfaction rates. The final allocations under the median flow conditions for the four provinces were 54.92%, 28.95%, 8.50% and 7.63%, respectively. The developed three-stage water allocation model considers the multi-dimensional attributes of water resources and is expected to support the cooperation of water agents, enabling collective bargaining and group negotiation and improving the acceptability and stability of allocations.

Keywords Bankruptcy Rules · Nash Bargaining Theory · TOPSIS · Collective Bargaining · Group Negotiation

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1 Introduction

Freshwater demand has increased, globally and in many cases nationally, due to population growth and associated competition from industrial, agricultural, and environmental requirements (Qureshi and Ashraf 2019; Hussain et al. 2020). This has led to water scarcity and degradation in water quality, especially in developing and underdeveloped countries – a situation that is exacerbated by climate change. It is estimated that by 2030, almost 5 billion of the world's population will be affected by water shortage (Schewe et al. 2014). Rivers, the main fresh surface water resources, also have important roles in the natural ecology as they have the ability to moderate climate change and adjust hydrological regimes (Madani and Lund 2010). Amidst inefficient water use and unorganized human activities, the world is suffering from depleting aquatic ecosystems and water shortages, which endangers future surface water flows (Qin et al. 2019). This situation has especially profound implications where rivers cross political boundaries.

Approximately 60% of global river flows occur in transboundary river basins, of which there are an estimated 276 shared among 148 riparian countries. Inevitably, each country (or riparian agent) has an interest in the utilization and development of water resources (Degefu and He 2015; Degefu et al. 2016; Yuan et al. 2022). However, when two or more agents share a limited water resource, the utilization of water and water resource developments such as the construction of storage reservoirs and hydropower dams, can threaten water availability to downstream agents and riparian ecosystems and lead to water conflict (Degefu et al. 2016).

Conventional water allocation methods, such as Prior Appropriation Doctrine (Lee et al. 2020; Cobourn et al. 2022), Cooperative Agreements (Wang et al. 2008; Kronaveter and Shamir 2009) and Command and Control Regulation (Oh and Tinggaard Svendsen 2015; Guo et al. 2021) cannot adequately deal with conflicting behavior and strategic interaction between agents (Wei et al. 2009). Game theoretical approaches offer an improved way of dealing with socio-economic factors and externalities, such as water stress, water depletion, groundwater table decline, drought risk and seasonal variability in water use, in water allocation decisions. The application of such approaches has potential to ensure more equitable and collaborative water allocation among the competing agents (Madani et al. 2014; Oftadeh et al. 2016; Janjua et al. 2024).

Indeed, game theoretical approaches are increasingly implemented in addressing regional water security challenges (Lee 2012; Yuan et al. 2016; Tian et al. 2022; Lagogiannis et al. 2024). For example, Dinar et al. (1992) proposed two empirical applications of game theory in order to ensure regional cooperation of irrigation water. Bender and Simonovic (2000) applied a fuzzy compromise planning approach to analyze the water resource system under uncertainty. The results showed that this compromised planning approach was helpful for group decision-making. Eleftheriadou and Mylopoulos (2008) used interconnected game models to resolve the water conflicts between Bulgaria and Greece, expanding the options available to the conflicting agents and finding a compromise solution acceptable to both parties. Wei et al. (2009) used cooperative and non-cooperative games to simulate and analyze the benefit conflicts in water resources management. They found that when the net benefits of cooperation were transferred from winner to loser, all agents could benefit, and proposed the "Prisoner's Dilemma" theory to solve such problems. A composite water resource allocation model was introduced by Kucukmehmetoglu (2012) by integrating the Pareto

Frontier concept and game theory for the Tigris-Euphrates River Basin. A multi-objective model of game theory was proposed by Lee (2012) for addressing the environmental and economic concerns in the water allocation decision-making scenarios. An asymmetric Nash bargaining solution was proposed by Degefu and He (2016) for resolving the water sharing disputes in the transboundary river basin. A mathematical programming model and hybrid game theory were proposed by Zeng et al. (2019) for solving transboundary water conflicts, which considered the quantity and quality of water. A water allocation model based on multi-objective optimization and game theory was developed by Fu et al. (2021) for the reasonable allocation of water resource under scarcity.

Apart from these studies, various researchers also used non-cooperative game theory and optimization methods for the allocation of water resources (Auman and Maschler 1985; Gallastegui et al. 2002; Casas-Méndez et al. (2011); Madani and Zarezadeh (2012); Mianabadi et al. (2014); Janjua and Hassan (2020a, b) used Bankruptcy Theory for the fair allocation of water resources under scarcity. Degefu et al. (2017) combined the Bankruptcy Theory with the asymmetric Kalai-Smorodinsky bargaining concept for the transboundary water allocation under scarcity. A multi-objective optimization model was developed by Kazemi et al. (2020) for the water allocation in the Sefrood River Basin, Iran. The main objective of this model was to minimize the Gini index (an indicator of injustice) and maximize revenue; results showed that the Gini index increases with an increase in the number of dams. Fu et al. (2024) proposed a Rubinstein bargaining conceptual model for transboundary water conflict resolution, incorporating fairness, efficiency, and minimum survival water demand principles.

The above articles used the game theory and multi-objective optimization for the design of flexible water allocation mechanisms for the river basins under water scarcity. However, both cooperation and competition of agents coexist in transboundary river basins, and a main concern with these methods is that they do not consider the multiple water negotiation processes that may be required for a successful outcome (Yazdi and Moridi 2017). In reality, the negotiation process for transboundary water allocation under scarcity involves heterogeneous water demands, with different interests and goals for the agents under different environmental and socio-economic conditions (Yazdi and Moridi 2017).

To devise satisfactory and mutually-agreed solutions for the allocation of limited resources among agents having multiple optimization goals, the agents must use a multi-stage negotiation process (Yuan et al. 2016; Medeiros et al. 2017; Lagogiannis et al. 2024). Garrick et al. (2018) suggest that, in such situations, a participatory process should be followed as distributive negotiations often lead to a win-lose solution, which might not be acceptable for all the agents involved in a water conflict. This participatory process provides better-informed and sustainable decisions in situations where stakeholders are engaged in the management of scarce water resources (Devente et al. 2016).

