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Resolving conflicts over trans-boundary rivers using bankruptcy methods

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Abstract

A bankruptcy approach is proposed for resolving trans-boundary rivers conflicts in which the total water demand or claim of the riparian parties is more than the available water. Bankruptcy solution methods can allocate the available water to the conflicting parties with respect to their claims. Four bankruptcy rules are used here to allocate the available water to the riparian parties. Given the non-uniform spatial and temporal distribution of water across river basins, bankruptcy optimization models are proposed to allocate water based on these rules with respect to time sensitivity of water deliveries during the planning horizon. Once allocation solutions are developed, their acceptability and stability must be evaluated. Thus, a new stability index method is developed for evaluating the acceptability of bankruptcy solutions. To show how the bankruptcy framework can be helpful in practice, the suggested methods are applied to a real-world tarns-boundary river system with eight riparians under various hydrologic regimes. Stability analysis based on the proposed stability index method suggests that the acceptability of allocation rules is sensitive to hydrologic conditions and demand values. This finding has an important policy implication suggesting that fixed allocation rules and trans-boundary treaties may not be reliable for securing cooperation over trans-boundary water resources as they are vulnerable to changing socio-economic and climatic conditions as well as hydrologic non-stationarity.

1 Introduction

Conflicts are integral to managing trans-boundary rivers due to the externalities associated with growing demand and development in riparian states. There are 148 riparian countries creating about 276 trans-boundary river basins in the world (De Stefano et al., 2012). These basins cover over 45 % of the earth's land surface and provide about 60 % of the global river flows (Wolf et al., 2006). To facilitate the cooperation over trans-boundary rivers over 400 international agreements were signed in the 20th

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century (De Stefano et al., 2012), reflecting a great potential for cooperation over trans-boundary natural resources (Wolf et al., 2006). However, stability of these agreements could be affected by the socio-economic and political changes in the riparian states as well as the climatic and hydrologic changes. Dinar et al. (2010) reported 112 complaints about water deficit in trans-boundary river systems during droughts and floods in the 1950–2005 period, underlying the vulnerability of cooperation over trans-boundary water systems to abnormal hydrologic conditions.

Game theory – the mathematical study of competition and cooperation – is a useful method for studying trans-boundary river conflicts. Both non-cooperative and cooperative game theory methods have been used in the past to study trans-boundary water conflicts (Parrachino et al., 2006; Madani, 2010).

Non-cooperative game theoretic methods are useful in studying the strategic behaviors of the riparian parties, feasibility of cooperative solutions, and providing strategic insights into the conflicts (Madani and Hipel, 2011; Madani, 2013). Example trans-boundary river conflicts analyzed by non-cooperative game theory concepts include the conflict over flooding of Ganges and Brahmaputra rivers between India and Pakistan (Rogers, 1969), the Lower Mekong river basin conflict between Cambodia, Laos, Thailand, and Vietnam (Dufournaud, 1982), the Jordan river conflict between Jordan, Israel, Lebanon, Palestine, and Syria (Madani and Hipel, 2007), and the Nile river conflict between Burundi, Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania, and Uganda (Elimam et al., 2008). These methods normally rely on qualitative information to find the likely outcomes of conflicts based on various stability definitions, which incorporate a range of decision makers' (players') characteristics such as risk attitude, foresight level, information quality (Madani and Hipel, 2011; Madani, 2013). While these methods provide valuable insights into strategic conflicts and can help finding the possible resolutions of the conflict, their results are not necessarily quantitative and in most cases are appropriate for studying games with discrete solutions (strategies or actions).

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Cooperative game theory solution methods normally seek allocating the incremental benefits of cooperation (cost savings, added values, etc.) among the cooperating parties. In the context of trans-boundary river management, cooperative game theory concepts can be used to develop functional water allocation schemes. Example trans-boundary river conflicts analyzed by cooperative game theory include the Ganges river conflict between Bangladesh and India (Kilgoure and Dinar, 2001), the Euphrates and Tigris rivers conflict between Iraq, Syria, and Turkey (Kucukmehmetoglu and Guldmen, 2004), and the Syr Darya river basin conflict between Kyrgyzstan, Uzbekistan and Kazakhstan (Teasley and McKinney, 2011). Cooperative game theory methods are appropriate for quantitative problems with a continuous solution domain. However, in the water resources field, their application has been mostly limited to problems in which utility information is available for all parties and the incremental benefits of cooperation can be determined. Therefore, challenge remains in developing cooperative schemes for managing shared water systems for which utility information might not be readily available, agreeable, or reliable (common in trans-boundary river systems).

The objective of this study is to bridge the gap of previous trans-boundary conflict resolution studies by developing a new quantitative framework for developing a new water allocation mechanism that: (1) does not necessarily require the players' utility information (e.g., economic benefits of each beneficiary from the allocated water); (2) its application is not limited to problems in which cooperation must result in extra quantifiable benefit; (3) provides allocations solutions with respect to the temporal and spatial variability of water flows in trans-boundary river systems.

2 River bankruptcy problem

Water conflicts can develop when the yield of a water system is not sufficient to fully satisfy the demands of all beneficiaries. Such a situation is similar to a bankruptcy state in which the total asset of an individual/entity is not enough to fully satisfy his/its debts. In other words, in a bankruptcy problem the total value of the claims of the beneficiaries is more than the value of the available resource. Such a similarity between a water allocation problem and a bankruptcy problem has been the main motivation for using bankruptcy methods, rooted in the economics and mathematics literature (O'Neil, 1982; Aumann and Maschler, 1985; Dagan and Volij, 1993), to solve water resource bankruptcy problems (Sheikhmohammady and Madani, 2008; Ansink and Ruijs, 2008; Sheikhmohammady et al., 2010; Grundel et al., 2011; Ansink and Weikard, 2012; Madani and Zarezadeh, 2012; Mianabadi et al., 2013; Madani and Dinar, 2013).

