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# Addressing the supply-demand gap in shared rivers using water diplomacy framework: utility of game theory in the Indus river within Pakistan

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## Abstract

The question of how to govern and manage transboundary river basin for competing and often conflicting demands due to limited supplies continues to be an issue of concern, conflict, and cooperation. A key novelty of this paper is the use of the Water Diplomacy Framework (WDF) to address supply-demand mismatch using the notion of collaborative problem-solving and joint fact-finding. It builds on innovative applications of game-theoretic approaches and uses equity and sustainability as guiding principles to address the supply-demand mismatch. Five different bankruptcy methods (net benefit ranges between US$17,462M to US$18,201M) and the Nash Bargaining Solution (net benefit ranges between US$18,132M to US$19,216M) are used to resolve supply-demand mismatch in the Indus basin among four provinces within Pakistan. The maximum total benefit generated from the Nash Bargaining Solution is 5.5% higher compared to the best bankruptcy method. Moving from the non-cooperative and rule-based bankruptcy methods to the Nash Bargaining Solutions provided increased benefit for all stakeholders. Reallocation of these increased benefits among the four provinces is done by applying the Nash Bargaining Solutions for homogenous and heterogeneous weights. These findings suggest that aspects of WDF – cooperative problem-solving approaches involving joint fact-finding and exploring different options – has the potential to simultaneously resolve supply-demand mismatch and generate more benefits for all stakeholders.

*Keywords:* Bankruptcy rules; Equity; Nash bargaining theory; Sustainability; Water diplomacy

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## Highlights

- Resolve supply-demand gaps in transboundary river basins.
- Use the Water Diplomacy Framework (WDF) to resolve this gap.
- Explore options through joint fact-finding and collaborative problem solving.
- Use game-theoretic approaches to operationalize the WDF.

## Introduction

Conflicts related to the transboundary river basins (TRBs) are not new. The question of how to govern and manage TRB for human consumption, irrigation, hydropower, urban and industrial development, socio-cultural needs, and sustainability of ecosystems continues to be an issue of concern, conflict, and cooperation. Academic literature and policy practice suggest interactions of many natural, societal, and political elements (hereafter, elements will be used to mean variables, processes, actors, and institutions within a TRB system) shape the nature and evolution of TRB dynamics. Context, complexity, and contingency are terms that are now in frequent use in addressing TRB issues. There are multiple schools of thought and scholarship (Wolf, 1999; Swain, 2001; Salman, 2007); however, there appears to be a void of actionable ideas on *what to do and how*.

This paper will look at supply-demand mismatch as a key attribute leading to the complexity of TRB management. Although many technical solutions are discussed and debated to address this aspect of TRB management, still there appears to be no general consensus on how to effectively address this key aspect of TRB conflicts: supply-demand mismatch. An alternative to the traditional techno-focused approach to water management is provided by the Water Diplomacy Framework (WDF) (Islam & Susskind, 2012). The WDF diagnoses water problems, identifies intervention points, and proposes sustainable and equitable resolutions that are sensitive to diverse viewpoints and uncertainty as well as changing and competing demands.

The Indus Water Treaty resulted in the partitioning of the rivers between India and Pakistan. The 1960 IWT has created new challenges regarding the allocation of the Indus water among the provinces within Pakistan. We use water allocation among four provinces within Pakistan to show how innovative game-theoretic approaches, along with the WDF, can be used as an effective tool to address the supply-demand mismatch in the Indus Basin within Pakistan.

A variety of frameworks, models, and tools – from systems engineering, game theory, negotiation, and social choice methods – were used to address the supply-demand mismatch of TRB conflicts. Game-theoretic approaches can be useful in situations when the market mechanism fails, and traditional systems optimization are not effective (Madani, 2010; Dinar & Hogarth, 2015). The game-theoretic approaches have been increasingly used to address TRB water allocation problems beginning with the pioneering work of Ransmeier (1942), for the Tennessee Valley Authority investment project, yet there appears to be no general consensus regarding which game-theoretic approach works best for what type of TRB conflict and why. In this paper, we will look at the utility of game-theoretic approaches (e.g. Wang, 2003; Kucukmehmetoglu & Guldmann, 2004; Madani & Dinar, 2011; Mianabadi *et al.*, 2015; Janjua & Hassan, 2020a, and references therein) to address supply-demand gaps in TRBs using the WDF (Islam & Susskind, 2012, 2018).

Stakeholder's desire to have a larger share of available water creates a supply-demand mismatch. To address this mismatch we need a process to examine the implications of different allocation options. A systematic modeling exercise can help facilitate this process. However, if the stakeholders do not understand the basic structure of a model, they may not actively participate in a problem-solving process. Consequently, the acceptance and implementation of the findings from such a process may not materialize. The notion of joint fact-finding – a key aspect of the WDF – facilitates co-creation of models to explore different options for resolving conflicting needs and competing demands. Here, we will use different bankruptcy methods and the Nash Bargaining solutions to examine different aspects and consequences of addressing supply-demand mismatch in the Indus basin within Pakistan. A key new feature of this paper is the use of WDF to address the supply-demand gap using different tools from game theory. This paper builds on some of our earlier work published in Janjua & Hassan (2020a) with significant new analyses, including the Nash Bargaining Solution for water allocation for different scenarios based on groundwater usage, agricultural productivity, and population.

The paper is organized as follows: the next section discusses the methodology followed by a description of the Indus basin case study. Next, the results are discussed, and the following section discusses issues related to choice of metrics for allocation. Finally, a summary of the findings and conclusions is provided.

## Methodology

### *Water diplomacy framework*

Due to the crossing of multiple boundaries and the involvement of various stakeholders, the TRB issues are complex. If one views water as a limited resource, it may create conflicts over its access and allocation. A reframing of water use and allocation problems can transform a finite water quantity into a flexible resource. We need to synthesize scientific (explicit) and contextual (tacit) water knowledge for such a reframing. Such a framework needs to build on the objectivity of science and be cognizant of contextual differences inherent to water issues – the Water Diplomacy Framework (WDF) initially proposed in Islam & Susskind (2012) is a step in that direction. An evolving version of the WDF (Islam & Smith, 2019) is based on the following premise:

- Water is not a fixed resource.
- The complexity of water problems arises from the coupling of natural and human systems.
- Solution space for these complex problems – with interdependent variables, processes, actors, and institutions – cannot be pre-stated. The use of dualistic representations (numbers or narratives; facts or values; objective or subjective) for these problems is inadequate.
- Differentiate complexity from deterministic certainty and statistical uncertainty; instead, identify the conditions (rather than the cause) for emergent patterns.
- Use the rigor of scientific methods as the principle to derive facts with an adherence to a negotiated application of sustainability and equity as guiding values to design and implement pragmatic interventions.
- Focus on identifying and implementing societally relevant technological solutions given the context, constraints, and capacity of a given system.