To allocate such resources efficiently and equitably through a multi-stage negotiation process, we propose a three-stage water allocation process. In the first stage, the riparian agents put forward a positive and negative ideal allocation plan based on the five bankruptcy rules. In the second stage, allocation of water among the agents is conducted using the Nash bargaining solution based on the positive and negative ideal solution. This way, agents can cooperate to create value and improve their collective utility. In the third stage of the allocation process, the agents' allocations are adjusted according to geographic, hydrological, climate, ecological and other socio-economic factors. This third stage is also called the value claiming stage where the agents will demand adjustment in their water allocation based on these factors.

The proposed three-stage water allocation model, as described above, is a novel approach as it is the first to integrate bankruptcy rules, Nash bargaining solution and a value-claiming stage. It accounts for the dynamic interplay of hydrological and socio-economic factors. The approach also ensures adaptability, efficiency and equity in transboundary water allocation. Its application in Pakistan's Indus Basin aims to demonstrate its potential for resolving conflicts in diverse socio-economic settings. The proposed methodology integrates the three methods to tackle the complex interplay of fairness, satisfaction and risk in the final water allocation. This approach, unlike more traditional methods, ensures a dynamic negotiation process among the agents involved in a water dispute by considering multidimensional factors. It also ensures adaptability to varying hydrological and socio-economic conditions.

This paper outlines the construction of a three-stage cooperative game model for the equitable and collaborative allocation of shared water resources among competing agents. It then provides a case study application of the approach in the transboundary Indus River Basin of southern Asia.

2 The Proposed Three Stage Water Allocation Model

The cooperative game model proposed in this study comprises three stages to better support water allocation decisions that optimize the allocation of water resources while satisfying both group utility and the individual requirements of affected agents. In the first stage of the allocation process, the agents determine their maximum and minimum water demands. The second stage requires the agents to engage in negotiations aimed at maximizing the collective utility and individual rationality, and creation of value, through cooperative negotiation. The main aim of this stage is to reach a situation where no agent can be made better off without making the other agent worse off, also known as pareto-optimality. In the third stage, the agents will require adjustments in the water allocation based on two different dimensions (level of satisfaction and level of risks they face) and claim their value. We assume that the agents competing for a limited water resource carry out these negotiations based on their needs and interests.

The main steps of the three-stage water allocation framework are given in Fig. 1 and briefly outlined here, with a more detailed discussion provided below. In the first stage of the negotiating process, the agents resolve any stalemate that might occur through collective negotiation over their initial offers. This is done by applying the three non-cooperative rules of Bankruptcy, namely the Proportionate (Pro) Rule, the Constraint Equal Award (CEA) Rule, and the Constraint Equal Loss (CEL) Rule (Kim et al. 2010; Sechi and Zucca 2015; Li et al. 2018; Tian et al. 2022). After the initial allocation of water using these three bankruptcy rules, each agent chooses their most favored allocation plan. Using these rules, the positive and negative ideal water allocations of the agents are defined.

In the second stage, keeping in view the positive and negative ideal allocation of each agent, the Nash bargaining solution (NBS) is applied to fairly allocate water among the agents. The NBS incorporates the important characteristics of the water allocation problem, which includes fairness and equity (Pande and McKee 2007). It also confirms the principles

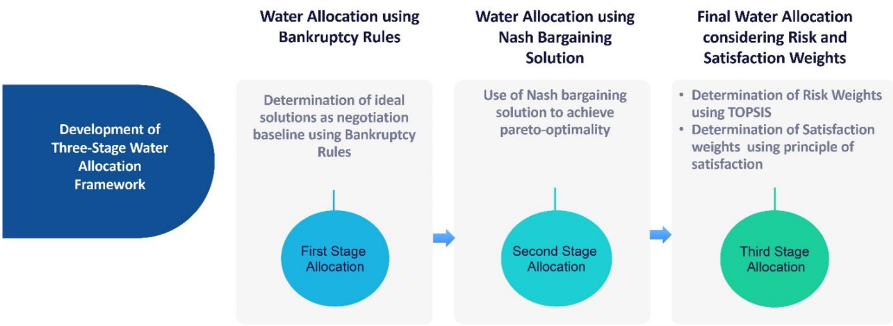

Fig. 1 Three-stage water allocation model: Stage 1 establishes ideal solutions as a negotiation baseline. Stage 2 uses Nash bargaining to achieve pareto-optimality and Stage 3 adjusts the allocations for water risk and satisfaction using TOPSIS to achieve equitable allocations

of individual and collective rationality (Dagan and Volij 1993). Therefore, in this second stage, Bankruptcy Theory is combined with the NBS to yield collaborative allocations.

In the third stage of the negotiation process, the agents claim value to achieve their goals and interests. The agents may present the case for an adjustment of the second-stage allocations based on their circumstances and risks (Appendix A). All water agents will differ in their internal and external circumstances with respect to their water demands. These include geographic, hydrological, climatic, ecological and other socio-economic factors. Therefore, in this stage of the allocation process, which is also called the value claiming stage, the agents will demand adjustment in their water allocation based on these factors. In addition, the agents will compare themselves against other agents with regard to their satisfaction level. In this stage of the process, all the agents will firstly need to understand that no agent can achieve the absolute maximization of their benefits under water scarce conditions; as a result, they will be more inclined to take the principle of satisfaction (Chu et al. 2023).

Ideally, each agent accepts the water allocation mechanism, which guarantees some target level of satisfaction. When comparing the satisfaction level after the second stage allocation, the less satisfied agents may require a higher allocation while the more satisfied agents will be required to make concessions. As the allocation of the limited water resource depends on the agents' agricultural and industrial development, the protection of their ecological environment, the quality of the surface and groundwater available in their area and other socio-economic factors, the agents are then asked to adjust the allocations based on the level of risk they face. Those agents who are exposed to higher risks may require a higher allocation, while those who face less exposure to these risks or are in a more water secure situation may make some concessions. All the above three factors are considered in the final allocation process.