Bankruptcy methods can be categorized as cooperative game theory solutions (Sheikhmohammady and Madani, 2008). Nevertheless, these methods are different in principle from the commonly used cooperative game theory methods such as Nash-Harsanyi bargaining solution (Harsanyi, 1959), Shapley Value (Shapley, 1953), and Nucleolus (Schmeidler, 1969), among others. While the bankruptcy methods focus on allocation of the total deficit (the difference between the total claim and the value of the available resource) between the parties, the cooperative game theoretic solution methods have been primarily developed for allocation of the incremental benefits of cooperation among the cooperating parties. Therefore, they are not readily applicable to the bankruptcy situations with no incremental benefit out of cooperation or to cases in which the available information about the utilities of the parties from their shares are missing or are not reliable. In some river basins, developing agreeable utility functions to estimate the utility (e.g., economic gain) of each riparian from its water use is very challenging due to the lack of trust and information as well as the absence of cooperative tendencies in the region. Therefore, river sharing games are often played as zero-sum games in which parties are mainly bargaining about their volumetric shares from the river, while in reality, due to the difference in the non-linear utility functions of the parties these games are not zero-sum (Madani, 2011; Madani and Lund, 2012). In fact, the zero-sum perception of the riparian parties is one of the main reasons for competition rather than cooperation, which makes economically-efficient cooperative game theoretic institutions (Madani and Dinar, 2012) or other mechanisms such as water trading and markets impractical and unacceptable. To address these

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issues, bankruptcy methods can be applied for developing water allocation solutions. Although bankruptcy methods provide solutions, which are economically less efficient than those provided by common cooperative game theory methods, they are potentially more publically acceptable and practical. Most bankruptcy methods are based on common sense and are relatively easy to understand by the general public, unfamiliar with the economic principles and fairness rationales of the mathematically sophisticated cooperative game theory methods. This advantage has been the main reason for the success of some of the bankruptcy methods in practice since the ancient times (Dagan and Volij, 1993) in different eras and locations. The proportional cutback principle is an example of one of the oldest bankruptcy methods that has been commonly used for water resources management during droughts in different areas of the world (e.g., qanat water allocation in the Persian Empire and groundwater allocation in California).

The two essential elements of a bankruptcy problem include (1) the amount of resource available; and (2) the values of beneficiaries' claims. In most water resources bankruptcy problems, the first element simply equals the available water to be allocated to the beneficiaries in a given location at a specific time. Also finding the claim values is straightforward in some water systems (e.g., claims of groundwater users in case of groundwater bankruptcy are determined based on their groundwater rights in a regulated system). Therefore, bankruptcy solutions have been already used in the literature for solving water allocation problems with known (predetermined) claims and without temporal and spatial variability in resource availability (Sheikhmohammady and Madani, 2008; Ansink and Ruijs, 2008; Sheikhmohammady et al., 2010; Grundel et al., 2011; Ansink and Weikard, 2012; Mianabadi et al., 2013; Madani and Dinar, 2013). Nevertheless, solving trans-boundary river bankruptcy problems with the bankruptcy methods can be challenging for two reasons: (1) lack of an acceptable method by all parties to estimate the credible claims of the beneficiaries; and (2) the temporal and spatial change of the flow along the river basin.

Determination of the beneficiaries' in trans-boundary systems is challenging and highly controversial, due to a lack of information, unreliability of parties' claims and narratives, and a lack of globally acceptable framework for determining the credible claims of riparian parties. Thus, this paper suggests three different methods as possible claim estimation methods in trans-boundary river bankruptcy problems with potential applications in real-world trans-boundary water conflicts.

Due to the change of the flow over time and space, especially in river systems with multiple tributaries, solution approaches that are based on simple applications of bankruptcy methods, as done previously, may produce infeasible results because water is not necessarily available at a given location at a specific time to be allocated as suggested by the bankruptcy method. Therefore, this paper proposes new water allocation optimization methods, which solve trans-boundary river bankruptcy problems with consideration of the physical constraints imposed by temporal and spatial distribution of water. The proposed methods are based on conventional bankruptcy methods. However, given their attention to physical characteristics of water systems (i.e, temporal and spatial water variability) their results are not necessarily similar to those of conventional bankruptcy methods. Therefore, this paper extends the bankruptcy literature by proposing new methods for solving bankruptcy problems with temporal and spatial resource availability constraints.

To highlight the applicability and utility of the bankruptcy framework for resolving real-world trans-boundary water allocation conflicts, the suggested methods are applied to develop bankruptcy-based water allocation schemes for resolving a real-world trans-boundary river conflict in Iran's Qezelozan-Sefidrood river involving eight riparians. Given that that the developed bankruptcy allocation solutions have no practical value unless they are acceptable and are considered to be fair by the beneficiaries, evaluating the acceptability of the developed solutions is essential. While various methods have been used in the literature to evaluate the stability and acceptability of water allocation solutions (Dinar and Howitt, 1997; Teasley and McKinney, 2011; Madani and Dinar, 2012; Read et al., 2013), these methods cannot be readily used to evaluate the acceptability of bankruptcy solutions. Therefore, a new stability index is developed in

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this study to evaluate the potential acceptability of the proposed bankruptcy solutions in practice.

Normally, in water allocation negotiations, the amount of available water in a given time-step (e.g. month) is determined based on the average historical flows in that time-step. Given that the water flows are different in dry, wet, and normal years, water allocation agreements can vary depending on the hydrologic conditions. Water allocation based on historical flows might make allocation agreements vulnerable to hydrologic variability and uncertainty. Therefore, instead of relying on fixed water shares, riparian parties can try to agree over a flexible allocation framework that adjusts allocation solutions considering the changing conditions of the system. This study seeks to propose a new bankruptcy solution framework proposed which can provide water allocation solutions that are not vulnerable to changing conditions and can update allocation solutions accordingly.