To operationalize the WDF, in this paper, we will examine the utility of game-theoretic approaches to address supply-demand mismatch and help develop effective TRB management strategies.

*Water allocation using simple bankruptcy rules*

In economics, the bankruptcy rules are used when the available assets are not enough to satisfy the claim of stakeholders. When the resources are smaller 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 bankruptcy methods, which represent 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 have different demand (claim) levels. Bankruptcy methods (O'Neill, 1982; Dagan & Volij, 1993) can be used to fairly address the supply-demand gap in allocating available resources among the contending parties. Different notions of fairness have resulted in the development of various bankruptcy rules. For its relative simplicity and wide applications, we will begin with the bankruptcy rules to allocate water in the Indus River within Pakistan. Here, five classical rules of bankruptcy are used for the allocation of the resource among the stakeholders when the total assets are not enough to satisfy the needs of all stakeholders.

Let us assume a set $N$ of $n \geq 2$ agents who are the claimants, and their claims are $c_i \geq 0$; $C = (c_1,\ldots,c_n)$. In river systems, the bankruptcy problem is defined as F $(n, E, c_i, a_i)$; $i = 1, 2,\ldots,n$, where $n$ = number of agents, $E$ = total resources, $c_i$ = claim of the agent $i$ and $a_i$ = contribution of the agent $i$. The aim of the bankruptcy method is to determine the allocation to each agent, denoted by $F\ (N, E, c_i, a_i) = x_i$ where $x_i \geq 0$; $x = (x_i,\ldots,x_n)$. For a resource allocation problem, we have:

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

$$C = \sum_{i=1}^{n} c_i \tag{2}$$

$$\sum_{i=1}^{n} a_i = \sum_{i=1}^{n} x_i \tag{3}$$

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

Equation (1) is the contribution of the agents whereas Equation (2) is the claims of the agents respectively. According to Equation (3), all the assets are allocated whereas according to Equation (4) the assets cannot be negative and cannot be greater than its claims.

*Proportional rule (PRO)*

This rule is given by:

$$x_i^{pro} = \rho c_i \text{ where } \rho = \frac{E}{C} \tag{5}$$

where $E$ is the total assets and $C$ is the total claims.

*The constrained equal award (CEA) rule*

This rule is given by:

$$x_i^{CEA} = min\,(\lambda,\, c_i) \text{ where} \sum_{i \in N} min\,(\lambda,\, c_i) = E \tag{6}$$

*The constrained equal losses (CEL) rule*

This rule is defined as:

$$x_i^{CEL} = max\,(0,\, c_i - \lambda) \text{ where} \sum_{i \in N} max\,(0,\, c_i - \lambda) = E \tag{7}$$

Under the CEL rule, each claimant is allocated a share of the asset such that their losses in comparison with their claims ($\lambda$) are equal, constrained to no claimant receiving a negative allocation.

*The Talmud rule*

The Talmud Rule is derived by combining the CEA and CEL rules and is given by:

$$x_i^{TAL} = \begin{cases} CEA\left\{\frac{1}{2}c_i,\, E\right\} & if\ E \leq \frac{C}{2} \\ \frac{1}{2}c_i + CEL\left\{\frac{1}{2}c_i,\, E - \frac{1}{2}C\right\} & otherwise \end{cases} \tag{8}$$

*The Piniles rule*

For each $c_i$, $x_i^{Pin}$ is calculated as follow (Bosmans & Lauwers, 2011):

$$x_i^{Pin} = \begin{cases} CEA\left\{\frac{1}{2}c_i,\, E\right\} & if\ E \leq \frac{C}{2} \\ \frac{1}{2}c_i + CEA\left\{\frac{1}{2}c_i,\, E - \frac{1}{2}C\right\} & otherwise \end{cases} \tag{9}$$

These rules work well when the notion of fairness embedded in a given rule is agreed upon by the contending parties. A key challenge is: Who decides what criteria to choose among the competing bankruptcy rules to ascertain the notion of fairness? Is agricultural productivity more important than the ecological sustainability of the Indus basin while allocating water? Can (and how much) groundwater be used to supplant the supply-demand mismatch of available surface water for the Indus basin within Pakistan? These questions cannot be addressed by pure technical solutions like the bankruptcy rules. We need an allocation process with certain desirable properties like equity and sustainability, as discussed in the Water Diplomacy Framework.

*Water allocation using a combination of Nash bargaining theory and water bankruptcy concept*

Building on earlier works (Sgobbi, 2011; Safari *et al.*, 2014; Degefu & Weijun, 2016; Qin *et al.*, 2019), and using equity and sustainability as guiding principles from the WDF, we plan to use a water allocation framework which combines the asymmetric Nash bargaining solution concept with the bankruptcy theory for solving the water sharing problem among four provinces within Pakistan.

For the water bankruptcy situations, the water allocation problem can be formulated as $(N, E, c, x^{-})$, here, $N$ is the number of riparians involved in a water dispute, $E$ is the total amount of water available for sharing among the riparians, $c$ is the amount of water claimed by the riparians and $x^{-}$ is the amount of water allocated to the riparian. In this step, the Asymmetric Nash bargaining theory is combined with the bankruptcy concept and applied in the transboundary river basin for the allocation of water when the supply-demand gap exists. While applying this methodology, the disagreement allocation points $(m_1, m_2, m_3, \ldots, m_n)$ and the bargaining weights $(w_i = w_1, w_2, w_3, \ldots, w_n)$ of the riparians were also considered to ensure equity and self-enforceability in a closed and bounded space. Apart from having a unique solution, such an optimization solution also satisfies a set of desirable properties. The solution maximizes the area between the Pareto-optimal frontier $(x^{-})$ and the disagreement point $(m_i)$.