2.1 First Stage Allocation

In the first stage allocation, the agents competing for a limited water resource will define their positive and negative ideal solutions. Once the total water availability and demands for each agent are determined, the allocation process will be carried out based on bankruptcy rules to arrive at a preliminary allocation plan. In this study, we employ the three classical non-cooperative bankruptcy rules including the Proportionate (Pro) rule, the Constraint Equal Award (CEA) rule, and the Constraint Equal Loss (CEL) rule (Kim and Kinoshita 2011; Mianabadi et al. 2015; Janjua and Hassan 2020a) owing to their relative simplicity and wide application.

Let us assume a set N of $n \geq 2$ agents who are the claimants, and their claims are $c_i \geq 0$, $i \epsilon N$. In river systems, bankruptcy rules determine the allocation to each agent, generally given by:

$$x_i = \mathrm{F}\left(n, A, c_i, a_i\right) \tag{1}$$

where $x_i \geq 0$ is the water allocation to each agent; A the total water resources, c_i the claim of the agent i and a_i the contribution of the agent i – the water generated in the area of the agent i. The allocation and variables in Eq. (1) satisfy constraints, given by:

$$\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} a_i = A \tag{2}$$

$$C = \sum_{i=1}^{n} c_i > A \tag{3}$$

$$0 \leq x_i \leq c_i \tag{4}$$

where A is the total available water resources and C is the total claims. We consider three bankruptcy rules including:

Proportional (PRO) rule:

$$x_i^{pro} = \rho c_i; \rho = \frac{A}{C} \tag{5}$$

The Constrained Equal Award (CEA) rule:

$$x_i^{CEA} = \min\left(\lambda, c_i\right) \tag{6}$$

where λ is the loss of claimants being relative to their claims.

The Constrained Equal Losses (CEL) rule:

$$x_i^{CEL} = \max\left(0, c_i - \lambda\right) \tag{7}$$

Each bankruptcy rule j gives an allocation plan $\boldsymbol{E}_j = \{e_{ji}; i \in \{1, 2, \ldots, n\}\}$, where e_{ji} is the water allocation ratio for an agent i being proposed by a bankruptcy rule j, satisfying

$\sum_{i=1}^{n} e_{ji} = 1$. Together, all the allocations proposed by all the three rules determine the water allocation matrix $\boldsymbol{E}$:

$$\boldsymbol{E} = \begin{bmatrix} e_{11} & e_{12} & .. & e_{1n} \\ e_{21} & e_{22} & .. & e_{2n} \\ e_{31} & e_{32} & .. & e_{3n} \end{bmatrix} \tag{8}$$

All water allocation plans are then compared, and a positive ideal allocation plan is given by,

$$\boldsymbol{E}^{+} = \left\{ e_1^{+}, e_2^{+}, \ldots, e_n^{+} \right\} \tag{9}$$

where $e_i^{+} = \max\{e_{ji}\}_{j\in\{1,2,3\}}$; $\boldsymbol{E}^{+}$is the ideal plan that provides the largest allocation for each agent as per the bankruptcy rules. However, under the positive ideal allocation plan based on bankruptcy rules, the demands of all the agents might exceed the total available water supply, $\sum_{i}^{n} e_i^{+} > 1$. On the other hand, using the three bankruptcy rules, a negative ideal allocation is determined by:

$$\boldsymbol{E}^{-} = \left\{ e_1^{-}, e_2^{-}, \ldots, e_n^{-} \right\} \tag{10}$$

where $e_i{}^{-} = \min \{e_{ji}\}_{j\in\{1,2,3\}}$; $\boldsymbol{E}^{-}$ is the plan that delivers the minimum allocations that the agents are able to accept. In the second stage of the allocation process, the agents negotiate to achieve an allocation plan that falls between the positive and negative ideal plans.

2.2 Second Stage Allocation

The objective of the second stage of water allocation among the agents is to maximize the agents' total utility based on cooperation and negotiation. The modified Nash bargaining theory states that the optimal concession ratios satisfy the following maximization conditions as the equilibrium solution of the bargaining situation (Kalai 1977; Safari et al. 2014; Fu et al. 2018; Nehra and Caplan 2022; Wu et al. 2022), given by

$$\max \left[\left(e_1^{+} - s_1 - e_1^{-} \right)^{w_1} * \left(e_2^{+} - s_2 - e_2^{-} \right)^{w_2} * \cdots * \left(e_n^{+} - s_n - e_n^{-} \right)^{w_n} \right] \tag{11}$$

and subject to

$$\sum_{i=1}^{n} \left(e_i^{+} - s_i \right) = 1 \tag{12}$$

$$e_i^{+} - s_i \geqslant e_i^{-} \tag{13}$$

In the above equation and constraints, s_i is the concession ratio which must be shared by an agent i, w_i is the relative importance or bargaining weight of each agent. In this stage of the allocation procedure, the bargaining weights of all the agents are assumed to be equal.

After applying the Nash bargaining solution, the initial allocation of agent *i* is $e_i^+ - s_i$, and $\sum_{i=1}^{n}\left(e_i^+ - s_i\right) = 1$ whose walkaway threshold is $e_i^+ - s_i \geqslant e_i^-$.

The concession ratios are determined from Eq. (11), given by

$$s_i{}^* = e_i^+ - e_i^- - w_i\left(1-\sum_{i=1}^{n} e_i^-\right) \tag{14}$$

The water allocation to each agent is:

$$r_i = e_i^+ - s_i^* = e_i^- + w_i\left(1-\sum_{i=1}^{n} e_i^-\right) \tag{15}$$

The second stage allocation $\boldsymbol{R}$ to all the agents is:

$$\boldsymbol{R} = \{r_1, r_2, \ldots, r_n\} \tag{16}$$

The main objective is to achieve individual rationality, value creation and collective optimality. However, after achieving this, the agents will claim value to obtain greater benefits for themselves based on their geographic, hydrological, climate, ecological and other socio-economic factors.