3 Bankruptcy allocation models

Figure 1 shows a schematic of simple trans-boundary river system with a lake (sink) at the outlet and m riparians ($i = 1, 2, \ldots, m$), each having different types of water demand (e.g., domestic, agricultural, and environmental). Water bankruptcy occurs when the total demand of the riparians exceeds the stock of water. This paper uses different bankruptcy methods as the basis to formulate new optimization models that allocate the available water stock to the riparian parties. Given the uneven spatial and temporal distribution of water along river systems, these optimization models need to be formulated such that they allocate water to the riparians with respect to the physical water availability constraints.

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3.1 Proportional (P) rule

The P rule satisfies an equal proportion of the creditors' claims. A percent (λ_P) is calculated based on this ancient bankruptcy method such that an equal proportion, i.e. total available resource divided by total demand, is met respecting all beneficiaries' claims. Given the time-sensitivity of water deliveries, proportional cutbacks over the whole planning horizon might result in highly undesirable results as in such a case beneficiaries might receive excessive amount of water when the water is less valuable and low amount of water when water is highly valuable. This, of course, will not be an issue of concern in systems with enough storage capacity to regulate and carry over the water. When storage is not available, water can be allocated proportionally in multiple time steps (e.g., days, weeks, and months) during the planning horizon (e.g., one year, five years, and 10 yr). In this case, proportional cutbacks decisions in each time-step are independent from other time-steps.

The P rule's water allocation optimization model for river systems is proposed in the following mathematical form:

$$\text{Minimize } \lambda_{P_t} - \prod_{i=1}^{m} \lambda_{P_{i,t}} \tag{1}$$

subject to:

$$\mathrm{TAW}_{i,t} = I_{i,t} + O_{i-1,t} \quad \forall i \tag{2}$$

$$O_{i,t} = \mathrm{TAW}_{i,t} - \mathrm{WS}_{i,t} \quad \forall i \tag{3}$$

$$\mathrm{WS}_{i,t} \le C_{i,t} \quad \forall i \tag{4}$$

$$\mathrm{WS}_{i,t} \le \mathrm{TAW}_{i,t} \quad \forall i \tag{5}$$

$$O_{0,t} = 0 \tag{6}$$

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$$O_{m,t} = \mathrm{SD}_t \tag{7}$$

$$\sum_{i=1}^{m} \mathrm{WS}_{i,t} \leq \sum_{i=1}^{m} I_{i,t} - \mathrm{SD}_t \tag{8}$$

$$\mathrm{WS}_{i,t} \geq 0 \quad \forall i,t \tag{9}$$

$$\lambda_{P_{i,t}} = \frac{\mathrm{WS}_{i,t}}{C_{i,t}} \quad \forall i \tag{10}$$

$$\lambda_{P_{i,t}} \leq \lambda_{P_t} \quad \forall i \tag{11}$$

where for $i = 1, 2, \ldots, m$ in a given time step t:

$\mathrm{TAW}_{i,t}$ is total available water in riparian i's territory; $I_{i,t}$ is riparian i's contribution to the river system through the tributaries originating in its territory; $O_{i,t}$ is the total outflow from riparian i to the downstream riparian state $(i+1)$; $\mathrm{WS}_{i,t}$ is the allocated water supply to riparian i in each month; $C_{i,t}$ is the claim (demand) of riparian i; SD_t is the sink demand at the system's outlet; $\lambda_{P_{i,t}}$ is the riparian i's proportional allocation coefficient, and λ_{P_t} is the overall proportional allocation coefficient.

Equations (2)–(9) are essential to all bankruptcy optimization models developed in this paper. The uneven spatial and temporal distribution of water over river systems requires incorporating these equations into trans-boundary river bankruptcy models to set the initial, continuity, and mass balance conditions. This is what necessitates using optimization models, making the river bankruptcy problem different from conventional water bankruptcy problems.

While the sink node at the system's outlet can be treated as a riparian, here we assumed that the environmental need of the sink has a high priority. Therefore, Eq. (7) ensures that the lake's environmental demand is fully met. Equations (10) and (11) are specific to proportional bankruptcy, making sure that the allocation to each riparian does not exceed its proportionally reduced claim.

3.2 Adjusted Proportional rule (AP)

Curiel et al. (1988) introduced this method. Based on this rule, what remain for beneficiary i once all other creditors are satisfied is the basis for allocation. To determine the initial amount of allocation to creditor i, the summation of claims of all other beneficiaries is compared with the available stock of water. In case of surplus, the initial allocation to stakeholder i is equal to the remaining water stock once all others are satisfied. Otherwise, the initial allocation to i is set to 0. It is assumed that the initial allocation calculated through this procedure is agreeable by all beneficiaries. Once initial allocations are determined claims are revised. Claim of a given beneficiary is set equal to the minimum of the remaining water and the difference between its initial claim and its initial allocation. The P rule is then applied to the remaining water stock and the revised claims.