The disagreement points can be determined by the Nash equilibrium point, the minimum benefit of each riparian, the maximum and the minimum point, and by other methods. In our case, the vector of disagreement points $(d_1, d_2, \ldots di, \ldots, d_n)$ is defined as the benefits of minimum water allocation $(I_1, I_2, \ldots, I_n)$ to the riparians. This represents the minimum benefits that the riparians can accept. It is, therefore, necessary that the individual rationality requirements are reflected before the cooperation of the followers so that the maximal and minimal solutions are satisfied. For each riparian, the disagreement point formula is defined as:

$$d_i = u_i(m_i) \tag{10}$$

In order to solve the problem of minimal water allocation to each riparian, the bankruptcy theory can be used when the total available water is less than the total water demands. The minimal water allocation formula for each riparian is given by:

$$m_i = \max\left(0,\ E - \sum_{k \neq i} c_i\right) \tag{11}$$

Subject to:

$$E < C \tag{12}$$

The minimum water allocation to any riparian, especially to the riparians with smaller claims, may become zero if we use the above method of bankruptcy theory for the minimum water allocation. However, each riparian will demand a minimum amount of water $\lambda_i$ 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 for each riparian $\lambda_i$. Therefore, in order to avoid the case of unreasonable minimum water allocation by bankruptcy theory, we have proposed the following formula which determines the minimum water allocation and considers the minimum requirement for each riparian:

$$I_i = \max\left(\lambda_i,\ E - \sum_{k\neq i} c_i\right) \tag{13}$$

where $\lambda_i$ is the minimum water requirement of each riparian, which in our study is taken as half of the claim of any riparian.

For the optimization problem, the respective water claims of the riparians serve as the upper bound core. According to Harsanyi (1982), the optimization problem for the allocation of water under the bankruptcy scenario is given by:

$$\begin{aligned} Maximize\ N^w = &\left(x_1^- - \left(E - \sum_{i\in N/\{1\}} c_i\right)\right)^{w_1} \left(x_2^- - \left(E - \sum_{i\in N/\{2\}} c_i\right)\right)^{w_2} \\ &\left(x_3^- - \left(E - \sum_{i\in N/\{3\}} c_i\right)\right)^{w_3} \cdots \left(x_n^- - \left(E - \sum_{i\in N/\{n\}} c_i\right)\right)^{w_n} \end{aligned} \tag{14}$$

The above 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 in Pakistan's Indus Basin can be formulated as below:

$$\begin{aligned} Maximize\ N^w = &\left(x_p^- - \left(E - \sum_{i\in N/\{P\}} c_i\right)\right)^{w_p} \left(x_S^- - \left(E - \sum_{i\in N/\{S\}} c_i\right)\right)^{w_S} \\ &\left(x_B^- - \left(E - \sum_{i\in N/\{B\}} c_i\right)\right)^{w_B} \left(x_K^- - \left(E - \sum_{i\in N/\{K\}} c_i\right)\right)^{w_K} \end{aligned} \tag{15}$$

Here:

$$\sum_{i=1}^{n} w_i = 1$$

In Equation (15) $x_P^-$ is the optimized water allocation for Punjab; $I_P$ is the lower core bound for Punjab; $x_S^-$ is the optimized water allocation for Sindh; $I_S$ is the lower core bound for Sindh; $x_B^-$ is the optimized water allocation for Baluchistan; $I_B$ is the lower core bound for Baluchistan; $x_K^-$ is the optimized water allocation for Khyber Pakhtunkhwa (KPK); $I_K$ is the lower core bound for Khyber Pakhtunkhwa (KPK); $N^w$ is the weighted Nash objective function which should be maximized.

The following constraints should be set for this allocation model:

1. The allocation of water to each riparian (province) should be more than or equal to its lower core bound.

$$x_i^- \leq I_i, \ i = 1, 2, \ldots, n \tag{16}$$

2. The water allocation to each riparian (province) should be more than its lower core bound and less than its claim.

$$I_i \leq x_i^- \leq c_i \tag{17}$$

3. The total water allocation in the basin should be equal to or less than the total available water.

$$\sum_{i=1}^{n} x_i^- \leq E \tag{18}$$

*Determination of bargaining weights*

The optimization model in Equation (15) is applied to the Indus River Basin in Pakistan. In this article, three cases were analyzed. The bargaining weights of all the provinces in the first case were assumed to be equal. According to Kalai (1977), asymmetric Nash solutions induce symmetric Nash solutions, and the converse is also true. All the riparian provinces, in reality, are different in terms of their environmental and socio-economic status and hence they have a different groundwater usage, therefore in the second case, the bargaining weights of the riparian provinces were taken according to their groundwater usage to show the importance of using different bargaining weights. The total groundwater potential in Pakistan is about 68 $km^3$, out of which 60.5 $km^3$ is being extracted. Punjab is extracting 54 $km^3$ of groundwater, Sindh 3.1 $km^3$, KPK 2.5 $km^3$, and Baluchistan 1.2 $km^3$ (Ghazanfar, 2009). According to these usages of groundwater, the bargaining weights for the provinces of Punjab, Sindh, Baluchistan, and KPK are 0.05, 0.20, 0.25, and 0.50, respectively. These bargaining weights are inversely proportional to their rate of groundwater usage, that is, the greater the groundwater usage, the lesser will be the bargaining weight of the province. In the third case, the bargaining weights of the riparians were taken in terms of their crop productivity. Higher crop productivity will lead to higher weight and hence more allocation. The groundwater usage, crop production benefits, and population for different provinces are shown in Table 1.

Table 1. Groundwater use, crop production and population (adapted from Ghazanfar, 2009).

| | Punjab (P) | Sindh (S) | Baluchistan (B) | KPK (K) |
|---|---|---|---|---|
| Groundwater use (cubic kilometers) | 54.0 | 3.1 | 2.5 | 1.2 |
| Crop production benefits, per cubic kilometer of water (US$ million) | 153 | 65 | 224 | 249 |
| Population (million) | 110 | 48 | 12 | 30 |

*Sharing of mutual benefits using the Nash bargaining theory*

After the water resources to each riparian are allocated, the next stage is to distribute the maximum monetary benefits among the riparians (provinces). Asymmetric Nash bargaining theory was once again applied, this time, for the allocation of the monetary benefits among the riparians. The minimum benefits or welfare allocation for each riparian are given by:

$$I_i = \max\left(\lambda_i,\ T - \sum_{k\ \neq i} B_i\right) \tag{19}$$

where $I_i$ is the minimum benefit which the riparian is willing to accept; $T$ is the total benefits, $B_i$ is the benefit claimed by the riparian $i$; and $\lambda_i$ is the minimum benefit for each riparian which in our study is taken as half of the benefits claim of riparian $i$.