2.3 Third Stage Allocation

In this third stage of the negotiation process, the agents negotiate water allocations based on their water satisfaction and risk.

2.3.1 Allocation Adjustment Based on Water Satisfaction Level

In this step, the water satisfaction coefficient of all the agents will be calculated. As per Tversky and Kahneman (1992), the satisfaction level of the agents not only depends on the allocation per se, but also their allocation as compared to other agents. Here, r_i is the allocation ratio of the agent *i* in the second stage of allocation process, and e_i^+ is the positive ideal allocation ratio as defined in the first stage allocation. The level of satisfaction with the second stage allocation of agent *i* is given by:

$$k_i = \frac{r_i}{e_i^+} \tag{17}$$

An agent with a lower satisfaction level will demand more water. On the contrary, an agent with a higher satisfaction level will be required to make a concession to reduce its water allocation. Therefore, a satisfaction degree can be defined by,

$$s_i' = \frac{1}{s_i}. \tag{18}$$

The satisfaction coefficient is obtained by normalizing the satisfaction degree of the second stage allocation as:

$$wsc_i = \frac{s'_i}{\sum_{i=1}^{n} s'_i} \tag{19}$$

The satisfaction coefficient of all the agent is therefore:

$$WSC = \{wsc_1, wsc_2, \dots, wsc_n\} \tag{20}$$

2.3.2 Allocation Adjustment Based on Water Risks

All water-sharing agents experience differing levels of risks, which include hydrological, climate, ecological and other socio-economic factors (Tversky and Kahneman 1992; Gao et al. 2019). In this third stage of the allocation process, the agents facing greater risks will highlight these risks (Appendix A) and request additional water.

These risks are difficult to quantify; therefore, we apply the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Choudhary and Shankar 2012; Patil and Kant 2014; Kusumawardani and Agintiara 2015; Samanlioglu et al. 2018; Sirisawat and Kiatcharoenpol 2018; Azari et al. 2022; Nazim et al. 2022), which is a multi-criteria decision analysis method to evaluate the water risk coefficient, given by:

$$\boldsymbol{WRC} = \{wrc_1, wrc_2, \dots, wrc_n\} \tag{21}$$

This method considers five risk factors including water stress, water depletion, groundwater table decline, drought risk, and seasonal variability to determine the weights of the agents in terms of their risks. The process delivers three outcomes: a negative ideal solution; a positive ideal solution; and weights specific to each agent.

TOPSIS is based on the selection of the best alternative that is furthest from the negative ideal solution and closest to the positive ideal solution. The final ranking of the factors is done on the basis of relative closeness to the ideal solution (Ilangkumaran and Kumanan 2009). In the general TOPSIS process, *'m'* denotes the number of alternatives being evaluated, while *'f'* signifies the total number of attributes (criteria) under consideration. Within these criteria, *'i'* typically denotes the cost criteria, representing factors where lower values are preferable, while *'j'* represents the benefits criteria, where higher values are preferred. The general TOPSIS process has following steps (Gumus 2009; Joshi et al. 2011).

Step 1:

Construct normalized decision matrix. The calculation of normalized value z_{ij} is done by:

$$r_{ij} = \frac{z_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}};\ i = 1, \ldots, m; j = 1, \ldots, f. \tag{22}$$

Step 2:

Construct the weighted normalized decision matrix. Assume we have a set of weights for each criterion w_j for $j = 1, \ldots, f$ and $\sum_{j=1}^{f} w_j = 1$. Each column of the normalized decision matrix is then multiplied by its weight. An element of the new matrix is given by,

$$\eta_{ij} = w_j * r_{ij};\ i = 1, \ldots, m; j = 1, \ldots, f. \tag{23}$$

Step 3:

Determination of positive ideal and negative ideal solutions.

For positive ideal solution.

$$\boldsymbol{\eta}^+ = \left\{\eta_1^+, \eta_2^+, \ldots, \eta_n^+\right\} \tag{24}$$

where,

$$n_j^+ = \{max\,(\eta_{ij})\,, i = 1, \ldots, m\}\,, j = 1, \ldots, f. \tag{25}$$

For negative ideal solution.

$$\boldsymbol{\eta}^- = \left\{\eta_1{}^-\ , \ldots\ldots.., \eta_n{}^-\right\} \tag{26}$$

where,

$$\eta_j^- = \{min\,(\eta_{ij})\,, i = 1, \ldots, m\}\,, j = 1, ., f. \tag{27}$$

Step 4:

Calculation of separation measures.

From the positive ideal alternative, the separation measure is:

$$S_i^+ = \left\{\sum{}_{j=1}^{n}\left(\eta_{ij} - \eta_j^+\right)^2\right\}^{1/2} i = 1,\ \ldots\ ,\ m. \tag{28}$$

From the negative ideal alternative, the separation measure is:

$$S_i^- = \left\{\sum{}_{j=1}^{n}\left(\eta_{ij} - \eta_j^-\right)^2\right\}^{\frac{1}{2}} i = 1,\ \ldots\ ,\ m. \tag{29}$$

Step 5.

Calculation of relative closeness from the ideal solution.

$$C_i = \frac{S_i^-}{\left(S_i^+ + S_i^-\right)}, \ i = 1. \ \ldots \ , \ m. \ C_i \in \ \{0. \ 1\} \tag{30}$$

In TOPSIS method, C_i will denote the final score. The water risk coefficients are therefore given by:

$$WSC = \{wsc_1, \ wsc_2, \ , , , , , , wsc_n\} \tag{31}$$

Step 6:

The final weights of the agents can then be calculated.