The mathematical formulation of the AP river bankruptcy optimization model is proposed as follows:

$$\text{Minimize } \lambda_{\mathrm{AP}_t} - \prod_{i=1}^{m} \lambda_{\mathrm{AP}_{i,t}} \tag{12}$$

subject to: Equations (2)–(9)

$$\mathrm{SC}_{i,t} = \sum_{j \neq i} C_{j,t} \quad \forall i \tag{13}$$

$$v_{i,t} = \frac{\sum_{i=1}^{m} I_{i,t} - SC_{i,t} + \left| \sum_{i=1}^{m} I_{i,t} - \mathrm{SC}_{i,t} \right|}{2} \quad \forall i \tag{14}$$

$$C^{*}_{i,t} = \mathrm{Min}\left(C_{i,t}, \sum_{i=1}^{m} I_{i,t} - \mathrm{SD}_t \right) \quad \forall i \tag{15}$$

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$$\lambda_{\mathrm{AP}_{i,t}} = \frac{\mathrm{WS}_{i,t} - v_{i,t}}{C^*_{i,t} - v_{i,t}} \quad \forall i \tag{16}$$

$$\lambda_{\mathrm{AP}_{i,t}} \le \lambda_{\mathrm{AP}_t} \quad \forall i \tag{17}$$

$$\lambda_{\mathrm{AP}_t} \le \frac{\sum_{i=1}^{m} I_{i,t} - \sum_{i=1}^{m} v_{i,t}}{\sum_{j=1, j\neq i}^{m} (C^*_{j,t} - v_{j,t})} \quad \forall i \tag{18}$$

where for $i = 1,2,\ldots,m$ in a given time step t:

$\mathrm{SC}_{i,t}$ is the summation of all riparian claims excluding riparian i; $v_{i,t}$ is the initial allocation to riparian i (amount of water conceded to riparian i by all other riparians); $\lambda_{\mathrm{AP}_{i,t}}$ is the riparian i's AP allocation coefficient, and λ_{AP_t} is the overall proportional (AP) allocation coefficient.

3.3 Constrained Equal Award rule (CEA)

This ancient rule, adopted by rabbinical legislators (Dagan and Volij, 1993) allocates the minimum of λ_{CEA_t} and $C_{i,t}$ to all beneficiaries, provided that the sum of allocations equals the total available resource. CEA tries satisfying the lower claims to the extent possible to minimize the number of unsatisfied creditors. This rule is supposed to favor the lower claims, normally belonging to weaker beneficiaries who can get more affected by losses (Madani and Dinar, 2012). Based on CEA, the initial allocation to all beneficiaries is equal to the lowest claim, provided that the sum of initial allocations does not exceed the demand. The fully-satisfied creditor is then excluded and the process continues with the remaining creditors after updating their unsatisfied claims and the remaining resource value. At any stage (including the initial stage) when allocating the amount equal to the lowest claim to all remaining creditors is not feasible (due to unavailability of enough resource amount) the remaining resource is distributed evenly among all remaining creditors.

The mathematical formulation of the CEA river bankruptcy optimization model is proposed as follows:

$$\text{Minimize } \lambda_{\text{CEA}_t} - \frac{\prod_{i=1}^{m} \lambda_{\text{CEA}_{i,t}}}{(\text{CEA}_t)^{m-1}} \tag{19}$$

subject to: Equations (2–9)

$$\lambda_{\text{CEA}_{i,t}} = \text{WS}_{i,t} \quad \forall i \tag{20}$$

$$\lambda_{\text{CEA}_{i,t}} \le \lambda_{\text{CEA}_t} \quad \forall i \tag{21}$$

where for $i = 1, 2, \ldots, m$ in a given time step t:

$\lambda_{\text{CEA}_{i,t}}$ is the feasible allocation to the riparian i, and λ_{CEA_t} is the highest feasible allocation to the creditors in time step t (different from the cut-back coefficients introduced earlier).

3.4 Constrained Equal Loss rule (CEL)

This rule can be viewed as an opposite of CEA, as it gives priority to satisfying the highest claims (more powerful creditors) first. Once the highest claim is satisfied, the process is repeated with the remaining resource and creditors. The process stops at any stage (including the first stage) if the available resource is not sufficient to satisfy the highest claim of the remaining creditors. At this stage, the remaining resource is split equally among the remaining creditors. By doing this, CEL allocates $C_i - \lambda_{\text{CEL}_i}$ to all beneficiaries whose claims are bigger than λ_{CEL_i}, allocating 0 to those who do not fall in this category. So, the final allocation to each beneficiary is equal to $\max\left\{0, C_i - \lambda_{\text{CEL}_i}\right\}$.

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The CEL river bankruptcy optimization model is proposed as:

$$\text{Minimize } \lambda_{\text{CEL}_t} - \frac{\prod_{i=1}^{m} \lambda_{\text{CEL}_{i,t}}}{\left(\lambda_{\text{CEL}_t}\right)^{m-1}} \tag{22}$$

subject to: Equations (2–9)

$$\lambda_{\text{CEL}_{i,t}} = \text{WS}_{i,t} \quad \forall i \tag{23}$$

$$\lambda_{\text{CEL}_{i,t}} \leq \lambda_{\text{CEL}_t} \quad \forall i \tag{24}$$

where for $i = 1, 2, \ldots, m$ in a given time step t:

$\lambda_{\text{CEL}_{i,t}}$ is the unmet claim of the riparian I, and λ_{CEL_t} is the maximum unmet claim of all riparians.

It should be noted that the proposed bankruptcy optimization models in this study are only appropriate for bankrupt river systems, i.e. when the total demand exceeds the total available water, making $\sum_{i=1}^{m} I_{i,t} - \text{SD}_t \leq \sum_{i=1}^{m} C_{i,t}$ a necessary condition for validity of the proposed models.

Based on the proposed models, water allocations are time-step specific. So, the total allocation to each riparian over the whole planning horizon (e.g. year) is the summation of bankruptcy allocations in multiple time-steps within the planning horizon (e.g. twelve months). In unregulated system with no storage capacity, allocations can be determined independently in different time steps (e.g. month), but in regulated systems the allocations might be determined for the whole planning horizon (e.g. a year).