The maximum benefit a riparian can secure if it is rewarded with its full water claim, that is, ($w_{Max_i} = \ \propto_i c_i$) is the upper bound. Here $\propto_i$ is the benefit per km$^3$ of water in million (US$). The economic bankruptcy problem arises in these cases when the total benefit claims of the riparian provinces or countries are more than the total maximized welfare. During these bankruptcy situations, the welfare allocation problem can be written as ($N,\ W_T,\ w_{Max},\ w_i$). Here, $N$ is the number of riparian provinces or countries, $W_T$ is the total welfare that can be divided among the riparians, $w_{Max}$ is the benefit of the riparian province or the country $i$ and $w_i$ is the optimized welfare or benefit variable to riparian province or country $i$. For the basin sharing provinces or countries, the utility function can be defined as a linear interval function. Hence, the function can be formulated as follows, considering their welfare claims, disagreement welfare apportionments, and optimized welfare assignments of riparian states:

$$f_i\ (w_i)\ =\ \frac{w_i\ -\ w_i^-}{w_{Maxi} - w_i^-} \tag{20}$$

The following equation is used for disagreement utility:

$$d_i\ =\ f_i\ (w_i^-) \tag{21}$$

The Nash optimization solution (Fu *et al*., 2018) is again applied for the allocation of total water benefits. The optimization problem can be modified according to Harsanyi (1982), and the bargaining weights of the riparians can also be considered. In this allocation, the bargaining weights are different from the bargaining weights assigned to the riparian states when allocating scarce water resources. These weights are based on the population of each province (Table 1). The reason for assigning the weights on the basis of the population was that every province has a different population dependent on it, and the allocation of the benefits by assigning equal weights to each province may not be accepted by every province. The weighted welfare distribution problem for the case considered in this study can be written as follows:

$$Maximize\ N^{w_i}\ =\ (f_P(w_P) -\ d_{w_P})^{w_P}\ (f_S(w_S) -\ d_{w_S})^{w_S}\ (f_B(w_B) -\ d_{w_B})^{w_B}\ (f_K(w_K) -\ d_{w_K})^{w_K} \tag{22}$$

given that:

$$\sum_{i=1}^{n} w_i = 1$$

where $f_P(w_P)$ is the functional utility of Punjab; $d_{w_P}$ is the lower core bound for Punjab; $f_S(w_S)$ is the functional utility of Sindh; $d_{w_S}$ is the lower core bound for Sindh; $f_B(w_B)$ is the functional utility of Baluchistan; $d_{w_B}$ is the lower core bound for Baluchistan; $f_K(w_k)$ is the functional utility of KPK; $d_{w_K}$ is the lower core bound for KPK; and $N^{w_i}$ is the weighted Nash objective function which should be maximized.

The feasibility space of this optimization problem is assumed to be closed, convex, and bounded. Both the feasibility and individual rationality should be satisfied by this optimization problem:

$$\sum_{i \in N} w_i = W_{Total} \tag{23}$$

and

$$w_i^- \leq w_i \leq w_{Maxi} \tag{24}$$

## Case study

### *Description of the study area*

Pakistan has an area of 803,940 km$^2$ and lies between the latitude 23.5–37.5°N and longitude 62–75°E in the western region of South-Asia. It is bounded by the Arabian Sea at its south, India in the east, Iran and Afghanistan at the west and China at its north (Rahman *et al.*, 2019). The Indus River, being the main river within the Indus basin, originates from the Tibetan Plateau and flows through Kashmir and Pakistan before it drains into the Arabian Sea. River Kabul, Sutlej, Ravi, Beas Chenab, and Jhelum are the other rivers that flow through the Indus Basin (Shahid & Rahman, 2020). Pakistan has four provinces or administrative units, namely Punjab, Sindh, Baluchistan and Khyber Pakhtunkhwa, along with the small areas of Gilgit Baltistan and Federally Administered Tribal Areas (Figure 1). The principal natural resources of Pakistan are water and arable land. According to Anwar & Bhatti (2017), agriculture accounts for about 19.8% of the gross domestic product (GDP). Punjab has the highest proportion of the cultivated land, followed by Sindh, KPK, and Baluchistan, according to the Agricultural Census Organization (ACO, 2010).

At present, the water sharing between the provinces of Pakistan is governed by the Water Apportionment Accord of 1991. Unfortunately, this Accord has fixed allocations, and it does not adopt to the changing conditions over time. Table 2 shows the current water distributions among the provinces of Pakistan as per the Water Apportionment Accord of 1991. The distribution of water among the provinces is done by the Indus River System Authority, which is a federally administered government


Fig. 1. River network of Indus Basin, Pakistan. (*Source*: Aquastat; available online: www.fao.org/nr/water/aquastat/basins/indus/print1.stm).

Table 2. Water allocation among provinces (*Source:* Indus Water Accord 1991).

| Province | Water share ($km^3$) | Balance supply shares[a] in % |
|---|---|---|
| Punjab | 69.03 | 37 |
| Sindh[b] | 60.17 | 37 |
| Baluchistan | 4.78 | 12 |
| KPK | 7.13 | 14 |
| Ungauged canals[c] | 3.70 | |
| Total | 144.87 | 100 |

[a]Including future storages and flood flows.
[b]Including already sanctioned urban and industrial uses for Karachi.
[c]Ungauged canals above rim stations in KPK.

organization. The Water Apportionment Accord of 1991 has several shortcomings, which are highlighted below.

The average canal water diversions or the water diverted for irrigation purposes since the construction of Tarbela Dam has only been 127 $km^3$, whereas the accords entitlement is 144 $km^3$, as shown in Figure 2. As there is no defined mechanism in the Water Apportionment Accord for the sharing of water deficits, it therefore creates a dispute among the provinces (Condon *et al.*, 2014; Janjua & Hassan, 2020a). Also, the two small provinces (population-wise) of KPK and Baluchistan are exempted by the water shortages by an act of 2003; this is deemed unfair by Punjab and Sindh as they have to share the water deficit during the shortage (Janjua & Hassan, 2020b).

Fixed water allocation is another serious problem in the Accord. As fixed water allocation creates a quantified entitlement, it often leads to allocations which are unacceptable for the provinces, especially during the drought season. The Accord and the water allocation were done almost 28 years ago, and since then, the water demands of provinces have increased significantly due to the increase in irrigated area and population. As a result, the gap between the water supply and water demand has increased considerably, resulting in disputes among the provinces.