2.4 Final Allocation

The final allocation ratio is denoted by x_i. This is decided by the Nash bargaining allocation in the second stage of the process and the adjustment in the water satisfaction and risk in the third stage. The equation below is the final allocation for agent *i*:

$$x_i = \frac{\left(wsc_i + \ wrc_i\right) \ r_i}{\sum \ _{i=1}^{n} \left(wsc_i + \ wrc_i\right) \ r_i} \tag{32}$$

In Eq. 32, r_i is the allocation of each agent using Nash bargaining solution as stated in Eq. (15). wsc_i is the satisfaction coefficient as stated in Eq. (19) and wrc_i is the risk coefficient as stated in Eq. (31).

3 Case Study Description

Pakistan has the world's largest contiguous irrigation system in the world. The Indus Basin Irrigation System (IBIS) of Pakistan supports the majority of the domestic, industrial, agricultural, and environmental demands of the country (Briscoe J 2006). The Indus Basin spans all four provinces, namely Punjab, Sindh, Balochistan and Khyber Pakhtunkhwa (KPK) of Pakistan. It predominantly relies on surface water supplies from the Himalayan Mountains, with its headwaters in India and Nepal. Further details of the case study area is provided in Appendix B.

4 Formulation of Scenarios

Based on the information provided on the canal diversions from the Indus River System Authority (IRSA) from 1975 to 2020 (Appendix B), three scenarios were devised: low (minimum), average, and high (maximum) canal diversions (Table 1).

Table 1 Water demands for different IRB provinces under three scenarios

Scenarios	Agent	Water Demand (Km^3)	Total Water Availability (Km^3)	Water Deficit (Km^3)
Scenario-1 (Minimum Canal Diversions)	Punjab	109.49	94.00	76.56
	Sindh	43.37		
	Balochistan	9.42		
	KPK	8.28		
Scenario 2 (Average canal diversions)	Punjab	109.49	125.61	44.95
	Sindh	43.37		
	Balochistan	9.42		
	KPK	8.28		
Scenario 3 (Maximum canal diversions)	Punjab	109.49	137.00	33.56
	Sindh	43.37		
	Balochistan	9.42		
	KPK	8.28		

4.1 Source: Indus River System Authority (IRSA) and Janjua and Hassan (2020b)

4.1.1 Low (Minimum) Canal Diversions Scenario

In this scenario, the canal diversions are at their minimum level which indicates low water availability for agricultural agents. This scenario arises due to factors such as drought or upstream water diversions that reduce inflow into the Pakistani section of the river system. This low canal diversions scenario presents a significant challenge for the fair and equitable allocation of water among the agents.

4.1.2 Average Canal Diversions Scenario

This scenario represents a situation where the availability of water is neither exceptionally high or low. This average canal diversion scenario serves as a baseline for comparison with the other two scenarios.

4.1.3 High (Maximum) Canal Diversions Scenario

This scenario considers canal diversions at the maximum level possible, where water availability for the agents is at its highest. This scenario may occur due to abundant rainfall or increased water flow into the river system.

In all of the above scenarios, a supply-demand gap exists. Applying the Nash bargaining solution will ensure fair and equitable water allocation among the agents considering their preferences, bargaining power, and constraints. The water requirements, total water availability and water deficits of all four agents are given in Table 1.

5 Results

5.1 First Stage Allocation Results

The water allocation using the three rules of bankruptcy for the three scenarios are shown in Table 2. Here, we postulate that the agents are negotiating over the water allocation. As per results in Table 2, the positive ideal allocation (values are km^3) for the four agents for Scenarios 1, 2 and 3 would be:

$$\mathrm{E_{Sce1}}^{+} = \{850.17,\ 400.59,\ 80.81,\ 100.02\}$$

$$\mathrm{E_{Sce2}}^{+} = \{760.32,\ 340.53,\ 60.59,\ 70.50\}$$

$$\mathrm{E_{Sce3}}^{+} = \{730.77,\ 310.66,\ 60.04,\ 60.88\}$$

Similarly, the negative ideal allocation for the three scenarios would be:

$$\mathrm{E_{Sce1}}^{-} = \{400.59,\ 140.83,\ 00.00,\ 00.00\}$$

$$\mathrm{E_{Sce2}}^{-} = \{510.38,\ 230.68,\ 00.00,\ 00.00\}$$

$$\mathrm{E_{Sce3}}^{-} = \{550.42,\ 250.43,\ 00.00,\ 00.73\}$$

5.2 Second Stage Allocation Results

In the second stage of water allocation, we use Eq. (11) for the allocation of water among the agents under all three scenarios. The concession ratio for each agent needs to satisfy:

- *Scenario 1*:

Table 2 Water Allocation for the four provinces using bankruptcy rules (First Stage Allocation), where scenario 1 is minimum canal diversions; scenario 2 is average canal diversions; and scenario 3 is maximum canal diversions

	Riparian Province (n)	Scenario 1	Scenario 2	Scenario 3
		Water Allocation (%)		
Proportionate Rule (PRO)	Punjab	64.19	64.19	64.19
	Sindh	25.43	25.43	25.43
	Balochistan	4.85	4.85	4.85
	KPK	5.52	5.52	5.52
Constraint Equal Award Rule (CEA)	Punjab	40.59	51.38	55.42
	Sindh	40.59	34.53	31.66
	Balochistan	8.81	6.59	6.04
	KPK	10.02	7.50	6.88
Constraint Equal Loss Rule (CEL)	Punjab	85.17	76.32	73.77
	Sindh	14.83	23.68	25.51
	Balochistan	0.00	0.00	0.00
	KPK	0.00	0.00	0.73

$$Max\ \ [(85.17 - S_{Pun} -\ 40.59)\ \ (40.59 - S_{Sin} -\ 14.83)\,(8.81 - S_{Bal} -\ 0.00)\,(10.02 - S_{KPK} -\ 0.00)]$$

$$st.\ \begin{cases} S_{Pun} + S_{Sin} + S_{Bal} + S_{KPK} = 44.59 \\ 85.17 - S_{Pun} \geq 40.59 \\ 40.59 - S_{Sin} \geq 14.83 \\ 8.81 - S_{Bal} \geq 0.00 \\ 10.02 - S_{KPK} \geq 0.00 \end{cases}$$