It is noteworthy that the optimized trans-boundary river bankruptcy allocations might not be necessarily equal to bankruptcy allocations under these rules if the total available resource were equally accessible by all (e.g. monetary assess or groundwater resources in the simplest case). This is due to the physics of river systems and the non-uniform special and temporal distribution of water. For example, the available amount

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of water in one upstream riparian in a given month might not be sufficient to meet its proportionally reduced demand or even full demand. So, this beneficiary will receive an allocation which is closest to the ideal cutback level (e.g., λ_{AP_t}) determined by the P river bankruptcy optimization level. On the other hand, a downstream riparian might receive a share which is higher than the other upstream riparians with equal claims due to the physics of the river system (e.g. access to some downstream tributaries).

4 Example: the Qezelozan-Sefidrood River bankruptcy problem

The Qezelozan-Sefidrood river basin (Fig. 2) is located in the intersection of the Iran's Alborz and Zagros mountain ranges, with an area about 59 400 km^2, making it the largest basin of the nation. The basin overlaps with eight provinces (Kurdistan, Hamadan, Zanjan, Eastern Azerbaijan, Ardebil, Tehran, Qazvin and Gilan) and the river provides the basis for important economic activities in these provinces.

The Qezelozan-Sefidrood river basin is an example of a trans-boundary river basin, in which serious conflict has arisen as a result of recent socio-economic (i.e., population increase and development), political (i.e., changes in the water resources management structure), and hydrologic and climatic (i.e., frequent droughts) changes. As a result of political changes in the country, the Qezelozan-Sefidrood river, which was historically shared by six Iranian provinces and managed by only one water resources authority, is now shared by eight provinces and managed by eight water authorities. As a result of population increase and development in the region, each province is trying to increase its share from the river and minimize the outgoing flow, resulting in significant reduction of water flowing into downstream provinces. To increase their water uses from the river, the upstream provinces have aggressive water resources development plans. These development plans include construction of multiple new reservoirs, which are currently under construction or in the study phase. Complete implementation of these plans will negatively impact the downstream provinces, which historically have had more access to the Qezelozan-Sefidrood river due to their stronger political and economic power as

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well as higher populations. Therefore, the political tension has increased in the basin, making Qezelozan-Sefidrood river the subject of one of the most intractable conflicts over water resources in Iran. To show the utility of the proposed model in solving trans-boundary water allocation conflicts, the proposed framework is applied to derive new water allocation schemes for the Qezelozan-Sefidrood river system.

To first step in river bankruptcy problems is determining the legitimate claims of the riparian parties. This step is challenging in unregulated systems without established water rights. In case of Qezelozan-Sefidrood river, we propose three alternatives for determining the claims of the riparian parties. These alternatives, which help setting the upper and lower boundaries of the claims include:

1. Historical uses: based on this alternative, historical uses of Qezelozan-Sefidrood river, based on the historical water use data are set as the claims of the riparians. The water use values are calculated based on the difference between the recorded inflows and outflows of each province at the hydrometric satiations. This alternative sets the lower claim boundary for each riparian.

2. Planned uses: Iran is one of the countries with a high number of under-construction dams. Currently, several water storage projects are under development at different locations in the riparian states of Qezelozan-Sefidrood river. These projects have received approval from the central government, receiving financial support from the central and provincial governments. Each project has an associated estimation of sectorial water demands (i.e. domestic, agricultural, industrial, and environmental) used for calculation of the required storage capacity. Based on this alternative, total claim of each riparian is set equal to the total documented water demands of different Qezelozan-Sefidrood river-related reservoirs within its boundaries which are already in operation or under development.

3. Future uses: beside under-construction projects, each riparian state has plans for getting approval for constructing additional water storage infrastructure to meet

its increasing water demand as a result of development. Based on this claim estimation alternative, water demands of these additional facilities will be added to the water claims calculated based on alternative 2, only if plans for construction of these facilities have been publicly announced. This alternative sets the upper claim boundary for each riparian.

Figure 3 indicates the estimated monthly water claims of the riparian states of the Qezelozan-Sefidrood river based on the three proposed methods. Detailed calculations of water claims based on the proposed claim determination alternatives can be found in Zarezadeh (2011).

Given that allocation solutions can be sensitive to climatic/hydrologic conditions, three different water availability scenarios, representing three distinct hydrologic conditions, normal (average), dry, wet, were initially considered for solving the Qezelozan-Sefidrood river bankruptcy problem. In the normal scenario river flows are based on the average monthly river discharges during the 1956–2006 period. Dry scenario flows match the average monthly river discharges during the major 1998–2001 drought in the region. The wet scenario flows are based on the monthly flows during the 1968–1969 period.

The annual river discharge under the wet scenario will be sufficient to meet the historical, planned, and future claims of the riparian states and the Caspian Sea's water demand (Fig. 4). Therefore, river bankruptcy problem is solved only for the normal and dry cases. Figure 5 indicates the monthly water yield of the Qezelozan-Sefidrood river system under the normal and dry conditions as well as the total monthly claims of the riparian parties (including Caspian Sea's water demand). This figure clearly shows the water bankruptcy situation in the Qezelozan-Sefidrood river system in almost half of the year, especially in warmer months with higher agricultural water demands.

The four proposed bankruptcy optimization models in Sect. 3 were run under two hydrologic scenarios to calculate bankruptcy allocations under normal and dry conditions. First, models were first run on a monthly basis to calculate the monthly allocations. Summation of 12 monthly allocations based on each model with a given set of claims under a given hydrology determines the corresponding annual allocation of each province. The annual bankruptcy allocations based on different bankruptcy models, claims, and hydrologies are presented in Fig. 6.