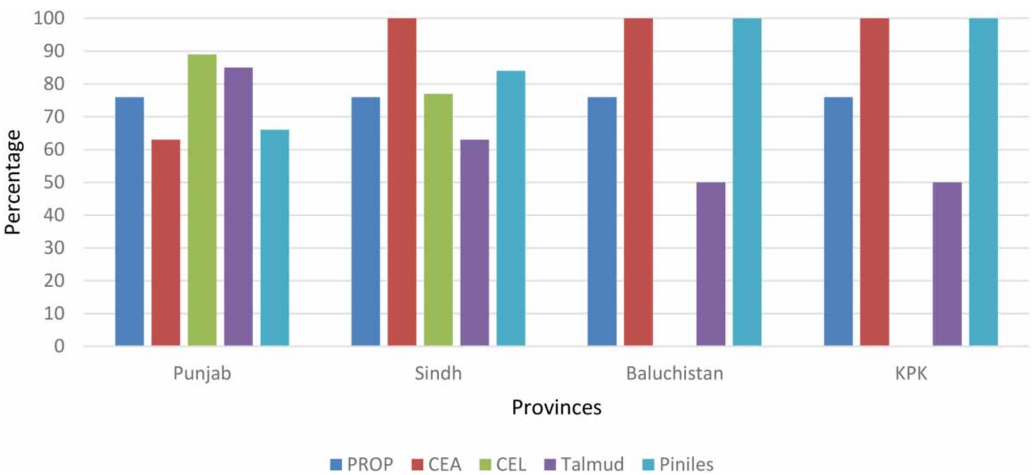


Fig. 2. Water allocation for different provinces using five bankruptcy rules (percentage of allocation with respect to individual water demand).

*Surface and groundwater resources*

Figure 1 shows the Indus River and its major tributaries, which are a major source of Pakistan's water supply. The water of the Indus River is shared by all the four provinces of Pakistan. The main sources of river flows are glacier melt, runoff, rainfall, and snowmelt. The median canal diversions from 1975 to 2013 were only 130 km$^{3,}$ according to Hassan (2016).

Out of the total groundwater potential of 68 km$^3$ in Pakistan, 60.5 km$^3$ is being extracted. Punjab has the highest extraction of groundwater (54 km$^3$) followed by Sindh (3.1 km$^3$), KPK (2.5 km$^3$), and Baluchistan (1.2 km$^3$) (Ghazanfar, 2009).

*Agricultural water requirements for Pakistan and water deficits in the Indus Basin*

The water requirements in this study were taken from the latest study conducted by Janjua & Hassan (2020a), according to which the water requirements are 157.25 km$^3$. According to various studies, the water required for the 'Environmental Flows' is 12.3 km$^3$ (Archer *et al*., 2010). This requirement for the environmental flows has not been catered for the in the Water Apportionment Accord as well. The total water requirements, including the environmental flows, is therefore 170.56 km$^3$ (Table 3). The water requirements for all the provinces are also shown in Table 3.

The total water diverted for irrigation purposes is 128 km$^3$ according to Qureshi (2011), whereas according to Hussain *et al*. (2011), it is 130 km$^3$. From these figures, if the total water diversion is taken as 130 km$^3$, the deficit becomes 40.56 km$^3$. Qureshi (2011) stated that 128 km$^3$ of water is diverted for irrigation. According to Hussain *et al*. (2011), the total water supply for the agriculture sector is 130 km$^3$. From the above figures, if we take the total surface water diversions for agriculture to be 130 km$^{3,}$ the total deficit, that is, the difference between the water demand and water availability, is 40.56 km$^3$.

## Results

Table 4 shows water allocation among the four provinces of Pakistan using the five commonly used bankruptcy rules. The water demands or claims of the provinces of Pakistan are 170.56 km$^3$, whereas

Table 3. Water requirement of various crops (*Source:* Janjua & Hassan, 2020a).

| Water requirements for various crops | Punjab (km$^3$) | Sindh (km$^3$) | KPK (km$^3$) | Baluchistan (km$^3$) | Total (km$^3$) |
|---|---|---|---|---|---|
| Wheat | 26.72 | 5.17 | 3.05 | 1.20 | 36.12 |
| Rice | 17.66 | 3.97 | 0.41 | 2.10 | 24.16 |
| Cotton | 14.29 | 2.97 | 0.00 | 0.20 | 17.46 |
| Sugarcane | 8.07 | 2.72 | 0.88 | 0.01 | 11.68 |
| Maize | 2.04 | 0.01 | 1.69 | 0.02 | 3.76 |
| Barley | 0.10 | 0.04 | 0.10 | 0.04 | 0.28 |
| Other crops | 40.62 | 15.20 | 2.14 | 5.85 | 63.80 |
| All crops | 109.49 | 31.07 | 8.28 | 9.42 | 157.25 |
| All crops after Sindh's requirement for environmental flows | 109.49 | 43.37 | 8.28 | 9.42 | 170.56 |

*Note*: The requirements for Sindh include an additional 12.3 km$^3$ as environmental flows.

Table 4. Water allocation for different provinces using bankruptcy rules.

Total available water supply = 130 $km^3$

Total water demand by four provinces = 170.56 $km^3$

| | Riparian province ($n$) | Water demand ($km^3$) | Water allocation ($x_i$; $km^3$) | Allocation percentage ($p$; %) |
|---|---|---|---|---|
| Proportionate rule (PRO) | Punjab | 109.49 | 83.45 | 76 |
| | Sindh | 43.37 | 33 | 76 |
| | Baluchistan | 9.42 | 7.17 | 76 |
| | KPK | 8.28 | 6.31 | 76 |
| Constraint equal award rule (CEA) | Punjab | 109.49 | 68.93 | 63 |
| | Sindh | 43.37 | 43.37 | 100 |
| | Baluchistan | 9.42 | 9.42 | 100 |
| | KPK | 8.28 | 8.28 | 100 |
| Constraint equal loss rule (CEL) | Punjab | 109.49 | 98.06 | 89 |
| | Sindh | 43.37 | 31.94 | 77 |
| | Baluchistan | 9.42 | 0 | 0 |
| | KPK | 8.28 | 0 | 0 |
| Talmud rule (TAL) | Punjab | 109.49 | 93.635 | 85 |
| | Sindh | 43.37 | 27.515 | 63 |
| | Baluchistan | 9.42 | 4.71 | 50 |
| | KPK | 8.28 | 4.14 | 50 |
| Piniles rule (PIN) | Punjab | 109.49 | 72.68 | 66 |
| | Sindh | 43.37 | 39.62 | 84 |
| | Baluchistan | 9.42 | 9.42 | 100 |
| | KPK | 8.28 | 8.28 | 100 |

the total available surface water supply is 130 $km^3$. Results from these bankruptcy rules (Figure 2) suggest that different provinces may choose different rules based on their allocation percentage. For example, Punjab may choose the constraint equal award rule (89%) because this rule provides maximum allocation to Punjab while providing no water to Baluchistan or KPK. As these bankruptcy rules do not consider other factors such as population, water use efficiency, and amount of groundwater usage for each province, a particular rule is not likely to be acceptable to all provinces. To account for other factors, the Nash bargaining method, as a popular approach, was used as an alternative allocation method.