- *Scenario 2*:

$$Max\ \ [(76.32 - S_{Pun} -\ 51.38)\ \ (34.53 - S_{Sin} -\ 23.68)\,(6.59 - S_{Bal} -\ 0.00)\,(7.50 - S_{KPK} -\ 0.00)]$$

$$st.\ \begin{cases} S_{Pun} + S_{Sin} + S_{Bal} + S_{KPK} = 24.93 \\ 76.32 - S_{Pun} \geq 51.38 \\ 34.53 - S_{Sin} \geq 23.68 \\ 6.59 - S_{Bal} \geq 0.00 \\ 7.50 - S_{KPK} \geq 0.00 \end{cases}$$

- *Scenario 3*:

$$Max\ \ [(85.17 - S_{Pun} -\ 40.59)\ \ (40.59 - S_{Sin} -\ 14.83)\,(8.81 - S_{Bal} -\ 0.00)\,(10.02 - S_{KPK} -\ 0.00)]$$

$$st.\ \begin{cases} S_{Pun} + S_{Sin} + S_{Bal} + S_{KPK} = 18.34 \\ 73.77 - S_{Pun} \geq 55.42 \\ 31.66 - S_{Sin} \geq 25.43 \\ 6.04 - S_{Bal} \geq 0.00 \\ 6.88 - S_{KPK} \geq 0.73 \end{cases}$$

We use MATLAB software to solve the functions for all the three scenarios. The optimal concession ratios for the three scenarios come out to be:

$$\left.\begin{matrix} S_{Pun} = 31.70 \\ S_{\mathrm{Sin}} = 12.87 \\ S_{Bal} = 0 \\ S_{KPK} = 0 \end{matrix}\right\} Scenario - 1,\quad \left.\begin{matrix} S_{Pun} = 18.70 \\ S_{\mathrm{Sin}} = 4.61 \\ S_{Bal} = 0.36 \\ S_{KPK} = 1.26 \end{matrix}\right\} Scenario - 2,\quad \left.\begin{matrix} S_{Pun} = 13.74 \\ S_{\mathrm{Sin}} = 1.63 \\ S_{Bal} = 1.44 \\ S_{KPK} = 1.54 \end{matrix}\right\} Scenario - 3$$

The second stage allocation for all the three scenarios is therefore:

$$R_{Sce-1} = \{r_{Pun},\ r_{Sin},\ r_{Bal}, r_{KPK}\} = \{53.46,\ 27.70,\ 8.80,\ 10.02\}$$

$$R_{Sce-2} = \{r_{Pun},\ r_{Sin},\ r_{Bal}, r_{KPK}\} = \{57.61,\ 29.91,\ 6.24,\ 6.24\}$$

$$R_{Sce-3} = \{r_{Pun},\ r_{Sin},\ r_{Bal}, r_{KPK}\} = \{60.03,\ 30.03,\ 4.60,\ 5.34\}$$

5.3 Third Stage Allocation Results

- Adjustment for water satisfaction

Satisfaction level of the four agents with the second stage allocation is given by:

$$s_i = \left\{ \frac{r_{Pun}}{e_i+\ (Pun)}, \frac{r_{Sin}}{e_i+\ (Sin)}, \frac{r_{Bal}}{e_i+\ (Bal)}, \frac{r_{KPK}}{e_i+\ (KPK)} \right\}$$

For the three scenarios, the level of satisfaction is therefore, given by:

$$\begin{aligned} s_{i_{Sce-1}} &= \{0.62,\ 0.68,\ 1.00,\ 1.00\} \\ s_{i_{Sce-2}} &= \{0.75,\ 0.86,\ 0.94,\ 0.83\} \\ s_{i_{Sce-3}} &= \{0.81,\ 0.94,\ 0.76,\ 0.77\} \end{aligned}$$

After applying Eqs. 9 and 11, the water satisfaction coefficient is given by:

$$WSC = \{wsc_{Pun},\ wsc_{Sin},\ wsc_{Bal},\ wsc_{KPK}\ \}$$

For the three scenarios, the water satisfaction coefficient is given by:

$$\begin{aligned} WSC_{sce-1} &= \{0.31,\ 0.28,\ 0.19,\ 0.19\} \\ WSC_{sce-2} &= \{0.27,\ 0.24,\ 0.22,\ 0.25\} \\ WSC_{sce-3} &= \{0.25,\ 0.21,\ 0.26,\ 0.26\} \end{aligned}$$

- Adjustment for water risks

To calculate the importance index of each risk criteria, the Aqueduct Water Risk Atlas was used (Institute 2023). As discussed, water risks are urgent global challenges and must be incorporated into the water allocation mechanism to ensure equitable and fair allocation of water resources. The Aqueduct Water Risk Atlas maps and analyses current and future water risks across locations.

The TOPSIS method was used to rank and weight each agent with respect to its water risks, as discussed in Section III.

Using the TOPSIS methodology, the risk evaluation scores for each agent were calculated to be {0.2068, 0.3582, 0.3593, 0.0758}. The TOPSIS technique was employed as a structured approach to determine the weights of water-related risks (as explained in Appendix A) with respect to the agents (in our case, provinces) involved. These calculated weights were subsequently utilized as input into our allocation model, effectively transforming them into “water risk” weights.