As expected based on definition, the CEL method favors the creditors with the highest claim (in this the downstream Province of Gilan). The opposite is true for the CEA method which gives priority to satisfy the claims of the creditors with lower claims (in this the provinces upstream of Gilan). The AP and *P* methods can be considered as moderate allocation methods which result in allocations that are between the high and low allocations estimated by the other two methods. In comparison with *P*, the AP method allocates a higher share to the parties with lower claims and a lower share to the parties with higher claims, trying to address the bias toward higher claims in the *P* method. The difference between the allocation values for different claims and hydrologies underline the sensitivity bankruptcy allocation schemes to the difference in claim values and hydrologic conditions in bankruptcy problems.

5 Stability evaluation

The suggested bankruptcy optimization models provide different allocation solutions, based on different notions of fairness. Therefore, their acceptability is always questionable, given that there is always at least one beneficiary who finds a given rule, unfair because she can gain more under another rule (Madani and Lund, 2011). As one of the most commonly used social choice (voting) methods (Sheikhmohammady and Madani, 2008; Shalikarian et al., 2011), plurality index is considered as a good indicator of potential acceptability of a decision rule in multi-participant decision-making problems. Based on this index, the number of stakeholders who prefer one method to the others is a simplest way of estimating the degree of acceptance of that method (Dinar and Howitt, 1997).

The higher the allocation to a riparian state, the more preferred the allocation rule (bankruptcy method) by that state. Table 1 shows the Plurality Index (number of votes

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received) of each bankruptcy solution method for different claim values under different hydrologies. Given that the Hamadan Province has no historical or planned claim, its vote is only counted when future claims are considered. Based on plurality index the CEA method, which highly satisfies the riparians with lower claims (majority in this case) in both normal and dry conditions, is the winner. However, given the absolute objection of the most powerful province, i.e. Gilan, to this method, which allocates low shares to this province, this solution is not practical without strong intervention of the central government or providing strong cooperation incentives to Gilan.

Majority does not necessarily win in multi-participant decision-making problems with asymmetric decision-makers' powers, especially when the minority group is powerful. Therefore, other methods can be used to quantify the potential acceptability of allocation solutions (Read et al., 2013). Loehman et al. (1979) introduced the following power index (α_i) to evaluate the power of players in cooperative game theory problems in which players are trying to find the a method for allocating the incremental benefits of cooperation to coalition members:

$$\alpha_i = \frac{X_i - C_i}{\sum_{j \in N}(x_j - C_j)}, \quad i \in N, \quad \sum_{i \in N} \alpha_i = 1 \tag{25}$$

where C_i and x_i are the claim of player i and the allocated benefit to player i, respectively.

A high power index value reflects less power or a higher willingness to cooperate. A stable allocation solution can be achieved when the power is distributed more or less equally among the players (Dinar and Howitt, 1997). Therefore, the coefficient of variation of powers, also known as stability index (S_α) is a good indicator of the stability of allocation solutions (Loehman et al., 1979):

$$S_\alpha = \frac{\sigma_\alpha}{\overline{\alpha}} \tag{26}$$

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where σ_α is the standard deviation of powers and $\overline{\alpha}$ is mean power. The lower the index, the more stable the allocation solution.

Given that cooperation in bankruptcy problems does not have incremental benefits and parties' gains are zero in the status-quo, the power index is not readily quantifiable in bankruptcy problems. Therefore, we propose modification of power index for bankruptcy problems as follows:

$$\alpha_i = \frac{x_i - v_i}{\sum\limits_{j \in N} (x_j - v_j)}, \quad i \in N, \sum_{i \in N} \alpha_i = 1 \tag{27}$$

$$v_i = \frac{E - \mathrm{SC}_{i,t} + |E - SC_{i,t}|}{2} \tag{28}$$

where E is the total asset value to be shared ($E = \sum\limits_{i=1}^{m} I_{i,t} - \mathrm{SD}_t$ in river bankruptcy problems). To estimate the stability of bankruptcy allocation solutions, the suggested Bankruptcy stability index considers the distribution of satisfactions and claims.

Table 2 shows the calculated bankruptcy stability index for each bankruptcy solution under a given hydrology for a unique claim set. Based on this table, the CEL method is the most stable method under the normal hydrology even though this method is not the most popular method (based on the popularity index). Given that stability (feasibility) is more important than popularity (social optimality) in conflict resolution (Madani, 2010) we can conclude that CEL is the best mechanism for water allocation in the bankruptcy study case. Nevertheless, the stability of this method is sensitive to the hydrological conditions and this method becomes the least stable allocation method under dry conditions. Under the dry conditions, the P rule is the most stable with lower demands. As the demands increase, the CEA method (the most popular method) becomes more stable. The change in the stable allocation rule with demand under the dry case shows that not only stability of allocation mechanism is sensitive to the hydrologic conditions, but also to the claim set. Future studies can focus on understanding the correlation

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between the claim set characteristics (magnitude of claims, heterogeneity of claims, etc.) and stability of allocation rules.

6 Conclusions

Using the Qezelozan-Sefidrood river conflict as a complex real-world river bankruptcy problem, this work formed the basis and set practical guidelines for developing allocation schemes for resolving trans-boundary water allocation conflicts based on bankruptcy methods. Although the suggested approach does not necessarily maximized the total welfare in the basin and might result in sub-optimal allocations from the economic standpoint, it can be used to develop practical solutions when side-payments are not feasible, parties are not highly cooperative (or not interested in implementing solutions based on conventional cooperative game theory solutions), and utility information is not available. Four bankruptcy optimization models were proposed based on four conventional bankruptcy rules, i.e. Proportional (P), Adjusted Proportional (AP), Constrained Equal Award (CEA), and Constrained Equal Loss (CEL), for trans-boundary water allocation with respect to its non-uniform spatial and temporal variability.