Table 5 shows the allocation of water among the Provinces in the Indus Basin by applying the Nash bargaining method. The Nash bargaining method is applied under three scenarios. In the first scenario, the provinces are assigned equal weights. In the second scenario, the provinces are assigned weights according to their groundwater usage (more groundwater usage leads to less weight), whereas in the third scenario, the provinces are assigned weights according to their agricultural productivity (more agricultural productivity assigns higher weight). The water allocation using the Nash Bargaining Theory is shown in Figure 3.

The groundwater usage of the four provinces (Ghazanfar, 2009) and their agricultural productivity in the form of water benefits (in millions per cubic kilometer of water (PWP, 2001) are shown in Table 1. The Nash bargaining solution allocates 73, 83, 100 and 100% of the water demand to Punjab, Sindh, Baluchistan, and KPK respectively under the homogenous weights, whereas the allocation percentage

Table 5. Water allocation for different provinces using the Nash bargaining theory.

| Total available water supply = 130 $km^3$ | | | |
|---|---|---|---|
| Total water demand by four provinces = 170.56 $km^3$ | | | |
| | Riparian province | Bargaining weights | Allocation percentage |
| Scenario 1 | Punjab | 0.25 | 73 |
| Homogeneous weights | Sindh | 0.25 | 83 |
| | Baluchistan | 0.25 | 100 |
| | KPK | 0.25 | 100 |
| Scenario 2 | Punjab | 0.05 | 66 |
| Heterogeneous weights (groundwater use) | Sindh | 0.2 | 100 |
| | Baluchistan | 0.25 | 100 |
| | KPK | 0.5 | 100 |
| Scenario 3 | Punjab | 0.22 | 77 |
| Heterogeneous weights (crop productivity) | Sindh | 0.10 | 71 |
| | Baluchistan | 0.32 | 100 |
| | KPK | 0.36 | 100 |

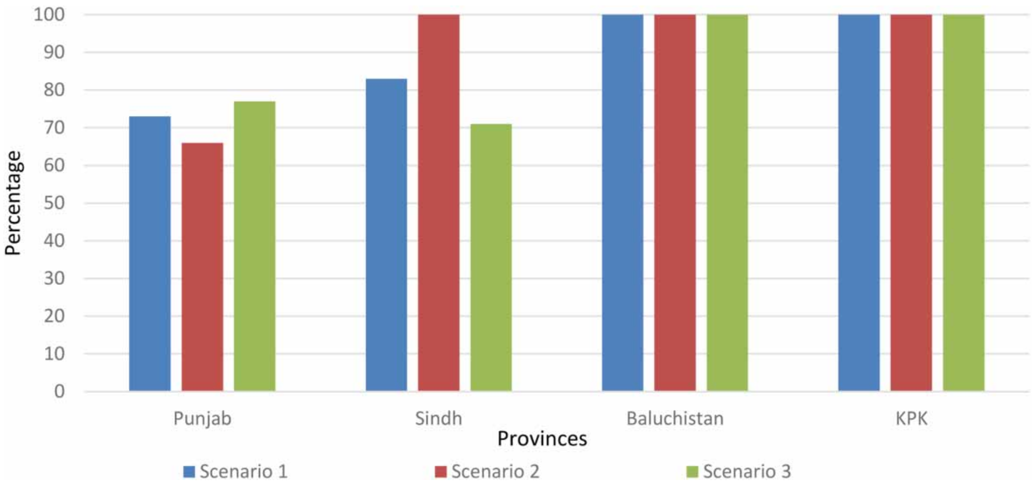


Fig. 3. Water allocation using the Nash bargaining theory with three scenarios (percentage of allocation with respect to individual water demand).

for the second scenario under the heterogeneous weights (based on groundwater use) is 66, 100, 100, and 100% respectively. In this scenario, Punjab gets the lowest allocation because it uses a significant amount of groundwater. For the third scenario related to agricultural productivity, the water allocation is 77, 71, 100, and 100% of their demand, respectively. Here, Sindh gets a lower allocation (71%) because of its lower agricultural productivity.

These three different scenarios, used as example scenarios, open the possibilities for discussion among four provinces about the implications and consequences of different scenarios for individual provinces as well as for the entire basin within Pakistan. For example, issues like the sustainability of groundwater usage can be discussed with respect to agricultural productivity in resolving the supply-demand gap.

Table 6 shows the total monetary benefits generated using five bankruptcy rules, whereas Table 7 shows the monetary benefits generated using the Nash bargaining theory for three different scenarios. The total monetary benefits are the highest when the water allocation is guided by the Nash bargaining theory with the crop productivity scenario.

The maximum total benefit derived using different bankruptcy methods is US$18,201 million (Table 6), while the maximum benefit estimated by using the Nash bargaining theory is US$19,216 million (Table 7). It appears that moving from the bankruptcy methods to the Nash bargaining theory results in a 5.5% increase in the total monetary benefit. These findings are consistent with the premise of WDF, highlighting that cooperative problem-solving approaches involving joint fact-finding and modeling have the potential to simultaneously resolve supply-demand mismatch and generate more benefits for all stakeholders.