5.4 Final Allocation and Adjusted Final Allocation

The final water allocation is determined using Eq. (29). For all three scenarios, after incorporating risk and satisfaction weights, these are given by:

$$\begin{aligned} X_{i_{Sce-1}} &= \{x_{Pun},\ x_{Sin},\ x_{Bal}, x_{KPK}\} = \{51.65,\ 33.95,\ 9.41,\ 4.99\} \\ X_{i_{Sce-2}} &= \{x_{Pun},\ x_{Sin},\ x_{Bal}, x_{KPK}\} = \{54.05,\ 34.96,\ 7.06,\ 3.93\} \\ X_{i_{Sce-3}} &= \{x_{Pun},\ x_{Sin},\ x_{Bal}, x_{KPK}\} = \{53.36,\ 34.43,\ 7.88,\ 4.34\} \end{aligned}$$

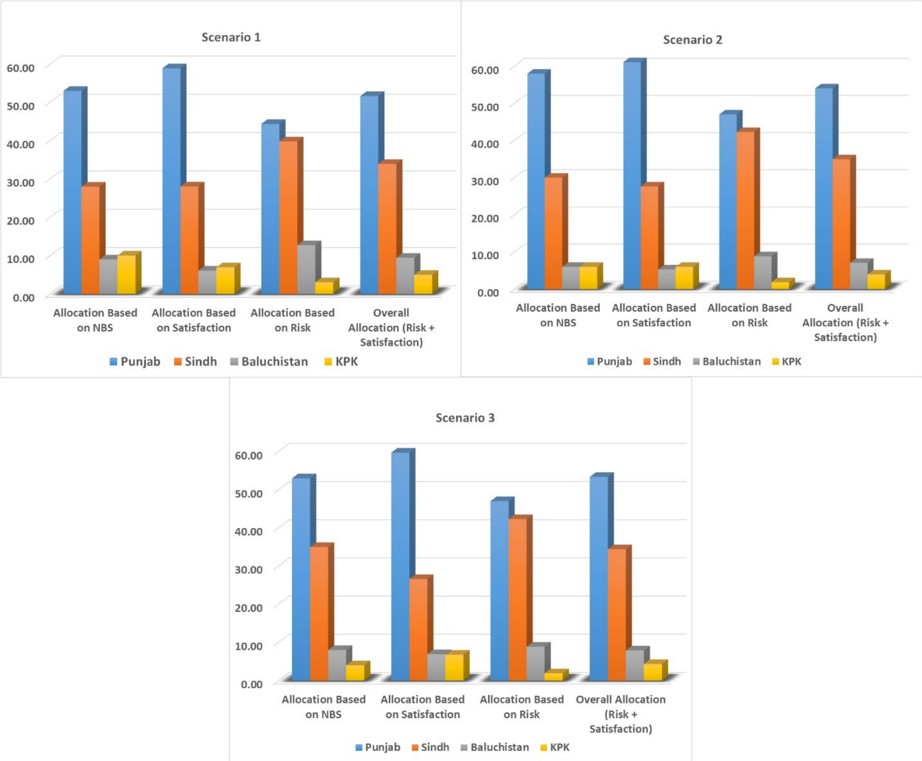

Fig. 2 Comparison of allocation adjustments for the four provinces based on different coefficients for all three scenarios, where Scenario 1 is minimum canal diversions; Scenario 2 is average canal diversions; and Scenario 3 is Maximum canal diversions

The results shown in Fig. 2 depict the water allocation based all three scenarios. For example, if we look at Scenario 3 and compare the water allocation based on NBS it can be seen that, based on "Satisfaction", the water allocation for Punjab and KPK was high as they have low satisfaction level as compared to Sindh and Baluchistan. Similarly, for the allocation based on "Risks", the water allocation increases for Sindh and Baluchistan as compared to allocation based on NBS, addressing their high risks. Lastly, the allocation based on the "Satisfaction" and "Risks" combined balances allocations by moderately reducing Punjab and KPK's shares while increasing Sindh and Baluchistan's, achieving a fair trade-off.

6 Discussion

6.1 General Overview

Here, we have used a combination of approaches to develop and test a three-stage water allocation framework to better ensure the equitable sharing of scarce water resources amongst competing agents, thereby also reducing the potential for conflict. Using a case study of four riparian provinces in the Indus River basin, our results highlight that addressing satisfaction alone benefits the less satisfied provinces, while focusing solely on risks prioritizes vulnerable provinces. Our combined approach achieves an acceptable compromise based on both "Satisfaction" and "Risk" that balances equity and efficiency in water allocation. Therefore, it is expected that the outcome would be acceptable to all four agents.

6.2 Policy Recommendations

The proposed methodology offers a significant advantage over more conventional approaches for resolving cross-boundary conflicts among agents as it provides a more transparent and equitable water allocation process. Moreover, the model's flexibility allows for adaptation to suit the unique geopolitical dynamics and water-related challenges of each riparian region, thereby enhancing its applicability and effectiveness in diverse contexts.

6.3 Limitations and Future Directions

The three-stage allocation framework proposed in this study is primarily based on group decision-making among the agents, whereby the agents negotiate and form their positive and negative ideal solutions to reach an allocation result that satisfies individual rationality and group utility. As such, the proposed study has a number of potential limitations. Firstly, this model can only be successful if all the contending parties agree to engage in cooperative decision making. Where river basin water resources have been the basis of international disputes, this cooperation may be hindered by historical animosities and political tensions. Secondly, the model's effectiveness may be impacted by data limitations, particularly for countries with inadequate telemetry systems or unreliable data sources. For future works, robust data collection and enhanced data sharing mechanisms among riparian countries would strengthen the model's reliability. Additionally, confidence building among the contending parties and the fostering of diplomatic initiatives amongst them would be crucial for creating an enabling environment necessary for the successful implementation of the proposed methodology.

7 Conclusions and Policy Recommendations

The significant challenges of water resource allocation have been considered in this study. Issues related to governance and management of shared river basins for competing and often conflicting demands in the midst of limited supplies continue to be of concern, driving conflict, and limiting cooperation. To address the multi-dimensional attributes of water resources, a three-stage allocation model has been proposed and the allocation of water has been conducted under three potential scenarios for a case study region. These three scenarios are used for illustration purposes only. To expand the scope of the conversation, one may explore other scenarios, including the effects of changes in populations, environmental conditions and regulations.

The proposed three-stage water allocation model is a novel approach that improves on traditional methods of water allocation. Firstly, employing the rules of bankruptcy for the first (initial) stage water resource allocation ensures that stakeholders (agents) agree to a positive and negative ideal allocation and brings them to the table for further negotiation and cooperation. The Nash bargaining solution utilized for the second stage of the allocation process promotes cooperative decision making among the agents (provinces, countries). This stage of the three-stage allocation approach ensures individual rationality, value creation and collective optimality. In the third allocation stage, the incorporation of TOPSIS adds robustness by allowing consideration of various risks and uncertainties associated with water allocation decisions. This stage ensures that final water allocations are based on various factors such as water scarcity, water depletion, groundwater table decline, drought risks and seasonal variability, thereby leading to more informed, equitable and effective resource management.