Acknowledging the difference in the notion of fairness and the possibility of rejection of suggested allocations by the beneficiaries, who find certain allocation rules unfair, there is need for evaluating the acceptability of different bankruptcy solutions. While popularity of each solution is a simple indicator of the potential acceptability of a solution, it was argued that in case of asymmetric powers, majority cannot necessary determine the feasible solution, especially when the powerful parties do not support the most popular solution. Therefore, a new stability index was formulated for evaluating the acceptability/stability of allocation solutions with respect to distribution of claims and dissatisfaction among the beneficiaries.

Evaluation of the stability of different bankruptcy allocation solutions for different water demand and hydrologic scenarios suggested that acceptability is sensitive to both

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water demand (claim) and water availability. This finding has a significant policy implication for trans-boundary water management, suggesting that inflexible water allocation agreements and treaties that have been developed based on stationary assumptions are not resilient, especially in face of the expected socio-economic and climatic changes.

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Table 1. Plurality index of different bankruptcy solutions for different claims and hydrologies.

Claim	Hydrology									
	Normal					Dry				
	P	AP	CEL	CEA	Winner	*P*	AP	CEL	CEA	Winner
Historical	0	0	1	6	CEA	0	0	1	6	CEA
Planne	0	0	1	6	CEA	0	1	1	5	CEA
Future	0	1	1	6	CEA	0	2	1	5	CEA

Table 2. Bankcruptcy index values of different bankcruptcy solutions for differnet claims and hydrologies.

Scenario	Bankruptcy Stability Index							
	Normal				Dry			
	P	AP	CEL	CEA	*P*	AP	CEL	CEA
Historical	0.11	0.10	0.07	0.15	0.90	1.00	1.33	1.27
Planne	0.31	0.31	0.21	0.43	1.11	1.01	1.68	0.77
Future	6.57	6.49	3.48	9.65	1.01	0.95	1.54	0.73

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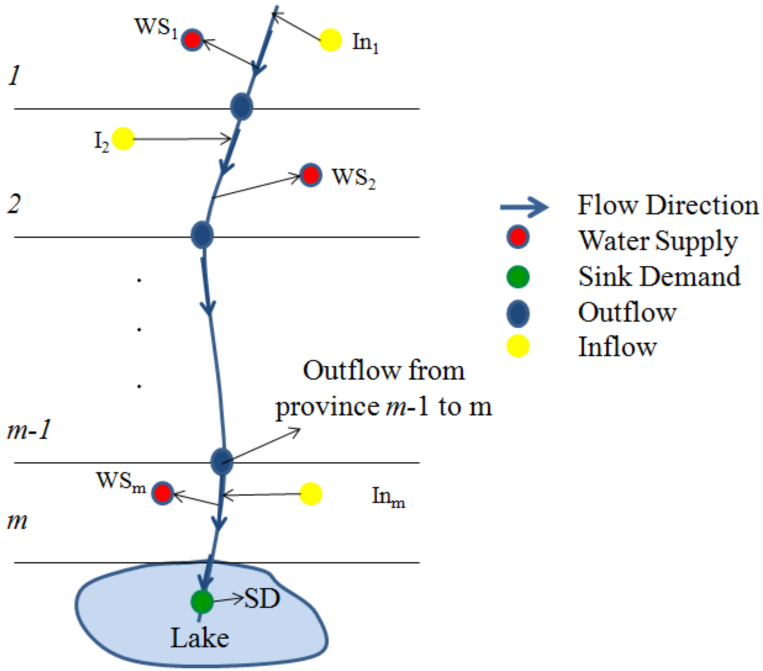

Fig. 1. Schematic map of a trans-boundary river basin.

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Fig. 2. Qezelozan-Sefidrood river basin and its eight riparian provinces.

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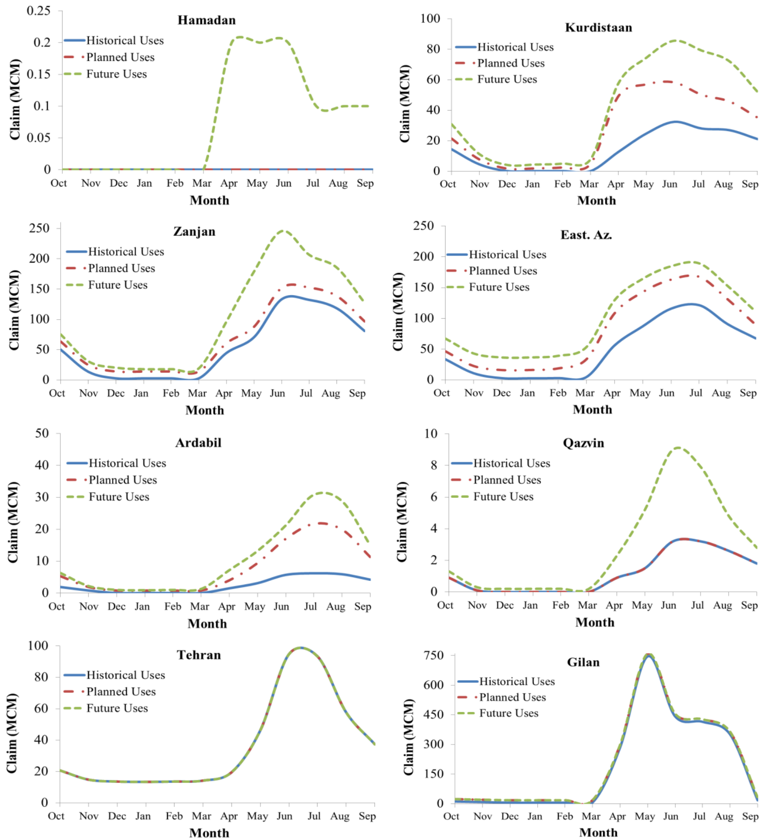

Fig. 3. Estimated monthly claims of the riparian provinces based on the three proposed claim calculation methods.