To distribute this increased monetary benefit among the provinces, we again apply the Nash bargaining solution. The maximum monetary benefit a province can claim is estimated using its maximum water claim and crop productivity. For Punjab, as an example, the maximum benefit is estimated to be US$16,752 (($109.49\ km^3$ water)* US$153 crop productivity per $km^3$), as shown in Table 8. The

Table 6. Total monetary benefits from water allocation using the bankruptcy rules.

| | Province | Crop production benefits, per cubic kilometer of water (million US$) | Total benefits from water allocation (million US$) |
|---|---|---|---|
| Proportionate rule (PRO) | Punjab | 153 | 12,768 |
| | Sindh | 65 | 2,145 |
| | Baluchistan | 224 | 1,606 |
| | KPK | 249 | 1,571 |
| | Total | | 18,090 |
| Constraint equal award rule (CEA) | Punjab | 153 | 10,546 |
| | Sindh | 65 | 2,816 |
| | Baluchistan | 224 | 2,110 |
| | KPK | 249 | 2,062 |
| | Total | | 17,534 |
| Constraint equal loss rule (CEL) | Punjab | 153 | 15,003 |
| | Sindh | 65 | 2,459 |
| | Baluchistan | 224 | 0 |
| | KPK | 249 | 0 |
| | Total | | 17,462 |
| Talmud rule (TAL) | Punjab | 153 | 14,326 |
| | Sindh | 65 | 1,789 |
| | Baluchistan | 224 | 1,055 |
| | KPK | 249 | 1,031 |
| | Total | | 18,201 |
| Piniles rule (PIN) | Punjab | 153 | 11,120 |
| | Sindh | 65 | 2,575 |
| | Baluchistan | 224 | 2,110 |
| | KPK | 249 | 2,062 |
| | Total | | 17,867 |

Table 7. Total monetary benefits from water allocation using Nash bargaining theory.

| | Province | Crop production benefits, per cubic kilometer of water (million US$) | Total benefits from water allocation (million US$) |
|---|---|---|---|
| (Scenario 1) | Punjab | 153 | 12,336 |
| Water allocation using homogeneous weights | Sindh | 65 | 2,329 |
| | Baluchistan | 224 | 2,110 |
| | KPK | 249 | 2,062 |
| | Total | | $18,837 |
| (Scenario 2) | Punjab | 153 | 11,141 |
| Water allocation using heterogeneous weights (based on groundwater use) | Sindh | 65 | 2,819 |
| | Baluchistan | 224 | 2,110 |
| | KPK | 249 | 2,062 |
| | Total | | $18,132 |
| (Scenario 3) | Punjab | 153 | 13,026 |
| Water allocation using heterogeneous weights (based on crop productivity) | Sindh | 65 | 2,018 |
| | Baluchistan | 224 | 2,110 |
| | KPK | 249 | 2,062 |
| | Total | | $19,216 |

Table 8. Allocation of benefits among the provinces.

Total benefits = US$19,216 million
Total benefit demanded by four provinces = US$23,743 million

| | Riparian province ($n$) | Maximum value ($c_i$), in million dollars | Population in millions | Bargaining weights ($w_i$) | Disagreement point ($m_i$) | Optimization results ($x_i$) | Benefit allocation percentage ($p$ %) |
|---|---|---|---|---|---|---|---|
| Water allocation using homogeneous weights (Scenario 1) | Punjab | 16,752 | 110 | 0.25 | 9,455.28 | 12,225 | 73 |
| | Sindh | 2,819 | 47 | 0.25 | 1,409.5 | 2,819 | 100 |
| | Baluchistan | 2,110 | 12 | 0.25 | 1,055 | 2,110 | 100 |
| | KPK | 2,062 | 30 | 0.25 | 1,030.86 | 2,062 | 100 |
| Water allocation using heterogeneous weights (based on population) (Scenario 2) | Punjab | 16,752 | 110 | 0.55 | 9,455.28 | 12,969 | 77 |
| | Sindh | 2,819 | 47 | 0.24 | 1,409.5 | 2,819 | 100 |
| | Baluchistan | 2,110 | 12 | 0.06 | 1,055 | 1,438 | 68 |
| | KPK | 2,062 | 30 | 0.15 | 1,030.86 | 1,989 | 96 |

allocation of benefits is shown in Table 8 and Figure 4 using homogenous and heterogeneous weights. The heterogeneous weights are assigned based on the population of each province. If we allocate the maximum benefit (US$19,216) derived from using the Nash bargaining theory under the agricultural productivity scenario (Table 7) with homogeneous weights, Sindh, Baluchistan, and KPK get 100% of their claimed benefits while Punjab gets only 73% of their claimed benefit. On the other hand, if we assign heterogeneous weights based on population, Punjab gets a higher share of benefits (77%),

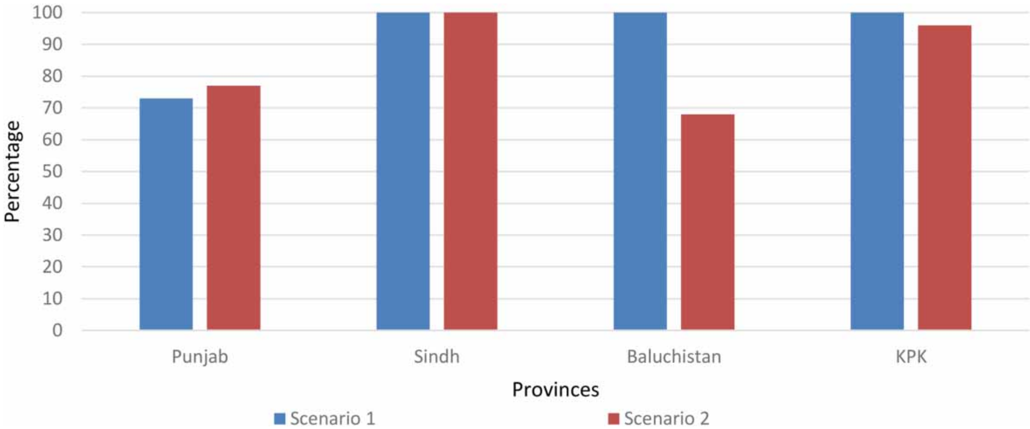


Fig. 4. Allocation of benefits among provinces using Nash bargaining theory under Scenarios 1 and 2 (percentage with respect to individual maximum demand).

while the benefits for Baluchistan are reduced to 68% (Table 8). The decrease in the benefit allocation to Baluchistan using heterogeneous weights was due to the fact that Baluchistan's population is smaller compared to the other three provinces.

### *Choice and consequences of a metric for allocation of benefits*

We have presented findings from eight different allocation rules (five bankruptcy methods and three scenarios using the Nash bargaining solutions) on how to resolve the supply–demand gap among the four provinces. Choosing the 'most appropriate' allocation rule is an important step to help contending provinces to reach an agreement. There is no easy answer to this choice. Each choice will have different consequences for different parties. As an example, if we choose the constraint equal award rule (CEA; Table 4), three provinces get 100% of their allocation while Punjab gets the lowest allocation (63%) compared to any other bankruptcy method. If we choose, the majority of stakeholders win as a metric; then, CEA becomes a preferred allocation rule. However, CEA provides only US$17,534 monetary benefits compared to US$18,201 for the Talmud rule (Table 6). Using monetary benefit as a metric, on the other hand, will make the Talmud rule a preferred allocation rule. In addition, if we use the Nash bargaining solution with crop productivity based heterogeneous weights (Table 7) as a metric, we obtain the highest monetary benefits (US$19,216). To sum, the choice of metrics matters and there is no objective criteria to choose one metric over the other without a collaborative discussion.