Appendix A

Table A1 Risk indicators to be considered in the final stage of water allocations

Type of Risk	Description
Water stress	Water stress measures the ratio of total water demand to available renewable surface and groundwater supplies. Water demand includes domestic, industrial, irrigation, and livestock uses. Available renewable water supplies consider the impact of upstream consumptive water users and large dams on downstream water availability. Higher water stress values indicate more competition among users.
Water depletion	Water depletion measures the ratio of total water consumption to available renewable water supplies. Total water consumption includes domestic, industrial, irrigation, and livestock consumptive uses. Available renewable water supplies consider the impact of upstream consumptive water users and large dams on downstream water availability. Higher values indicate more significant impact on the local water supply and decreased water availability for downstream users. Water depletion is like baseline water stress; however, instead of looking at total water demand (consumptive plus non-consumptive), baseline water depletion is calculated using consumptive withdrawal only.
Groundwater table decline	Groundwater table decline measures the average decline of the groundwater table. Higher values indicate higher levels of unsustainable groundwater withdrawals.
Drought risk	Drought risk measures where droughts are likely to occur, the population and assets exposed, and the vulnerability of the population and assets to adverse effects. Higher values indicate a higher risk of drought.
Seasonal variability	Seasonal variability measures the average within-year variability of available water supply, including both renewable surface and groundwater supplies. Higher values indicate wider variations of available supply within a year.

Source: World Resource Institute, AQUEDUCT (https://www.wri.org/aqueduct)

Appendix B

With the population of Pakistan growing rapidly, the demand for water is increasing, causing a widening gap between supply and demand. Therefore, fair distribution of water is crucial for all provinces (Khan 2014; Podger and Ahmad 2014). The Indus River System Authority (IRSA) was established by the Government of Pakistan in 1992 to regulate and monitor the allocation of water resources of the Indus River Water Apportionment Accord (WAA). The authority responsible for water apportionment comprises representatives from all four provinces and the federal government. However, the current water apportionment accord's non-legal status, lack of detail, and fixed water allocation model make it challenging to implement in practice. Additionally, the sharing mechanisms of the Accord are interpreted differently by each province, leading to disputes and mistrust (Iucn 2010; Anwar et al. 2018; Lohano and Marri 2020). The river network of Indus Basin, Pakistan is shown in Figure B1 (Appendix-B)

Fig. B1 River Network of Indus Basin, Pakistan Source: FAO Aquastat (http://www.fao.org/nr/water/aquastat/basins/indus/print1.stm)

A 2019 report by the World Bank (William. J Young et al., 2019) highlighted the need to revise Pakistan's Indus water-sharing mechanism in response to the increase in water demands, changing resource availability and loss of storage capacity because of sedimentation (Ahmad et al. 2023). The increased water demands and hence, the supply-demand gap, is negatively impacting relations between the provinces; greater cooperation between these agents is required to bring greater water resource utility. A rational (more equitable, adaptive) water allocation model is urgently needed to prevent conflict between the provinces

Various studies indicate that the total surface water resources available in Pakistan's Indus Basin are insufficient to meet the water demands of all four provinces (Laghari et al., 2012; Yang et al. 2014; Molnar et al. 2017; Amin et al. 2018; Boretti and Rosa 2019; He et al. 2021). The Indus River is a major water source for Pakistan. Made up of six tributaries, namely Ravi, Sutlej, Beas, Chenab, Jhelum, and Indus itself, river flows are mainly supplied by glacier melt, snowmelt, rainfall, and runoff. These waters support significant agricultural production and the livelihoods of numerous smallholders farmers, as well as urban populations and industrial sectors (Hussain et al. 2011; Laghari et al., 2012; McCracken and Wolf 2019). The Indus River System Authority (IRSA) provides information about the median, minimum, and maximum canal diversions from 1975 to 2020, as shown in Figure B2 (Appendix-B). Based on the canal diversion data provided by the IRSA, three scenarios were formulated for this study: low (minimum), average, and high (maximum) diversions, each representing different levels of water usage (details in Sect. 4). Nash bargaining solution was then employed to negotiate equitable water allocation among stakeholders (in this case, the four provinces) under these scenarios, considering their interests and constraints

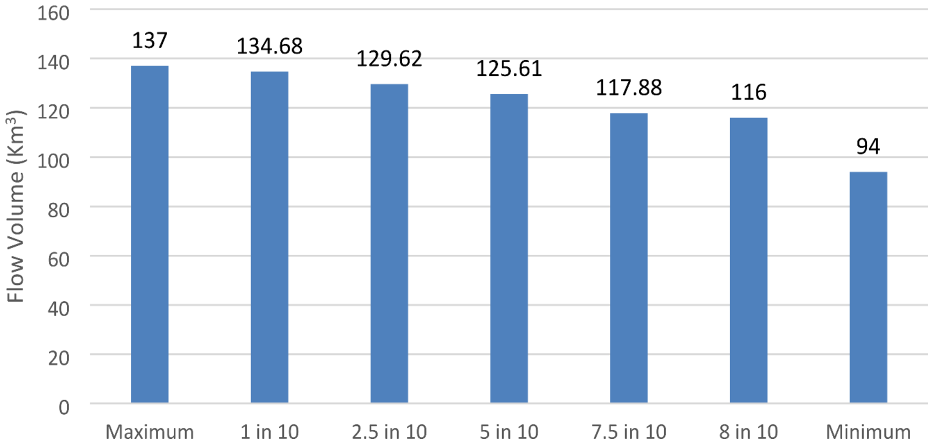

Fig. B2 Canal diversions (cubic kilometers) during 1975–2020 Source: Indus River System Authority (IRSA)

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