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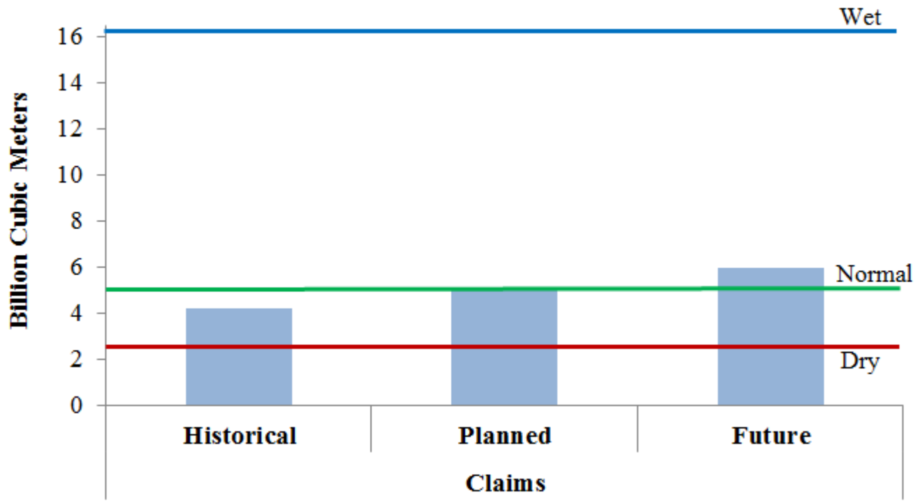

Fig. 4. Total annual claims (including Caspian Sea's water demand) based on three different claim estimation methods and total annual water yield under three different hydrologic scenarios.

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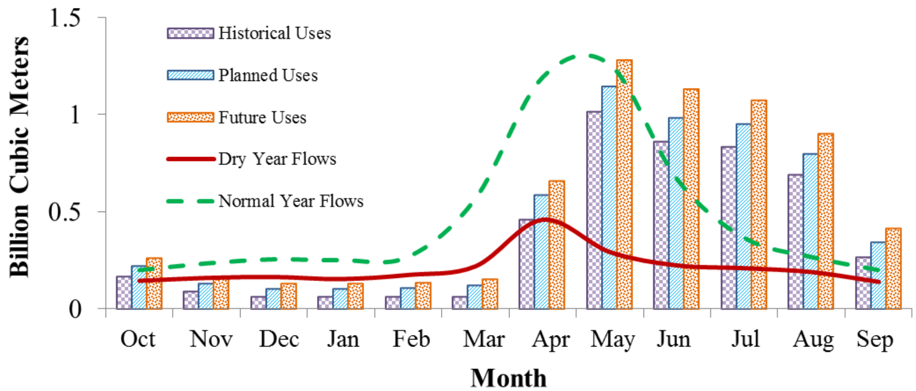

Fig. 5. Total monthly claims (including Caspian Sea's water demand) based on three different claim estimation methods and total annual water yield under normal and dry hydrologies.

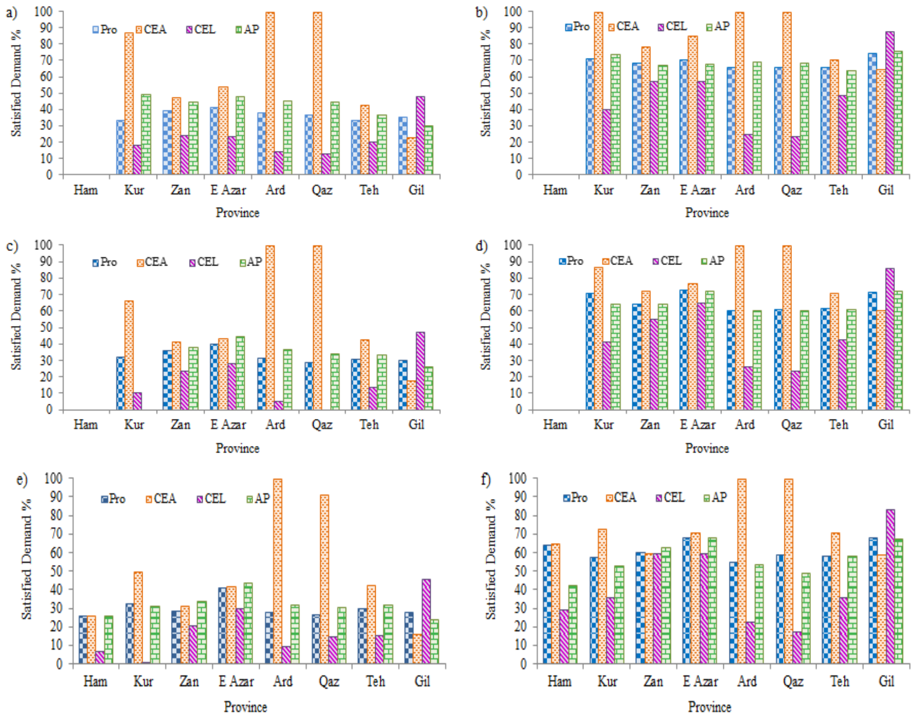

Fig. 6. Annual water allocations to riparian provinces based on different bankruptcy solution methods for different claims and hydrologies (**(a)**: historical claim in normal year, **(b)**: historical claim in dry year, **(c)**: planned claim in normal year, **(d)**: planned claim in dry year, **(e)**: future claim in normal year, and **(f)**: future claim in dry Year).

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