A key point highlighted by the WDF is to acknowledge the role of these conflicting choices in resolving the supply–demand gap. The WDF encourages a facilitative process for exploring the consequences of choosing a metric through joint fact-finding, involving all contending parties. As an illustrative example, we apply the method proposed by Janjua & Hassan (2020a). This method is based on the principle that the most appropriate rule is the one that has the lowest dispersion. The priority vectors $\Omega$ are set for this reason with the elements of $w_i$. Here, $w_i$ is a vector that has elements of $\vartheta_j^i$, where $w_i$ are the preference vectors, $i$ is the number of rules, and $j$ is the number of stakeholders. In the current study, $1 \le i \le 8$ and $1 \le j \le 4$.

The priority vector set for our study is $\Omega = \{w_1, w_2 \ldots\ldots w_n\}$ in which $w_1 = (4, 4, 2, 2)$, $w_2 = (8, 1, 1, 1)$, $w_3 = (1, 5, 4, 4)$, $w_4 = (2, 7, 3, 3)$, $w_5 = (7, 2, 1, 1)$, $w_6 = (5, 3, 1, 1)$, $w_7 = (6, 1, 1, 1)$ and $w_8 = (3, 6, 1, 1)$. A priority vector $w_i$ is used for each bankruptcy rule. The priority vector which has the lowest distance from the intermediate value will be considered as the best one, which is denoted by $\bar{w}$. The dispersion around the mean of vector $i$, $\delta_i$, is calculated by:

$$\delta i = \frac{\sum_{j=1}^{n} (\vartheta_{ji} - \bar{w})^2}{n} = \frac{\sum_{j=1}^{n} \left( \vartheta_{ji} - \frac{\sum_{j=1}^{n} \vartheta_{ji}}{n} \right)^2}{n} \tag{25}$$

As an example, for the Talmud rule, we have:

$$\bar{w}_4 = \frac{2+7+3+3}{4} = 3.75$$

$$\delta_4 = \frac{(5-4)^2 + (6-4)^2 + (4-4)^2 + (4-4)^2}{4}$$

$$\delta_4 = 3.6875$$

$\delta_i$ for all the rules are presented in Table 9. The rule which has the lowest $\delta_i$ will be considered as the best allocation rule. With this metric, the proportional rule ranks first, and the CEA rule is ranked last (Table 9). As the supply–demand gap changes, the value of $\delta$ will change, and the ranking will also change. Also, different provinces may prefer a different metric to maximize their interests and water usage. However, this joint exploration and examination of a metric to allocate available benefits opens the possibilities for dialogue among contenting parties. Such a dialogue can facilitate the conversation to develop a consensus metric that can simultaneously resolve supply–demand mismatch and highlight the importance of equity and sustainability.

## Conclusions

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 an issue of concern, conflict, and cooperation. This paper examines the use of WDF to address the supply–demand mismatch using the notion of collaborative problem-solving and joint fact-finding. It builds on innovative applications of game-theoretic approaches and uses equity and sustainability as guiding principles to propose a

Table 9. Ranking of the bankruptcy rules and the Nash bargaining solutions.

| Province | PRO | CEA | CEL | Talmud | Piniles | Nash bargaining (homogenous weights) | Nash bargaining heterogeneous weights (based on groundwater use) | Nash bargaining heterogeneous weights (based on agricultural productivity) |
|---|---|---|---|---|---|---|---|---|
| $\delta_i$ | 1 | 9.18 | 2.25 | 3.68 | 6.18 | 2.75 | 4.68 | 4.18 |
| Rank | 1 | 8 | 2 | 4 | 7 | 3 | 6 | 5 |

problem-solving process that has the potential to simultaneously resolve supply–demand mismatch and generate increased benefits for all contending parties.

The initial allocation of water among the provinces is performed using five commonly used bankruptcy rules. Findings from these bankruptcy rules suggest that different provinces may prefer different rules based on their claimed demands. As these bankruptcy rules are primarily mathematical and do not consider other factors such as population, water use efficiency, and agricultural productivity, any given rule may not be acceptable to all contending provinces. The Nash bargaining solution is then used for water allocation using three different scenarios. These three scenarios are used for illustration only. To expand the scope of the conversation, one may explore other scenarios, including the effects of changing population, growing population, and changing regulations.

The maximum total benefit generated by using different bankruptcy methods is US$18,201M, while the maximum benefits estimated by using the Nash bargaining approach is US$19,216M. The total monetary benefits generated by the allocation of water using heterogeneous weights based on crop productivity and the Nash bargaining theory provides the highest monetary benefits. These findings suggest that moving from the non-cooperative bankruptcy rules to the Nash bargaining solutions provides an additional US$1,015M and 5.5% increase in the total monetary benefit. Reallocation of these total benefits among the four provinces of Pakistan is carried out by applying the Nash bargaining theory under homogenous and heterogeneous weights. The key findings of this paper are as follows:

- The allocation of benefits using the homogenous weights gave Sindh, KPK and Baluchistan their full claimed benefits while Punjab received only 73% of their claimed benefit.
- Allocation of benefits using the heterogeneous weights – using population of each province as a criterion – gave Sindh and KPK 100 and 96% of their claimed benefits respectively, while the benefit allocation of Punjab was increased to 77% of its claim and Baluchistan's benefit was reduced to 68% of its claim. From a population perspective, this was deemed equitable because Punjab has the highest percentage of Pakistan's population, and Baluchistan has the lowest.
- The findings also suggest that the basic water demand among the provinces can be satisfied by proposed disagreement points, and the bargaining weights can highlight the role of different levels of groundwater usage, irrigation efficiencies, and variations in population among the provinces.
- Instead of using non-cooperative and rule-based bankruptcy methods, the use of the Nash bargaining solutions provided increased benefit for all stakeholders.

These findings suggest that aspects of WDF – cooperative problem-solving approaches involving joint fact-finding and modeling – has the potential to simultaneously resolve supply–demand mismatch and generate more benefits for all stakeholders. We hope this proposed framework will find more innovative applications for other transboundary river basins across the world.

## Data availability statement

All relevant data are included in the paper or its Supplementary Information.

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